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A Rational Method of Surface Treatment Selections for Concrete Decks

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Thin polymer overlays (TPOs) enhance the safety of bridge decks by increasing skid resistance, but they also act as barriers to chloride ingress. TPOs are often applied to concrete bridge decks before they are opened to traffic and have a 10-to 15-year service life. It was hypothesized that delaying the application of the TPO and allowing some chlorides to penetrate the deck would not compromise the service life of the bridge deck and offset the application and repair costs. A program modeling chloride ingress was developed to predict the optimum time for TPO application to prevent chloride concentration from reaching threshold concentration and maximize the service life of the first TPO.

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A RATIONAL METHOD OF SURFACE TREATMENT SELECTIONS FOR CONCRETE DECKS

FINAL REPORT

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EXECUTIVE SUMMARY

The service life of bridge decks exposed to deicing- and anti-icing agents is limited by chloride-induced corrosion of the reinforcing steel. The chloride concentration at the level of steel reinforcement controls the service life of steel-reinforced concrete bridge decks in Minnesota as well as other anti-icing states.

Chloride ions reach the level of reinforcing steel through diffusion through pore spaces in the concrete. The diffusion is driven, in part, by a concentration gradient between the surface and any internal point, so when there is a concentration of chloride ions at or slightly below the surface, diffusion will occur more quickly as the chloride concentration tries to achieve equilibrium concentration throughout the thickness of the bridge deck. One way to slow down diffusion is to decrease the gradient by cutting off chlorides from the deck surface, and there are many methods and materials that can do this. Historically, the most common way to protect bridge decks in Minnesota was applying a low-slump concrete overlay to the deck surface. Low-slump overlays are not feasible or desirable in all instances, so another option for protecting a bridge deck from chloride ions is a thin polymer overlay (TPO). TPOs are desirable due to cost, thickness, longevity, and impermeability.

When TPOs are used on a bridge deck in Minnesota, the timing of their application has been the responsibility of each Minnesota Department of Transportation (MnDOT) district. The catalysts for application are new construction or available money. TPOs require renewal every 20-25 years, so once they are applied, the cost of reapplying them becomes fixed in the maintenance budget of that deck. This purpose of this project is to develop a model that allows the DOT to estimate how long the delay in TPO application can be so that its application is cost effective from a life cycle cost perspective yet preserves the service life of the bridge deck.

Background research for this project explored the primary reasons for bridge deck deterioration, why overlays are needed, and how departments of transportation across the United States have used TPOs. Standardized tests for measuring the diffusion of chloride ions in concrete and their relationships were summarized. Fick’s second law is commonly used to model the diffusion of chloride ions in concrete. The decrease of the diffusion coefficient is controlled by the concrete’s pore system, which refines over time so the diffusion coefficient decreases over time. This decrease in the diffusion coefficient is represented in service life modeling by the decay coefficient.

The project consisted of two steps. Step one started with collecting chloride profile data from existing and new bridge decks to determine if there was a ballpark diffusion coefficient that could be used for modeling the service life of Minnesota bridge decks, depending on when the deck was constructed. The second step was developing a model that could be used to predict the most cost-effective timing of TPO application on bridge decks.

Diffusion coefficient is the concrete characteristic that determines the rate at which chloride ions migrate to the level of the reinforcing steel. One premise of this project is that applying a TPO to a bridge deck before a certain concentration of chloride ions diffuses into the concrete, eliminates the

surface concentration of chlorides at the concrete surface and slows down the diffusion of chlorides. The first experiment undertaken was verifying that the diffusion of chlorides through a TPO was zero. Next, chloride profiles, surface concentrations, and diffusion coefficients in bridges built before 2006 were evaluated from core samples collected from existing bridge decks and bridge deck chloride profiles measured by MnDOT over the past 10 years. Another task consisted of collecting cylinder samples from new bridge decks to measure diffusion coefficients of modern MnDOT bridge deck concrete mixtures. The NTBuild 492 non-steady state chloride diffusion test was the standardized test used to evaluate the permeability of a TPO product and measure the diffusion coefficient in new concrete.

The primary conclusions drawn from step one are the following:

1. Diffusion of chlorides through a typical TPO product is zero
2. The apparent diffusion coefficients of in-service Minnesota bridge decks calculated from MnDOT-provided chloride profiles were assumed to be steady state diffusion coefficients representing concrete that has been in service for up to 95 years. The diffusion coefficients were split into two groups: one for monolith or unknown deck design and another for decks that had received low-slump overlays. The calculated diffusion coefficients showed a broad range as the core and chloride profiles were collected from bridge decks representing a broad range of specifications, regions, and construction practices.
3. When modeling service life or validating the chloride profile of an existing bridge deck in Minnesota, an average starting diffusion coefficient for a monolithic deck is 1.68 x 10^{-12} m^2/s. For decks with low-slump overlays, this average starting diffusion coefficient is 2.62 x 10^{-12} m^2/s. These diffusion coefficients are ballpark values if there is not a chloride profile or diffusion coefficient for an individual deck. These diffusion coefficients do not represent the diffusion coefficient of the concrete after more than 15 years in service rather than the 28-day diffusion coefficient.
4. The concrete cylinder samples from bridge decks constructed in 2016 fell into two categories. In one category, the concrete mixtures contained 100% Portland cement with a total cementitious content of 535 lbs/cy. In the other category, the total cementitious content ranged from 570-600 lbs/cy and class f fly ash replaced 30% of the total cementitious content. The water-to-cement ratio was 0.42 for all mixtures. The average 1-year diffusion coefficient of the 100% Portland cement mixtures was 12.3 x 10^{-12} m^2/s. The average 1-year diffusion coefficient for the 30% fly ash/70% Portland cement mixtures was 4.42 x 10^{-12} m^2/s. It is important to note the large difference between the average diffusion coefficients. Modeling the service life of a bridge deck with these diffusion coefficients, the deck with 30% fly ash replacement for Portland cement was three times that of the 100% Portland cement mixture.

In addition to these findings, chloride profiles were obtained for bridge decks that had been in service for a long time before they received a TPO to extend service life. In some cases, chloride profiles were obtained from the bridge decks before and after the TPO was applied and these profiles were compared. The following conclusions were drawn from this exercise:

1. 4-5 years is not enough time to observe significant chloride redistribution in concrete with a significant chloride load and with the diffusion coefficient of 1.5×10^{-12} m^2/s.
2. There may have been more obvious redistribution of chlorides near the surface, but the sample horizons were too broad to capture that redistribution.
3. The chloride concentration in the wear course, especially from 0-2 in. was close enough to the assumed surface chloride concentration that cutting off the surface chlorides did not reduce the gradient.

In another case, a TPO was placed on one lane of a bridge deck and a Methylmethacrylate flood seal was placed on the opposing lane at the same time. Chloride profiles suggest that the TPO significantly slowed chloride ingress compared to the Methylmethacrylate seal.

The second step involved writing a model to predict the chloride ion diffusion through concrete when a TPO is added at various times after the bridge deck is placed. The model is very similar to any concrete service life model, in that it uses the finite difference method to solve Fick's Second Law of chloride diffusion. The model allows boundary conditions to change at any time step, simulating when a TPO is added, when the TPO begins to deteriorate, and when the TPO must be replaced. The model also considers concrete cracking by modifying the diffusion coefficient with the Smeared Crack Model depending on average crack thickness and spacing. Although the model was developed to predict TPO timing, the MnDOT bridge office has already found that it is useful for predicting service life of bridge decks and timing of repairs and overlays to prolong service life.

The primary goal of the thin polymer overlay (TPO) model is to approximate chloride diffusion and chloride concentration at the level of the reinforcing steel in bridge decks. This is done so that chlorides may be allowed to accumulate within the concrete up to a certain concentration before the TPO is applied, delaying the initial investment in the TPO as well as subsequent maintenance and replacements. Once the TPO is applied, the existing chlorides in the deck will continue to diffuse and redistribute throughout the thickness of the deck but will do so without the diffusion-driving force of a concentration gradient.

In modeling, the TPO is accounted for by setting the surface chloride concentration to zero until a time at which the TPO is significantly cracked.

The TPO spreadsheet can do the following:

1. Help decision makers estimate the most economical timing for thin polymer overlay (TPO) application to bridge decks.
2. Predict rate of chloride ingress into cracked and uncracked concrete considering diffusion coefficient, decay coefficient, and pavement thickness that may vary over time due to mill and overlay procedures.
3. Plot chloride concentration over time at multiple levels below the deck surface.
4. Plot chloride concentration through the deck thickness at various deck ages.

CHAPTER 1: INTRODUCTION

The service life of bridge decks exposed to deicing- and anti-icing agents is limited by chloride-induced corrosion of the reinforcing steel. The chloride concentration at the level of steel reinforcement dominates the service-life modeling of steel reinforced concrete bridge decks in Minnesota as well as other anti-icing states.

The migration of chloride ions into concrete occurs mainly by diffusion. The primary driving force of chloride diffusion is the concentration gradient. When concrete is exposed to deicing salts, the chloride concentration at the surface builds up and becomes the driving force for the concentration gradient through the thickness of the concrete section.

In addition to limiting cracking, an effective way to extend the service life of a bridge deck is to extend the time it takes to accumulate chlorides at threshold concentration at the level of the reinforcing steel. This can be done by increasing the concrete cover over steel reinforcing and by limiting or eliminating the surface chloride concentration. Chloride inhibiting admixtures theoretically increase the chloride threshold concentration at the level of the reinforcing steel.

One way to alter the concentration of surface chlorides is to apply an overlay onto the bridge deck. This overlay will remove the source of chlorides from the original deck surface for as long as the overlay remains uncracked, adhered to the original deck surface, and, in the case of a concrete overlay, until the chlorides diffuse through the overlay thickness.

MnDOT evaluates polymer overlays against concrete overlays for life-cycle cost, speed of construction, longevity and impermeability. In either a concrete or polymer overlay application, there is some preparation of the surface that aims to remove surface or near-surface chlorides. Preparation for traditional concrete overlays includes uniform removal of deteriorated and near surface chloride-contaminated concrete before the concrete wearing course is applied. In contrast, concrete surfaces prepared for thin polymer overlays either receive a steel shotblast treatment or shallow concrete removal (grinding or scarifying) to leave a roughened and clean surface. Both preparations include localized removal and patching of deeper delaminations. Chlorides that remain in the concrete would continue to migrate farther in toward the steel. Once a polymer overlay is applied there would be no new chlorides (except at crack or spall locations) coming in, and chlorides already present would realize a reduction in gradient responsible for establishing the rate of further ingress.

Currently, MnDOT allows its districts to determine when to apply TPOs. The choice to use a TPO rather than a low-slump concrete overlay depends on the following:

- Box girder superstructures and major river crossings represent an elevated preservation risk and such bridges are selected as TPO candidates
- Newly constructed bridge decks with less than 3” concrete cover
- High cracking levels in existing decks or concrete overlays

- Availability of funding for existing deck preservation installations
- Concern for traffic safety as TPO increases bridge deck surface friction

1.1 PROBLEM STATEMENT

The time of application of thin polymer overlays is variable. Sometimes, thin polymer overlays are applied immediately after construction and sometimes they are applied months or years after construction. Occasionally, they are considered for bridge decks that have been in service for greater than 10 years or longer, which may have significant chloride concentrations at the level of top reinforcing steel. The purpose of this work is to develop a rational basis for determining the most cost-effective time(s) to apply thin polymer overlays to extend the service life of bridge decks.

The premise of this project is that a thin polymer overlay (TPO) should not immediately be applied to new bridge decks. Despite allowing some accumulation of chlorides in the concrete, a delayed TPO application will cut off the source of new chlorides at a time that deck service life will still be realized. Eliminating the surface chloride concentration slows the diffusion of chlorides through the concrete for a period (until the TPO significantly cracks or spalls) by decreasing the chloride concentration gradient. By decreasing the concentration gradient, the threshold concentration of chlorides at the level of the steel will take longer to reach. A TPO application as a deck protective wearing course requires a repetitive investment, with an expected life cycle between 7 and 15 years. As the TPO is not immediately needed, delaying its application defers the capital investment in a TPO and subsequent investment recurrence intervals while not sacrificing service life of the concrete deck.

Figure 1.1 shows chloride accumulation over time at multiple depths below the surface of a bridge deck (or any concrete member) for a constant surface concentration of chlorides over 45 years. A thin polymer overlay can dramatically reduce the rate of penetration of chloride ions into the surface of the concrete by providing a nearly impermeable barrier that effectively cuts off the source of chlorides. Figure 1.2 illustrates the effect of interrupting the ingress of chlorides into the concrete surface with a TPO. All other variables remaining the same, after 5 years of exposure to chloride ions, the application of a TPO is modeled as zero surface chloride concentration.

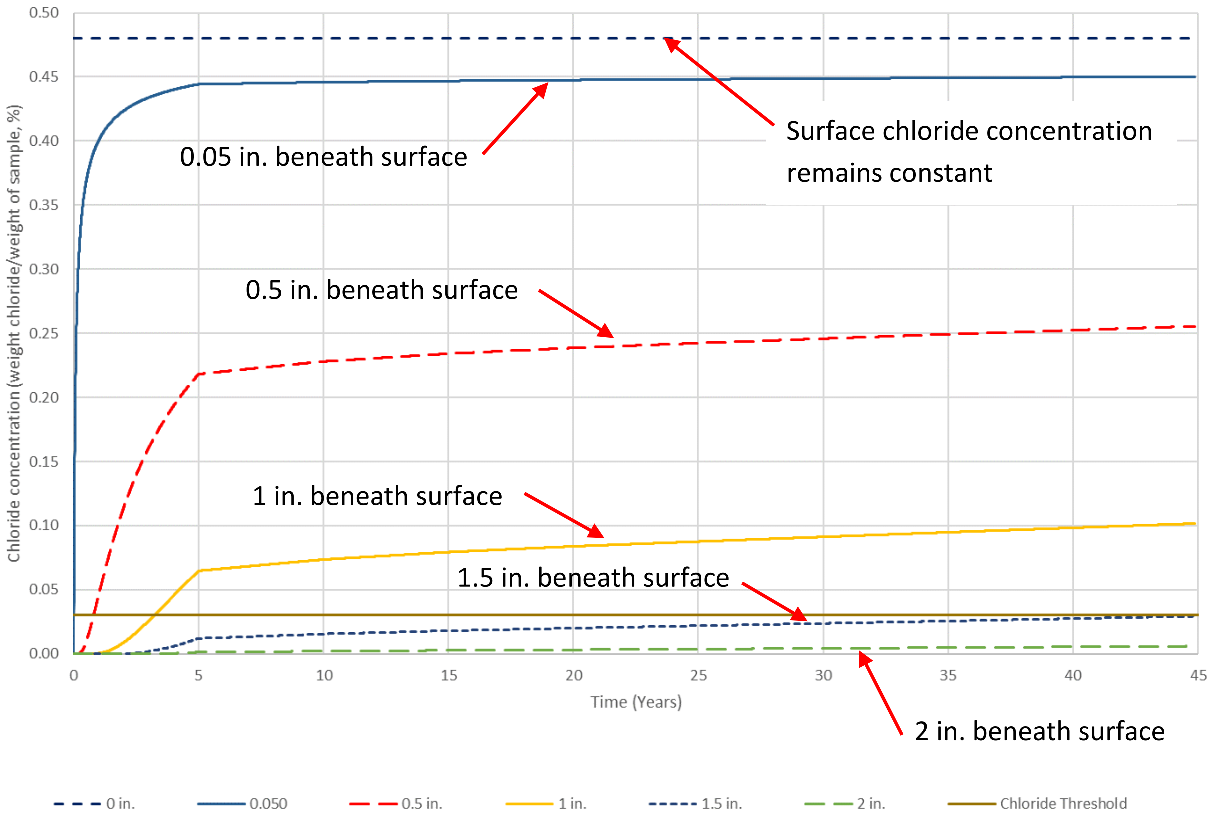


Figure 1.1 Concrete is exposed to a uniform chloride concentration for 45 years. The closer the concrete is to the surface, the more quickly it responds to the surface boundary condition.

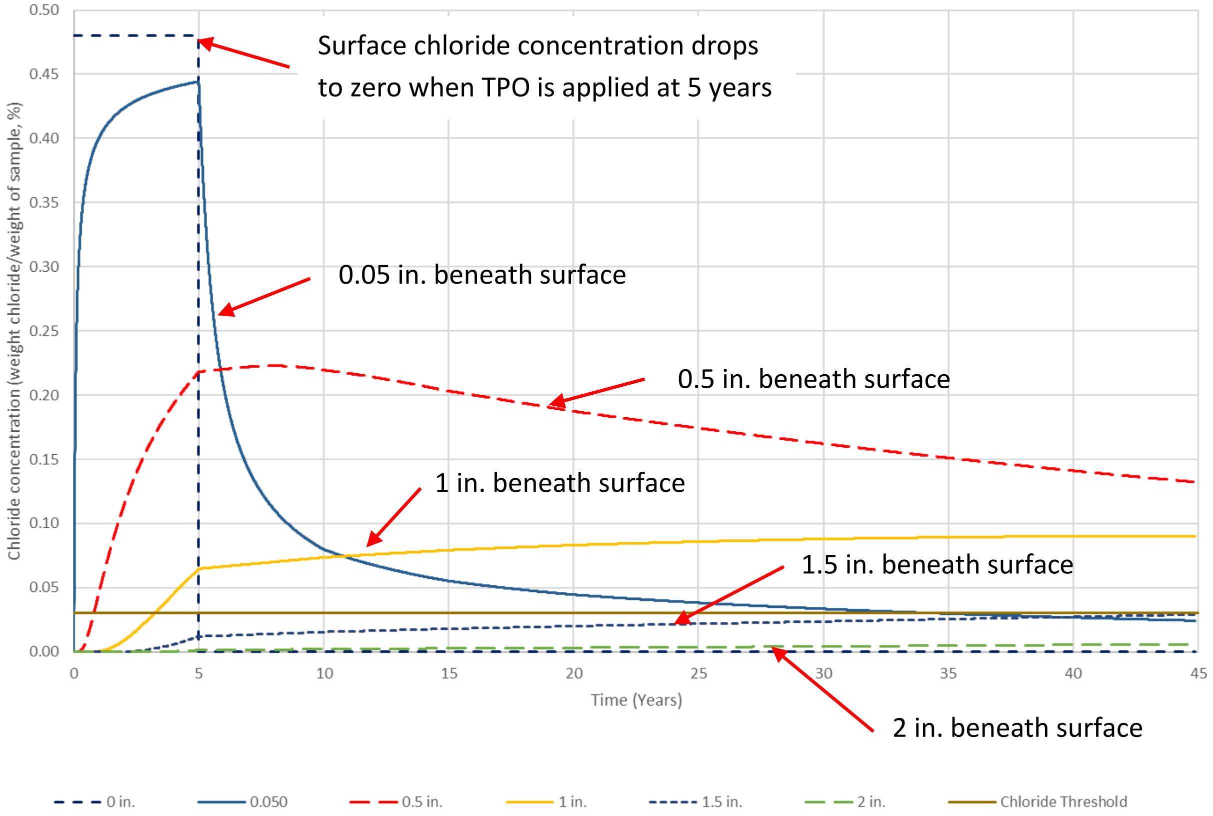


Figure 1.2 After exposure to deicing salts for 5 years, a thin polymer overlay is applied so that no additional chlorides can migrate into the concrete, after some time the chlorides already present migrate farther into the concrete. The closer the concrete is to the surface, the more quickly it responds to the surface boundary condition.

1.2 PROJECT GOALS

The final product of this project is a spreadsheet model that allows MNDOT to estimate the best time for thin polymer overlay (TPO) application on bridge decks. The basis of the model will be chloride diffusion using Fick's Second Law and is like other concrete service life software, but with very specific inputs regarding bridge decks, overlays, and chloride diffusion. The most important model inputs are the concrete's diffusion coefficient and surface chloride concentration. These two variables control the speed at which the threshold chloride concentration is reached at the level of the reinforcing steel. Chloride profiles, the chloride concentration at specific depths below the surface, are used to determine diffusion coefficient and surface chloride concentration. Chloride profiles can be measured on in-situ bridge decks or they can be assessed on concrete cylinders through ASTM C1556 *Standard Test Method Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion* and NTBuild 492, the Nord Test method for determining the non-steady state diffusion coefficient of concrete. Therefore, much of this document will be dedicated to the evaluation of the diffusion coefficient and surface chloride concentration of new and existing concrete used on MNDOT bridge decks.

1.3 PROJECT OUTLINE

Chapter 2 presents a literature review of thin polymer overlays. The scope of the literature review includes a general discussion of bridge deck service life, the types of thin polymer overlays and best practices for their application, their overall performance, and the experiences of various state and provincial highway agencies in their performance. Common test methods used to determine the rate or propensity of chloride ingress into concrete are reviewed and the correlations between tests discussed.

Chapter 3 presents a short experiment that verifies the diffusion coefficient of uncracked TPOs is zero using NTBuild 492.

The next three chapters quantify the diffusion coefficient and chloride concentration of existing and new bridge deck concrete throughout Minnesota. Chapter 4 explores the diffusion coefficients of existing Minnesota bridge decks from chloride profiles provided by MnDOT. The chloride profiles came from all MnDOT districts and were taken from bridge decks that had been in service for more than 10 years. Many of the decks sampled had been rehabilitated after 1979. Some of the decks had received the standard low-slump overlay while others were monolithic without overlay.

Diffusion coefficients of new MnDOT bridges were assessed and are discussed in Chapter 5. NTBuild 492 was used to assess the diffusion coefficient of concrete cylinders obtained from bridge deck pores occurring in 2016. The samples are primarily from the Metro District but also include some from greater Minnesota districts.

Chapter 6 explores the diffusion coefficient of in-situ concrete bridge decks that have received a TPO. Chloride profiles were obtained from bridges in Carlton and Hennepin counties where TPOs had been applied to bridge decks that had been service for 27 and 17 years, respectively. A third set of chloride profiles was collected from a Hennepin County bridge deck in which half of the deck received a TPO, while the other half received a Methylmethacrylate flood seal. The bridge had been in service for 21 years before the surface was treated.

Chapter 7 is a user’s manual for the model. It documents the model, its inputs, calculations, and outputs.

Chapter 8 summarizes the use of diffusion coefficient in the model and recommends future work.

Chapter 9 lists the references.

Appendix A presents the diffusion coefficients determined from existing bridge decks. Appendix B presents the chloride profile data and diffusion coefficient information from a series of Central Minnesota Bridge decks. Appendix C consists of worked examples that model users can use to learn, calibrate and/or reset the model. Appendix D contains case studies, developed by MnDOT staff with the model, of chloride ingress predicted by the model compared to measured chlorides in bridge decks.

CHAPTER 2: LITERATURE REVIEW

The scope of the literature review includes a general discussion of bridge deck service life, the types of thin polymer overlays and best practices for their application, their overall performance, and the experiences of various state- and provincial highway agencies in their performance. Common test methods used to determine the rate or propensity of chloride ingress into concrete are reviewed and the correlations between tests discussed.

2.1 BASELINE DATA FOR CONCRETE BRIDGE DECK SERVICE LIFE

Nelson (2014) analyzed National Bridge Inventory condition code data for 2601 Minnesota concrete bridge decks dating back to 1983 to determine how long a bridge remains at a given condition code state and what factors contribute to deterioration. She sorted the data in accordance with three major policy changes pertaining to bridge deck protection: before 1975 (less than 3 in. of cover to the top mat of steel), 1975-1989 (3 in. of cover), and 1990-2014 (use of epoxy for all bars in deck). She found that bridges that received a deck overlay at least three years after initial construction deteriorated faster than those that still had their original deck. However, she noted that only bridge decks in poor condition would have received overlays, and that the chlorides present were not removed before the overlay was installed. She found that the use of epoxy-coated bars throughout the deck is effective in prolonging service life, as is the use of at least 3 in. of concrete cover over the top mat of bars. While this study is not directly relevant to the present work, it does provide a database of MnDOT's concrete bridge decks dating back to 1983 – an excellent basis for evaluating the performance of future or more recent thin-polymer overlay applications.

Pincheira (2009) selected six bridge decks in Wisconsin to develop a protocol for the performance of concrete deck- and crack sealers. The bridge decks ranged in age from 3 years to 28 years. Segments of two of the bridge decks were sealed with four different sealants that had been previously demonstrated to perform well, with an additional section of each bridges left unsealed as a control. Two concrete powder samples were taken in the wheel paths of each segment for acid-soluble chloride-ion analysis so that the performance of the sealers could be compared over time. Similar samples from two bridge decks that had been sealed shortly after construction indicated that early sealing was effective in reducing chloride-ion penetration into these decks. Pincheira stated the intent of monitoring the newly sealed bridge decks over at least five years. However, Dr. Pincheira had not been able to collect additional data subsequent to publication of his report (Pincheira, personal communication, 17 April 2017).

2.2 DOT EXPERIENCES WITH THIN POLYMER OVERLAYS

2.2.1 Application and Service Life

Krauss, Lawler, and Steiner (2009) developed guidelines for the selection of an appropriate repair method based on such factors as deck condition, traffic constraints, dead load limitations, overhead limitations, remaining service life, and exposure conditions. These guidelines were based on the results of a survey they conducted among state and provincial highway agencies. They found that use of polymer overlays ranging in thickness between 0.13 and 6 in. was increasing overall among the 44 highway agencies responding to their survey.

Krauss, Lawler, and Steiner (2009) observed that decks which are exposed to chlorides but have not yet accumulated much chloride are good candidates for sealers or membranes, while those with high chloride concentrations near the surface but little near the steel are good candidates for surface milling to remove the chlorides before overlaying. They state, “The service life of decks with high levels of chloride close to the level of reinforcing can be extended with overlays, but long-term performance may be reduced since corrosion initiation may be imminent.” Specifically, if the chloride concentration is relatively high just above the steel such that corrosion can be expected to initiate within the next 10 years, they recommend that the chloride-contaminated concrete be removed before placing the overlay.

Based on responses from 23 highway agencies, Krauss, Lawler, and Steiner (2009) determined that the advantages of using thin polymer overlays include rapid installation and reopening to traffic, ease of installation, light weight or low dead load, good waterproofing and low chloride ingress, durability, and skid resistance. Disadvantages included cost, installation problems (due to inadequate surface preparation or binder preparation), and poor durability under high traffic loads and in wheel paths. They found that polymer overlays were most commonly used in decks with cracking but otherwise in good condition without significant corrosion.

Fowler and Whitney (2011) conducted a literature review and surveyed state- and provincial highway agencies to develop a synthesis of then-current practice regarding thin polymer overlays. They found that at least 2400 thin polymer overlays had been installed in the United States and Canada. Nearly all of the responding agencies used epoxy resins; only California used mainly polyester-styrene in premixed overlays. The factors influencing overlay performance are substrate soundness, surface preparation, compatibility between overlay and substrate, aggregates, overlay thickness, bridge girder flexibility, environment, and constructability and workmanship. They concluded that thin polymer overlays are “particularly appropriate in high-traffic areas in which lane closures must be minimized and for structures that cannot accommodate significant increases in dead load.” They estimated the service life of properly installed thin polymer overlays at 20 to 25 years.

Tabatabai et al (2016) contacted selected state highway officials who had responded to Fowler and Whitney’s (2011) survey. The earlier survey was conducted in 2008; Tabatabai et al. conducted their follow-up interviews in 2013. They found that although Missouri had originally reported over 300 thin polymer overlay applications, past failures had resulted in more stringent criteria for their use. Specifically, deck delamination and damage must be less than 5% of the area. Since the adoption of the new criteria, very few thin polymer overlays had been applied. Illinois had applied 24 thin polymer overlays at the time of the original survey; in the follow-up interview they reported an additional 10 overlays. Illinois requires shot blasting of the deck; pull-out tests must indicate strengths greater than

175 psi and there must be no visible moisture on the surface before the overlay is installed. They did not report any problems with UV resistance, skid resistance, or overall failures of the overlays.

CTC & Associates (2012) surveyed 13 state departments of transportation to determine their practices related to ultra-thin polymer overlays. Their findings are summarized in Table 2.1. States use overlays for a variety of purposes. However, overlays are not effective in repairing large cracks or when large areas of the deck have delaminated; the condition of a deck must not be too poor to receive an overlay.

Frosch, Kreger, and Strandquist (2013) evaluated the use of thin polymer overlays, along with latex-modified concrete overlays and waterproofing membranes with asphalt overlays on behalf of the Indiana DOT. They reported that INDOT has been using thin polymer overlays since 1986, generally on relatively new bridge decks and in locations where lane closures must be limited due to heavy traffic. Comparing the expected service life of thin polymer overlays with that of several other types of bridge deck rehabilitation based on the data from several previous studies, they found that the 20 to 25-year service life of a thin polymer overlay is comparable to that of a membrane with an asphalt overlay, and that both were shorter than that of a latex-modified concrete overlay or a low-slump concrete overlay. They recommended thin polymer overlays “where quick installations are required and where a thin protective system is needed,” and on new bridge decks for preventive purposes. They consider the main advantages of thin polymer overlays to be light weight, thinness, minimal lane closure time, ease of installation, allowance for easy drainage of deck, flexibility, and ability to bridge cracks. The main disadvantages were identified as the relatively short service life, lowest durability, and reduction of skid resistance with loss of aggregate.

Table 2.1 State Practices Regarding Ultra-Thin Polymer Overlays. Source of data: CTC & Associates (2012)

State	Age at First Application	Purpose of Overlay	Comments
California	7 to 15 years	Restore skid resistance	
Illinois	20 years New decks	As sealer or when contractor has made an error	If cost of patching before placement exceeds 50% of cost of new deck, IDOT replaces the deck.
Kansas	When cracks reach 1 to 2 mm (0.039 to 0.079 in.) width		Deck must have less than 2% delaminations
Michigan	1 to 2 years	Preventive, not a "fix"	Must have a rating of 7 or better
Missouri			Must have a rating of 5 or 6 (15% delamination)
New York	15 to 20 years New decks	Restore friction Protection against salt and oxygen	In pretty good shape but beginning to show wear
Ohio		Restore friction Short-term fix pending deck replacement	ODOT prefers 1.5-in. silica-fume concrete overlay or 1.5-1.75-in. dense concrete overlay.
Oregon			Cracks beginning to show
Utah	New decks	Preventive measure	
Virginia	20 years New decks	In case of construction defects	Do not use if deck must be patched due to corrosion damage.
Washington	30 to 40 years	Experimental, or to prevent corrosion	WSDOT stopped using them because they don't last under studded tires.
Wisconsin	10 to 15 years		
Wyoming		Restore friction	Rating of 2 or 3 out of 5; beginning to show cracks

2.2.3 Best Practices

Fowler and Whitney (2011) determined from their surveys of state- and provincial highway agencies and of contractors experienced in the installation of thin polymer overlays that the main causes of failure included:

- Deck condition too poor to support overlay
- Repaired areas not sufficiently dry and/or not roughened
- Inadequate surface preparation
- Cool, damp weather during installation; rain; excessively high or low temperatures
- Deck too damp at time of installation. The contractor survey found that surface preparation by shot blasting provides a useful test: clogging of the shot in the shot blaster indicates that the deck is too damp.
- Construction problems
- Inadequate quality control
- Use of snow chains.

The most important factors for successful application of thin polymer overlays were identified by Fowler and Whitney (2011) as:

- Sound, dry substrate that requires quality repair procedures
- Adequate preparation to provide a clean, textured dry surface
- Environment including dry, warm weather
- Experienced application and good workmanship to ensure proper application of materials
- Involvement of resin supplier or manufacturer to assist contractor in proper handling, mixing, and application of resins
- Thermal compatibility that requires low-modulus resins and compatibility of resins and repair materials.

2.2.4 Thin Polymer Overlays and Subsequent Chloride-Ion Migration

Guthrie and Birdsall (2008) studied the timing of surface treatments to determine the latest application that would still prevent chlorides from accumulating in sufficient concentration to induce corrosion. They collected chloride concentration data from 12 bridge decks in the Interstate 215 corridor in Salt Lake City, UT. These bridge decks were between 16 and 21 years old; six of them had been constructed using stay-in-place metal forms. Samples were extracted in approximately 1-in. lifts and analyzed for water-soluble chloride concentration in accordance with ASTM C1218 to obtain chloride concentration profiles. Assuming a threshold chloride concentration of 2.0 lb/yd^3 of concrete, they used numerical modeling to determine a chloride loading function and a diffusion coefficient for each deck.

Using the NIST computer model, Guthrie and Birdsall (2008) simulated a series of chloride-ion ingress cases assuming cover thicknesses of 2.0, 2.5, and 3.0 in. and initial surface treatment at ages from 1 to 15 years, assuming that from the date treatment was applied, no additional chlorides would enter the concrete: “After the upper boundary condition was closed, no further chloride ion ingress was permitted, and the program then simulated the redistribution of chlorides already in the deck…” The simulation was continued to an age of 30 years for the bridge deck. The assumption of no further chloride ion ingress after the first thin polymer overlay is applied entails the assumption that the overlay is maintained or replaced as needed. Once the thin polymer overlay is applied, the chloride ions already present continue to migrate further into the concrete. The first application should occur when the chloride ion concentration at the level of the steel is still below the threshold. As chlorides continue to diffuse into the concrete, the chloride concentration at the level of the steel will increase and may reach the threshold concentration, but will decrease eventually. “For this reason, the chloride concentration at the level of the steel and the chloride concentration gradient in the concrete cover should both be considered by bridge engineers and managers responsible for programming surface treatment placements.”

Based on their analytical results, Guthrie and Birdsall (2008) determined a recommended timing of initial surface treatment “… by locating the year of surface treatment application nearest, but still below, the threshold value of 2 lb of chloride per cubic yard of concrete. This selection ensured that the bridge deck would never experience corrosion *as long as the surface treatment was maintained or replaced throughout the remainder of the deck service life* [emphasis added].” They found that for concrete mixture proportions and road salting practices typical of Utah, a bridge deck with a 2.0 -in. cover without a stay-in-place metal form should receive its first surface treatment application at the age of 5 years. Each additional 0.5 in. depth of cover beyond 2.0 in. allows an additional 5 years for decks without stay-in-place metal forms before a surface treatment must be applied. They emphasize, “The individual surface treatment applications proposed in this research are suggestions for the initial application only. Surface treatments may only last for a certain number of years, so repeated applications may be necessary to ensure that chlorides do not eventually enter the concrete deck.”

Young, Durham, and Bindel (2011) evaluated the performance of two thin bonded epoxy overlays on two concrete bridge decks in Colorado for mean texture depth, surface friction, bond strength, resistance to chloride ion intrusion, traffic safety, and installation cost. The primary focus of their study was traffic safety, as the overlays selected were designed to improve skid resistance, and the study examined crash data from before and after the installation of the overlays. One bridge was built in 2002, the other in 2003. The overlays were installed in October 2009 and May 2010.

The chloride contents of the bridge deck concretes were determined at 0.25 in., 0.75 in., and 1.25 in. below the bridge deck surface before and 18 months after installation of the overlays. Figure 2.1 shows the chloride profiles. The chloride contents of the decks before installation were “extremely high,” approximately 8000 ppm in the top 0.25 in. before the overlays were installed. As can be seen in Figure 2.1, 18 months after the overlays were installed both the chloride concentrations and the concentration gradients were dramatically reduced. Young, Durham, and Bindel (2011) noted, “A reduction in the chloride content was observed from cores taken from the bridge decks 18 months after the overlays were installed. It is hypothesized that this reduction is due to time between tests and differences in test depths.” While the preparation of the surface to receive the overlay may have removed a small amount of the surface concrete, it is likely that the surface depths before and after installation of the overlays represent essentially the same concrete. The data in Figure 2.1 show how interruption of a chloride source reduces the concentration gradient, the driving force of chloride diffusion, and how chlorides redistribute within a bridge deck without a chloride source.

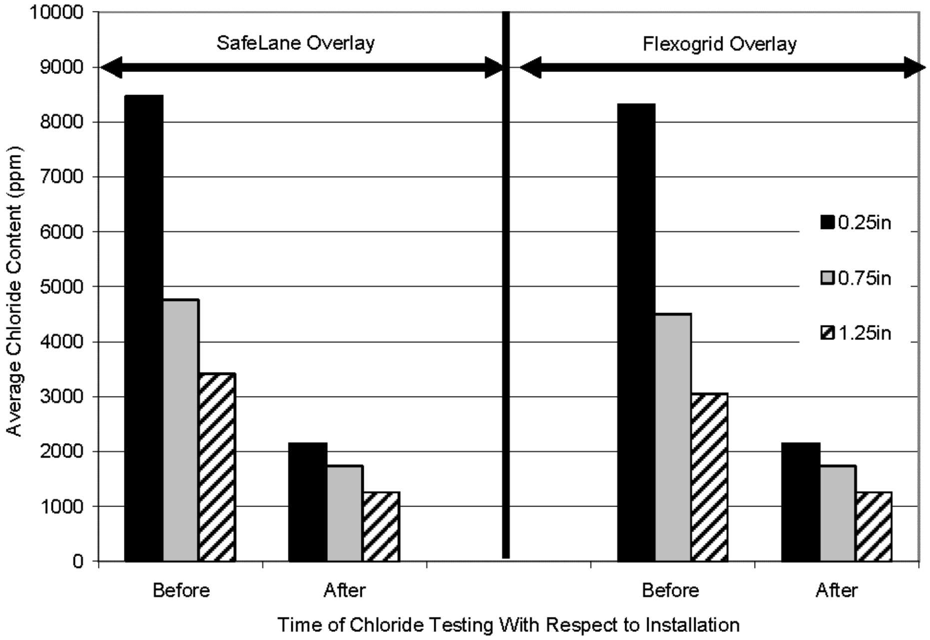


Figure 2.1 Chloride ion concentrations taken from 2-inch-diameter cores at depths of 0.25 in., 0.75 in., and 1.25 in. from the surface in two bridge decks before and 18 months after installation of a thin-bonded epoxy overlay. Both the concentrations and the gradients have been dramatically reduced by the overlay. CDOT uses magnesium chloride as a deicer on its bridge decks. Source: Young, Durham, and Bindel (2011)

Tabatabai et al. (2016) tested nine different thin polymer overlays using accelerated corrosion; freeze-thaw cycling; cycles of heat, ultraviolet light, and rain; and wear due to tires and snow plow blades. They exposed some of their specimens to chloride contamination before applying the overlays to simulate the use of overlays for repair or rehabilitation. The chloride exposure consisted of ponding with a 6% NaCl solution along with an electrical potential of 2 volts between the top and bottom bars of their specimens for periods of 1 and 2 weeks. Each week consisted of 4 days of ponding followed by 3 days of dry conditions, with the electrical potential maintained throughout. They concluded, “The addition of polymer overlays does not significantly reduce corrosion mass loss in bridge decks with moderate or high levels of chloride contamination. Therefore, the placement of a thin polymer overlay on a chloride contaminated bridge deck undergoing active corrosion of the embedded steel cannot be considered to be a corrosion mitigation strategy.”

Tabatabai et al. (2016) concluded, “The addition of polymer overlays does not significantly reduce corrosion mass loss in bridge decks with moderate or high levels of chloride contamination. Therefore, the placement of a thin polymer overlay on a chloride contaminated bridge deck undergoing active corrosion of the embedded steel cannot be considered to be a corrosion mitigation strategy … [Overlay application] may still be taken for other reasons such as improving friction or providing a smooth riding surface over a limited time period. However, the overlay must be installed on sound concrete under all circumstances, and it must be realized that the overlay will eventually fail due to corrosion of the underlying reinforcement, if not for other factors."

Another conclusion from Tabatabai et al. stated, "If the purpose for the installation of the thin polymer overlay is to protect an uncontaminated deck against corrosion, a more cost-effective approach may be to apply penetrating sealer instead shortly after construction and repeating the sealer application on a one- or two-year cycles thereafter." This conclusion has been debated within the DOT community and there remains disagreement. Certainly, many DOT's see value in placing more robust polymer overlays applied at longer intervals rather than frequent applications of penetrating sealants. Repeat applications of penetrating sealants come at a cost of more frequent traffic interruptions and higher use of labor.

2.3 CHLORIDE-ION MIGRATION IN CONCRETE

Stanish, Hooton, and Thomas (1997) observed that the most familiar mechanism of chloride-ion transport in concrete is diffusion, the movement of chloride ions under a concentration gradient from areas of high concentration to areas of lower concentration. For this to occur, there must be a continuous liquid phase in addition to a concentration gradient. A second mechanism of chloride migration in concrete is by absorption (capillary flow), which is driven by moisture gradients. A third mechanism of chloride migration in concrete is by permeation, which is migration under an applied hydraulic pressure head. Of these three, the primary mechanism of chloride migration is diffusion.

Stanish, Hooton, and Thomas (1997) note that chloride ions do not diffuse through a homogeneous solution, but through a porous matrix with both solid and liquid components. Because diffusion through the solid components is negligible, the rate of diffusion is controlled by the coefficient of diffusion through the pore solution and by the physical characteristics of the capillary pore structure. For this reason, the effective coefficient of diffusion includes both pore solution and capillary structure characteristics.

Sandberg, Tang, and Andersen (1998) partially submerged reinforced concrete slabs in seawater off the west coast of Sweden and analyzed the total chloride contents at various exposure times at elevations representing the submerged-, splash-, and atmospheric exposure zones. They did this to provide data for the calibration of mathematical models of chloride-ion penetration into concrete. The concretes had water-cementitious materials ratios ranging from 0.25 to 0.50 and contained up to 10% silica fume and up to 20% fly ash. High-performance concrete with water-cementitious materials ratios of 0.25 to 0.30 and 5 to 10% silica fume had an effective chloride diffusivity of 2×10^{-13} to 4×10^{-13} m^2/s after 5 years. A typical Swedish bridge concrete with 0.40 water-cement ratio and no supplementary cementitious materials could be expected to have an effective diffusion coefficient of 9×10^{-13} to 14×10^{-13} m^2/s. (With diffusion coefficients, lower is better.) They found that the calculated effective diffusion coefficient, assuming linear chloride binding and constant diffusivity, decreases linearly with time.

2.3.1 Modeling Diffusion Coefficient

Fick's second law is commonly used to model the diffusion of chloride ions into concrete as well as to fit chloride profile data. The chloride concentration, C_x, at a depth x is expressed in Equation 2.1.

$$C_x = C_0(1 - \operatorname{erf}\left[\frac{x}{2\sqrt{D_c * t}}\right]) \qquad \text{[Equation 2.1]}$$

where C_0 = near-surface chloride concentration

D_c = coefficient of diffusion

t = time

While this equation fits chloride-profile data well mathematically, it is a simplification of a more generalized model of diffusion. It is based on three assumptions (Pettersson, 1994):

1. The material in which diffusion takes place is permeable and homogeneous.
2. The diffusion properties of the material do not change with time or with concentration of the diffusant.
3. There is no chemical reaction or physical binding between the diffusant and the material.

Pettersson (1994) points out that in the case of chloride ions diffusing through concrete, all three assumptions are violated:

1. Concrete is permeable but not homogeneous. Interconnected pores, cracks, microcracks, and aggregate particles all affect the ability of chloride ions to migrate into the concrete.
2. The diffusion properties of concrete change as hydration proceeds. They may also be affected by chloride ion concentration.
3. The hydration products of the aluminates in the cement and/or supplementary cementitious materials (particularly slag cement) bind chloride ions, preventing their further migration.

2.3.2 Service Life Limit State

In discussing the mathematical models used to predict the service life of concrete elements in saline environments, ACI Committee 365 (2000) points out that the limit state modeled is the service life of reinforcing steel. A commonly used and publicly available concrete service life model is Life-365 (no relation to the ACI committee). The Life-365 model assumes an initiation period during which no corrosion takes place. Corrosion is initiated when a sufficient concentration, known as the *threshold concentration*, of chloride ions accumulates at the steel surface and/or when carbonation reduces the pH of the concrete at the steel surface.

Once corrosion initiates, it continues at a constant rate through the propagation period until the concrete cracks due to pressures exerted by the expansion of the oxides formed. Normally the initiation period is considerably longer than the propagation period. For this reason, the remaining service life is usually taken to be the time for the chloride-ion concentration at the steel surface to reach the threshold concentration. Krauss, Lawler, and Steiner (2009) noted, “The generally accepted acid-soluble chloride concentration threshold for 6-bag mix concrete is 0.03% by weight of concrete or 0.2% by weight of cement. The water-soluble threshold may not be 0.03% by weight of concrete, but is commonly about 75 percent of that, or 0.023% by weight of concrete.”

Further comparisons have been made by Wiss, Janney, Elstner Associates, Inc. (WJE) on corrosion initiation concentration of epoxy coated reinforcement and uncoated reinforcement. In particular, “an estimate of the distribution for epoxy bar threshold concentration has been developed and is described by a normal distribution with mean and standard deviation of 1.15 and 0.35 percent by weight of cement, respectively.”

2.3.3 Service Life Modelling Considerations

Mangat and Molloy (1994) observed that concrete diffusion coefficients decrease with time. Therefore, using a diffusion coefficient obtained for relatively young concrete without accounting for this decrease will result in overestimation of chloride concentrations at depth. They developed a method for predicting chloride ingress based on the chloride concentration at a known depth at a given time – data that would be obtained during routine inspection of a structure exposed to a chloride environment.

Bridge decks are subjected to seasonal rain, which washes some of the chlorides out of the top surface. Paulsson-Tralla and Silfwerbrand (2002) examined the differences in chloride concentration profiles taken from a bridge in Sweden between the end of one deicing season and the beginning of the next. They found that washing of the chloride ions from the surface affected the total chloride concentration to a depth of at least 10 mm (0.39 in.), “which roughly corresponds to the convective depth of concrete subjected to cyclic wetting and drying.” If this phenomenon is not considered in analyzing the chloride profile data, the apparent diffusion coefficient will be underestimated because the actual chloride exposure is harsher than assumed. They found that a slightly higher chloride concentration than measured in the outer 2 mm (0.079 in.) should be used in the numerical model to improve its accuracy.

Paulsson-Tralla and Silfwerbrand (2002) modeled the chloride concentration at the concrete surface using several distinct functions to see which would give the best fit to the actual concentration profiles found on a bridge in Sweden. Two of these functions considered the washing out of the chlorides during the late spring, summer, and early autumn; one modeled the application of chlorides during the late autumn through early spring with no application the rest of the year, but no loss due to washing out. In the latter case “The chloride ions present in the concrete simply redistribute themselves during this period, and the [surface concentration] is lowered by the inward transport of chloride ions.” The surface concentration was increased again during the deicing season. All of these models were compared to a constant chloride ion concentration at the surface. They found that the models that included washing out predicted a service life that was 30% longer than the others. Models that did not include washing out of the chlorides predicted little difference in service life between intermittent and constant application of chlorides.

Paulsson-Tralla and Silfwerbrand (2002) modeled a potential change in deicing practices from application of NaCl to use of 2-mm (0.079-in.) crushed aggregate. In the model, they assumed no washing out of chlorides from the surface. They found clear benefits to cutting off the supply of NaCl, but these benefits decreased after 40 years and had only minimal effect after 60 years.

2.3.4 Considerations for Diffusion Coefficient in Cracked Concrete

Boulfiza et al. (2003) point out that diffusion is the dominant transport mechanism of chloride ions in saturated, uncracked concrete. However, in unsaturated and/or cracked concrete, advection (movement of chlorides by flow of fluid) becomes the dominant mechanism, particularly when there are cycles of wetting and drying. They developed a numerical model of chloride ion migration that considers the effects of drying and cracking.

Garces Rodriguez and Hooton (2003) induced parallel-walled cracks ranging in width from 80 to 680 µm (0.0031 to 0.027 in.) in concrete and used a 40-day bulk diffusion test to measure chloride ion diffusion. While cracking significantly increased the diffusivity, crack width had no effect within the range of crack widths studied. They determined that the cracks acted as free surfaces from which the chloride ions diffused into the concrete. In comparing concretes with w/cm of 0.40, the concrete with 25% slag cement had lower diffusion coefficients than the portland cement concrete whether cracked or not.

Djerbi et al. (2008) studied the effects of cracking on the diffusion of chloride ions in ordinary and high-performance concrete with and without silica fume; none of the mixtures contained slag cement. They found that the diffusion coefficient for all three types of concrete increased linearly with crack width; for crack widths above about 80 µm (0.0031 in.), the diffusion equaled that in free solution independent of the properties of the concrete. This is consistent with the findings of Garces Rodriguez and Hooton, who examined cracks wider than 80 µm (0.0031 in.).

Paulsson-Tralla and Silfwerbrand (2002) observe, “The net effect of cracks … on the service life is hard to quantify, but the chloride profiles obtained from cracked concrete overlays clearly indicate that the overall ingress rate increases considerably due to cracks. The main parameter seemed to be the depth of the crack. Shallow cracks (depths less than 30 mm [1.2 in.]) did not affect the service life of bridge decks with 80 to 100 mm [3.1 to 3.9 in.] overlays. Crack depths larger than 50 mm [2 in.], however, were estimated to decrease the service life from 30 to 40% of the uncracked bridge deck’s service life.”

Otieno, Alexander, and Beushausen (2010) measured corrosion rates in concrete beams using several different non-destructive methods. For a given crack width, both water-cementitious materials ratio and concrete composition affected the rate of corrosion; the slag-cement concrete with 0.55 *w/cm* had a lower corrosion rate than the portland-cement concrete with 0.40 *w/cm*. The portland-cement concretes were also more sensitive to the presence of cracks. They concluded that it is not possible to determine a single crack width above which the crack becomes significant to corrosion, as the binder type and *w/cm* also play a role.

Lu et al. (2012) used 3-D image-based modeling to examine chloride ion migration and binding in cracked concrete. The basic diffusion was modeled using Fick's second law, modified to include the effect of binding of chlorides by the cement hydration products, taking the bound chlorides as 80% of the total chloride content based on previous experimental work on uncracked concrete. They validated their model with micro-X-ray fluorescence imaging of the chloride-ion concentration profile of a notched concrete sample subjected to a 30-day ponding test.

2.4 TEST METHODS FOR CORROSION-RELATED PROPERTIES

As Stanish, Hooton, and Thomas (1997) point out, every test method that measures corrosion-related properties of concrete has both strengths and weaknesses. Some reflect the conditions to which concrete is subject in the field but take several months to complete. Other tests can be done quickly but do not relate well to field conditions. Still others fall somewhere in between. They observe, "no one test is a panacea, and different situations may require different tests. A proper understanding of the limitations of each testing procedure as well as what is required for the situation at hand will allow for the correct selection of testing procedure in each case."

2.4.1 Diffusion

Diffusion coefficients can be determined by several methods. A commonly used and rigorous method in the United States is ASTM C1556, which is a steady state diffusion test. This test takes a minimum of 2.5 months to complete. For this reason, it is more common in the United States to use ASTM C1202 "Rapid Chloride Permeability (RCP) test" which can be completed in a few days following a 28-day standard curing period. The Northern European alternate to ASTM C1202 is called NT Build 492, where NT stands for Nord Test. NT Build 492 contrasts with ASTM C1202 because it produces a diffusion coefficient instead of coulombs passed, a relative indicator of how quickly chloride ions diffuse through concrete. The following section describes these tests as well as others commonly used to determine the diffusion coefficient (or proclivity of chloride ingress) of concrete.

2.4.1.1 Bulk Diffusion with ASTM C1556 and NTBuild 443

One of the more respected methods for measuring the ability of chlorides to reach reinforcing steel is NTBuild 443 (also ASTM C1556), commonly referred to as the bulk diffusion test. The challenge with this test is that the time from casting samples to results is around three months (longer for a 90-day ponding period). With plenty of time to plan and prepare, this is not a problem. However, often there is not enough time to wait three months or longer to know whether a concrete mixture is a viable candidate for construction. Other test methods take less time but the outcomes are not as meaningful as the bulk diffusion coefficient. Stanish, Hooton, and Thomas (1997) characterize the bulk diffusion test (NTBuild 443) as intended to address the deficiencies of the salt ponding test. Rather than drying the specimen, it is saturated with limewater to avoid the effects of sorption. Wicking is prevented by coating all faces of the specimen except the one that is exposed to a 2.8 M NaCl solution. After at least 35 days' exposure (90 days for high-quality concrete), the specimen is mounted in a lathe and layers approximately 0.5 mm

(0.02 in.) thick are milled to obtain a chloride concentration profile, which is used to obtain the diffusion coefficient and the surface chloride concentration. ASTM C1556, “Standard Test Method of Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion” is a similar test.

2.4.1.2 Rapid Chloride Permeability

In AASHTO T277, “Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration” (comparable to ASTM C1202), a water-saturated, 50-mm (2 in.) thick, 100-mm (4 in.) diameter concrete specimen is mounted between two reservoirs, one containing a 3.0% NaCl solution and the other a 0.3 M NaOH solution. The specimen is subjected to 60 V direct current for 6 hours. The total charge passed (measured in Coulombs) are compared to ranges of Coulombs passed to rate the concrete’s chloride ion penetrability as negligible, very low, low, moderate, or high (Table 2.2). A direct measurement of diffusion coefficient is not made by this test. Stanish, Hooton, and Thomas (1997) summarize the main drawbacks of this test: (1) the current passed relates to all of the ions in the pore solution, not just chloride ions; (2) the measurements are made before steady-state conditions are reached; and (3) the high voltage applied may result in an increase in temperature, which will accelerate ion migration, particularly for low-quality concrete. This test measures a combination of diffusion and electrical conductivity. The exact weighting of the individual mechanisms may vary with the type of concrete. While it is useful for quality assurance purposes, it is less useful for research because it can be difficult to differentiate the influences of the migration mechanisms. This test can be performed after 28 days of standard curing and only takes 2-3 days to complete, but the information gleaned from the test is relative and not useful for service life modeling.

Table 2.2 Chloride Permeability Based on Charge Passed (from ASTM C1202)

Charged Passed (Coulombs)	Chloride Permeability
> 4,000	High
2,000-4,000	Moderate
1,000-2,000	Low
100-1.000	Very Low
< 100	Negligible

2.4.1.3 Non-Steady State Diffusion NTBuild 492

NTBuild 492 is a similar test to the Rapid Chloride Permeability test in that it is an electrical method and is completed in 24-96 hours after 28 days of standard curing. It is different because the result is an actual diffusion coefficient instead of a number that correlates to a general level of chloride permeability, i.e. high, moderate, low, etc. The NT Build 492 test’s concrete sample is a 50 mm (2 in) slice cut from the middle of a cylinder. Following a 24-hour conditioning process, the NT Build 492 test applies an external electrical potential across the specimen to rapidly migrate chloride ions into the concrete. The concrete sample sits in a cell between a 10% NaCl catholyte solution and a 0.3 N NaOH anolyte solution, with the face of the sample that was nearer to the surface exposed to the catholyte solution. Depending on the initial current measured across the sample at 30 V power, the test runs for

24 to 96 hours. Figure 2.2 is a photograph of samples in cells while the NT Build 492 test is running. Figure 2.3 shows an individual cell that is labeled to show the catholyte solution receptacle, sample, and anolyte solution receptacle.

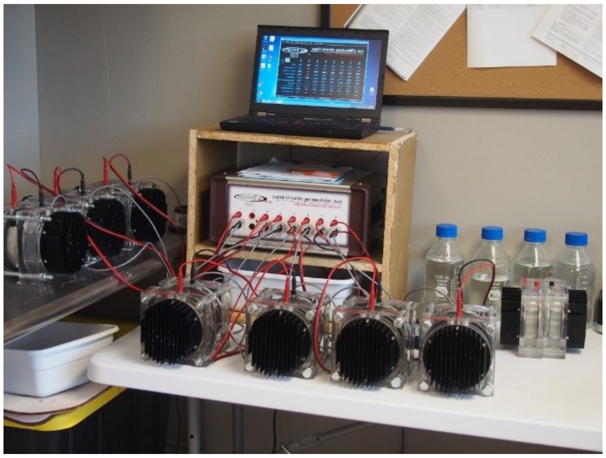


Figure 2.2 NT Build 492 Test in progress

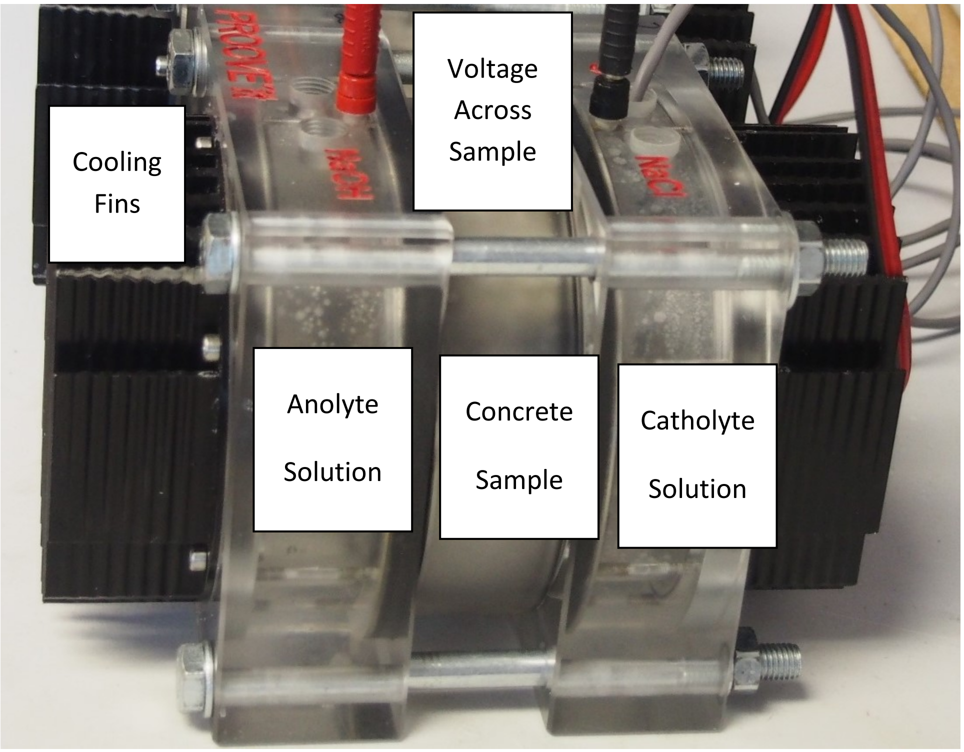


Figure 2.3 An individual NTBuild 492 cell

On completion of the test, samples are split in half and the fractured surface is sprayed with a 0.1 M silver nitrate solution. The silver nitrate precipitates on the surface of concrete containing chloride ions, turning the surface white, and does not react with concrete free of chlorides. The depth of chloride ion penetration into the sample is measured. The apparent diffusion coefficient is calculated based on the depth of chloride ion penetration, temperature, test duration, and thickness of specimen.

Hooton and Charmchi (2015) consider the advantages of NT Build 492 over ASTM C1202 to be: “(a) results are not influenced by pore fluid conductivity, (b) the depth of chloride penetration is measured directly, and (c) …the calculated migration coefficient can be used in service-life prediction models.” They also note that the results agree “fairly well” with those of bulk diffusion tests such as ASTM C1556.

2.4.2 Resistivity

While diffusivity is the most direct measurement of the ability of ions to migrate in concrete, in practice it is difficult to measure. On the other hand, electrical properties such as resistivity and conductivity (the reciprocal of resistivity) are relatively easy to measure.

2.4.2.1 Surface Resistivity

Hooton and Charmchi (2015) describe the surface resistivity test (Wenner probe, AASHTO TP95) as follows: “In this test, four equally-spaced electrical probes are pressed against the surface of a saturated concrete specimen. The two outer probes apply a low-frequency alternating current to the concrete while the voltage drop between the two inner probes is measured. The resistivity is calculated from the measured voltage, current and a geometric factor.” The test is relatively simple, and the equipment is commercially available.

Gowers and Millard (1999) studied the use of the Wenner probe to measure the surface resistivity of concrete as a means of assessing the rate of corrosion of embedded steel after it has become depassivated. Based on their work, they recommended the following.

1. Use the four-contact method to avoid influence from the contact surface area.
2. Use low-frequency AC applied current; do not use DC.
3. Ensure good electrical connection between the contact and the concrete surface.
4. Use a contact spacing of at least 1.5 times the maximum size of the aggregate.
5. The contact spacing should not exceed one quarter of the concrete section thickness.
6. Measurements should be taken at a distance from the edge of the concrete section at least twice the contact spacing.
7. Avoid taking resistivity measurements near reinforcing steel; use a cover meter to verify the locations of reinforcing steel.
8. If reinforcing steel cannot be avoided, use a contact spacing not exceeding two-thirds of the concrete cover.
9. Where the surface is wet, use a contact spacing of at least 40 mm (1.6 in).
10. Wait at least 24 hours after a rainfall.
11. Where the presence of a low-resistivity surface layer in unavoidable, use a contact spacing of at least eight times the thickness of this layer.

Hooton and Charmchi (2015) observe, “Recorded resistivity values will vary if an inappropriate probe spacing is used and also if the concrete specimen to be tested is not fully saturated … It has been found that the Wenner probe surface test results are influenced by the solutions applied to the surface of the concrete specimen since the electrical conductivity of the near-surface pore fluid can be altered substantially. This test method has the potential to be used in the field, but the structural elements to be tested need to be fully saturated before test, and any carbonation on the surface will affect measured results.”

Otieno, Alexander, and Beushausen (2010) studied various measurement techniques for assessing corrosion rates in concrete. They tested beams with no cracks, incipient cracks, 0.4-mm (0.016 in.) cracks, and 0.7-mm (.028 in.) cracks. The beams were subjected to cycles of wetting and drying, with 3 days’ ponding with a 5% NaCl solution and 4 days’ air drying for 32 weeks. Resistivity was measured using a Wenner probe at the end of each 3-day ponding period. They found that although the rate of corrosion increased with crack width, the measured resistivity was not significantly different for cracked and uncracked concrete. They attribute the lack of crack influence on these measurements to the saturation of the concrete with salt solution before each measurement. They concluded that it is not adequate to rely on a single non-destructive test method to assess corrosion in cracked concrete.

2.4.2.2 Bulk Resistivity

Resistivity is a fundamental concrete material property that assesses pore conductivity and pore connectivity. The bulk resistivity test is a rapid indication of concrete’s resistance to penetration of chloride ions by diffusion (ASTM C1760). In the bulk resistivity test, the total current passing through all phases of the concrete is measured. The current is produced by electrodes on either end of a cylinder sample that is typically 100 mm (4 in.) by 200 mm (8 in.), although certain testing apparatus allow the test to be conducted on any size cylinder sample.

2.4.3 Correlations Amongst Diffusion Coefficient and Resistivity Test Methods

Many studies have attempted to correlate the diffusion measurement tests and rapid chloride permeability tests with faster test methods such as surface resistivity and bulk resistivity, and to compare some of medium-length tests such as NT Build 492 with the longer-length tests such as ASTM C1556.

Gudimettla and Crawford (2015) analyzed data obtained by the Federal Highway Administration’s Mobile Concrete Laboratory from 11 concrete paving sites. All specimens were concrete cylinders cast in the field. They obtained good correlation among surface resistivity (Wenner probe), bulk resistivity (ASTM C1760), and rapid chloride (ASTM C1202) tests conducted on comparable specimens of the same age; however, for some mixtures the correlation between 28-day surface resistivity and 56-day rapid chloride test results was not very good. The coefficient of variation was lower for the surface resistivity and bulk resistivity tests than for the rapid chloride test.

Rupnow and Icenogle (2012) investigated the use of surface resistivity measurements (Wenner probe) in lieu of ASTM C1202 tests for quality assurance and acceptance of structural concrete for bridges. Concrete specimens from five mixtures at *w/cm* ratios of 0.35, 0.50, and 0.65 were tested for surface resistivity and chloride ion penetration (ASTM C1202) at the ages of 14, 28, and 56 days. They found fairly close correlation between the two test methods (Figure 2.4).

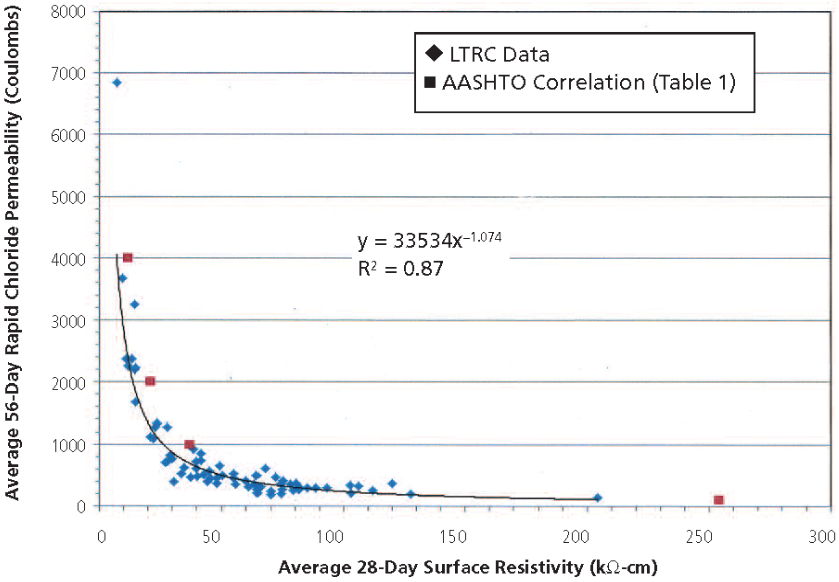


Figure 2.4 ASTM C1202 v. surface resistivity for five concrete mixtures with *w/cm* ranging from 0.35 to 0.65 (Rupnow and Icenogle, 2012)

Hooton and Charmchi (2015) compared three different commercially available bulk resistivity tests (ASTM C 1760) with rapid chloride permeability (ASTM C1202) and non-steady state diffusion coefficient (NTBuild 492). They found exponential relationships between the bulk resistivity test and either ASTM C1202 (Figure 2.5) or NTBuild 492 (Figure 2.6). Table 2.3 gives their approximately equivalent bulk resistivity values and non-steady state diffusion coefficients for commonly specified coulomb limits (ASTM C1202). They caution that these values require verification using a much larger data set before being included in specifications.

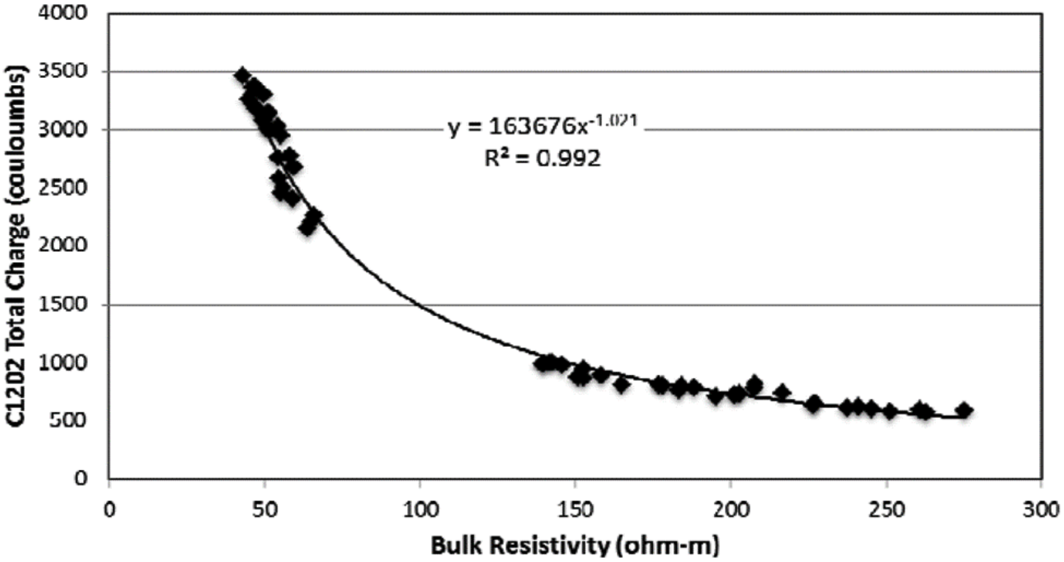


Figure 2.5 ASTM C1202 v. bulk resistivity (Hooton and Charmchi, 2015)

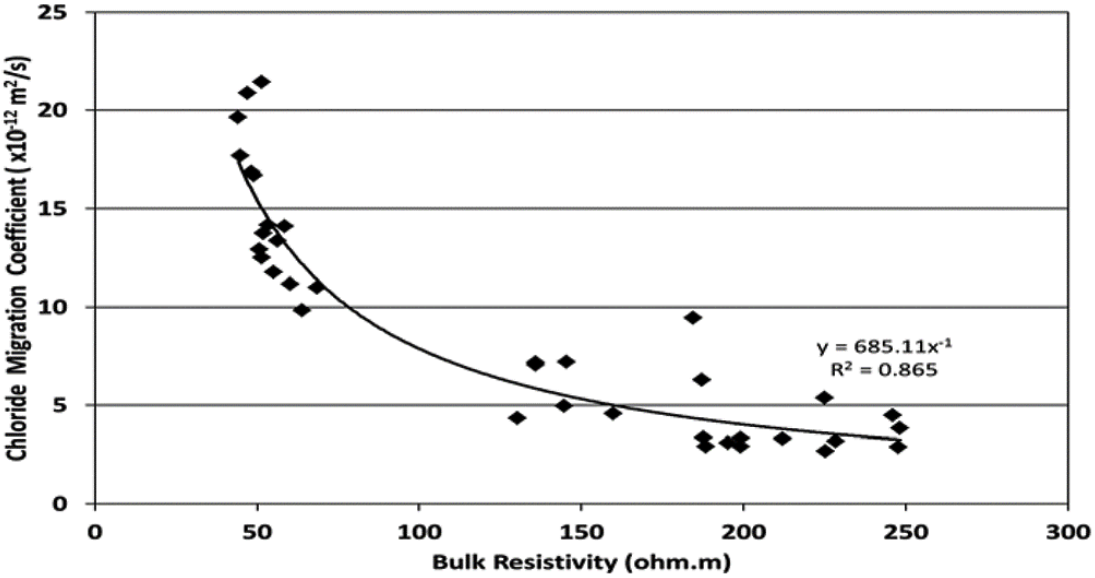


Figure 2.6 Correlation between NTBuild 492 diffusion coefficient and bulk resistivity (Hooton and Charmchi, 2015)

Table 2.3 Approximate equivalent bulk resistivity values for commonly specified coulomb (ASTM C1202) limits and NTBuild 492 diffusion coefficients. Data from Hooton and Charmchi (2015)

ASTM C1202 (coulombs)	Bulk Resistivity (ohm-m)	NT Build 492 diffusion coefficient (m^2/s)
1000	130	5 x 10^{-12}
1500	90	8 x 10^{-12}
2000	70	12 x 10^{-12}

Hooton and Charmchi (2015) note that bulk resistivity (ASTM C1760) was initially developed as an interim measure to shorten the procedure of ASTM C1202. Nokken and Hooton (2006) point out several advantages over ASTM C1202: no temperature rise due to the short duration of the test and the ability to measure a fundamental material property rather than calculate the integral of current passed vs. time. Even more beneficial than a correlation to ASTM C1202, is that the mathematics and material properties of the concrete that control diffusion and resistivity are the same. Therefore, bulk resistivity measurements can be correlated to the diffusion coefficient determined by ASTM C1556 or NTBuild 492, eliminating the need to run long and expensive tests to measure diffusion coefficient.

Diffusivity and resistivity are related in terms of the formation factor FF, which Stanish, Hooton, and Thomas (1997) describe with the Nernst-Einstein Equation (Equation 2.2):

$$FF = \sigma/\sigma_0 = D/D_0 \qquad \text{[Equation 2.2]}$$

where σ is the conductivity (conductivity is the inverse of resistivity) of the concrete, σ_0 is the conductivity of the concrete pore solution, D is the diffusion coefficient of the concrete (the quantity of interest), and D_0 is the diffusion coefficient of chloride ions in the pore solution. Determining the conductivity of the concrete pore solution may be difficult. Either the pore solution must be removed from the concrete or the concrete must be saturated with a solution of known conductivity. Extraction of pore solution, particularly from high quality or mature concretes, is difficult. Saturation of the concrete with a conductive solution also presents problems, as it is not possible to remove all the ions from the original concrete pore solution, and these will affect conductivity. Normally a highly conductive solution is used to minimize the effects of any remaining ions from the concrete pore solution.

CHAPTER 3: VERIFICATION OF ZERO DIFFUSION COEFFICIENT IN AN UNCRACKED THIN POLYMER OVERLAY

Beton crafted an experiment to prove the assumption that the epoxy layer of a TPO is impermeable by chloride ions. Sikadur 22 Lo-Mod FS is a typical epoxy resin binder used in the application of thin polymer overlays. Sika supplied this product to Beton to verify that the diffusion coefficient through the hardened epoxy resin is zero. A thin layer of the resin was applied to 3-cylinder samples from bridges 16008 (Cook County), 62892 (Mackubin St. Saint Paul), and 58821 (Pine County). The samples were chosen because Beton had multiple samples from each of the bridges and did not need the samples for other tests. The resin cured for a week and then cylinder samples containing the resin topping were cut to size for the NT Build 492 test. Deviating from the test method, the sample was not taken from the middle of the cylinder. Rather, the finished surface of the cylinder, which received the epoxy resin, was the surface exposed to the catholyte solution.

It is a generally accepted assumption that the diffusion coefficient of an uncracked thin polymer overlay (TPO) is zero. To verify this assumption, an epoxy from a TPO system was applied to cylinder samples of bridge deck concrete. Companion cylinders did not receive the epoxy. Samples with and without TPO and underwent the NT Build 492 test. Figures 3.1-3.3 show the samples from Bridges 16008 (Cook County), 62892 (Mackubin St., Saint Paul), and 58821 (Pine County), respectively. The photos on the left side of these figures show that diffusion of chloride ions through the epoxy is zero (concrete not discolored in the center) and that the chlorides bypassed the epoxy along the edges on all samples as determined by the white, precipitated silver nitrate at the edges. The concrete fragments observed near the surface of some of these samples are part of the other half of the sample that adhered to the epoxy after splitting. For comparison, the photos on the right side of the figures show the chloride ingress into the non-epoxied companion cylinders. Note the almost uniform depth to which the silver nitrate precipitates, indicating the depth of chloride ion penetration. Based on this testing, the assumption that the diffusion coefficient of thin polymer overlays is zero was validated.

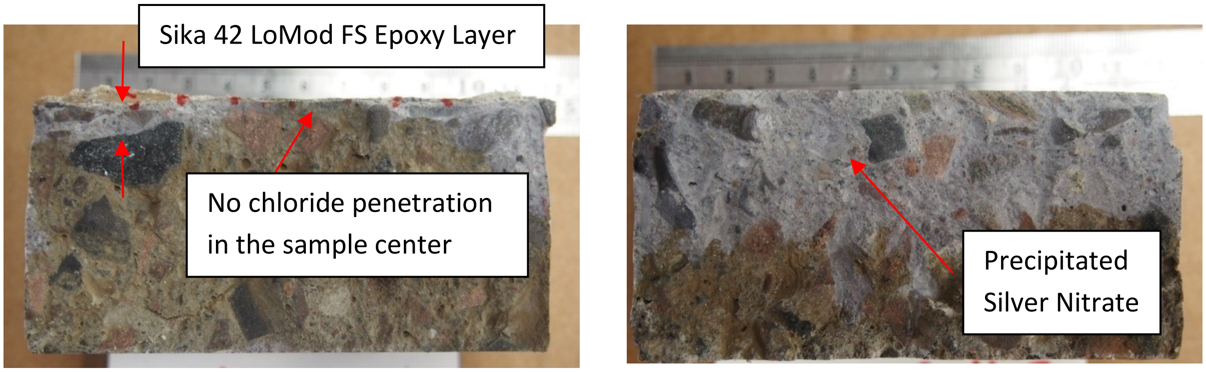


Figure 3.1 Concrete samples from Bridge 16008 (Cook County) with epoxy topping (left) and no epoxy topping (right) after the NT Build 492 test

Figure 3.2 Concrete sample from Bridge 62892 (Mackubin St., Saint Paul) with epoxy topping (left) and no epoxy topping (right) after the NT Build 492 test

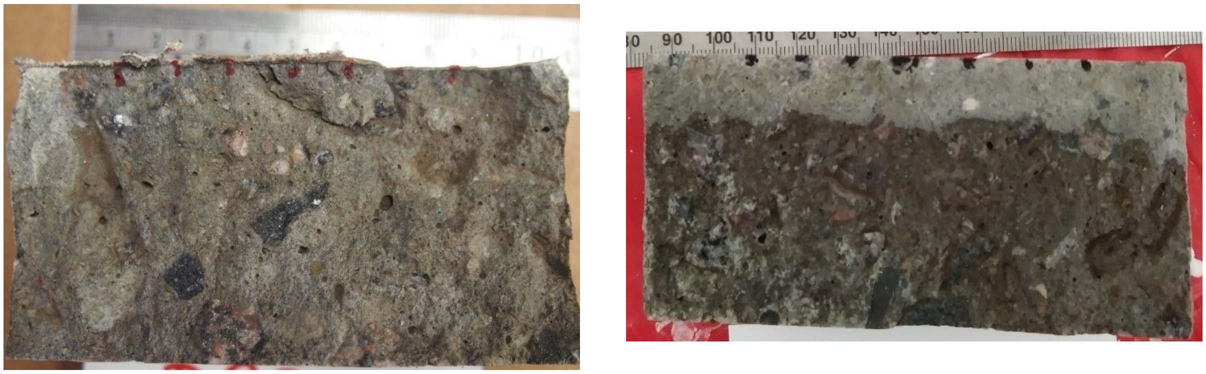


Figure 3.3 Concrete sample from Bridge 58821 (Pine County) with epoxy topping (left) and without epoxy topping (right) after the NT Build 492 test

The non-steady state apparent diffusion coefficient was not calculated for these samples because this experiment was used only to demonstrate that the diffusion coefficient through the TPO is zero rather than to determine the diffusion coefficient of the concrete.

CHAPTER 4: APPARENT DIFFUSION COEFFICIENT DETERMINED FROM BRIDGE DECK CHLORIDE PROFILES

The diffusion coefficients of existing bridge decks, some of which had been in service for over 40 years, were determined from existing chloride profiles provided by MNDOT in order to evaluate an average diffusion coefficient that could be used for modeling deck service life and TPO application timing if the deck's diffusion coefficient was not known. Typically, bridges in service for a long time would not be good candidates for TPO application if the purpose of the TPO was to slow down the diffusion of chlorides to the level of the reinforcing steel because it is likely that the chloride threshold concentration has already accumulated at the level of the steel.

4.1 APPARENT DIFFUSION COEFFICIENT DETERMINED FROM MNDOT CHLORIDE PROFILES

The apparent diffusion coefficients of multiple in-service Minnesota bridge decks were determined. The in-service bridge decks represented both monolithic decks and decks with low-slump overlays. Installing low-slump overlays has been a common practice for MNDOT starting in the 1970s. The diffusion coefficients for existing bridge decks were determined with chloride profiles and Fick's Second Law. A chloride profile assesses the total chloride content of concrete samples at the surface and multiple horizons below the surface. Many of the chloride profiles for individual bridge decks across Minnesota were provided by MNDOT. Selection of the bridges evaluated was not part of a strategic plan. Rather, the authors used existing chloride profile data or obtained samples based on opportunity.

4.1.1 Chloride Profiles

Chloride profiles are used, along with Fick's Second Law, to calculate diffusion coefficient. Chloride content of concrete samples can be determined either by the acid-soluble method or water-soluble method. The chloride measurements in this project are acid soluble chloride assessments. At least 10 g of powder are required for chloride analysis so concrete samples were either milled or crushed to obtain the powder. Powder samples were collected from horizons at multiple depths below the sample surface. A minimum of three horizons were sampled for each location for the decks assessed by MNDOT. The typical horizon depth was ½ in. to 1 in. and sampling depths varied from 3 to 6 inches below the surface. Chloride content was reported as ppm by weight of concrete. The specific test for acid-soluble chlorides is ASTM C1152 *Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete*.

4.1.2 Years in Service

The time a bridge deck was in service is also required to calculate diffusion coefficient. Time in service was determined by subtracting the sampling date from the year of concrete placement, overlay placement, or rehabilitation date recorded in bridge inventory data. For samples where bridge inventory data were not obtained, it was assumed that the overlay or deck had been in service from 1978 until the year the concrete samples were collected.

4.1.3 Apparent Diffusion Coefficient Calculation with Fick's Second Law

The apparent diffusion coefficient was calculated with the following steps:

1. The chloride profiles were plotted as the chloride concentrations vs. mean depth of the horizon (Figure 4.1).
2. Using Microsoft Excel, the chloride profile was fit with an exponential curve and the projected surface chloride concentration was assumed as the coefficient of the fitted equation (Figure 1).
3. Using the solution [2] to Fick's Second Law [1], the apparent diffusion coefficient was chosen as that which minimized the error between the measured and predicted chloride profile.

$$\frac{\partial C}{\partial t} = D_a \frac{\partial^2 C}{\partial x^2} \qquad \text{[Equation 4.1]}$$

$$C(x,t) = C_s - (C_s - C_i) * \operatorname{erf}\left(\frac{x}{\sqrt{4D_a t}}\right) \quad \text{[Equation 4.2]}$$

C(x,t) = chloride concentration, measured at depth x and exposure time t

C_s = projected chloride concentration at the interface between the exposure liquid and test specimen that is determined by the regression analysis

C_i = initial chloride-ion concentration of the cementitious mixture prior to exposure either to environmental chloride or submersion in the exposure solution (for standardized tests), (assumed as 0.005% or 30 ppm unless noted otherwise)

x = depth below the exposed surface (to the middle of a layer, m)

D_a = apparent chloride diffusion coefficient (m^2/s)

t = the exposure time in seconds

erf = the error function, described in the following equation:

$$erf(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^u du \qquad \text{[Equation 4.3]}$$

C(x,t) is determined at the same depths at which chloride concentration was measured. The process is iterative as the diffusion coefficient was chosen to minimize the difference between the calculated and measured diffusion coefficients. The error was minimized with Equation [4].

$$S = \sum_{n=2}^{N} \Delta C^2(n) = \sum_{n=2}^{N} \left(C_m(n) - C_c(n)\right)^2 \qquad \text{[Equation 4.4]}$$

S = Sum of squares to be minimized

N = number of horizons

$\Delta C(n)$ = difference between the measured and calculated chloride concentration of the nth layer

$C_m(n)$ = measured chloride concentration of the nth layer

$C_c(n)$ = calculated chloride concentration in the middle of the nth layer

If samples were obtained for more than one location on a bridge deck, the apparent diffusion coefficient was reported as the average.

Figure 4.1 shows an example of the plot used to determine the surface chloride concentration. The coefficient from the exponential fit is 4403 ppm, which is assumed as C_s in Equation 4.2. The difference between the measured chloride concentration (circles) and predicted chloride concentration (squares) was minimized by choice of diffusion coefficient.

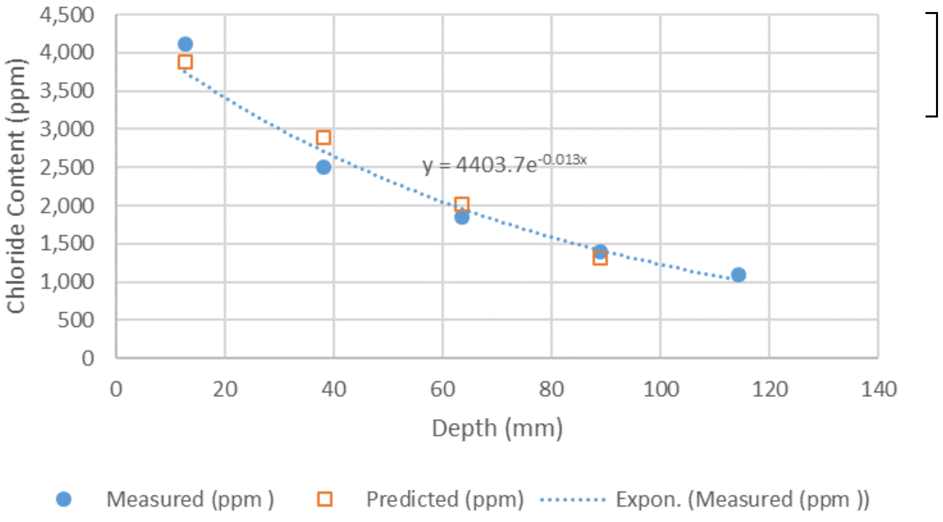


Figure 4.1 Example of the data and exponential fit equation used to estimate the surface chloride concentration of a sample set for determining apparent diffusion coefficient

Apparent diffusion coefficients of bridge deck concrete were determined in this manner from the following bridges:

3575A, 4011, 4017, 4018, 4019, 5151, 5772, 5900, 5962, 6347, 7272, 7276, 9090, 9103, 9451, 09823, 9832, 35007, 62080, 62515, 62523, 62527, 62528, 62530, 62532, 62533, 62541, 62544, 62581, 69002, 69003, 69006, 69109, 90378, 92797, 92798, 93619, T9392, 6870, 6897, 73566, 73804, 73805, 73806, 73807, 73808, 73809, 73811, 73812, 73813, 73815, 73816, 73817, 73818, 73819, 73820, 73842, 73850, 73852, 73853, 73854, 73857, 73860, 73861, 73862, 73864, 73865, 73866, 73868, 73869, 73870, 73873, 73875, 73876, 73877, 73878, 77802, 86530, 86802, 86803, 86807, and 86808.

4.2 RESULTS AND CONCLUSIONS

The apparent diffusion coefficients of in-service Minnesota bridge decks calculated from MNDOT-provided chloride profiles were assumed to be steady state apparent diffusion coefficients representing concrete that has been in service for up to 95 years. The apparent diffusion coefficients were split into two groups: one for monolithic (no separate concrete wearing course) or unknown deck design and another for decks that had received low-slump overlays. Figure 4.2 shows a scatter plot of the apparent diffusion coefficients plotted by year of deck construction or reconstruction based on inspection reports. The apparent diffusion coefficients for monolith/unknown decks are indicated with circles and those for low-slump overlay decks, with x's. Note that the y-axis is in log scale. The plots show a broad range of apparent diffusion coefficients calculated for the bridge decks. This can be expected as the sample set of bridges represented a broad range of specifications, regions, and construction practices. The apparent diffusion coefficient values are compiled in Appendix A attached to this report.

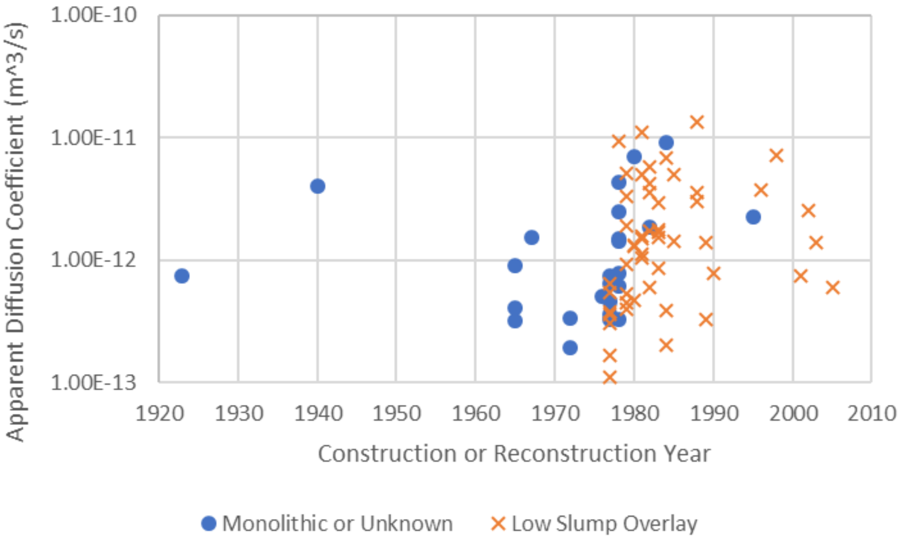


Figure 4.2 Scatter plot of calculated apparent diffusion coefficients for bridge decks with monolith or unknown and low-slump overlay bridge deck designs (semi-log scale)

Statistics were employed to evaluate the data sets. Figure 4.3 shows a histogram of the monolithic and unknown deck apparent diffusion coefficients and Figure 4.4 shows the histogram of the low-slump overlay apparent diffusion coefficients. Because the apparent diffusion coefficients are skewed to the left in both data sets (instead of being evenly distributed about the mean), the lognormal distribution was used to determine the mean and standard deviation of the diffusion coefficients.

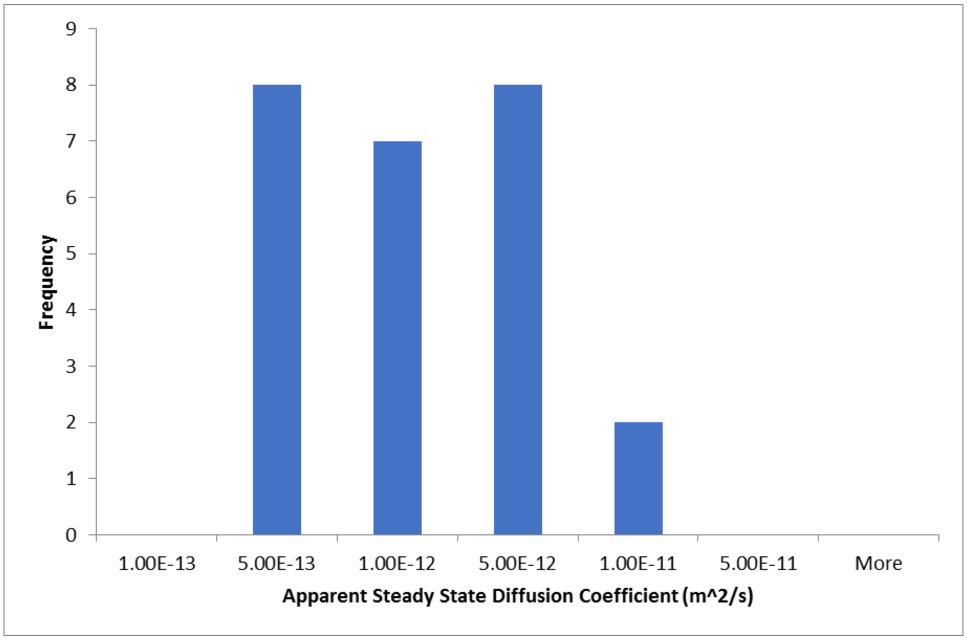


Figure 4.3 Monolithic and unknown deck concrete apparent diffusion coefficient histogram

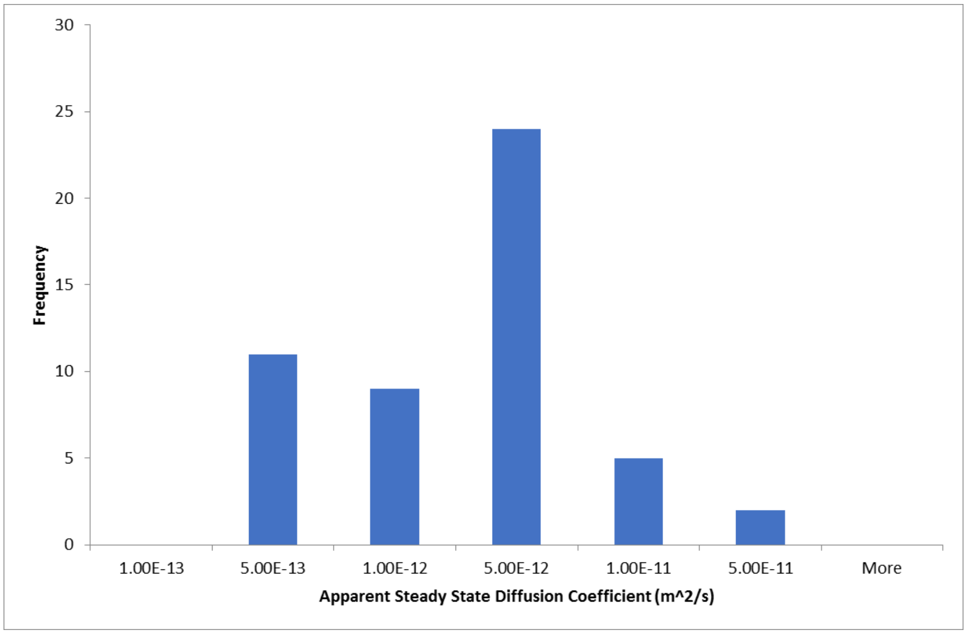


Figure 4.4 Low-slump overlay deck concrete apparent diffusion coefficient histogram

Table 4.1 shows the number of data points, mean, standard deviation, range, minimum value, and maximum value of both the monolith/unknown and low-slump apparent diffusion coefficient data sets. The low-slump overlay data set contained two apparent diffusion coefficients which were removed from the statistical analysis for being outliers (6.17 E-14 m^2/s and 1.0 E-10 m^2/s).

Table 4.1 Apparent diffusion coefficient summary statistics for decks with and without low-slump overlays

Statistic	Monolithic or Unknown Decks	Low-Slump Overlays
Number of Data Points	25	51
Mean (m^2/s)	1.68E-12	2.62E-12
Standard Deviation (m^2/s)	2.38E-12	4.29E-12
Range (m^2/s)	8.94E-12	11.34E-12
Min (m^2/s)	0.19E-12	0.11E-12
Max (m^2/s)	9.13E-12	13.50E-12

From this information, the following conclusions can be drawn:

1. In-service bridge deck concrete apparent diffusion coefficient data were lognormally distributed.
2. The range of measured apparent diffusion coefficients was large and the standard deviations are larger than the means. This can be attributed to variation in concrete mixtures, time in service, new construction practices, repair schedule and practices, sample collection procedure, and sample testing procedure.
3. The mean apparent diffusion coefficients for monolithic and unknown decks (1.68 x 10^{-12} m^2/s) and low lump overlays (2.62 x 10^{-12} m^2/s) reflect rational values that would be expected of bridge deck concrete that was in service for extended time. These diffusion coefficients could be used for estimating the timing of a TPO application/service life estimation in the absence of a chloride profile for a bridge deck built before 2013.

CHAPTER 5: APPARENT DIFFUSION COEFFICIENT OF MODERN MNDOT BRIDGE DECK MIXTURES BY ASSESSING CYLINDER SAMPLES WITH NTBUILD 492

The diffusion coefficient of new bridge decks was determined from cylinder samples using the NTBuild 492 non-steady state diffusion coefficient test to evaluate diffusion coefficient. The difference between steady state and non-steady state diffusion coefficient is explained within this chapter. This chapter also includes a discussion of the decay coefficient used to modify the bridge deck diffusion coefficients so they can be used to model service life.

5.1 APPARENT DIFFUSION COEFFICIENT DETERMINED FROM CYLINDER SAMPLES WITH NT BUILD 492

Beginning in 2005, MNDOT began phasing in the use of high performance concrete (HPC) in its bridge decks. Most bridge decks cast after 2013 were made with HPC. The HPC decks were designed to have very low shrinkage and permeability and often did not receive the low-slump overlay. The diffusion coefficients of several new bridge decks constructed in 2016 were determined with the NT Build 492 test. The cylinder samples were analyzed at approximately a year after they were cast. If NT Build 492 became a standard test for analyzing diffusion coefficients of bridge deck concrete, the samples would be tested at 28 days after casting.

Table 5.1 shows the diffusion coefficients measured on HPC concretes along with the MNDOT concrete classification of each cylinder, the total cementitious product in the mix design along with the percentage of cement and fly ash and the water-to-cement ratio (w/c).

There were multiple concrete suppliers for the concretes listed in Table 5.1, but the concrete mixtures fall into two categories—those that used between 570 and 600 lbs/yd^3 total cementitious with 25 to 30% fly ash for cement substitution, and those that use 535 lbs/yd^3 total cementitious with 100% cement. The w/c was consistently 0.42. Looking at the diffusion coefficients, the concretes made with fly ash and a slightly higher cementitious content were able to achieve lower diffusion coefficients than those that used 535 lbs/yd^3 portland cement and no fly ash.

Table 5.1 Diffusion coefficients of various HPCs made in 2016 and measured with NT Build 492 and total cementitious content, % cement, % fly ash, and w/c

Cylinder ID	D_{nssm} (m²/s)	MNDOT Concrete Classification	Total Cementitious (lbs)	% Cement	% Fly Ash	w/c
Br 62732-1	5.64E-12	3YHPC M9	595	75	25	0.42
Br 62732-2	8.40E-12	3YHPC M10	595	75	25	0.42
Br 85014 Dresbach	3.75E-12	3Y33HPC	570	70	30	0.42
Br. 85014 Dresbach-RDG3	1.47E-12	3Y33HPC	570	70	30	0.42
Br. 85014 Dressbach-RDG4	1.29E-12	3Y33HPC	570	70	30	0.42
Br 04029	12.90E-12	3YLCHPC-S	535	100	0	0.43
Br. 40009 3-CC	5.96E-12	3YHPC	600	70	30	0.42
Br. 40009 D3	4.83E-12	3YHPC	600	70	30	0.42
Br 16008 Cook County	11.70E-12	3YHPC-M	535	100	0	0.42
Br 62892 Mackubin Deck	3.69E-12	3YHPC-M9	595	75	25	0.42
Br 58821 Pine County	3.60E-12	3YHPC-M9	595	75	25	0.42
Br 27080 Hennepin County	3.89E-12	3Y33HP	573	71	29	0.42

A statistical analysis, presented in Table 5.2, was used to evaluate the diffusion coefficients of the concretes made with the 25 to 30% fly ash replacement mixtures. A histogram of the diffusion coefficients suggested that they were lognormally distributed so the lognormal distribution equations were used to evaluate the mean and standard deviation of the diffusion coefficients. With only two data points for HPC deck mixtures made with 100% Portland cement, it is not possible to perform a statistical analysis.

Table 5.2 Diffusion coefficient summary statistics for 2016 HPCs made with 70% cement, 30% fly ash, and a 0.42 w/c

Statistic	Value
Number of Data Points	10
Mean (m²/s)	4.42E-12
Standard Deviation (m^2/s)	2.84E-12
Range (m²/s)	7.11E-12
Min (m²/s)	1.29E-12
Max (m²/s)	8.40E-12

The average apparent diffusion coefficient for HPCs with partial cement replacement with fly ash determined from NT Build 492 was 4.42 x 10^{-12} m²/s. The average apparent diffusion coefficient for the two HPCs with 100% cement was 12.3 x 10^{-12} m²/s. The average apparent diffusion coefficient for the

HPCs with fly ash replacement was considerably lower than the HPCs without fly ash replacement. This difference shows the service life benefit of using fly ash to decrease diffusion coefficient.

5.2 DIFFUSION COEFFICIENT DECAY

The diffusion coefficient of concrete decreases over time because diffusion is controlled by the concrete's pore system which refines over time. The parameter used to asses this decrease is called the decay coefficient and is typically denoted "m". The decay coefficient can be measured, but this takes a significant amount of time. In the absence of a test, Alexander, M. and Thomas, M, 2015, proposed the following Equation 5.1 to approximate the decay coefficient:

$$m = 0.26 + 0.4\left(\frac{FA}{50} + \frac{SG}{70}\right) \qquad \text{[Equation 5.1]}$$

Where

m = diffusion decay coefficient

FA = percent fly ash of total cementitious in concrete mixture

SG = percent slag of total cementitious in concrete mixture

It may be necessary to convert the diffusion coefficient to a diffusion coefficient at the same age or to the 28-day diffusion coefficient, respectively. This would apply to cases where comparisons are being made between multiple bridge decks poured at various times, or when the diffusion coefficient is used in a service life model, which typically requires the input of a 28-day diffusion coefficient. Equation 5.2 (Stanish & Thomas, 2003) below can be used to determine the diffusion coefficient at a desired time if the diffusion coefficient at any age, the decay coefficient and the sample's age are known.

$$D(t) = D_{ref}\left(\frac{t_{ref}}{t}\right)^{m} \qquad \text{[Equation 5.2]}$$

Where

D_{ref} = diffusion coefficient at some time t_{ref}

t_{ref} = age of sample at time of testing

t = age of consideration

m = diffusion decay coefficient approximated with Equation 6 (Alexander, M. and Thomas, M., 2015)

Using Equation 5.1, bridge deck concrete with 30% fly ash has a decay coefficient of 0.5 and the bridge deck concrete using only Portland cement has a decay coefficient of 0.26.

5.3 SERVICE LIFE MODELING WITH LIFE365

The end of the useful service life is defined as the point when the chloride concentration at the level of the steel reaches the threshold value. It is at this concentration that the steel could start to depassivate, after which corrosion begins quickly. Using Life365, a service life modeling software, and keeping all variables constant except diffusion coefficient and decay coefficient, the predicted service life of the HPC deck mixtures were determined.

Before modeling service life, the HPC diffusion coefficients must be converted from 1 year to 28-day coefficients using Equation 5.2. D_{ref} is the 1-year diffusion coefficient determined with NTBuild 492, t_{ref} is 365 days, t is 28 days, and m is the decay coefficient. The 28-day diffusion coefficients for 30% fly ash and 100% Portland cement HPCs is shown in Table 5.3. Back calculating the 28-day diffusion coefficient from the 1-year diffusion coefficient is likely not appropriate as 16×10^{-12} and 24×10^{-12} m^2/s are unrealistically high given the concrete mix design. This suggests using the decay coefficient to back calculate diffusion coefficients may not be an appropriate step. Looking forward, it would be better to measure diffusion coefficient at 28 days for multiple new bridge decks.

Table 5.3 Using the decay coefficient to determine the 28-day diffusion coefficient from the diffusion coefficient measured at 1 year.

HPC Concrete ID	NT Build 492 Diffusion Coefficient at 1 year (m^2/s)	Decay coefficient	Diffusion coefficient for HPC at 28 days (m^2/s)
HPC 30% Fly Ash	4.42×10^{-12}	0.5	16×10^{-12}
HPC 100% Portland Cement	12.3×10^{-12}	0.26	24×10^{-12}

For service life comparison between the bridge deck concretes with and without fly ash, the input parameters for Life365 are listed in Table 5.4.

Table 5.4 Life365 input parameters for comparing the service life of HPCs with fly ash and no fly ash replacement of cement

Life 365 Input Variable	Value
Type of Structure	Slabs and walls
Thickness	200 mm (8 in.)
Reinforcement Depth	60 mm (2.36 in.)
Area	10000 square m (107,639 sqft)
Chloride Concentration Units	% wt. concrete
Max Surface Concentration	1%
w/c	0.42
% fly ash (HPC with fly ash)	30%
% fly ash (HPC without fly ash)	0%
Rebar steel type	Epoxy coated
D (HPC with fly ash)	16×10^{-12} m^2/s
D (HPC without fly ash)	24×10^{-12} m^2/s
m (with fly ash)	0.50
m (without fly ash)	0.26
Hydration	25 years
Chloride Threshold (Ct)	0.2% (by weight of concrete)
Propagation	6 years

The predicted service life of HPC with fly ash replacement was 75 years—almost three times that of the HPC deck without fly ash replacement which was predicted as 26 years. What is most important about this analysis is that an additional 60 lbs. of portland cement and substitution of 30% of the portland cement with Class F fly ash can increase the service life by 300%.

5.4 CORRELATION BETWEEN NON-STEADY STATE AND STEADY STATE DIFFUSION COEFFICIENTS

The advantage of the NTBuild 492 test to measure the non-steady state diffusion coefficient of concrete is that it can be completed relatively rapidly (28 plus a few days), and the outcome is an actual diffusion coefficient. NTBuild 492 is regularly compared to ASTM C1202, which is the rapid chloride permeability (RCP) test. The testing apparatus is similar for NTBuild492 and ASTM C1202, but the outcome of the RCP test is simply coulombs passed, which correspond to a level of chloride permeability (negligible, very low, low, moderate, or high). ASTM C1556 is the test used to determine steady-state bulk diffusion coefficient of concrete. Because it is a steady-state test, its results are very useful for determining concrete service life, but the test's downside is that its minimum result time exceeds 70 days.

Concrete diffusion coefficients determined with NTBuild492 test can be used instead of ASTM C1556 with the understanding that the non-steady state diffusion coefficients will be larger than the steady-state diffusion coefficients. As diffusion coefficient is primarily dependent on pore structure, the tests can be correlated with any data, not just data specific to the mixtures considered for a particular project. BCE has been collecting NTBuild 492 and ASTM C1556 results for a variety of concretes incorporating various quantities of Portland cement and various levels of pozzolan (fly ash and slag) replacement of Portland cement. Figure 5.1 shows the plot used to develop the correlation equation between NTBuild 492 and ASTM C1556.

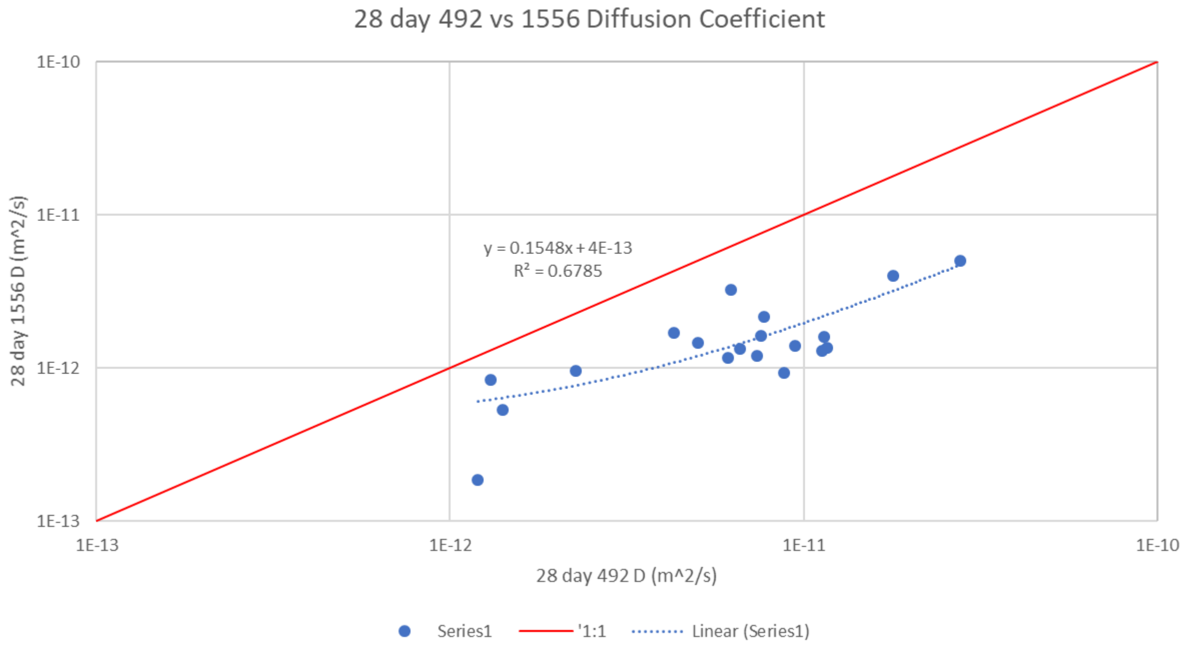


Figure 5.1 Correlation plot between the non-steady state diffusion coefficient determined with NTBuild492 and the steady-state diffusion coefficient determined with ASTM C1556.

It is important to know the distinction between the diffusion coefficients determined by NTBuild 492 and ASTM C1556 because the difference in diffusion coefficient accounts for significant difference in service life. If the point of knowing the diffusion coefficient is a ballpark value or for comparison to other like concrete mixtures, the NTBuild 492 test is a good option. If the diffusion coefficient is necessary for service life calculation, the diffusion coefficient determined with ASTM C1556 is required. As discussed, there are considerable time and cost differences between NTBuild 492 and ASTM C1556, with NTBuild 492 requiring less than half the time as ASTM C1556 at a reduced price. With the correlation equation, the diffusion coefficients determined with NTBuild 492 can be transformed into an estimate of the steady-state diffusion coefficient.

5.5 SUMMARY

When modeling TPO application timing for a new bridge deck in the absence of a measured diffusion coefficient, a diffusion coefficient for HPC deck mixtures with between 570 and 600 lbs/yd^3 total cementitious and 25 to 30% fly ash substitution for cement of 16 x 10^{-12} m^2/s can be assumed. For HPC deck mixtures with less than 570 lbs/yd^3 total cementitious with 100% being cement a diffusion coefficient of $24x10^{12}$ m^2/s can be assumed. The diffusion coefficient analysis of high performance concrete bridge decks from throughout Minnesota shows that concrete mixtures using around 600 lbs/yd^3 and 30% fly ash replacement of the Portland cement have a significantly lower diffusion coefficient than mixtures using less than 570 lbs/yd^3 total cementitious without fly ash substitution. The difference in service life, as determined with Life365, between these two concretes was 300%.

For this project two methods for determining concrete diffusion coefficient were used. The first was NTBuild 492, a non-steady state method that can be completed in around 35 days. The second is a steady-state bulk diffusion test called ASTM C1556. This test provides valuable information about the concrete's diffusion coefficient, but it takes more than 70 days to complete. Diffusion coefficients measured with NTBuild 492 are typically higher than those measured with ASTM C1556. For comparing concretes, the difference between the two tests is irrelevant. For service life modeling in Life365, however, the 28-day steady state diffusion coefficient is an input. A correlation equation between diffusion coefficients determined using NTBuild 492 and ASTM C1556 was introduced that will be incorporated into the TPO timing model so diffusion coefficients determined by either method may be used in the model.

For modeling TPO application timing on new bridge decks in the absence of a measured diffusion coefficient, the 28-day non-steady state diffusion coefficient input for decks utilizing around 600 lb/yd^3 cementitious with 30% fly ash replacement for portland cement should be $16x10^{-12}$ m^2/s. For decks utilizing around 530 lb/yd^3 portland cement without fly ash replacement, the 28-day non-steady-state diffusion coefficient input should be $24x10^{-12}$ m^2/s. The model will convert these non-steady state diffusion coefficients into steady-state diffusion coefficients using the correlation equation provided by a best fit line to a plot of NTBuild 492 vs. ASTM C1556 diffusion coefficients.

Moving forward, it is recommended that a 28-day NTBuild 492 test be specified as part of the concrete mix design submittal for bridge decks with a specified maximum diffusion value. The specified target diffusion value for the 28-day diffusion coefficient could be based on service life requirement chosen by MnDOT (i.e. 75 years, 100 years).

CHAPTER 6: APPARENT DIFFUSION COEFFICIENT DETERMINED FROM CHLORIDE PROFILES OF BRIDGE DECKS WITH THIN POLYMER OVERLAYS

Chloride profiles of existing bridge decks with TPOs were obtained for the purpose of observing the chloride profile shape and, where possible, how the diffusion of chlorides was altered after the TPO application. TPOs block new chloride ion intrusion into the deck concrete until the TPO is removed, worn down, or severely cracked. Theoretically, removing the chloride source should slow the rate of chloride diffusion through the concrete because it decreases the concentration gradient of chlorides between the surface and steel. As the chloride ion concentration equilibrates across the thickness of the deck, the chloride ions move both towards the surface and towards the steel.

The bridges with TPOs evaluated in this study include Bridges 09823 in Carlton County, MN and 69006 in Virginia, MN; Bridges 9213 (82nd St. over I-35W) and 9093 (86th St. over I-35W) in Bloomington, MN; and Bridge 27758 (Penn Ave. over I-394 in Minneapolis, MN). These decks were evaluated in three ways to develop a well-rounded view of the chloride-contaminated condition:

1. Chloride profile (plot of the chloride concentration vs. the mean horizon depth)
2. Surface chloride concentration
3. Apparent diffusion coefficient

6.1 BRIDGES 09823 IN CARLTON COUNTY, MN AND 69006 IN VIRGINIA, MN

MNDOT supplied chloride profiles for two bridges—09823 and 69006—for the years of 2010, 2011, and 2014. Bridge 09823 is on southbound I-35 over CSAH 61 in Carlton County. Bridge 69006 was on northbound US 53 over 2nd Ave. southbound in the city of Virginia, MN. The TPO was applied to these bridges in 2009 although they were constructed many years earlier. The chloride profiles from Bridges 09823 and 69006 were taken as part of a separate MNDOT Study entitled, “Comparative Performance Study of Chip Seal and Bonded Wear Course Systems Applied to Bridge Decks and Approaches.” The design and repair histories of these bridges are detailed followed by analysis of the chloride profiles.

6.1.1 Bridge 09823 History

Bridge 09823 was constructed in 1965 and received a low-slump concrete wearing course in 1982 after widening. The original through-deck and transverse deck sections are shown in Figures 6.1 and 6.2.

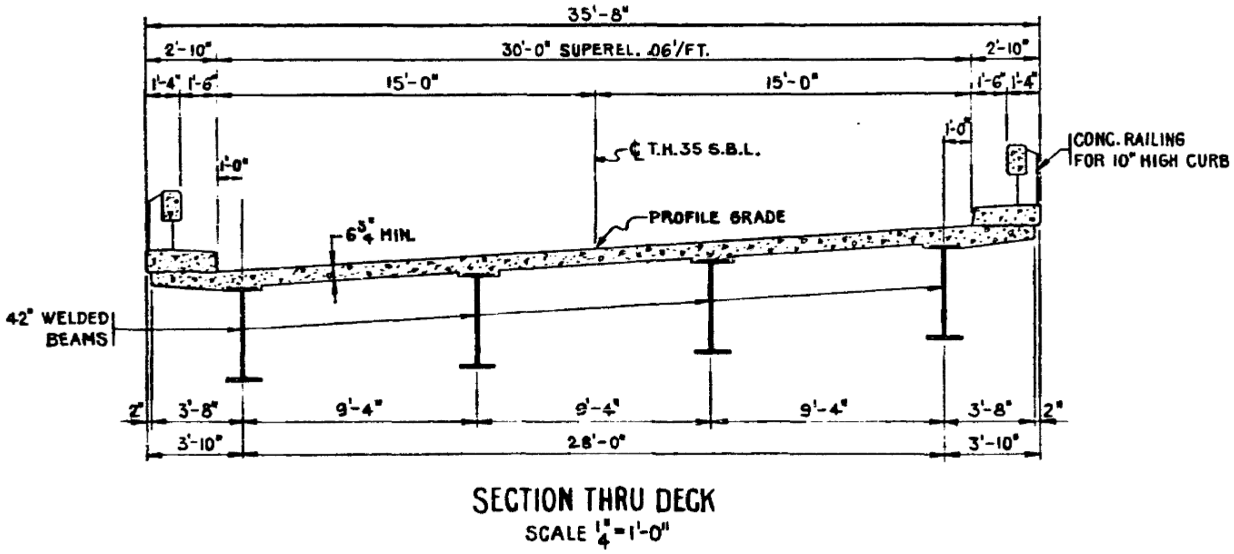


Figure 6.1 1965 bridge deck for BR 09823 in Carlton County, MN.

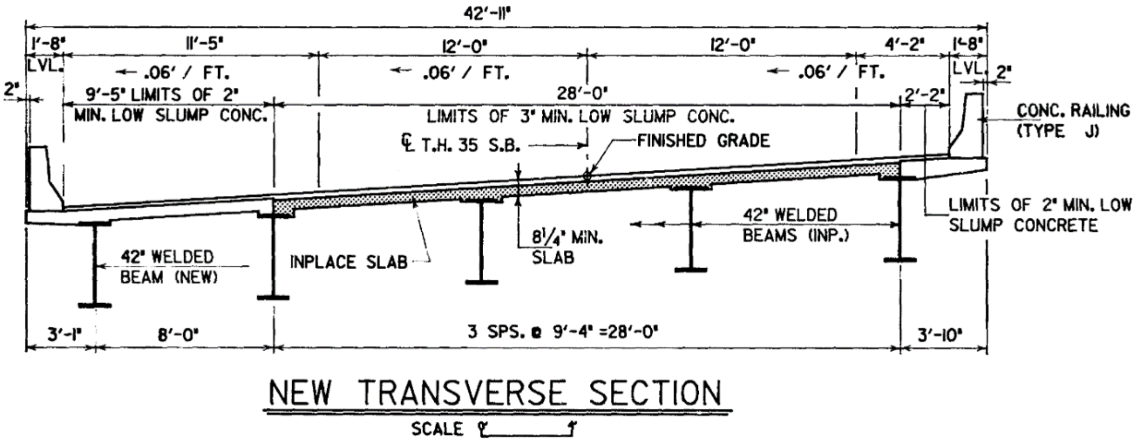


Figure 6.2 1965 bridge deck for BR 09823 in Carlton County, MN.

The original 1965 concrete deck on Bridge 09823 has largely remained in place as of 2017. The widened portion made in 1982 used epoxy coated top reinforcement and uncoated bottom reinforcement. Both the original concrete deck and 1982 widening were topped by a 1982 low-slump concrete wearing course, with thickness varying as shown. In 2009, deck patching was performed and a 3/8 in. TPO was placed in two lifts with taconite aggregate. After 8 years in service the TPO has held up well, exhibiting some cracking and polishing due to plows in ridges where a longitudinal joint was made. Figure 6.3 shows the deck and polished TPO topping in 2013.

Figure 6.3 Br 09823 in Carlton County, MN, 2013 condition with some porosity due to unclean aggregate in 2009 TPO construction. Exhibiting a polished ridge along construction joint due to plows.

6.1.2 Bridge 69006 History

Bridge 69006 was constructed near Virginia, MN, in 1969. The 8-in. bridge deck was constructed with a 2 ½ in. concrete cover to the uncoated top reinforcement. Figure 6.4 shows the bridge deck in 1972. Figure 6.5 shows a deck section from the original drawings. It was opened to traffic in 1969. In July of 1977 the deck received a waterproof membrane (“Protectowrap”) topped by a 2 ¼ in. bituminous overlay. Chloride profiles were taken 9 years later in 1986, which are shown in Figure 6.6 along with the calculated apparent diffusion coefficients and plotted in Figure 6.7. In 1987 the bituminous wearing course was replaced (due to block cracking on a 2.5-foot grid) with a 2 ½ in. low-slump wearing course along with new expansion joints, barriers and approaches. The low-slump wearing course performed satisfactorily until deck patching was performed in 2009 in conjunction with a 3/8 in. TPO. In 2017 the bridge was removed from service as part of a local reconfiguration of the crossing.

Figure 6.4 Bridge 69006 near Virginia, MN, in 1972 looking northwest.

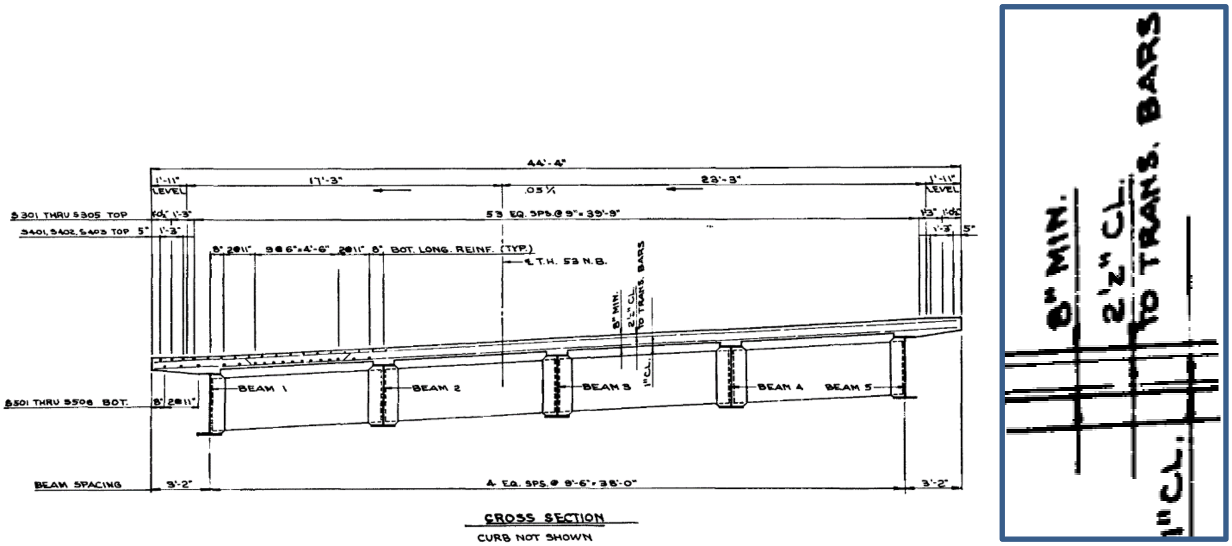
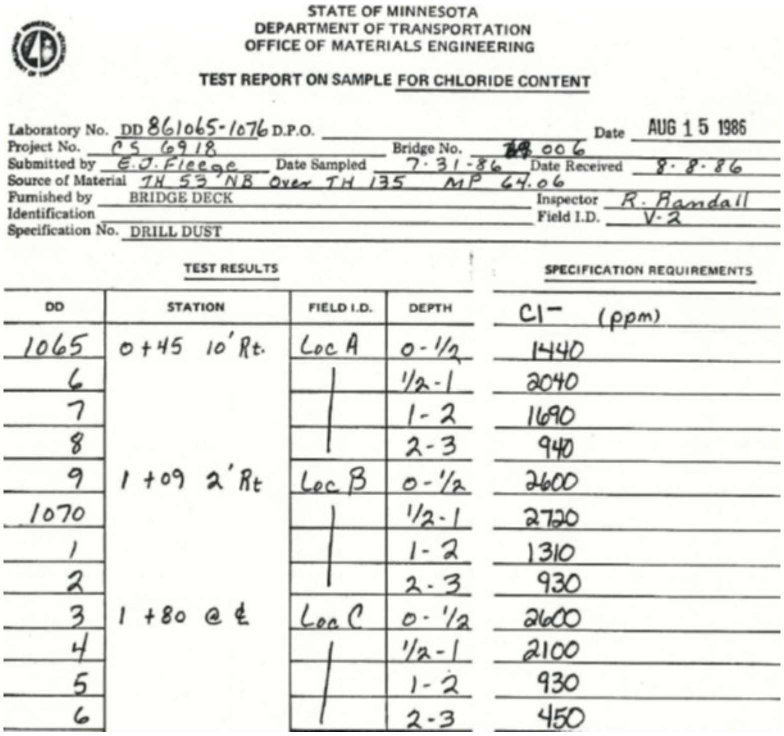


Figure 6.5 BR 69006 near Virginia, MN, 1969 deck with 2 ½-in. concrete cover.



STATE OF MINNESOTA
DEPARTMENT OF TRANSPORTATION
OFFICE OF MATERIALS ENGINEERING

TEST REPORT ON SAMPLE FOR CHLORIDE CONTENT

Laboratory No. DD 861065-1076 D.P.O. ______ Date AUG 15 1986
Project No. CS 6918 Bridge No. 69006
Submitted by E.J. Fleege Date Sampled 7-31-86 Date Received 8-8-86
Source of Material TH 53 NB Over TH 135 MP 64.06
Furnished by BRIDGE DECK Inspector R. Randall
Identification ______ Field I.D. V-2
Specification No. DRILL DUST

TEST RESULTS | SPECIFICATION REQUIREMENTS

DD	STATION	FIELD I.D.	DEPTH	Cl⁻ (ppm)
1065	0+45 10' Rt.	Loc A	0-1/2	1440
6			1/2-1	2040
7			1-2	1690
8			2-3	940
9	1+09 2' Rt	Loc B	0-1/2	2600
1070			1/2-1	2720
1			1-2	1310
2			2-3	930
3	1+80 @ ℄	Loc C	0-1/2	2600
4			1/2-1	2100
5			1-2	930
6			2-3	450

D = 4.8E-12 m^2/s

D = 2.67E-12 m^2/s

D = 1.41E-12 m^2/s

Mean D = 2.96E-12 m^2/s

Figure 6.6 Bridge 69006 chloride profiles from 1986 and calculated diffusion coefficients. 1000 ppm = 0.1% wt. of sample.

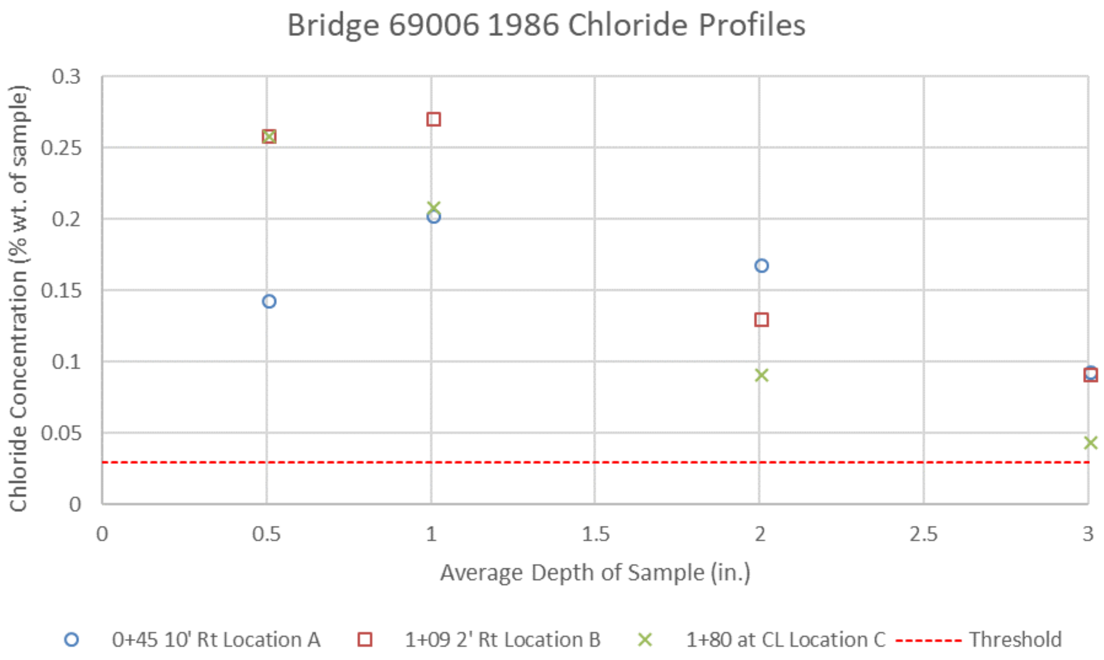


Figure 6.7 Chloride concentration vs. depth for Bridge 69006 near Virginia, MN, circa 1986

The chloride profiles in the deck as of 1986 show that the threshold chloride concentration is exceeded at the level of the reinforcing steel (2.5 in.). The chloride profiles at locations A and B show a lower chloride concentration between 0 and 1/2 in. than between 1 and 2 in. Either the surface chlorides were flushed by rain or deck maintenance before the Protectowrap and bituminous layer were installed in 1977 were applied, or the bituminous layer lowered the concentration gradient through the deck, lowering chloride concentration near the surface. At the same time, it was reported that the bituminous layer experienced severe map cracking which could have allowed chlorides to penetrate to the surface, so the constantly decreasing chloride profile at location C is believable.

6.1.3 Bridges 09823 and 69006 Chloride Profile, Surface Chloride, and Apparent Diffusion Coefficient Evaluation

TPOs were applied to Bridges 09823 (Carlton County, MN) and 69006 (Virginia, MN) in 2009, after each bridge had been in service for many years. In 2010, 2011, and 2013, multiple chloride profiles were measured for these bridges. Plots of chloride concentration versus mean horizon depth showed that chloride concentration decreased with depth in all chloride profiles. Considering the overlays, the top reinforcing steel in Bridge 09823 deck is at approximately 5.5 in. below the top of wear course, and the top reinforcing steel in Bridge 69006 deck is at approximately 5 in. below the top of the wear course. Figure 6.8 shows a plot of Bridge 09823 chloride concentration vs depth for years 2010, 2011, and 2014. Figure 6.9 shows a plot of Bridge 69006 chloride concentration vs depth for years 2010, 2011, and 2014. The 1986 chloride profiles are also plotted in Figure 6.9 at the approximate depth in the original deck and relative to the 2.5 in. wearing course applied in 1987.

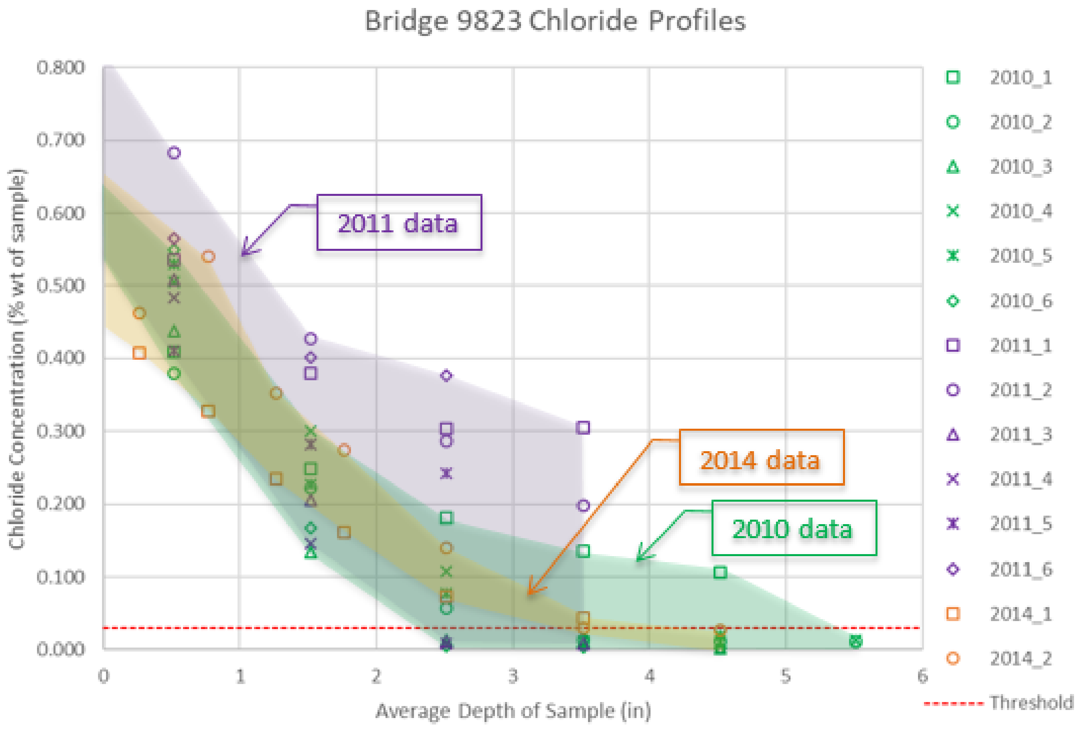


Figure 6.8 Bridge 09823 Chloride Profiles from years 2010, 2011, and 2014

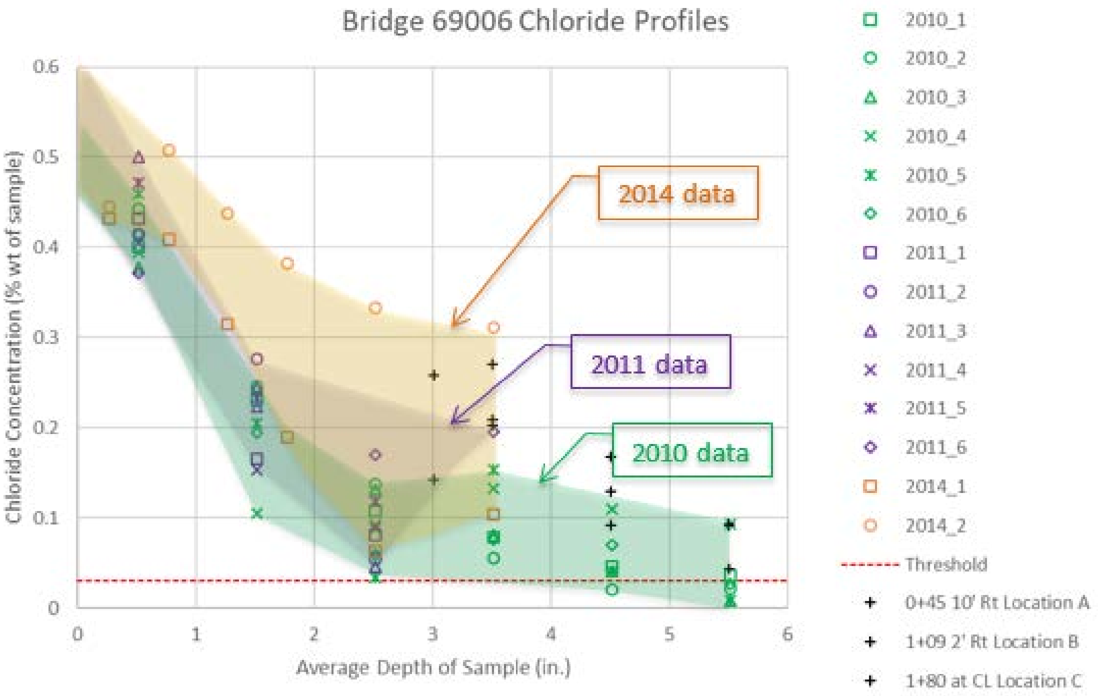


Figure 6.9 Bridge 69006 Chloride Profiles from years 1986, 2010, 2011, and 2014

Considering the chloride profiles for Bridge 09823 in Figure 6.8, the chloride concentration at the level of the reinforcing steel (5.5 in.) was less than the threshold level (0.03%). Considering the chloride profiles for Bridge 69006 in Figure 6.9, the chloride concentration at the level of the steel (5 in.) was less than that measured in 1986. All but one data point from the 2010 chloride profiles show a chloride concentration below threshold level. Also noteworthy is that a significant quantity of chlorides entered the deck between 1986 and 2010. In 1986, 17 years after construction, the chloride concentration 0.5 in. below the original deck surface was between 0.15% and 0.27%. By 2010, 23 years after the wear course was applied, the chloride concentration 0.5 in. below the wear course was between approximately 0.38% and 0.46%.

The projected chloride surface concentration for each sample set and the averages by bridge and year are shown in Figure 6.10. The projected surface chloride concentrations were extrapolated from the exponential fit equations for each chloride profile. It appears that the surface chloride concentrations at individual sample points show significant variability in concentration on both decks in a single year and over time, but the average surface chloride concentrations (larger open circles in the plot) do not show significant variation from 2010 to 2011 or 2011 to 2014. This suggests that the application of the TPO prevented further accumulation of chlorides near the deck surface.

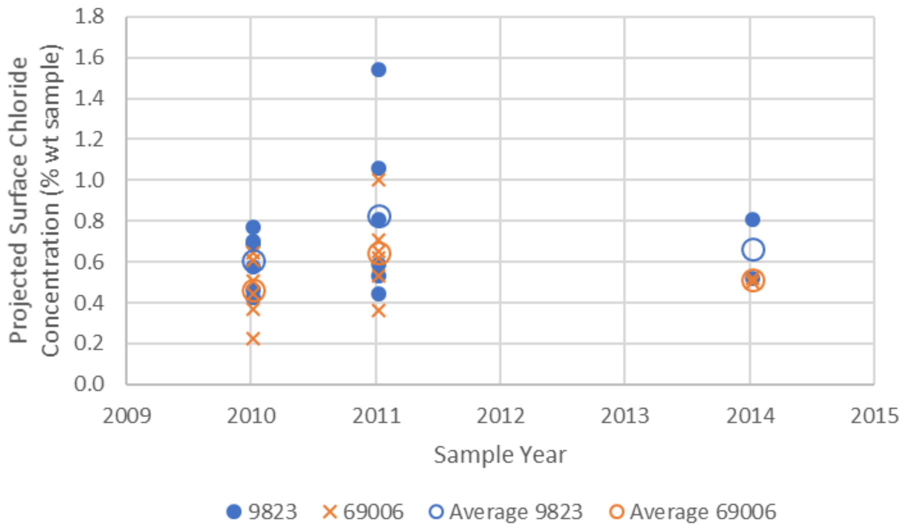


Figure 6.10 Projected surface chloride concentrations from chloride profiles by year and bridge.

Observing the general trends of chloride profiles and surface chloride concentrations for the years 2010, 2011, and 2014 in Bridges 09823 and 69006, there isn't a recognizable redistribution of chlorides due to the application of the TPO. Reasons for this include:

1. 4-5 years is not enough time to observe significant chloride redistribution in concrete with the diffusion coefficient measured (1.5 x 10^{-12} m^2/s).
2. There may have been more obvious redistribution of chlorides near the surface, but the sample horizons were too broad to capture that redistribution.

3. The chloride concentration in the wear course, especially from 0-2 in. was close enough to the assumed surface chloride concentration that cutting off the surface chlorides did not reduce the gradient.

The chloride profiles were used to find diffusion coefficient for Bridges 09823 and 69006 decks. The apparent diffusion coefficients calculated from the chloride profiles for Bridges 09823 and 69006 are shown in Tables 6.1 and 6.2, respectively.

Table 6.1 Apparent diffusion coefficients calculated from Bridge 09823 chloride profiles in Carlton County, MN

Bridge	Year Sampled	Driving or Passing Lane	Sample #	Da (m^2/s)	Mean Da (m^2/s)
09823	2010	Driving	1	4.05E-12	1.36E-12
			2	1.25E-12	
			3	0.61E-12	
		Passing	1	0.93E-12	
			2	0.72E-12	
			3	0.62E-12	
	2011	Driving	1	8.99E-12	4.15E-12
			2	2.54E-12	
			3	0.26E-12	
		Passing	1	0.65E-12	
			2	4.88E-12	
			3	7.57E-12	
	2014	Driving	1	0.85E-12	0.86E-12
		Passing	1	0.86E-12	

Table 6.2 Apparent diffusion coefficients calculated from Bridge 69006 chloride profiles near Virginia, MN

Bridge	Year Sampled	Driving or Passing Lane	Sample #	Da (m^2/s)	Mean Da (m^2/s)
69006	1986	NA	0+45 10’ Rt	4.80E-12	2.96E-12
			1+09 2’ Rt	2.67E-12	
			1+80 @ CL	1.41E-12	
	2010	Driving	1	1.70E-12	2.43E-12
			2	1.20E-12	
			3	1.00E-12	
		Passing	1	7.50E-12	
			2	1.30E-12	
			3	1.90E-12	
	2011	Driving	1	0.71E-12	1.43E-12
			2	0.30E-12	
			3	0.54E-12	
		Passing	1	0.85E-12	
			2	0.95E-12	
			3	5.20E-12	
	2014	Driving	1	1.00E-12	5.25E-12
		Passing	1	9.50E-12	

Beginning with Bridge 09823, the diffusion coefficient appears to increase between 2010 and 2011 and then decrease between 2011 and 2014. Looking at the measured diffusion coefficients in 2011, there are two diffusion coefficients that are significantly higher than the others. These diffusion coefficients were 8.99 x 10^{-12} m^2/s and 7.57 x 10^{-12} m^2/s in the driving a passing lane, respectively. Because they are comparatively high, it is possible that these samples were taken near a crack or at a location with abnormally high chloride ingress. If those data points are disregarded, the average diffusion coefficient for 2011 would more closely resemble that of 2010 and 2014.

Looking at the measured diffusion coefficients for Bridge 69006, the difference between 2010 and 2011 diffusion coefficients is reasonable and within the expected variability of the test method and material behavior. In 2014, only two samples were collected. The driving lane sample shows a diffusion coefficient similar to those measured in 2010 and 2011. The passing lane sample is large and similar to the anomalies discussed in 2011 on Bridge 09823. If it is assumed that the 2014 passing lane diffusion coefficient was measured from a sample near a crack, then the diffusion coefficients calculated for Bridge 69006 are consistent between 2010-2014.

For modeling, the diffusion coefficient could be assumed as 1.5 x 10^{-12} m^2/s for both bridges.

6.2 BRIDGES 9213 (82ND ST. OVER I-35W) AND 9093 (86TH ST. OVER I-35W)

The second set of bridge decks with TPOs evaluated by Beton included two bridges in Bloomington, MN, which share a similar history. These bridges were redecked in 1996 with a standard MnDOT full-depth deck mix at the time labeled 3Y33. In 2013, both bridges were rotomilled 3/8”, and a 3/8” TPO was applied. Chloride profiles were measured from each core sample so the diffusion coefficients could be calculated. Figure 6.11 shows the chloride profiles of 4 core samples collected from Bridges 9213 and 9092 (2 each).

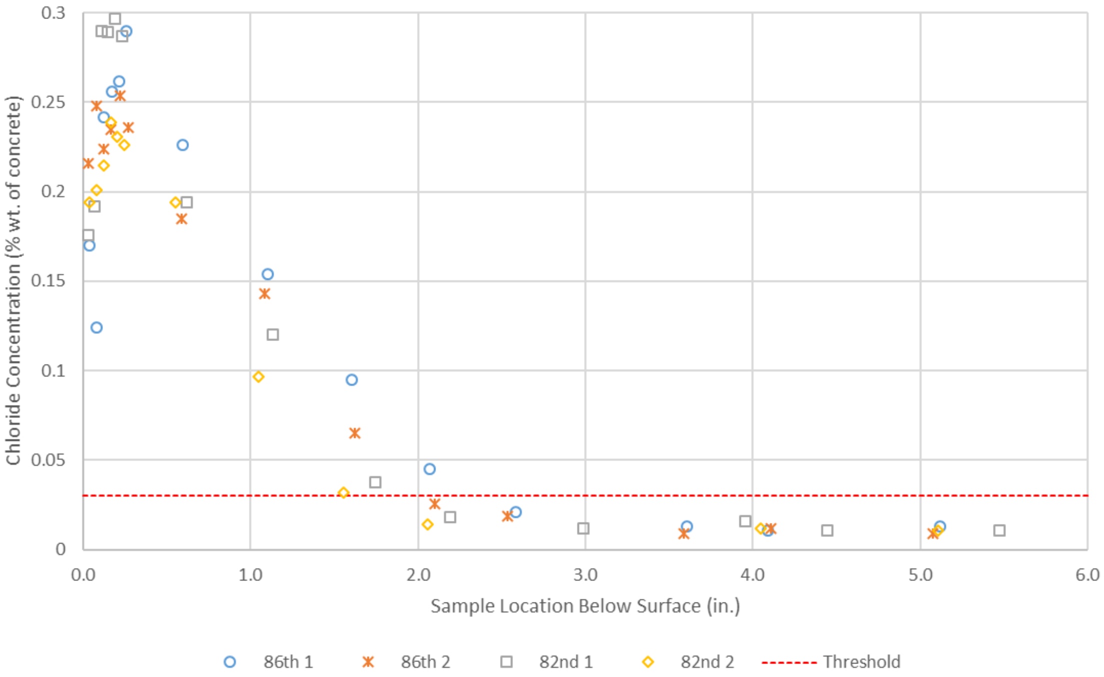


Figure 6.11 Chloride concentration vs. depth for Bridges 9213 (35W and EB 82nd St.) and 9039 (35W and EB 86th St.)

There are two interesting observations from Figure 6.11. First, assuming that the reinforcing steel is 2.5-3 in. below the deck surface, the chloride concentration at the level of the steel is below the threshold concentration in both decks. Secondly, the chloride profiles from the 82nd and 86th St. Bridges showed a peak 0.16 to 0.24 in. below the surface with a steeper sloped decrease in chloride concentration towards the surface than towards the steel. The reason for the shape of these chloride profiles may be explained by the surface preparation of the bridge deck for the TPO application. Prior to applying the TPOs in 2013, the top 3/8 in. of both decks was removed. The process removed the part of the original deck that likely had the highest chloride concentration.

Capturing the chloride concentrations close to the surface in small-depth sample horizons allowed this observation. Chloride concentrations in most of the MNDOT-supplied chloride profiles were evaluated in 1/2 to 1 in. increments, which is typical. The chloride concentrations in cores from the profiles from Bridges 9213 and 9039 were tested every 1 mm (0.039 in.). It is likely that the chloride concentration dip near the surface was not captured for most bridges because the sample horizons were too broad.

The surface chloride concentrations (C_s) and apparent diffusion coefficients of Bridges 9213 and 9039 deck concrete were determined from the data points in the chloride profiles that occurred after the peak. Table 6.3 shows the projected surface chloride concentration (Cs) and mean calculated apparent diffusion coefficients for the Bridge 9213 deck cores. Table 6.4 shows the same calculated values for the Bridge 9039 deck cores. In calculations, the background chloride concentration (Ci) was assumed as 0.01 % because it was at this concentration that the chloride profiles leveled out. Background chloride concentration is the chloride concentration that would be measured in the concrete from internal sources such as aggregates and admixtures.

Table 6.3 Mean apparent diffusion coefficients calculated for Bridge 9213 deck concrete

ID	Cs (mass %)	Ci (mass %)	Da (m^2/s)
9213-1	0.33	0.01	460E-12
9213-2	0.27	0.01	410E-12
Mean			**435E-12**

Table 6.4 Mean apparent diffusion coefficients calculated for Bridge 9039 deck concrete

ID	Cs (mass %)	Ci (mass %)	Da (m^2/s)
9039-1	0.28	0.01	490E-12
9039-2	0.24	0.01	400E-12
Mean			**445E-12**

The apparent diffusion coefficients of Bridge 9213 and Bridge 9039 deck concrete were high, allowing chloride penetration at a rate twice the mean apparent diffusion coefficient determined from the large MnDOT chloride profile data set. The explanation for the high apparent diffusion coefficients may be one or more of the following:

1. Due to refined sampling horizons, the chloride profile is not continuously decreasing. Rather there is a peak at some distance from the surface.
2. It is possible that the specification requirements, environment, concrete supplier error, or construction practices contributed to bridge deck concrete that had substandard durability characteristics.
3. Although the diffusion coefficient was high, the quantity of chloride ions at the depth of steel (assuming 2.5 in.-3.0 in.) was not yet at threshold level, which is assumed to be 0.03% by weight of concrete. Threshold level is the quantity of chlorides at the level of the steel that it takes to initiate depassivation of the steel, which then leads to corrosion.

6.2.1 Bridge 27758 (Penn Ave. over I-394 in Minneapolis, MN)

Bridge 27758 on Penn Avenue over I-394 in Minneapolis, MN, illustrated in Figure 6.12, was originally built in 1986 with a cast-in-place deck. This bridge is pertinent to this study because in 2007, the northbound lane received a thin polymer overlay while the southbound lane received a Methylmethacrylate (MMA) flood seal. Bridge 27758 had been in service for around 21 years before the TPO and flood seal were placed, so chlorides had been allowed to diffuse through the deck with a constant source of chlorides for a significant amount of time.

Figure 6.12 Bridge 27758 (Penn Ave. over I-394 in Minneapolis, MN) with a thin polymer overlay on the northbound lane (right lane) and a Methylmethacrylate flood seal on the southbound lane (left lane) placed in 2007

In September 2017, one core sample was extracted from the northbound lane and one from the southbound lane. The purpose of collecting a core from each lane was to evaluate the chloride content and apparent diffusion coefficient from similar concrete in similar environments where one sample had been covered by a TPO for 10 years and the other treated with a different repair material (MMA). The chloride profiles, predicted surface chloride values, and exponential best fit lines were plotted for the TPO and MMA samples in Figures 6.13 and 6.14, respectively.

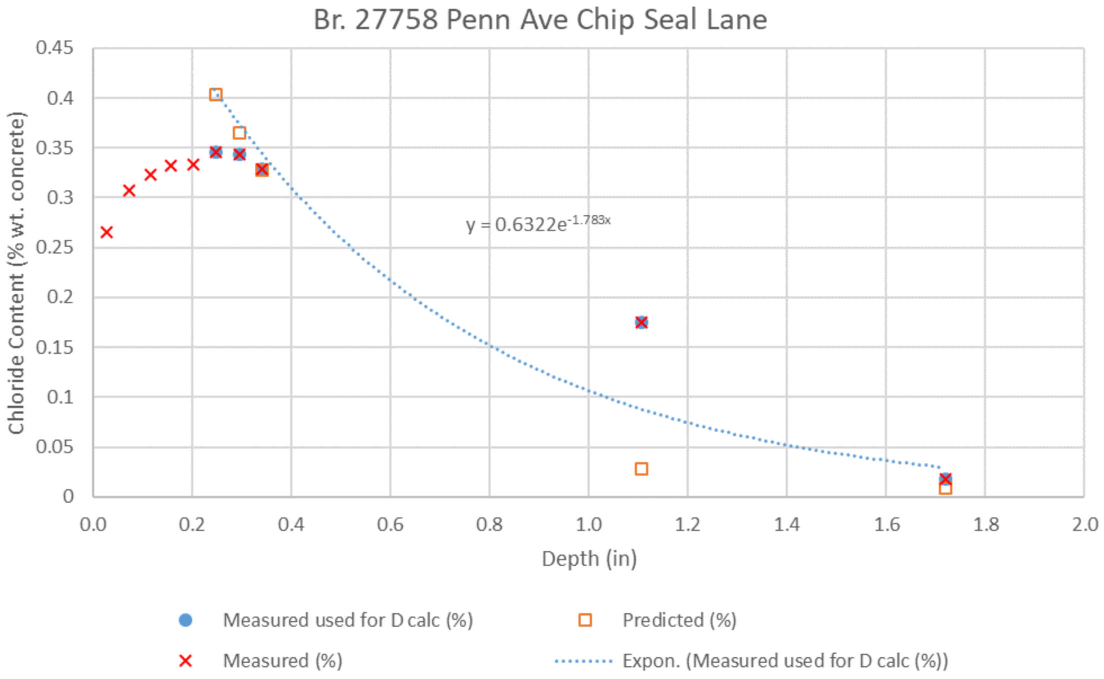


Figure 6.13 Br 27758 (Penn Ave. over I-394 in Minneapolis, MN) NB Lane (TPO applied 2007) measured and predicted chloride profiles

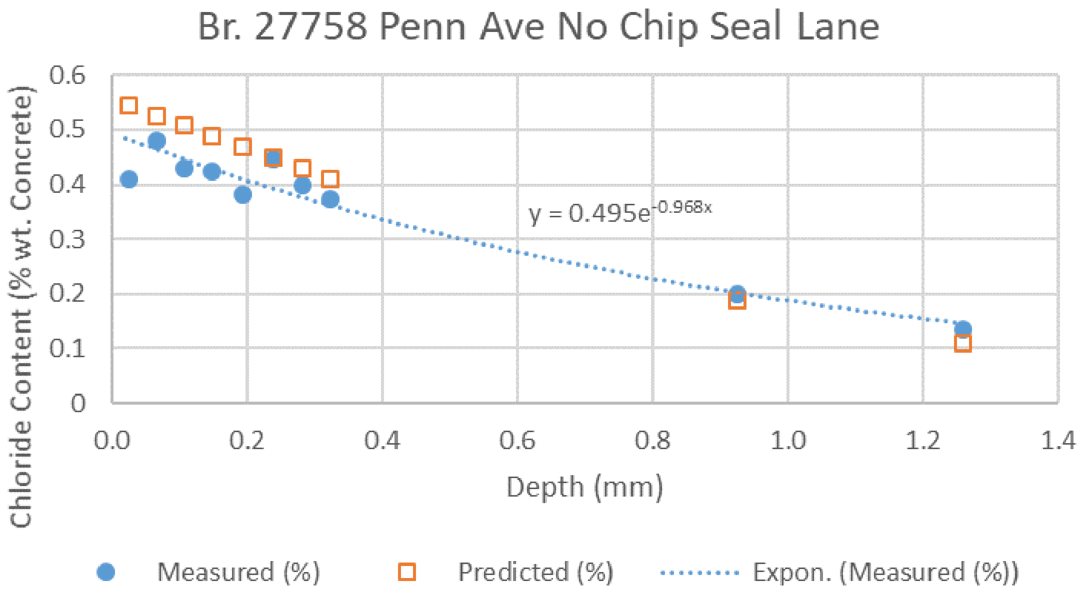


Figure 6.14 Br 27758 (Penn Ave. over I-394 in Minneapolis, MN) SB Lane (MMA Flood Seal applied 2007) measured and predicted chloride profiles

The chloride profiles, surface chloride contents, and apparent diffusion coefficients of the cores from the TPO and MMA sides of Bridge 27758 are compared in Table 6.5.

Table 6.5 Comparison of chloride profiles from two cores extracted from Br 27758 (Penn Ave. over I-394 in Minneapolis, MN) where a TPO was applied to the NB deck and a Methylmethacrylate flood seal was applied to the SB deck in 2007 after 21 years in service

	Deck Sample without TPO	Deck Sample with TPO
Chloride content within 0.31 in. of surface	varied between 0.4% and 0.5%	varied between 0.25% and 0.35%
Variability in chloride content within 0.31 in. of surface	varied by approximately 0.1% (peak value at 0.24 in. depth)	decreased by 0.1%
Chloride profile	linear and decreasing from surface to 1.5 in. below surface	nonlinearly increasing from surface to 0.24 in. then nonlinear decreasing through 1.5 in. below surface
Chloride value measure at 1 in. below surface	approximately 0.2%	approximately 0.2%
Chloride value measure at 1.5 in. below surface	0.15%	less than 0.05%

The TPO appears to have slowed the diffusion of chloride ions through the deck compared to the Methylmethacrylate flood seal as indicated by the lower chloride concentration at 1.5 in. below the surface. Since the un-cracked TPO blocks additional chloride ion accumulation on the deck surface, the existing chlorides continue to diffuse but also redistribute as shown by the chloride profiles. This is evident by comparing the chloride content within 0.031 in. of the surface between the TPO and MMA samples. The TPO sample showed chlorides 0.15% lower within 0.031 in. of the surface than the MMA sample. The MMA sample also showed that the highest chloride concentration was at the surface whereas the chlorides in the TPO sample had been redistributed throughout the depth of the deck. The dip in chloride concentration near the surface on the TPO side is corroborated by the chloride profiles observed in Bridges 09823, 69006, 9039, and 9123. The dip near the surface appears to not just be attributed to TPO surface preparation or coincidence but rather to chloride redistribution behavior after the chloride source is eliminated.

Assuming the top steel is 2.5 to 3 in. below the deck surface, and assuming a decreasing concentration of chlorides at depths greater than 1.5 in. below the surface, the current chloride content at the steel level is not yet at the critical chloride threshold of 0.2% by weight of concrete where depassivation of the steel is generally expected to start.

According to the inspection report, this bridge deck had experienced significant cracking and delamination since it was constructed, but delaminations had been repaired and cracks had been regularly sealed at 5-year intervals. During the 2016 inspection, cracks, minor delamination, and deep spalls were observed as well as exposed rebar flaking, rust, and section loss. These observations would suggest that the chloride contents should have been higher. It is probable that a majority of the corrosion in this deck is due to a high incidence of cracks where microcell corrosion has occurred versus general and widespread corrosion throughout the deck.

CHAPTER 7: EXPLANATION AND DOCUMENTATION FOR TPO APPLICATION MODEL

The primary goal of thin polymer overlay (TPO) model is to approximate chloride diffusion and chloride concentration at the level of the reinforcing steel in bridge decks. This is done so that chlorides may be allowed to accumulate within the concrete up to a certain concentration before the TPO is applied, delaying the initial investment in the TPO as well as subsequent maintenance and replacements. Once the TPO is applied, the existing chlorides in the deck will continue to diffuse and redistribute throughout the thickness of the deck but will do so without the diffusion-driving force of a concentration gradient.

In modeling, the TPO is accounted for by setting the surface chloride concentration to zero until a time at which the TPO is significantly cracked.

The TPO spreadsheet can do the following:

5. Help decision makers estimate the most economical timing for thin polymer overlay (TPO) application to bridge decks.
6. Predict rate of chloride ingress into cracked and uncracked concrete considering diffusion coefficient, decay coefficient, and pavement thickness that may vary over time due to mill and overlay procedures.
7. Plot chloride concentration over time at multiple levels below the deck surface.
8. Plot chloride concentration through the deck thickness at various deck ages.

This chapter will serve as a guide to understanding what the TPO model does. The model was programed on an Excel Spreadsheet that includes macros. The loading time is relatively lengthy due to these macros, but once loaded, the processing occurs quickly.

The model inputs are well defined in the spreadsheet, which also includes pop-up notes regarding the inputs. On each worksheet, the cells are color coded. An orange cell requires an input (or the option to change the input). A yellow cell indicates that the cell value is referenced from another location in the spreadsheet. Cells without color indicate that the cell's value was determined by calculation. An explanation of the model, its inputs, and its calculations follows.

7.1 GENERAL INPUTS

The General Inputs page is the location where most of the model's inputs can be entered. This document will not comprehensively describe every input but will expound on some of the inputs which the authors deem to be less self-explanatory.

7.1.1 Project Information

The first input section asks for project information, the diffusion coefficient, crack information, and surface chloride concentration.

7.1.1.1 Diffusion Coefficient Input

There is space to input the 28-day diffusion coefficient for the wear course, if there is a wear course, and the concrete deck "slab". In the column next to these inputs, the user indicates if the diffusion coefficient was determined by steady-state method (drill dust samples from deck or ASTM C1556) or a non-steady state method (NTBuild 492). If NTBuild 492 is used, the diffusion coefficient is transformed into a steady-state diffusion coefficient with a correlation equation. This transformation is discussed in 5.4.

7.1.1.2 Crack Input

Deck cracks are accounted for in the model by increasing the diffusion coefficient based in cracking frequency and size. The user indicates if the deck slab or overlay is cracked and then specifies the crack width and spacing interval. There are columns dedicated to structural slab cracking and columns dedicated to wear course cracking. The Smeared Crack Model (Equation 7.1) is used to adjust the diffusion coefficient to accommodate cracking. The model automatically updates the diffusion coefficients to reflect cracking conditions.

$$D_{av} = D_o + \frac{w}{l} D_{cr} \qquad \text{[Equation 7.1]}$$

D_o = uncracked diffusion coefficient (m^2/day)
D_{cr} = cracked diffusion coefficient (m^2/day)
w (input in inches) = average crack width
l (input in feet) = average crack spacing

Small width cracks can be characterized as less than 1/32 in. (0.03125 in.). Larger width cracks vary from 0.035 in. and greater. Crack width must be averaged from inspection reports or assumed based on years in service/historical data from similar bridge decks/user experience. The model converts crack width to mm.

Widely spaced cracks are 3 feet apart or greater. Crack spacing must be averaged from inspection reports or assumed based on years in service/historical data from similar bridge decks/user experience. The model converts crack spacing to mm.

The user must input a cracked diffusion coefficient, D_{cr}. With or without an inspection report, this input is subjective. A D_{cr} of 5×10^{-11} m^2/s would be a reasonable cracked diffusion coefficient for a bridge deck that had been in service for greater than 15 years with light to moderate cracking. For a bridge deck with significant cracking, a D_{cr} of 5×10^{-10} m^2/s should be used. It is up to user discretion to interpolate between these values for moderate to moderate/severe cracking.

7.1.1.3 Mill and Overlay Input

It is not uncommon for bridge decks to have a mill and overlay or a wear course added at a time after initial placement. The model accommodates these instances. In the columns adjacent to those accepting crack information, the mill depth and wear course thickness can be input in the row corresponding to the time that they occurred. The inputs are in inches. The model automatically recalculates chloride profiles based on these inputs. See Figure 7.2 for an illustration of the modeling of a slab that has received a mill and overlay.

The largest thickness of the deck throughout the modeled timeframe must be used as the boundary condition for the Excel based calculations in order to report consistent results at a given depth. This means that the model thickness may not always be the same as the combined deck and concrete wearing course thickness. See Figure 7.1 for an example. If the slab were cast monolithically in original construction at 7” thick, and then 10-years into the service life that surface was milled 1/4” followed by an added 2” concrete wearing course, the new total concrete thickness would be 7”-1/4” + 2” = 8.75”. If this milling and overlay were the only activity with the model life, then 8.75” would be the model thickness throughout the life modeled. Modeling the thickest portion throughout the life enables chloride profiles at a given depth to be reported consistently as well as establishing consistent finite element boundary conditions at the bottom of slab. The effect of this model approach means that, for the previous example, the surface chloride loading must be applied to horizons below the model surface if there is no physical concrete present during that timeframe. Figure 7.1 illustrates the effect of model thickness as compared to physical thickness.

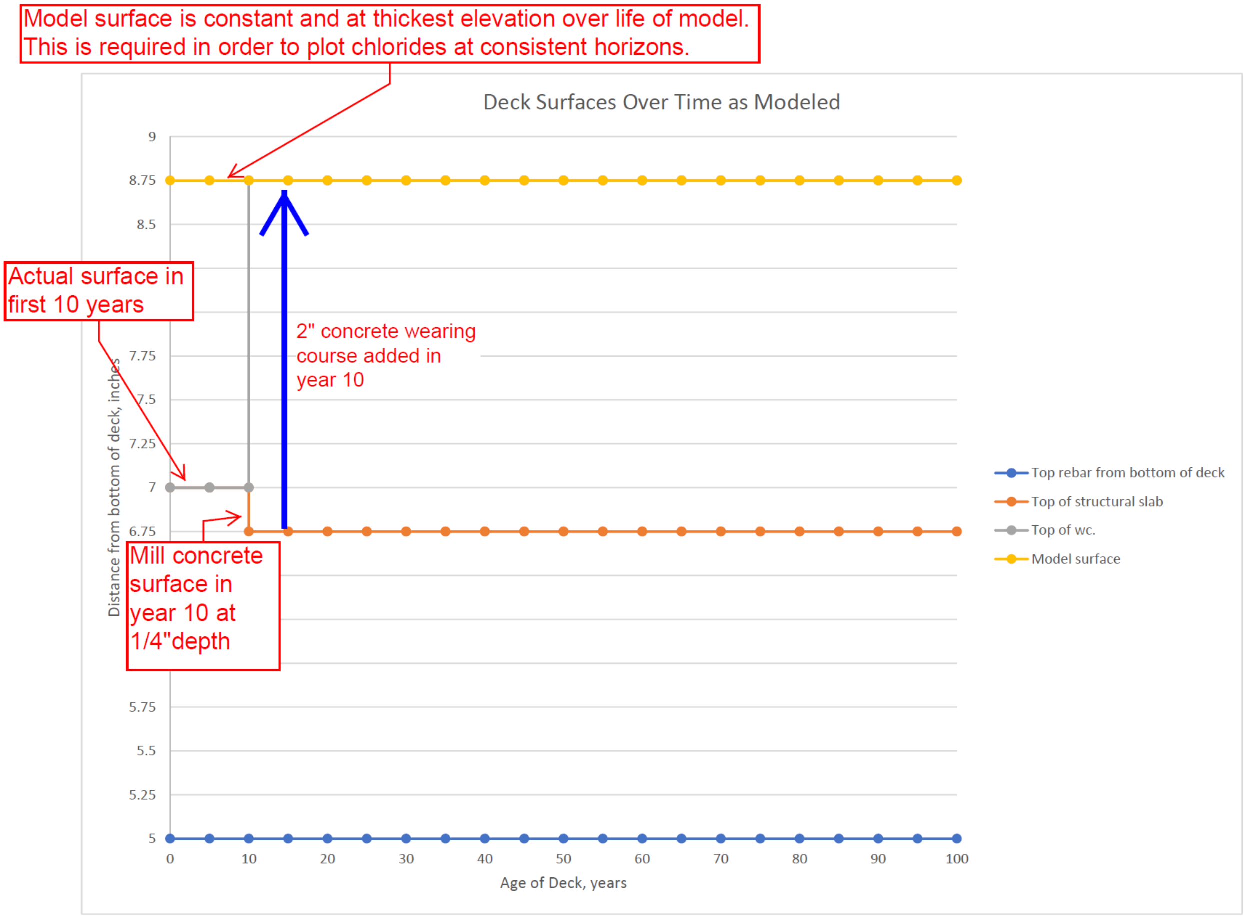


Figure 7.1 Model surface versus physical concrete surface as used in model.

A TPO is not represented by any thickness inclusion within the model, but rather it is captured by making the surface either impermeable to surface chloride or somewhat permeable if cracks are acknowledged. See the next section for further discussion.

7.1.1.4 Surface Chloride Concentration Input

There are three columns dedicated to surface chloride inputs. The values entered into these columns tell the model if there is a TPO, and when it was applied, and level of cracking. The columns ask for the surface chloride concentration without TPO, with TPO, and with a Cracked TPO. For calculations, column #22 asks for the largest value in the three columns. Although there are three columns available for surface chloride input, only the highest surface loading is used of the three columns.

As an explanation of input: if a TPO is applied at 5 years after placement, the “No TPO” chloride concentrations column should be set to zero at time = 5 years and all years following. The “TPO Intact” column should always be zero. If the TPO becomes substantially cracked, the third column will become non-zero. A starting point for chloride concentration of a cracked TPO is half the surface chloride concentration without any TPO. For example, if the starting surface chloride concentration is 0.6, then the cracked TPO surface chloride concentration would be 0.3.

The presence of three columns allows the user an opportunity to better document assumptions going into the model. In hindsight the three columns are inefficient presentation of inputs, but in the future these three columns may be revised for new input processing.

Surface chloride concentration can be estimated by evaluating chloride concentration of drill dust samples. In absence of a measured surface chloride concentration, use 0.6. The actual value at any given time is likely higher or lower, but 0.6 is a reasonable value if no other information is available. The surface chloride concentration for an intact TPO is 0. If the TPO is cracked, a starting assumption for surface chloride concentration is half that of the surface chloride concentration without a TPO.

The model was programmed to eliminate the need to run separate models when the thickness of the deck+ wearing course changed. To eliminate the requirement for a multi-spreadsheet analysis, a constant thickness deck + wear course was developed for the life of the bridge as described in 7.1.1.3. When there is a timeframe without a wearing course, it is treated as “air” and the surface chloride loading is treated as constant to the top of the actual surface at the time.

7.1.2 Definitions and Calculations

The next section of the General Inputs workbook is primarily a space where variables are defined, and assumptions are stated. The one input required in this section is “m”, which is the diffusion coefficient decay coefficient. The model requires the 28-day diffusion coefficient. The pore structure of the concrete will refine over time, so the diffusion coefficient will decrease over time. This decay coefficient defines how the diffusion coefficient will decrease. The decay coefficient is determined by Equation 5.1. For concrete mixtures with 100% Portland cement, the decay coefficient will be 0.26. The decay coefficient increases with Equation 5.1 depending on the percentage of fly ash and slag substituted for Portland cement. If the concrete mixture quantities are not known, use m = 0.56 for concrete mixtures containing at least 15% fly ash or slag and m = 0.26 for concrete mixtures using Portland cement only. A typical assumption is that the diffusion coefficient no longer decays after 25 years. This assumption is built into the model, so the decay coefficient ceases to modify the diffusion coefficient after 25 years. Where a new concrete wearing course is placed, the program restarts the wearing course age used in diffusion decay. The user should be aware that resetting the diffusion decay applies to the whole wearing course thickness even if there is a new concrete wearing course placed atop another. This is an important consideration because when a new concrete wearing course is placed with no chlorides, the model will also calculate diffusion of chlorides as moving upwards into the full thickness of the wearing course at the same time as new surface chlorides work downward through the concrete wearing course. If a new concrete wearing course were to be input as topping an old wearing course, the calculations would not recognize the chloride contamination of the topped wearing course.

7.1.3 Calculation Settings

This model determines the ingress of chlorides into concrete using the finite difference method, which defines how chloride concentration changes with time throughout the thickness of the concrete. The finite difference method requires inputs of time and distance intervals, and they are input into the model in this section of the General Inputs worksheet. A starting value for delta t (time) is 1 day. A starting value for delta y (distance) is 0.25 in. (6.4 mm). The model automatically converts inches into meters.

If the model appears to predict chloride concentrations that exceed infinity or become unstable, the increments of time and distance must be adjusted. For example, if a higher (less favorable) diffusion coefficient is used ($12x10^{-12}$ m^2/s) the model will require a larger distance (y) increment and a smaller time (t) increment than if the diffusion coefficient of the concrete was smaller—around $1x10^{-12}$ m^2/s.

The depth increments throughout the model are also referred to as horizons. In order to make the model useful for a variety of modeling scenarios, the Excel spreadsheet uses a fixed number of 31 horizons, or depths. Within these 31 depths, the first depth is always at the model surface and give 0-mm depth. In order to focus refined calculations in the upper portions of the model where concentrations are higher, the user-input y-increment is applied to any horizon less than 3” from the model surface. Beyond 3” the model distributes the horizons in expanding increments to reach the bottom of the modeled slab. Figure 7.1 illustrates the effect of changing the y-increment.

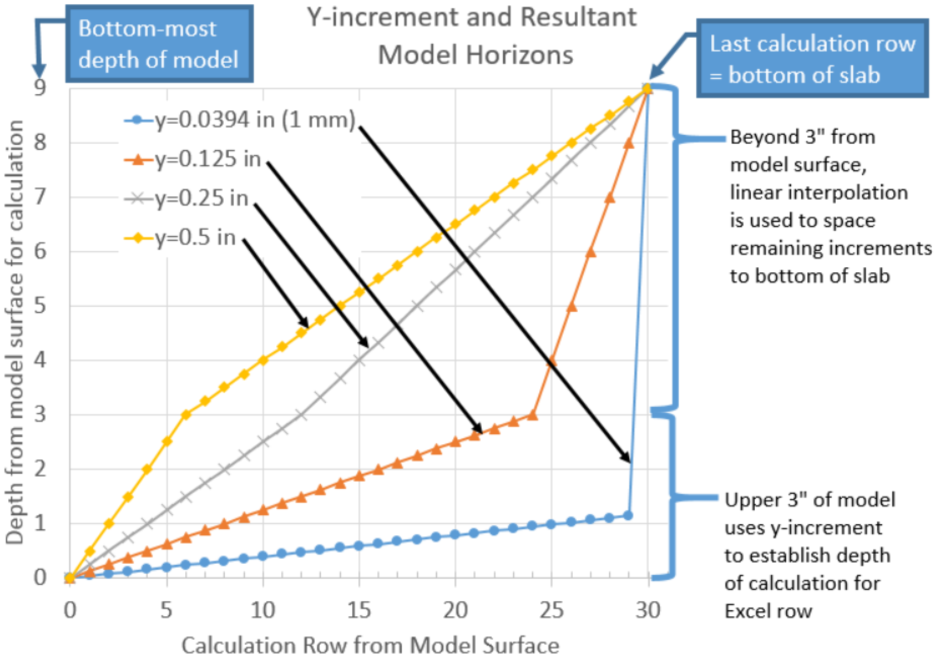


Figure 7.2 Input value of y-increment and corresponding effects on the calculation horizons for a 9” thick model. A smaller y-increment will focus more calculations within the depths closer to the model surface but spread out the depth calculations evenly beyond 3” depth to reach the bottom of slab.

7.1.4 Chart Plotting Inputs

In this section of the General Inputs worksheet, the user can adjust plotting inputs without having to manually adjust chart axes range and increments. The user must press the update button on the right side for plot settings to be updated.

7.2 CHLORIDE PROFILE

The Chloride Profile worksheet is where the user defines the chloride profile through the bridge deck.

Even for new bridge decks, the chloride concentration is never zero. All concretes contain chlorides from aggregates and admixtures, and this concentration is typically called the background chloride concentration. The background chloride concentration is typically very low, but not inconsequential. It can be measured but is often assumed. For materials used in Minnesota, the background chloride concentration can be assumed as 0.005%-0.01% total cementitious if an actual number is not available.

For new decks, the chloride profile will consist of depths (i.e. 0, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 5, 6, 7, 8, and 9 in.) and background chloride concentration (i.e. 0.01%). If the deck is in service, the user should have a chloride profile that has been measured. The user can input the chloride concentrations at the depths they were evaluated, filling in the background chloride concentration for depths not tested.

7.3 CALCULATIONS

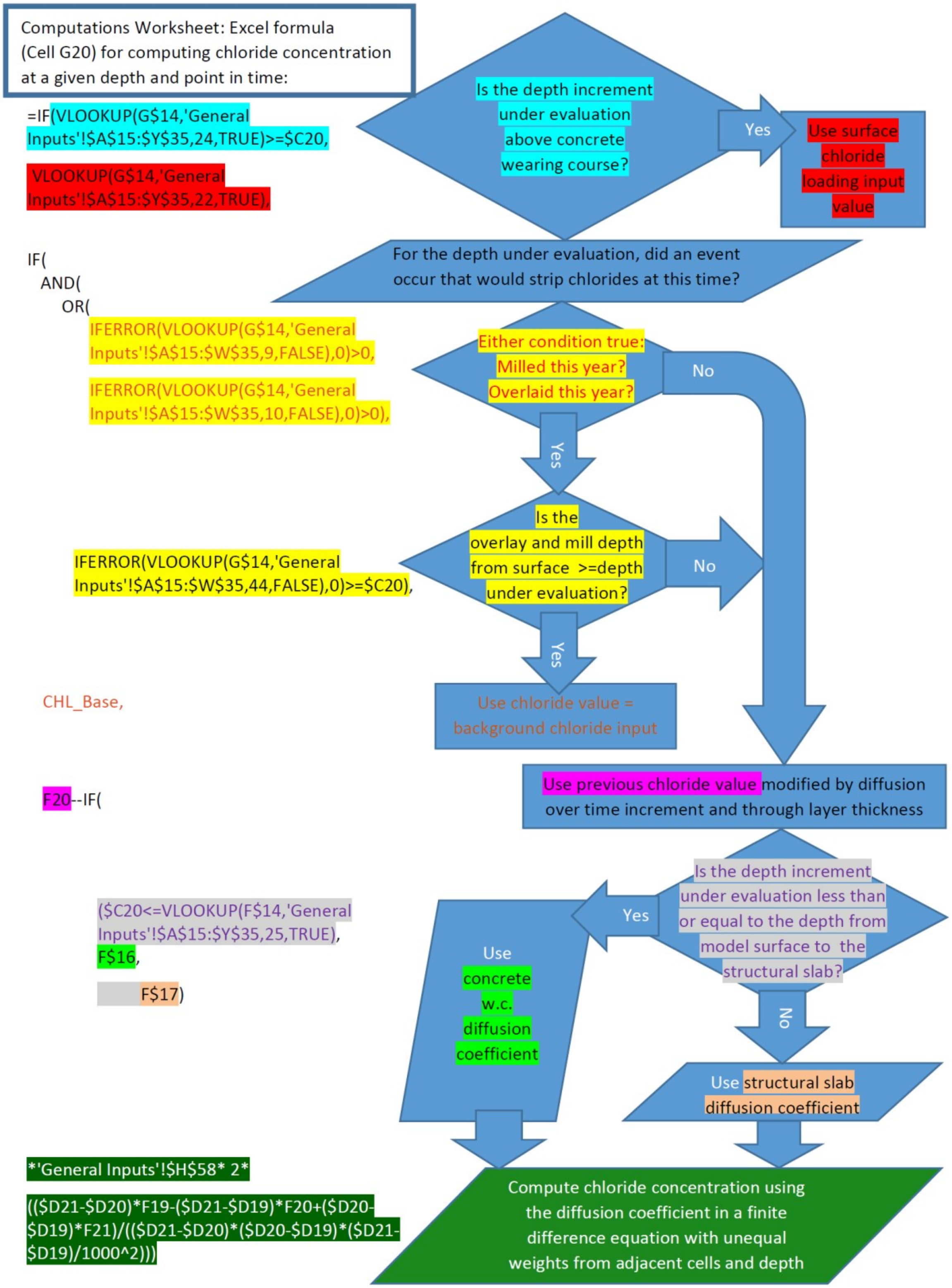
The calculations worksheet uses the central finite difference method to solve the differential equation that calculates the ingress of chloride ions into concrete. Fick's Second Law is used to calculate the chloride concentration at depth y and at exposure time, t. A discussion of Fick's second law is included in 4.1.3.

This worksheet is the engine of the spreadsheet. There are no user inputs required on this worksheet except to define how many calculation cells there are. Each column represents a time increment for which chloride levels are determined at each horizon depth. The formula for finite difference on unequal weights was adapted from A. Singh and B. S. Bhadauria paper, "Finite Difference Formulae for Unequal Sub-Intervals Using Lagrange's Interpolation Formula", for three-point finite difference:

$$f''(x) = \frac{2[h_2 f_0 - (h_1 + h_2) f_1 + h_1 f_2]}{h_1 h_2 (h_1 + h_2)} \qquad \text{[Equation 7.2]}$$

f_0 = chloride concentration from prior time increment and upward horizon
f_1 = chloride concentration from prior time increment and same horizon
f_2 = chloride concentration from prior time increment and next lower horizon
h_1 = depth increment between upward horizon and horizon under evaluation
h_2 = depth increment between next lower horizon and horizon under evaluation

There are a number of reference values that must be called to determine the chloride concentration at each instant in time and at each depth. A complete flowchart for one cell within the Excel computation worksheet is included in Figure 7.3. This flowchart illustrates the logic to determine whether a chloride should be diffused at the given depth and time or if there is an event or boundary condition that should override the normal finite difference distribution.



Computations Worksheet: Excel formula (Cell G20) for computing chloride concentration at a given depth and point in time:

```
=IF(VLOOKUP(G$14,'General
Inputs'!$A$15:$Y$35,24,TRUE)>=$C20,

VLOOKUP(G$14,'General
Inputs'!$A$15:$Y$35,22,TRUE),


IF(
  AND(
    OR(
        IFERROR(VLOOKUP(G$14,'General
        Inputs'!$A$15:$W$35,9,FALSE),0)>0,

        IFERROR(VLOOKUP(G$14,'General
        Inputs'!$A$15:$W$35,10,FALSE),0)>0),


      IFERROR(VLOOKUP(G$14,'General
      Inputs'!$A$15:$W$35,44,FALSE),0)>=$C20),


CHL_Base,


F20--IF(


        ($C20<=VLOOKUP(F$14,'General
        Inputs'!$A$15:$Y$35,25,TRUE),
        F$16,

              F$17)


*'General Inputs'!$H$58* 2*

(($D21-$D20)*F19-($D21-$D19)*F20+($D20-
$D19)*F21)/(($D21-$D20)*($D20-$D19)*($D21-
$D19)/1000^2)))
```

Figure 7.3 Calculation logic within one cell of calculations worksheet for computing chloride concentration.

Due to the small nature of the diffusion coefficient (on the order of 6×10^{-12}), the time increments must be set to 1-day duration or less in order for the finite difference method to function. With each column accumulating only a small time step, many columns of calculations are required to obtain a relevant analysis timespan. The number of small times steps using the finite difference method quickly uses the number of columns available in one spreadsheet, so rows of calculations representing the full slab thickness are stacked. The calculations can be continued as many times as the user requires to evaluate chloride migration over the time of interest (i.e. 10 years, 50 years, 100 years). The size of the file and computing speed are dependent on the number of calculation cells. The default spreadsheet has grown to 118 MB due to using calculations in four stacked sets of 31-rows and all available Excel columns. Once loaded, the user may evaluate different scenarios rapidly, iterating with diffusion coefficients to match a known chloride profile or to predict effects of different overlay strategies.

7.4 PLOTS

The model produces three plots.

The first is in the tab titled “Modeled Deck”. Here, the user can check that their modeled surface corresponds to the in-situ deck surface. This plot is especially important if the deck has received overlays and/or mill and overlays or wear courses. This plot also shows the depth of the top mat of reinforcing steel compared to the deck surface.

The second plot is in the tab titled C profiles time. Each curve represents the chloride concentration (wt. chloride/wt. of sample) at a depth during the time span indicated on the x-axis. Note that the surface chloride concentration goes to zero at whatever year the TPO is applied (vertical line).

The third plot is in the tab titled C profiles depth. Each curve represents the chloride concentration at a time in years at the range of depths below surface indicated in the x-axis. The time values are indicated in the legend and depend on what is set as the step interval on the calculation page. Black bar corrosion risk is shown in color bands.

The plotting data is accumulated and manipulated in the tab titled, “Plot Data”. There are no user inputs on this worksheet. However, the user may utilize empty cells for plotting known chloride profiles on the “C profiles depth” chart. Mapping of known chloride profiles on the chart enables the user to try to back-calculate the effective diffusion coefficient and effective surface loading necessary for a match. Such a match would enable the user to project chloride profiles moving forward in time. See Figure 7.4 for illustration of “C profiles depth” chart and a plot of predicted chloride profile against user-input chloride profile.

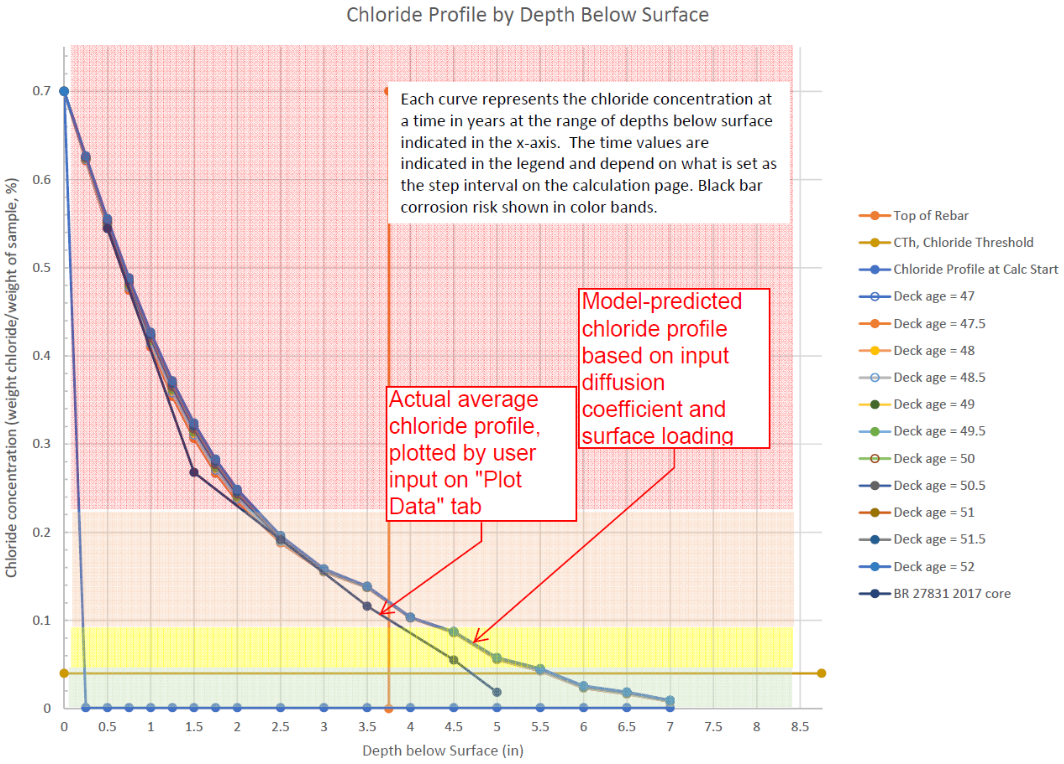


Figure 7.4 From a known average chloride profile, the user may iterate to determine the diffusion coefficient and surface loading parameters that will generate a matching chloride profile in the same service year that the chloride profile was obtained.

CHAPTER 8: SUMMARY AND RECOMMENDATIONS FOR FUTURE WORK

8.1 SUMMARY

The primary goal of this project was to develop a model that predicted the most cost-effective time after bridge deck placement for thin polymer overlay (TPO) application. The model uses Fick's Second Law and the Central Finite Difference Method to predict the concentration of chloride ions throughout the depth of the bridge deck at any time. Its primary inputs are diffusion coefficient, decay coefficient, concrete thickness, and time step. The model allows the user to alter the surface chloride concentration and thickness due to overlays and can modify the diffusion coefficient for cracking.

The model implements Fick's Law and works effectively with the input variables. However, accurately selecting input values and establishing chloride concentrations that represent deck end of life is a challenge to MnDOT asset management. Chloride threshold is the chloride concentration at the level of the reinforcing steel when corrosion initiates and can be used as an indicator for end of service life. There is not consensus on chloride threshold concentration limits, as it is determined, in part, by the number of defects in the reinforcement steel, reinforcement coating, and number of layers of reinforcing steel and coating. Life365, a commonly used service-life software, by default defines the end of service life as the time when the chloride concentration at the level of the reinforcing steel reaches the threshold concentration of 0.05% per weight of concrete (500 ppm). The literature review cites a source that defines threshold concentration as 0.03% by weight of concrete (300 ppm) or 0.2% by weight of cement. For epoxy-coated reinforcement, recent studies suggest an allowable mean chloride threshold of 1.15% by weight of cement with a standard deviation of 0.35%. The chloride concentration at the level of the reinforcing steel in many Minnesota bridge decks has far surpassed 0.03% (300 ppm) and there are no signs of corrosion or the corrosion is minimal. Assessing the optimal threshold chloride concentration for the Minnesota DOT is important for implementing the model as a standard assessment tool.

Besides TPOs, service-life predictions can guide decisions for wearing course toppings, maintenance, and bridge deck replacement. The model development is an initial effort to build logic towards these greater goals.

A secondary goal for this study was to approximate a diffusion coefficient that could be used for modeling the remaining service life of in-place bridge decks if no information about chloride concentration or concrete mixture design was known. For monolithic bridge decks, the average diffusion coefficient was 1.68×10^{-12} m^2/s as extrapolated from chloride profiles of aged decks. For low-slump overlays, the average diffusion coefficient was 2.62×10^{-12} m^2/s. Both of these average values encountered standard deviations that were greater than the mean diffusion coefficients. In this case, the variability in the data that makes up the mean was so large that the mean diffusion coefficient value was not reliable.

The case studies performed to date (See Appendices C and D) is exercise established that there is not a standard diffusion coefficient that can be used to estimate the service life of in-service bridge decks. Many of the bridge decks used to determine the average monolithic and low slump overlay diffusion coefficients were built under the same set of specifications, yet each bridge performed and behaved uniquely due to local materials, time of year constructed, or craftsmanship. Modeling decks from bridge opening date while using the mean diffusion coefficients underestimated chloride profiles later in bridge life when compared to measured chloride profiles. On the other hand, using higher initial diffusion coefficients that decayed to the average coefficients resulted in overestimating the chloride profile. This experience suggests that the model is best suited to predict chloride concentrations looking forward with confirmed current chloride profile and associated diffusion coefficient.

The diffusion coefficient for existing bridge decks was obtained by extrapolating from plots of laboratory chloride profiles as well as from ASTM C1556. Both these methods of determining diffusion coefficient are considered steady state, or long-term, diffusion results. The diffusion coefficients of new bridge decks were determined with NTBuild 492. This test is a non-steady state test rather than a steady state bulk diffusion coefficient test. There are many benefits of using NTBuild 492 to measure diffusion coefficient instead of ASTM C1556, including cost and test duration. The downside to this testing procedure is that it typically predicts a diffusion coefficient around 2×10^{-12} to 4×10^{-12} m^2/s *greater* than the steady state test. The model includes an equation for converting the non-steady state diffusion coefficient to a steady state diffusion coefficient. The correlation equation should be universal because diffusion coefficient measurements are based on pore structure, not mix constituents. MnDOT could further refine this relationship by testing bridge deck samples with both NTBuild 492 and ASTM C1556.

For new bridge decks placed in 2016, it was determined that bridge decks with 30% fly ash and around 600 lbs/cy cementitious material had diffusion coefficients almost an order of magnitude lower than bridge decks with no fly ash and around 530 lbs/cy cementitious material. The diffusion coefficients were measured when samples were 365 days instead of 28 days. A diffusion coefficient decay formula was used to back calculate the 28-day diffusion coefficient from the 365-day diffusion coefficient, but the resulting diffusion coefficients were large and questionable given the concrete mixtures used. Moving forward, it is recommended that two 4x8-in. cylinders be collected from each new concrete bridge decks placed for a period of two years and the diffusion coefficient evaluated using NTBuild 492. The data can be analyzed for variability and used to make decisions about bridge deck concrete specifications and service life.

8.2 ASSESSING INFLUENCE OF VARIABLES AFFECTING SERVICE LIFE PREDICTION

The accuracy of variables both included in the model and currently missing from the model requires discussion. The primary mechanism driving the model is the diffusion coefficient. If the diffusion coefficient is not accurate for a particular deck, the model's service life prediction will not be accurate. Diffusion coefficient values can vary between locations throughout the deck and are dependent on moisture influence (e.g., ponding location influence). Diffusion values also vary over time. The decay formula (Equation 5.1) is this model's approach to characterizing the reduction of the diffusion coefficient over time. Another variable that is difficult to define is the surface chloride concentration. Surface chloride loading varies according to bridge location and is not consistent throughout the year. Rain and wetting/drying cycles in non-salting months change the surface chloride concentration over time. While MNDOT maintenance districts can estimate the salt loading application to roads and bridge decks, determining how that translates to actual surface chloride concentration is more difficult. Chloride profiles give us a clue as to what that surface concentration should be (0.3-0.7%), but their reliability remains low. Temperature is also a factor that affects how chloride ions diffusion through concrete. In winter months, diffusion slows significantly. In summer months, chlorides can diffuse more quickly. A quick estimate of how diffusion is influenced by temperature in Minnesota using the Arrhenius equation suggests that temperature is only a small factor in diffusion. Ignoring it may lead to small errors in concrete service life predictions, but the error is insignificant compared to the variability and potential error introduced into service life prediction due to the measurement error of the diffusion coefficient.

Many of the surveyed bridge decks are cracked. MnDOT bridges undergo routine crack sealing as part of the maintenance protocol, but many times the sealant is missing or ineffective during the service interval. The model developed to predict TPO timing allows users to account for deck, wear course, and TPO cracking. The model uses the smeared crack model to modify the diffusion coefficient based on crack width and spacing. Crack width and spacing must be gleaned from inspection reports or site visits and their values averaged based on the condition of the whole deck. Model case studies to date have not been able to quantify the influence of cracks on deck service life predictions, nor has the smeared cracking model been validated for its influence in TPO-covered decks. While MnDOT deck cracking levels have diminished due to use of better construction, better concrete, and incorporation of nonmetallic fibers in the concrete mixtures, unsealed cracks remain a highly influential factor on deck service life.

8.3 FUTURE WORK

Either through a detailed study or through use, users must understand how the reliability of diffusion coefficient, decay coefficient, surface chloride concentration, actual diffusion time, and cracking affect the model's service-life prediction. Future work surrounds further use of the model to identify weaknesses as compared to other approaches previously taken. Similar to that found in Life365, a reliability could be assigned to each of these variables and the model could expand to include a probability analysis of the service life. At the time of finishing this research, modeling case studies had just been undertaken revealing new avenues for the model's improvement and the need to look into variables discussed which are not currently addressed into the model. For instance, currently the model does not recognize stopping salting of bridge decks from Mid-April through mid-October in Minnesota, and there is not a recognition of temperature effects on diffusion through the pore structure.

It is also believed that there may be value comparing model chloride versus time predictions to concrete patching levels experienced in Minnesota bridge decks. With enough case studies, relationships may be established mapping chloride exposure time and chloride concentration in the Minnesota environment to patching areas. Such an approach would greatly supplement the historical use of the chloride threshold as the end of service life. Recognizing many decks in MnDOT inventory perform well despite the chloride threshold being exceeded, the refinements in predicted patching levels would be very useful to balancing bridge preservation investment against delamination and spalling-induced service interruption risks.

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APPENDIX A: DIFFUSION COEFFICIENT CALCULATIONS FROM MNDOT CORES

Bridge #	Location	Year Built	Wear Course Year	Wear Type	Diff. coeff.		Core Depth (in)
3575A	St Paul/Ramsey county @ JCT Ford pkwy. 2074(MISS R BD) over Ravine.	1927 Remodeled 1973	1984	Mono.	9.13	E-12	4
4011	Watowan county	1923	NA		7.42	E-13	3
4017	NA	NA	NA		4.36	E-12	VARIES
4018	Mayville TWP. Houstan county	~1920	NA		3.26	E-13	VARIES
4019	NA	NA	NA		6.15	E-13	VARIES
5151 (2011)	Marshall/Lyon county @ 0.7mi SW of Marshall. TH 19 over Redwood river.	1932	2013	LS	1.13	E-12	VARIES
5151 (2012)	Marshall/Lyon county @ 0.7mi SW of Marshall. TH 19 over Redwood river.	1932	2013	LS	4.98	E-12	VARIES
5772	Duluth/St Louis county	1928 redecked 2010	2005	Bit.	BAD DATA		VARIES
5900	Winona/Winona county	1941 rehab 1985	1985	Mono.	4.06	E-12	VARIES
5962	St Paul/Ramsey county	1942 remodeled 1981	1981	LS	1.58	E-12	3
6347	Franconia/Chisago county	1953 redecked 1980 remodeled 2010	2010	OTHER	7	E-12	4
Bridge #	Location	Year Built	Wear Course Year	Wear Type	Diff. coeff.		Core Depth (in)

7272	St Paul/Ramsey county	1959 rehab 2000	1979	LS	0.535	E-12	3
7276	St Paul/Ramsey county	1959 rehab 1982	1982	LS	5.74	E-12	3
9090	East Grand Forks/Polk county at ND state line	1963	1984	LS	6.86	E-12	VARIES
9103	Redwing/Goodhue county @ JCT TH 63	1960	1978	LS	9.39	E-12	VARIES
9451	St Paul/Ramsey county @ Vandalia st. bridge	1967	1998	LS	7.22	E-12	4
09823	Lino Lakes/Anoka county @ 3.6miles NE of JCT TH 49. I35W over Rice Creek	1967	NA	Mono.	2.49	E-12	VARIES
9832	Twin Lakes/Carlton county @3.5mi S of JCT TH 210 I35 SB over CSAH 61	1965	1982	LS	4.24	E-12	VARIES
35007	St Vincent/Kittson county @ ND state line TH 171 over red river of the north	1982	NA	Mono.	1.86	E-12	VARIES
62080	St Paul/Ramsey county @ 0.5mi E of JCT TH 52 Kellogg blvd over RR& I94 & Comm & Fox st	1982	1983	LS	1.55	E-12	4
62515	St Paul/Ramsey county @ 0.2mi N of JCT MSAS 137. MSAS 113(Lafayet) over BNSF & CP rail	1969	1983	LS	1.78	E-12	4

Bridge #	Location	Year Built	Wear Course Year	Wear Type	Diff. coeff.		Core Depth (in)
62523	St Paul/Ramsey county @ 0.2mi N of JCT MSAS 164. Dale st over BNSF RR	1970	1986	LS	BAD DATA		VARIES
62527	St Paul/Ramsey county	1974	1990	LS	0.782	E-12	4
62528	St Paul/Ramsey county @ 0.47mi S of ford pkwy. MSAS 194(Cleveland) over CP RR	1975	1988	LS	3.56	E-12	4
62530	St Paul/Ramsey county @ 0.3mi S of JCT CSAH 31. CSAH 65(WHT BR ave) over UP RR	1975	1988	LS	3.01	E-12	4
62532	St Paul/Ramsey county @ 0.1mi SE of warner RD. MSAS 234(EB RP) over MSAS 234(Childs road) & RR	1980	1980	LS	1.34	E-12	4
62533	St Paul/Ramsey county @ 0.1mi E of JCT Payne ave. MSAS 108(MHAHA) over RCRRA & Strohs	1978	1988	LS	13.5	E-12	4
62541	St Paul/Ramsey county @ western ave. Como ave over BNSF RR	1985	1985	LS	1.42	E-12	3
62544	St Paul/Ramsey county @ 0.1mi N of M'haha ave. MSAS 179(Payne ave) over UP RR.	1985	1985	LS	4.95	E-12	4

Bridge #	Location	Year Built	Wear Course Year	Wear Type	Diff. coeff.		Core Depth (in)
62581	St Paul/Ramsey county @ 200' N of Maryland. Lorient st over Sewer.	1996	1996	LS	3.78	E-12	4
69002 core water sol	Hibbing/St Louis county @ 3.7mi S of N JCT TH 73. US 169 over DM&IR RY	1961	1978 + 2009	LS	3.69	E-12	VARIES
69002 core	Hibbing/St Louis county @ 3.7mi S of N JCT TH 73. US 169 over DM&IR RY	1961	1979 + 2009	LS	5.17	E-12	VARIES
69002 water sol	Hibbing/St Louis county @ 3.7mi S of N JCT TH 73. US 169 over DM&IR RY	1961	1980 + 2009	LS	2.35	E-12	VARIES
69002	Hibbing/St Louis county @ 3.7mi S of N JCT TH 73. US 169 over DM&IR RY	1961	1981 + 2009	LS	3.34	E-12	VARIES
69003 water sol	I169 up north	1961	1978 + 2009	LS	2.15	E-12	VARIES
69003	I169 up north	1961	1979 + 2009	LS	No data		VARIES
69006	Virginia/St Louis county @ 1.8mi SE of JCT TH 169. US 53 over 2nd ave SB	1969	1987	LS	1.71	E-12	6
69006 (2)	Virginia/St Louis county @ 1.8mi SE of JCT TH 169. US 53 over 2nd ave SB	1969	1987	LS	2.93	E-12	VARIES
69109	Duluth/St Louis county @ E JCT TH 35. US 2 EB on ramp over CP rail	1983	1983	LS	0.871	E-12	VARIES

Bridge #	Location	Year Built	Wear Course Year	Wear Type	Diff. coeff.		Core Depth (in)
90378	St Paul/Ramsey county @ JCT exchange st. MSAS 158(Kellogg) over MSAS 258(Exchange)	1936 + 1995	1984	Mono.	1.49	E-12	4
92797	NA	NA	NA	NA	2.27	E-12	4
92798	St Paul/Ramsey county @ market st	1936 + 1978	2001	LS	0.75	E-12	4
93619	St Paul/Ramsey county @ JCT market st. MUN 891(Hill st) over building.	1912 + 1984	NA	Bit.	0.791	E-12	4
T9R392	NA	NA	NA	NA	1.42	E-12	6

APPENDIX B: CHLORIDE PROFILES AND DIFFUSION COEFFICIENT DETERMINATION FROM CENTRAL MINNESTOA BRIDGE DECK CORES

6870	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.7909	0.005	9.99E-14		
2	0.1107	0.005	1.22E-12		
3	0.6444	0.005	8.20E-14		
Average			**4.67E-13**	yes	2.25-3 in.
ID	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.4376	0.005	2.20E-11		
2	0.4796	0.005	2.00E-12		
3	1.1923	0.005	9.00E-13		
Average			**8.30E-12**		
6897	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.2852	0.005	2.90E-12		
2	0.4016	0.005	3.40E-13		
3	0.1788	0.005	6.80E-13		
Average			**1.31E-12**	yes	2.25-2.5 in.
73566	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.8427	0.005	4.32E-13		
2	0.5364	0.005	1.14E-12		
3	0.6021	0.005	2.65E-12		
Average			**1.41E-12**	yes	2-2.5 in.
73804	**Cs(mass %)**	**Ci(mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.3762	0.005	4.99E-13		
2	0.667	0.005	3.59E-13		
3	0.3701	0.005	4.91E-13		
Average			**4.50E-13**	yes	3.5-3.75 in.

73805	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.3719	0.005	4.42E-12		
2	0.3224	0.005	8.60E-13		
3	0.3701	0.005	4.90E-13		

Average			**1.92E-12**	yes	1.75-2 in.
73806	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.3922	0.005	3.00E-13		
2	0.1803	0.005	8.30E-13		
3	0.5735	0.005	9.90E-14		
Average			**4.10E-13**		
73807	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.0832	0.005	7.00E-12		
2	0.4506	0.005	1.25E-12		
3	0.0728	0.005	2.50E-11		
Average			**1.11E-11**	Yes	2-2.25 in.
73808	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.2494	0.005	7.00E-13		
2	0.7645	0.005	3.52E-13		
3	0.0938	0.005	3.50E-12		
Average			**1.52E-12**	yes	2.75-3.25 in.
73809	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.2755	0.005	1.60E-12		
2	0.7392	0.005	9.70E-13		
3	0.5735	0.005	1.81E-13		
Average			**9.17E-13**	Yes	1.75 in.
73811	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.2677	0.005	1.30E-12		
2	0.0744	0.005	2.00E-11		
3	0.332	0.005	5.20E-13		
Average			**7.27E-12**	Yes	2.25 in.

73812	**Cs(mass %)**	**Ci(mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.2067	0.005	1.35E-12		
2	0.4797	0.005	4.92E-13		
3	0.2152	0.005	1.30E-12		
Average			**1.05E-12**	yes	2.75-3 in.

73813	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.7408	0.005	4.50E-12		
2	1.2068	0.005	7.40E-14		
3	1.1047	0.005	6.60E-14		
Average			**1.55E-12**		
73815	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.594	0.005	4.90E-13		
2	0.3618	0.005	4.50E-13		
3	1.0193	0.005	2.20E-13		
Average			**3.87E-13**	Yes	2.5-3.25 in.
73816	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.2678	0.005	2.30E-13		
2	0.1262	0.005	3.80E-13		
3	0.4486	0.005	3.58E-13		
Average			**3.23E-13**		
73817	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.0832	0.005	3.40E-12		
2	0.5537	0.005	2.10E-13		
3	0.2828	0.005	5.80E-13		
Average			**1.40E-12**	Yes	3.25
73818	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	1.0835	0.005	2.91E-13		
2	0.5048	0.005	5.00E-13		
3	0.3751	0.005	1.00E-12		
Average			**5.97E-13**	yes	2.5 in.

73819	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.3689	0.005	1.70E-12		
2	0.5911	0.005	1.10E-12		
3	0.5892	0.005	2.34E-12		
Average			**1.71E-12**	yes	2-2.25 in.
73820	**Cs(mass %)**	**Ci(mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.3943	0.005	3.59E-12		
2	0.333	0.005	5.70E-12		
3	0.1846	0.005	1.30E-12		
Average			**3.53E-12**	yes	2 in.
73842	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.8175	0.005	2.10E-13		
2	0.8046	0.005	2.45E-13		
3	0.8261	0.005	5.61E-13		
Average			**3.39E-13**		
73850	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.9951	0.005	6.40E-14		
2	0.0843	0.005	3.80E-13		
3	0.5236	0.005	1.60E-13		
Average			**2.01E-13**	yes	2.75-3 in.
73852	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.3693	0.005	1.32E-12		
2	0.882	0.005	7.11E-14		
3	0.5902	0.005	1.41E-13		
Average			**5.11E-13**		
73853	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	1.0752	0.005	5.60E-14		
2	0.4543	0.005	2.30E-13		
3	1.4633	0.005	5.00E-14		
Average			**1.12E-13**	yes	2.25-2.5 in.

73854	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.6586	0.005	4.25E-13		
2	0.7162	0.005	5.12E-13		
3	2.0192	0.005	5.59E-14		
Average			**3.31E-13**		
73857	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	1.322	0.005	6.90E-14		
2	1.2953	0.005	5.90E-14		
3	1.5692	0.005	5.70E-14		
Average			**6.17E-14**	yes	1.5-2 in.
73860	**Cs(mass %)**	**Ci(mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.5312	0.005	1.11E-13		
2	0.8268	0.005	9.12E-14		
3	0.4696	0.005	1.45E-13		
Average			**1.16E-13**	yes	2
73861	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.5744	0.005	1.00E-12		
2	1.1775	0.005	8.75E-14		
3	0.7862	0.005	1.61E-13		
Average			**4.16E-13**	yes	2-2.75 in.
73862	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.5143	0.005	1.55E-12		
2	0.7218	0.005	4.75E-13		
3	1.1778	0.005	1.32E-13		
Average			**7.19E-13**	yes	2.75 in.
73864	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	1.5136	0.005	8.90E-14		
2	1.0605	0.005	9.20E-14		
3	0.3133	0.005	1.30E-13		
Average			**1.04E-13**		

73865	Cs (mass %)	Ci (mass %)	Da (m/s^2)	Overlay?	Overlay Thickness
1	0.2009	0.005	4.90E-13		
2	0.3437	0.005	3.24E-13		
3	0.7922	0.005	9.90E-14		
Average			**3.04E-13**	Yes	2-2.25 in.
73866	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.4742	0.005	6.10E-13		
2	0.4104	0.005	1.10E-12		
3	0.0692	0.005	5.40E-13		
Average			**7.50E-13**		
73868	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.3005	0.005	4.15E-13		
2	0.2581	0.005	5.40E-13		
3	0.5105	0.005	1.75E-13		
Average			**3.77E-13**	yes	2-2.25 in.
73869	**Cs(mass %)**	**Ci(mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.2119	0.005	2.80E-13		
2	0.9598	0.005	6.90E-14		
3	0.668	0.005	1.50E-13		
Average			**1.66E-13**	yes	2.25-2.5 in.
73870	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.4774	0.005	2.52E-13		
2	0.2563	0.005	3.14E-13		
3	0.2088	0.005	5.26E-13		
Average			**3.64E-13**		
73873	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	1.9161	0.005	7.32E-14		
2	0.5943	0.005	9.40E-13		
3	1.3821	0.005	8.65E-14		
Average			**3.67E-13**	Yes	2.25 in.

73875	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.4863	0.005	2.55E-13		
2	0.3127	0.005	6.20E-13		
3	0.7224	0.005	5.10E-13		
Average			**4.62E-13**		
73876	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.5761	0.005	1.61E-12		
2	0.6543	0.005	9.99E-14		
3	0.5071	0.005	2.32E-13		
Average			**6.47E-13**	yes	2-2.25 in.
73877	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.1552	0.005	7.75E-13		
2	0.321	0.005	6.50E-13		
3	0.3642	0.005	2.30E-13		
Average			**5.52E-13**	Yes	2-2.25 in.
73878	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.557	0.005	2.93E-13		
2	0.4104	0.005	1.10E-12		
3	0.2088	0.005	5.25E-13		
Average			**6.39E-13**		
77802	**Cs(mass %)**	**Ci(mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.4215	0.005	1.23E-13		
2	0.2677	0.005	7.20E-13		
3	0.0265	0.005	1.90E-12		
Average			**9.14E-13**		
86530	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.9926	0.005	1.30E-13		
2	0.3954	0.005	7.90E-13		
3	0.2678	0.005	8.90E-13		
Average			**6.03E-13**	yes	1.75-2 in.

86802	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.4017	0.005	6.30E-12		
2	0.7229	0.005	6.60E-13		
3	0.6573	0.005	7.40E-13		
Average			**2.57E-12**	yes	1.75 to 2 in.
86803	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.9282	0.005	5.51E-13		
2	1.0992	0.005	2.39E-13		
3	1.115	0.005	2.00E-13		
Average			**3.30E-13**	yes	2.25-2.5 in.
86807	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.9247	0.005	4.84E-13		
2	0.4712	0.005	4.70E-13		
3	0.7571	0.005	2.40E-13		
Average			**3.98E-13**	yes	2.25 in.
86808	**Cs (mass %)**	**Ci (mass %)**	**Da (m/s^2)**	**Overlay?**	**Overlay Thickness**
1	0.6883	0.005	1.90E-13		
2	0.2507	0.005	2.90E-13		
3	0.4446	0.005	9.65E-14		
Average			**1.92E-13**		

APPENDIX C: CASE STUDIES USING THE MODEL DEVELOPED TO PREDICT OPTIMUM TPO APPLICATION TIMING

Appendix C will present a case study using the TPO model. The case study will consider TPO application timing on a new bridge deck placed in 2018 in three phases. The first phase, Baseline 1, will consider chloride ingress into a new bridge deck that never cracks and that does not receive a TPO. The second phase, Cracked Baseline 1, will consider chloride ingress into a new bridge deck that cracks. The third phase, TPO 1, will consider chloride ingress into a new bridge deck that is cracked and that receives a TPO after 5 years and the TPO is renewed every 15 years.

C.1 TPO APPLICATION TIMING OF A NEW BRIDGE DECK PLACED IN 2018

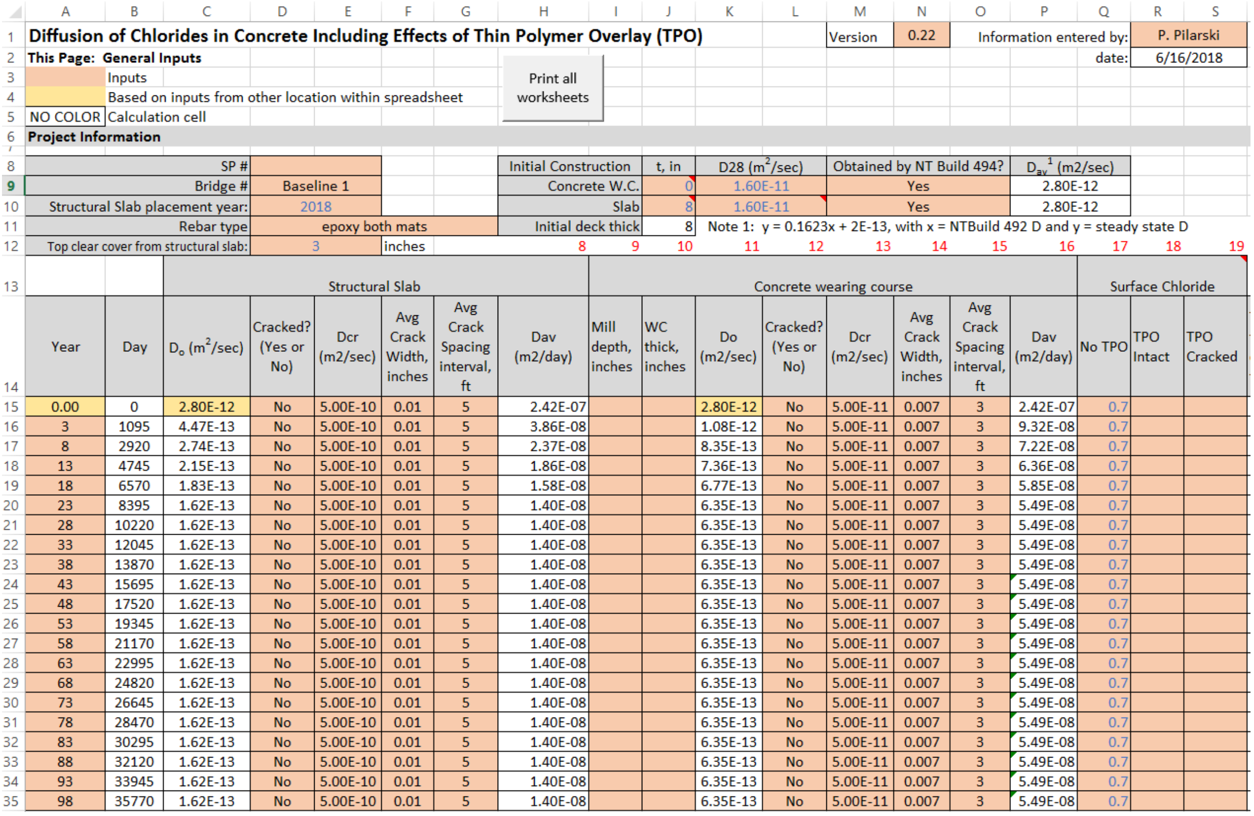
Model inputs and outputs will be provided for each phase, which were explained in detail within Chapter 7.

C.1.1 Case Study Scenario 1: Baseline 1

The first case study scenario will consider chloride ingress into a new bridge deck that never cracks. The diffusion coefficient and diffusion coefficient decay factor will be that determined for new bridge decks with 570-600 lbs/cy total cementitious material with 30% fly ash replacement of Portland cement.

Table C.1. Model Baseline 1 General Input parameters

Parameter	Value
Top Clear Cover to Reinforcing Steel	3 in.
Slab thickness	8 in.
Concrete W. C. (wear course)	0 in.
D_{28}	1.6 x 10^{-11} m^2/s
Obtained by NTBuild 492?	Yes
Year Start	0
Year Increment	5
Structural Slab Cracked?	No
Concrete Mill Depth/Wear Course	All cells blank
Concrete Wearing Course Cracked?	All cells no
Surface Chloride No TPO	All cells 0.7
Surface Chloride TPO Intact/TPO Cracked	All cells blank
M	0.5 (30% fly ash replacement for cement)
Delta t (day)	1
Incr. at upper 1.5” of deck	0.25
T_{start}	0
T_{end}	30
Start data series year	0
End data series year	30
Ymax, in.	8
Incr.	0.5



Diffusion of Chlorides in Concrete Including Effects of Thin Polymer Overlay (TPO)

Version 0.22 Information entered by: P. Pilarski

date: 6/16/2018

This Page: General Inputs

	Inputs
	Based on inputs from other location within spreadsheet
NO COLOR	Calculation cell

Project Information

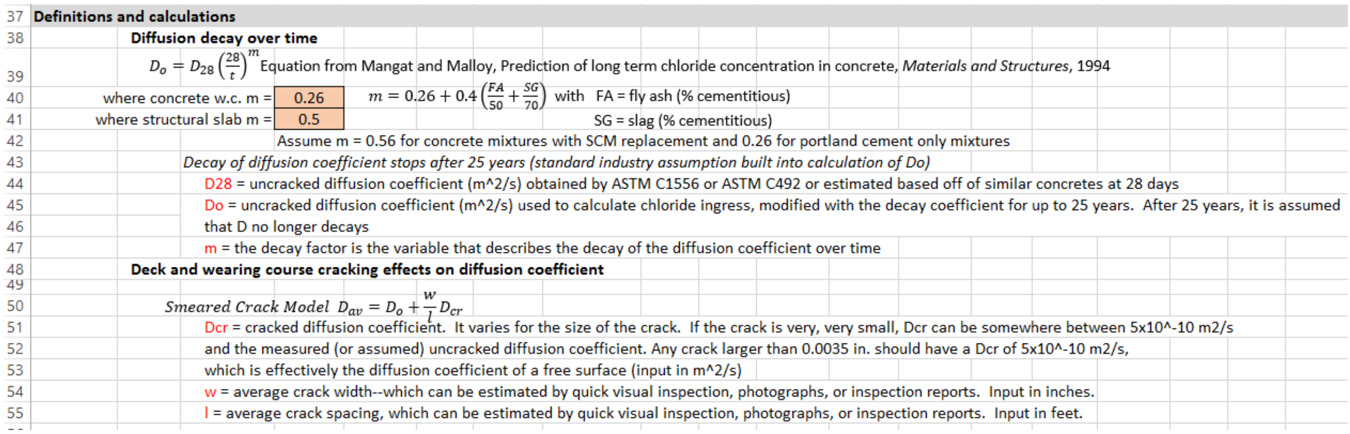
SP #	
Bridge #	Baseline 1
Structural Slab placement year:	2018
Rebar type	epoxy both mats
Top clear cover from structural slab:	3 inches

Initial Construction	t, in	D28 (m^2/sec)	Obtained by NT Build 494?	$D_{av}{}^1$ (m2/sec)
Concrete W.C.	0	1.60E-11	Yes	2.80E-12
Slab	8	1.60E-11	Yes	2.80E-12
Initial deck thick	8			

Note 1: y = 0.1623x + 2E-13, with x = NTBuild 492 D and y = steady state D

		Structural Slab						Concrete wearing course								Surface Chloride		
						8	9	10	11	12	13	14	15	16	17	18	19	
Year	Day	D_o (m^2/sec)	Cracked? (Yes or No)	Dcr (m2/sec)	Avg Crack Width, inches	Avg Crack Spacing interval, ft	Dav (m2/day)	Mill depth, inches	WC thick, inches	Do (m2/sec)	Cracked? (Yes or No)	Dcr (m2/sec)	Avg Crack Width, inches	Avg Crack Spacing interval, ft	Dav (m2/day)	No TPO	TPO Intact	TPO Cracked
0.00	0	2.80E-12	No	5.00E-10	0.01	5	2.42E-07			2.80E-12	No	5.00E-11	0.007	3	2.42E-07	0.7		
3	1095	4.47E-13	No	5.00E-10	0.01	5	3.86E-08			1.08E-12	No	5.00E-11	0.007	3	9.32E-08	0.7		
8	2920	2.74E-13	No	5.00E-10	0.01	5	2.37E-08			8.35E-13	No	5.00E-11	0.007	3	7.22E-08	0.7		
13	4745	2.15E-13	No	5.00E-10	0.01	5	1.86E-08			7.36E-13	No	5.00E-11	0.007	3	6.36E-08	0.7		
18	6570	1.83E-13	No	5.00E-10	0.01	5	1.58E-08			6.77E-13	No	5.00E-11	0.007	3	5.85E-08	0.7		
23	8395	1.62E-13	No	5.00E-10	0.01	5	1.40E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
28	10220	1.62E-13	No	5.00E-10	0.01	5	1.40E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
33	12045	1.62E-13	No	5.00E-10	0.01	5	1.40E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
38	13870	1.62E-13	No	5.00E-10	0.01	5	1.40E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
43	15695	1.62E-13	No	5.00E-10	0.01	5	1.40E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
48	17520	1.62E-13	No	5.00E-10	0.01	5	1.40E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
53	19345	1.62E-13	No	5.00E-10	0.01	5	1.40E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
58	21170	1.62E-13	No	5.00E-10	0.01	5	1.40E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
63	22995	1.62E-13	No	5.00E-10	0.01	5	1.40E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
68	24820	1.62E-13	No	5.00E-10	0.01	5	1.40E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
73	26645	1.62E-13	No	5.00E-10	0.01	5	1.40E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
78	28470	1.62E-13	No	5.00E-10	0.01	5	1.40E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
83	30295	1.62E-13	No	5.00E-10	0.01	5	1.40E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
88	32120	1.62E-13	No	5.00E-10	0.01	5	1.40E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
93	33945	1.62E-13	No	5.00E-10	0.01	5	1.40E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
98	35770	1.62E-13	No	5.00E-10	0.01	5	1.40E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		

Figure C.1: General input worksheet



Definitions and calculations

Diffusion decay over time

$D_o = D_{28}\left(\frac{28}{t}\right)^m$ Equation from Mangat and Malloy, Prediction of long term chloride concentration in concrete, *Materials and Structures*, 1994

where concrete w.c. m = 0.26 $m = 0.26 + 0.4\left(\frac{FA}{50} + \frac{SG}{70}\right)$ with FA = fly ash (% cementitious)

where structural slab m = 0.5 SG = slag (% cementitious)

Assume m = 0.56 for concrete mixtures with SCM replacement and 0.26 for portland cement only mixtures

Decay of diffusion coefficient stops after 25 years (standard industry assumption built into calculation of Do)

D28 = uncracked diffusion coefficient (m^2/s) obtained by ASTM C1556 or ASTM C492 or estimated based off of similar concretes at 28 days

Do = uncracked diffusion coefficient (m^2/s) used to calculate chloride ingress, modified with the decay coefficient for up to 25 years. After 25 years, it is assumed that D no longer decays

m = the decay factor is the variable that describes the decay of the diffusion coefficient over time

Deck and wearing course cracking effects on diffusion coefficient

$\mathit{Smeared\ Crack\ Model}\ \ D_{av} = D_o + \frac{w}{l} D_{cr}$

Dcr = cracked diffusion coefficient. It varies for the size of the crack. If the crack is very, very small, Dcr can be somewhere between 5x10^-10 m2/s and the measured (or assumed) uncracked diffusion coefficient. Any crack larger than 0.0035 in. should have a Dcr of 5x10^-10 m2/s, which is effectively the diffusion coefficient of a free surface (input in m^2/s)

w = average crack width--which can be estimated by quick visual inspection, photographs, or inspection reports. Input in inches.

l = average crack spacing, which can be estimated by quick visual inspection, photographs, or inspection reports. Input in feet.

Figure C.2: General input worksheet – decay and cracking properties

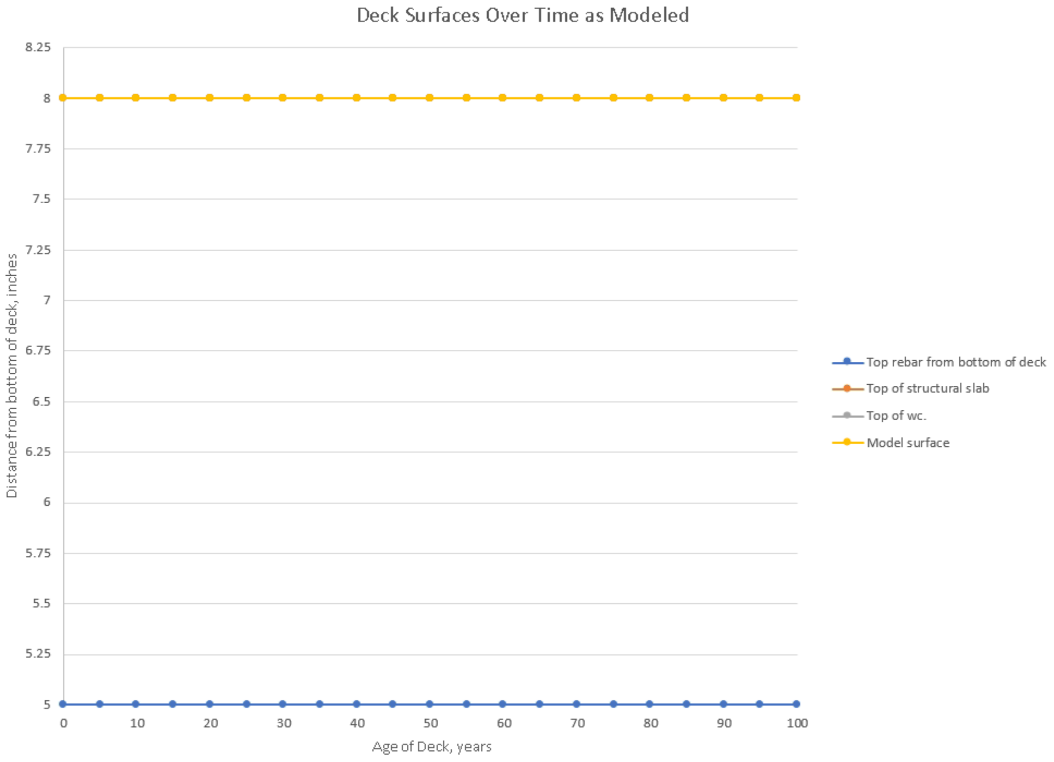
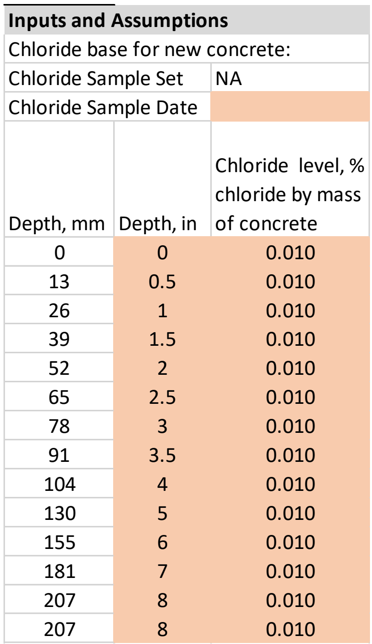


Figure C.3: Model plot

From the Chloride Profile tab in Model Baseline 1, Figure C.4 shows the inputs for starting chloride profile. The values reflect the background chloride in the concrete, which was selected as 0.01%.



Inputs and Assumptions		
Chloride base for new concrete:		
Chloride Sample Set		NA
Chloride Sample Date		
Depth, mm	Depth, in	Chloride level, % chloride by mass of concrete
0	0	0.010
13	0.5	0.010
26	1	0.010
39	1.5	0.010
52	2	0.010
65	2.5	0.010
78	3	0.010
91	3.5	0.010
104	4	0.010
130	5	0.010
155	6	0.010
181	7	0.010
207	8	0.010
207	8	0.010

Figure C.4 Model Inputs on the Chloride Profile tab

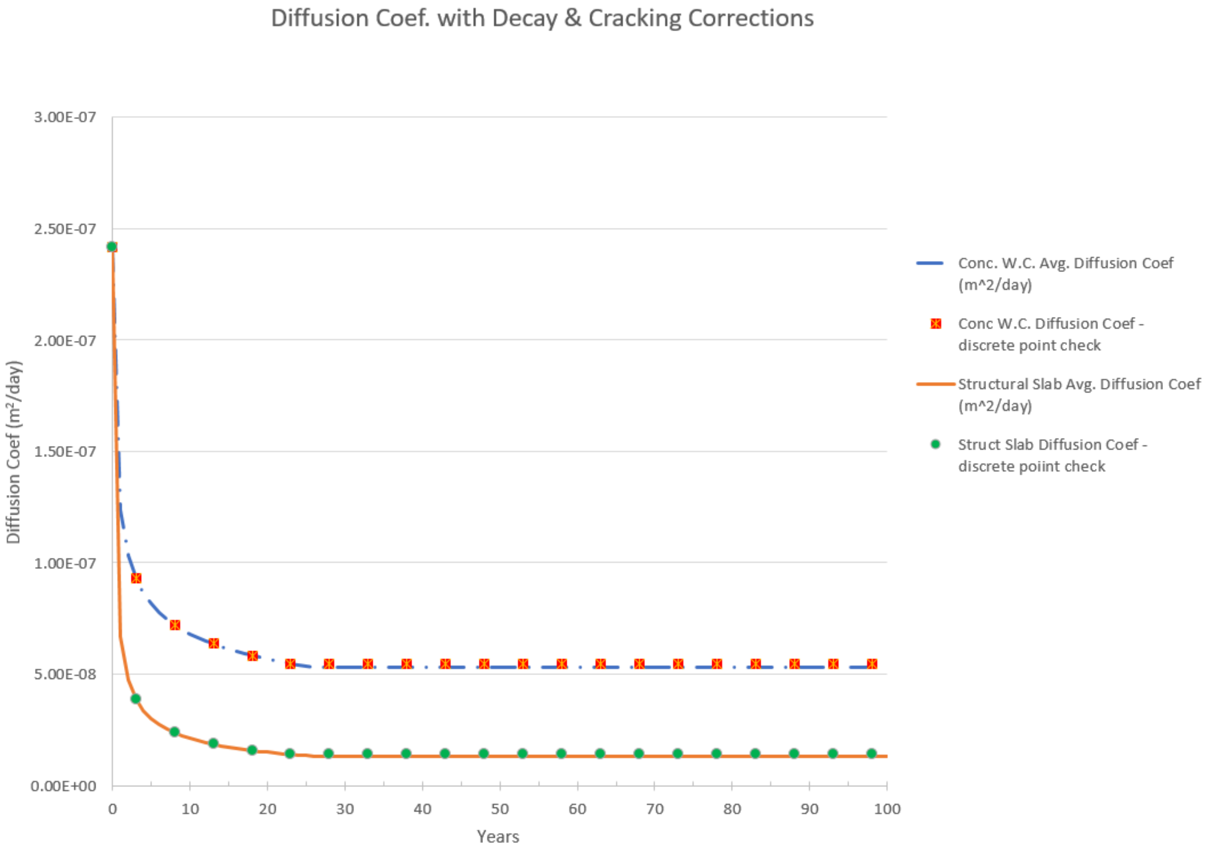
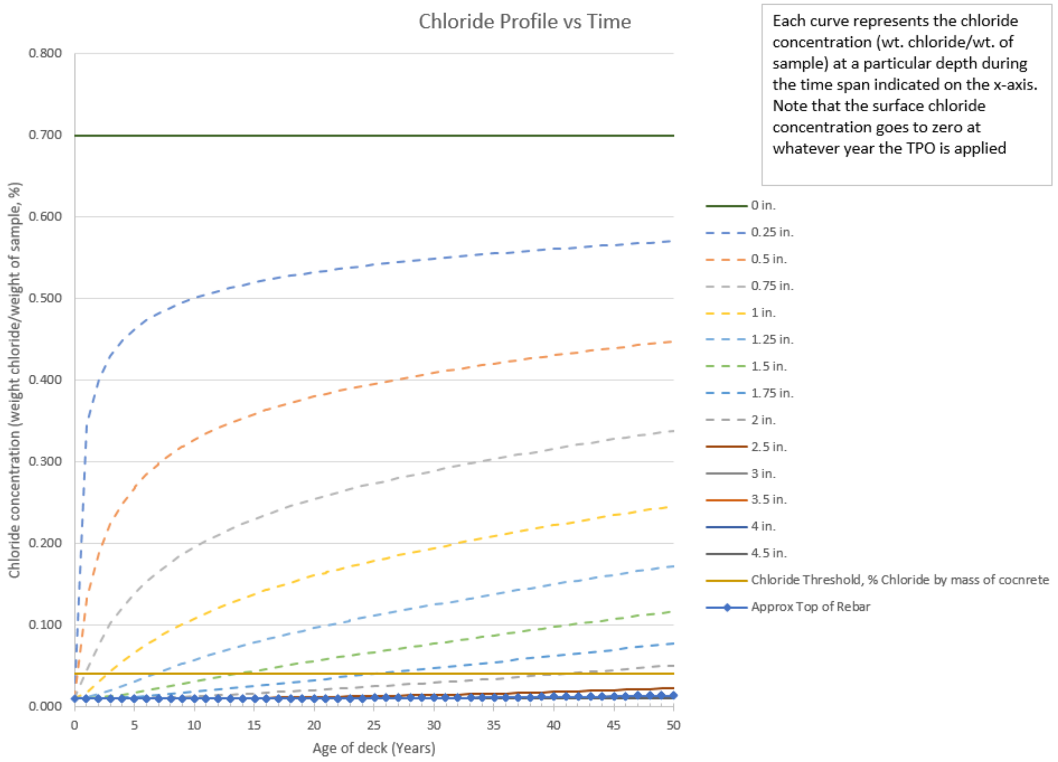


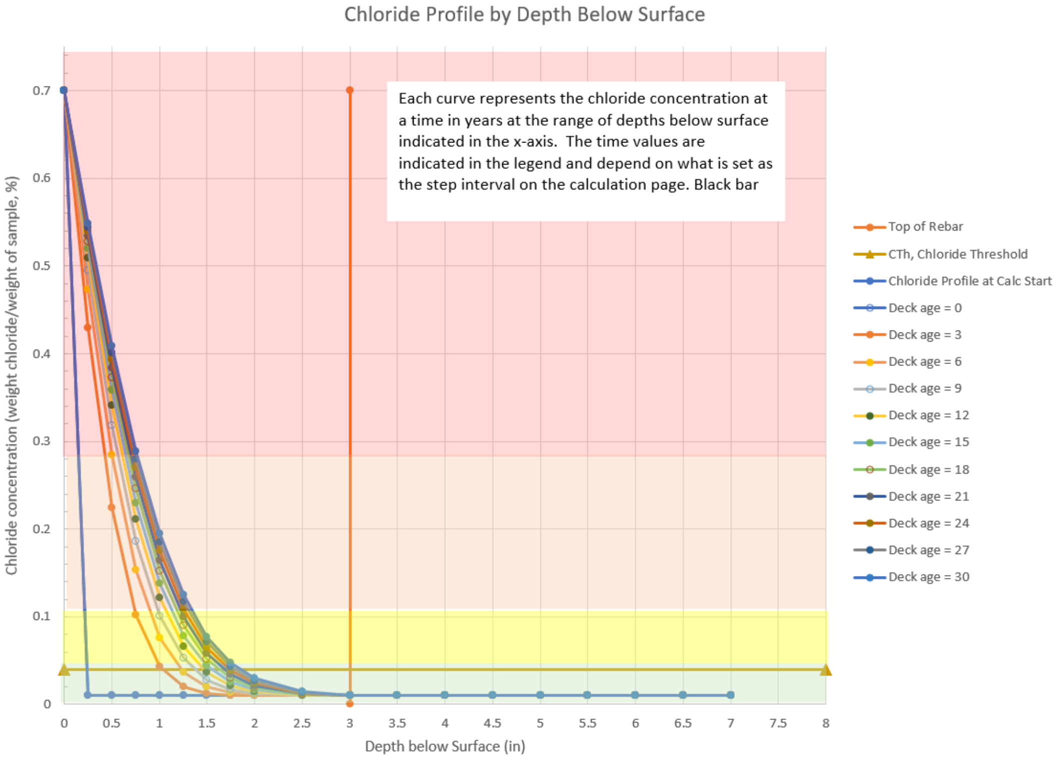
Figure C.5: Diffusion coefficients calculated within model over time. Note that the upper line represents a concrete wearing course, which is not incorporated into the calculations when the concrete wearing course is set to 0-inch thickness. The higher values for the same D28 input illustrate the effects of a different decay coefficient for a low-slump concrete wearing course mix.

Two plots were created by Model Baseline 1, “C Profiles Time” and “C Profiles Depth”. “C Profiles Time”, shown in Figure C.6, illustrates the chloride concentration in the deck (wt. chloride/wt. of sample) at multiple depths from 0 to 30 years. There is a separate curve plotting the chloride level at the level of rebar that is most nearly represented by in the finite increment. The model calculated chloride concentration through the deck from 0-100 years, but the plot was truncated to show more detail between 0-50 years.



Each curve represents the chloride concentration (wt. chloride/wt. of sample) at a particular depth during the time span indicated on the x-axis. Note that the surface chloride concentration goes to zero at whatever year the TPO is applied

Figure C.6: “C Profiles Time” plot from Model Baseline 1



Each curve represents the chloride concentration at a time in years at the range of depths below surface indicated in the x-axis. The time values are indicated in the legend and depend on what is set as the step interval on the calculation page. Black bar

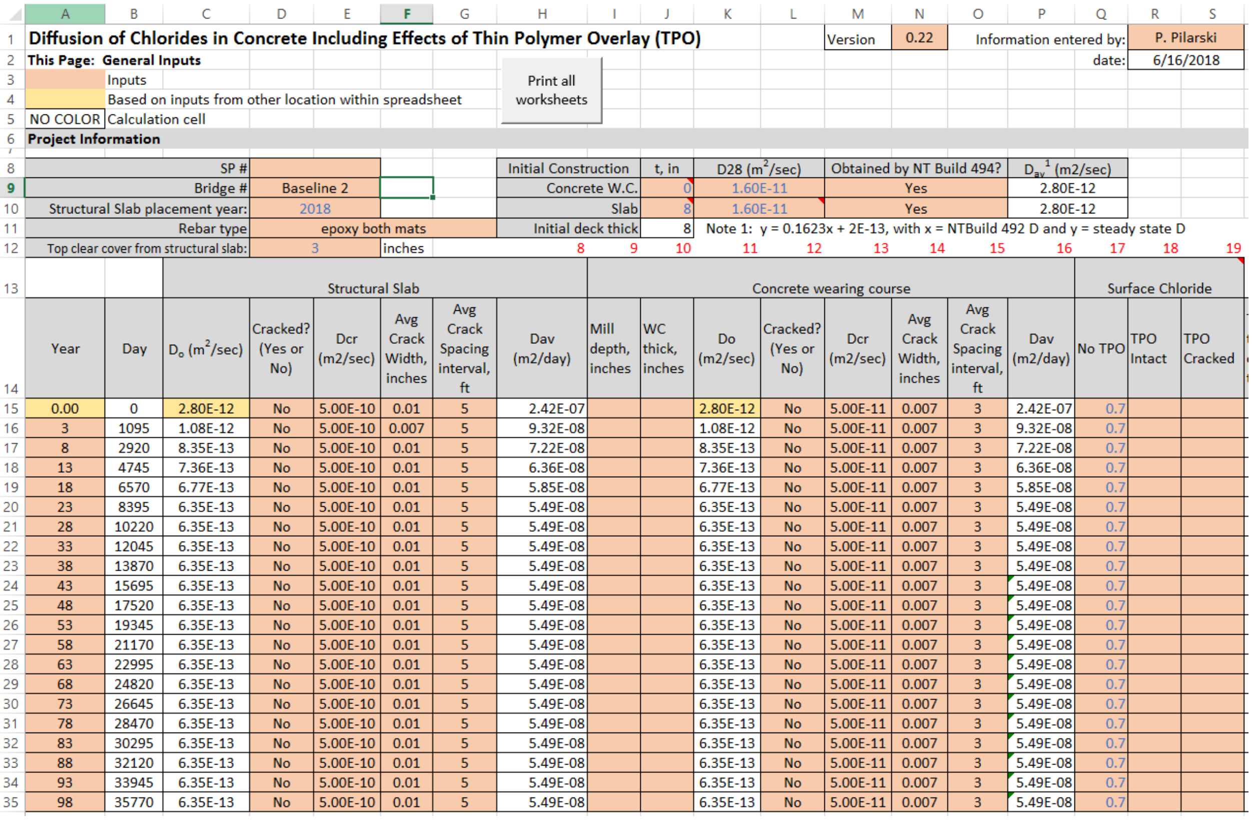
Figure C.7: “C Profiles Time” plot from Model Baseline 1 showing chloride profile change over 30 years

Each curve in Figure C.7 (“C Profiles Depth”) represents the chloride concentration at a time in years through the thickness of the deck. The depth of rebar is indicated by the straight vertical line at 3 in. The plots were limited to snapshots of the chloride profile projection at years 0, 6, 12, 18, 24, and 30.

Both figures C.6 and C.7 show that the chloride threshold has not reached the level of the reinforcing steel at 30 years, or looking at Figure C.6 even 50 years. The projection using a decay coefficient, m=0.50, with no cracks indicates the chlorides would not reach the rebar level for even 100 years. The next example, Baseline 2, will illustrate some insight into this theoretical performance by excluding flyash in this model.

C.1.2 Case Study Scenario 2: Baseline 2 (Without flyash or slag in mix)

Model “Baseline 2” will show the influence of flyash on the model. Holding all other inputs the same as Baseline 1 model, the decay coefficient is change to remove flyash and slag contributions. This can be seen in Figure C.8.



Diffusion of Chlorides in Concrete Including Effects of Thin Polymer Overlay (TPO) Version 0.22 Information entered by: P. Pilarski

date: 6/16/2018

This Page: General Inputs

	Inputs
	Based on inputs from other location within spreadsheet
NO COLOR	Calculation cell

Project Information

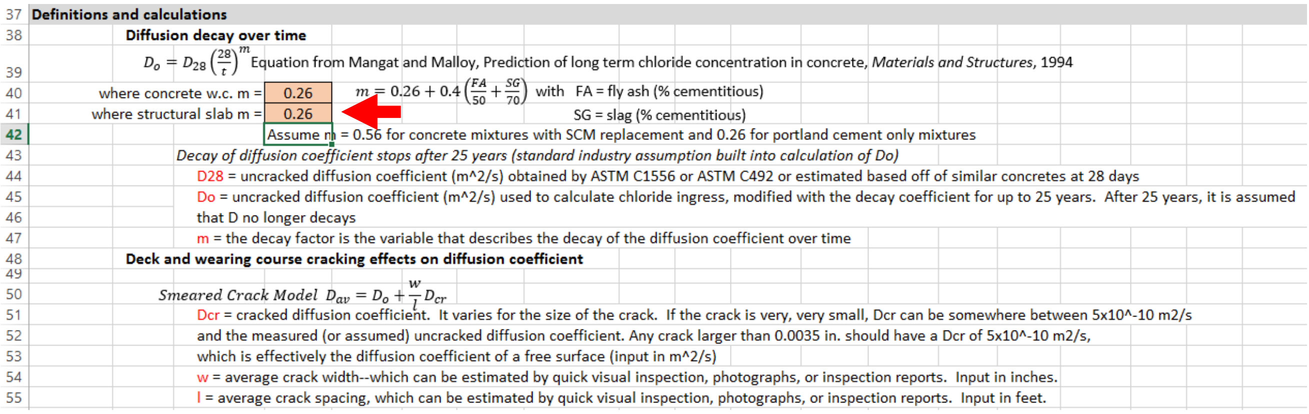
SP #			Initial Construction	t, in	D28 (m^2/sec)	Obtained by NT Build 494?	D_{av} [1] (m2/sec)
Bridge #	Baseline 2		Concrete W.C.	0	1.60E-11	Yes	2.80E-12
Structural Slab placement year:	2018		Slab	8	1.60E-11	Yes	2.80E-12
Rebar type	epoxy both mats		Initial deck thick	8			
Top clear cover from structural slab:	3	inches					

Note 1: y = 0.1623x + 2E-13, with x = NTBuild 492 D and y = steady state D

8 9 10 11 12 13 14 15 16 17 18 19

		Structural Slab						Concrete wearing course								Surface Chloride		
Year	Day	D_o (m^2/sec)	Cracked? (Yes or No)	Dcr (m2/sec)	Avg Crack Width, inches	Avg Crack Spacing interval, ft	Dav (m2/day)	Mill depth, inches	WC thick, inches	Do (m2/sec)	Cracked? (Yes or No)	Dcr (m2/sec)	Avg Crack Width, inches	Avg Crack Spacing interval, ft	Dav (m2/day)	No TPO	TPO Intact	TPO Cracked
0.00	0	2.80E-12	No	5.00E-10	0.01	5	2.42E-07			2.80E-12	No	5.00E-11	0.007	3	2.42E-07	0.7		
3	1095	1.08E-12	No	5.00E-10	0.007	5	9.32E-08			1.08E-12	No	5.00E-11	0.007	3	9.32E-08	0.7		
8	2920	8.35E-13	No	5.00E-10	0.01	5	7.22E-08			8.35E-13	No	5.00E-11	0.007	3	7.22E-08	0.7		
13	4745	7.36E-13	No	5.00E-10	0.01	5	6.36E-08			7.36E-13	No	5.00E-11	0.007	3	6.36E-08	0.7		
18	6570	6.77E-13	No	5.00E-10	0.01	5	5.85E-08			6.77E-13	No	5.00E-11	0.007	3	5.85E-08	0.7		
23	8395	6.35E-13	No	5.00E-10	0.01	5	5.49E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
28	10220	6.35E-13	No	5.00E-10	0.01	5	5.49E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
33	12045	6.35E-13	No	5.00E-10	0.01	5	5.49E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
38	13870	6.35E-13	No	5.00E-10	0.01	5	5.49E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
43	15695	6.35E-13	No	5.00E-10	0.01	5	5.49E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
48	17520	6.35E-13	No	5.00E-10	0.01	5	5.49E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
53	19345	6.35E-13	No	5.00E-10	0.01	5	5.49E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
58	21170	6.35E-13	No	5.00E-10	0.01	5	5.49E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
63	22995	6.35E-13	No	5.00E-10	0.01	5	5.49E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
68	24820	6.35E-13	No	5.00E-10	0.01	5	5.49E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
73	26645	6.35E-13	No	5.00E-10	0.01	5	5.49E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
78	28470	6.35E-13	No	5.00E-10	0.01	5	5.49E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
83	30295	6.35E-13	No	5.00E-10	0.01	5	5.49E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
88	32120	6.35E-13	No	5.00E-10	0.01	5	5.49E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
93	33945	6.35E-13	No	5.00E-10	0.01	5	5.49E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
98	35770	6.35E-13	No	5.00E-10	0.01	5	5.49E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		

Figure C.8: Model Baseline 2 input the same as Baseline 1 except changing title and decay coefficient.



Definitions and calculations

Diffusion decay over time

$D_o = D_{28}\left(\frac{28}{t}\right)^m$ Equation from Mangat and Malloy, Prediction of long term chloride concentration in concrete, *Materials and Structures*, 1994

where concrete w.c. m = 0.26 $m = 0.26 + 0.4\left(\frac{FA}{50} + \frac{SG}{70}\right)$ with FA = fly ash (% cementitious)

where structural slab m = 0.26 SG = slag (% cementitious)

Assume m = 0.56 for concrete mixtures with SCM replacement and 0.26 for portland cement only mixtures

Decay of diffusion coefficient stops after 25 years (standard industry assumption built into calculation of Do)

D28 = uncracked diffusion coefficient (m^2/s) obtained by ASTM C1556 or ASTM C492 or estimated based off of similar concretes at 28 days

Do = uncracked diffusion coefficient (m^2/s) used to calculate chloride ingress, modified with the decay coefficient for up to 25 years. After 25 years, it is assumed that D no longer decays

m = the decay factor is the variable that describes the decay of the diffusion coefficient over time

Deck and wearing course cracking effects on diffusion coefficient

Smeared Crack Model $D_{av} = D_o + \frac{w}{l} D_{cr}$

Dcr = cracked diffusion coefficient. It varies for the size of the crack. If the crack is very, very small, Dcr can be somewhere between 5x10^-10 m2/s and the measured (or assumed) uncracked diffusion coefficient. Any crack larger than 0.0035 in. should have a Dcr of 5x10^-10 m2/s, which is effectively the diffusion coefficient of a free surface (input in m^2/s)

w = average crack width--which can be estimated by quick visual inspection, photographs, or inspection reports. Input in inches.

l = average crack spacing, which can be estimated by quick visual inspection, photographs, or inspection reports. Input in feet.

Figure C.9: Model Baseline 2 decay coefficient input change from Baseline 1 model

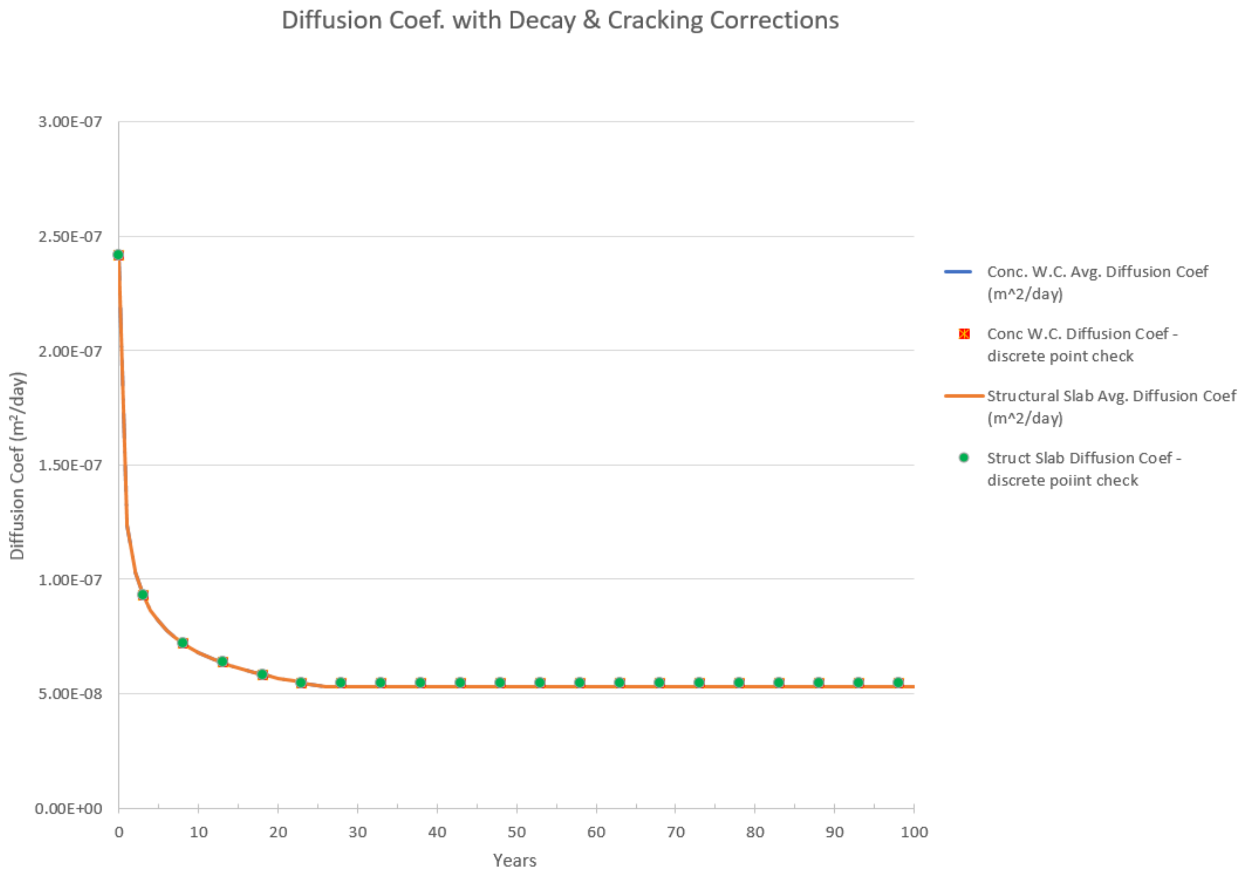
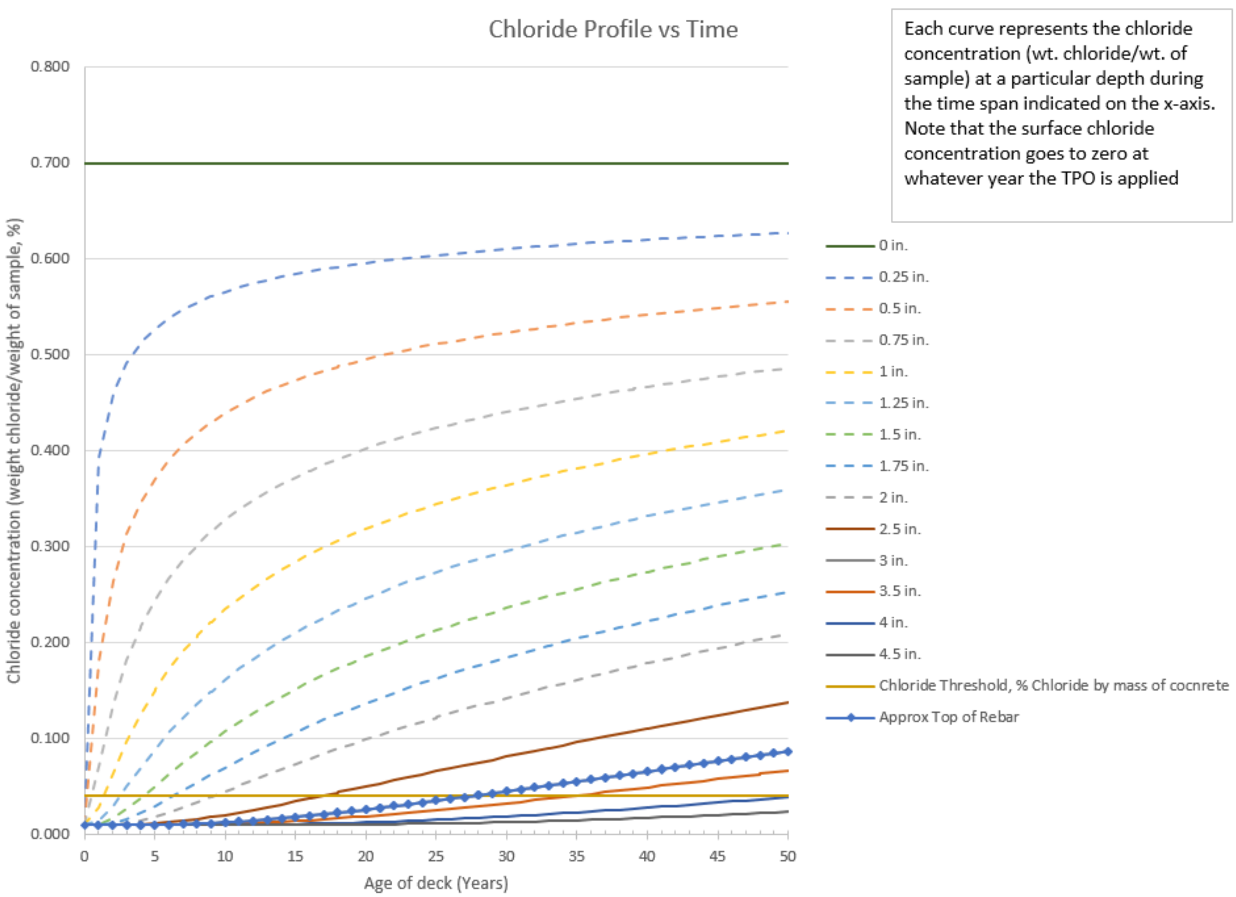


Figure C.10: Model Baseline 2 diffusion coefficient. Structural slab matches diffusion coefficient of a low-slump concrete wearing course if it were incorporated into the model.



Each curve represents the chloride concentration (wt. chloride/wt. of sample) at a particular depth during the time span indicated on the x-axis. Note that the surface chloride concentration goes to zero at whatever year the TPO is applied

Figure C.11: "C Profiles Time" plot from model Baseline 2. Chlorides have reached the input threshold of 0.04% Cl/weight of sample in year 27.

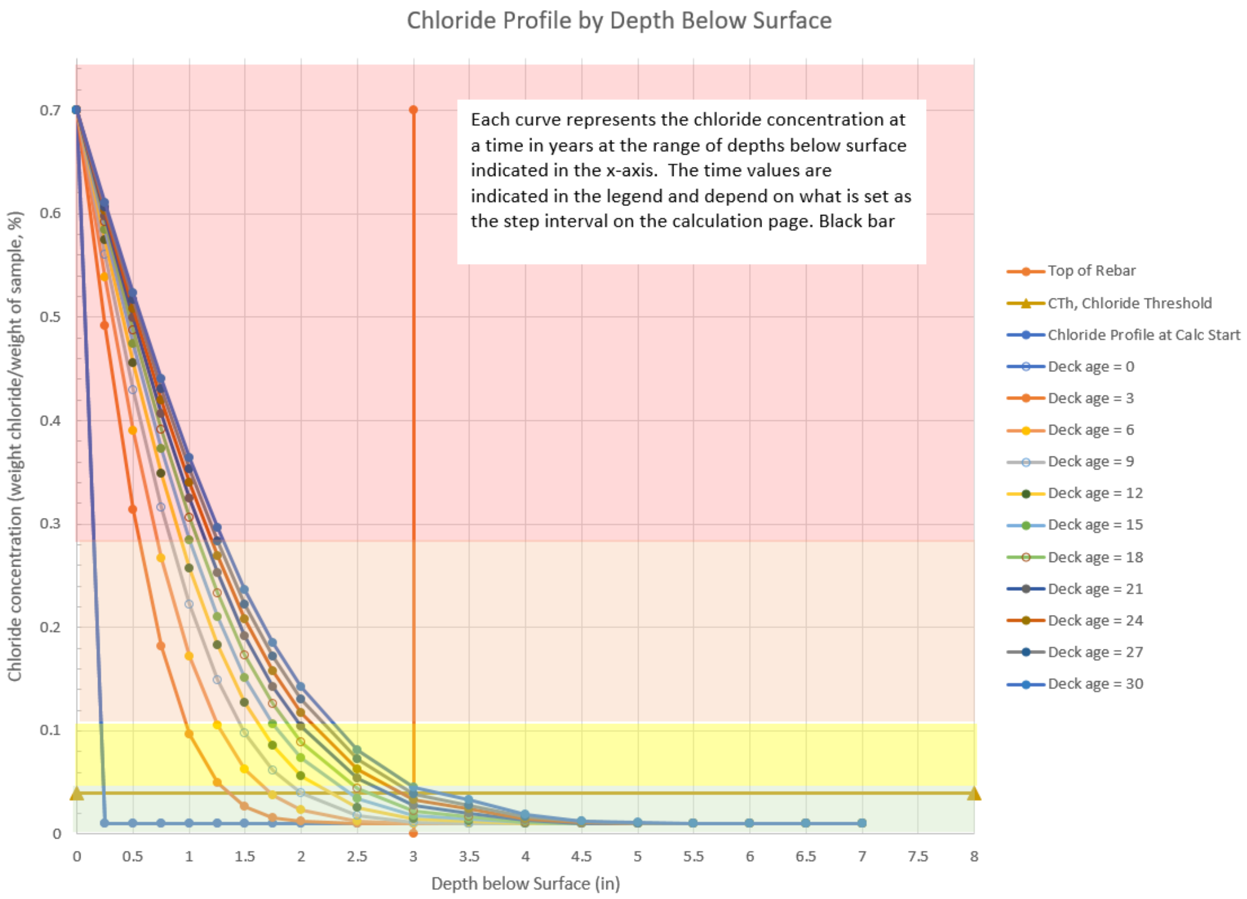
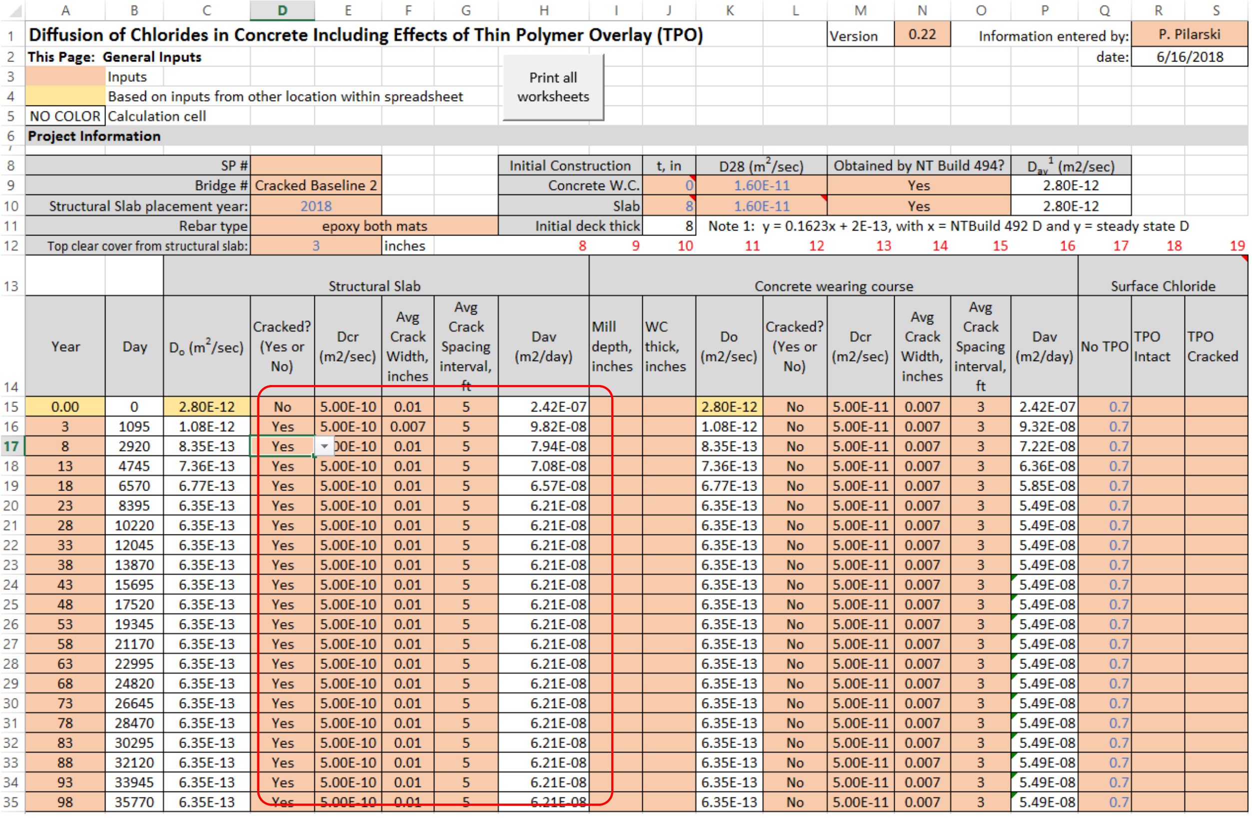


Figure C.12: "C Profiles Depth" plot from model Baseline 2 showing change in chloride profile in discrete years. Chlorides have reached the input threshold of 0.04% Cl/weight of sample in year 27.

Bsaeline 2 model shows the chloride breaching the concrete top cover at a concentration of 0.030%CH/sample threshold in year 22 and, in year 27 for a 0.040%CH/sample threshold. The comparison between Baseline 1 and Baseline 2 models is clearly illustrating the benefits of fly ash substitution into the mix. Baseline 1 had not permitted the chlorides to reach the reinforcement depth even in year 50 whereas Baseline 2 shows the threshold is met in year 27. The only change between models is the use of 0.26 for decay coefficient in Baseline 2 model versus 0.50 for Baseline 1 model. For the purpose of this research, subsequent case studies will use the Baseline 2 model because those decks would be gain greater benefit from a thin polymer overlay.

C.1.3 Case Study Scenario 3: Cracked Baseline 2

Model "Cracked Baseline 2" will illustrate chloride profile changes when cracks are introduced into the model. In Cracked Baseline 2, all inputs remain the same as Baseline 2 except for the cracking inputs. The cracking inputs are displayed in Figure C.13. It shows that there are no cracks for the first 3 years. Between 3 and 8 years, narrow cracks (crack width = 0.007 inches) occur approximately every 5 feet. At 8 years and beyond, the cracks have grown wider (0.01 inches) and the cracks are spaced approximately every 5 feet. Cracking increases the diffusion coefficient, after accounting for decay over time, by using the Smeared Crack Formula as discussed in section 7.1.1.2. Once the Smeared Crack Formula is applied the diffusion coefficient is converted to a daily diffusion rate as shown in the sixth column of the Figure C.13 and the plot in Figure C.14.



Diffusion of Chlorides in Concrete Including Effects of Thin Polymer Overlay (TPO)

Version 0.22

Information entered by: P. Pilarski

date: 6/16/2018

This Page: General Inputs

Inputs

Based on inputs from other location within spreadsheet

NO COLOR Calculation cell

Print all worksheets

Project Information

SP #:

Bridge #: Cracked Baseline 2

Structural Slab placement year: 2018

Rebar type: epoxy both mats

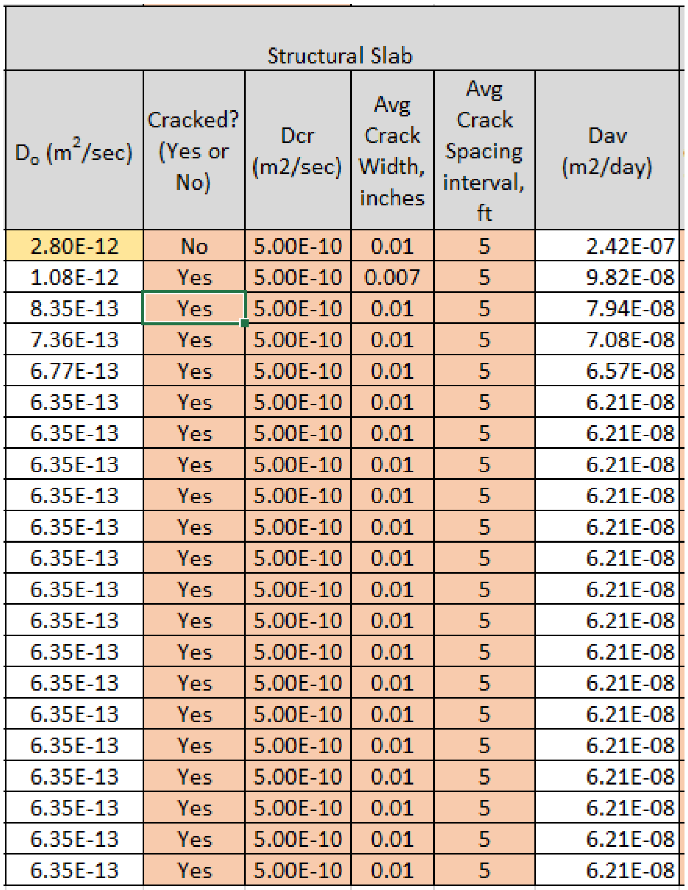
Top clear cover from structural slab: 3 inches

Initial Construction	t, in	D28 (m²/sec)	Obtained by NT Build 494?	D_{av} ¹ (m2/sec)
Concrete W.C.	0	1.60E-11	Yes	2.80E-12
Slab	8	1.60E-11	Yes	2.80E-12
Initial deck thick	8			

Note 1: y = 0.1623x + 2E-13, with x = NTBuild 492 D and y = steady state D

		Structural Slab								Concrete wearing course						Surface Chloride		
							8	9	10	11	12	13	14	15	16	17	18	19
Year	Day	D_o (m²/sec)	Cracked? (Yes or No)	Dcr (m2/sec)	Avg Crack Width, inches	Avg Crack Spacing interval, ft	Dav (m2/day)	Mill depth, inches	WC thick, inches	Do (m2/sec)	Cracked? (Yes or No)	Dcr (m2/sec)	Avg Crack Width, inches	Avg Crack Spacing interval, ft	Dav (m2/day)	No TPO	TPO Intact	TPO Cracked
0.00	0	2.80E-12	No	5.00E-10	0.01	5	2.42E-07			2.80E-12	No	5.00E-11	0.007	3	2.42E-07	0.7		
3	1095	1.08E-12	Yes	5.00E-10	0.007	5	9.82E-08			1.08E-12	No	5.00E-11	0.007	3	9.32E-08	0.7		
8	2920	8.35E-13	Yes	00E-10	0.01	5	7.94E-08			8.35E-13	No	5.00E-11	0.007	3	7.22E-08	0.7		
13	4745	7.36E-13	Yes	5.00E-10	0.01	5	7.08E-08			7.36E-13	No	5.00E-11	0.007	3	6.36E-08	0.7		
18	6570	6.77E-13	Yes	5.00E-10	0.01	5	6.57E-08			6.77E-13	No	5.00E-11	0.007	3	5.85E-08	0.7		
23	8395	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
28	10220	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
33	12045	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
38	13870	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
43	15695	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
48	17520	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
53	19345	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
58	21170	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
63	22995	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
68	24820	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
73	26645	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
78	28470	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
83	30295	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
88	32120	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
93	33945	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		
98	35770	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08	0.7		

Figure C.13 Model “Cracked Baseline 2” inputs for structural slab cracking



Structural Slab					
D_o (m^2/sec)	Cracked? (Yes or No)	Dcr (m2/sec)	Avg Crack Width, inches	Avg Crack Spacing interval, ft	Dav (m2/day)
2.80E-12	No	5.00E-10	0.01	5	2.42E-07
1.08E-12	Yes	5.00E-10	0.007	5	9.82E-08
8.35E-13	Yes	5.00E-10	0.01	5	7.94E-08
7.36E-13	Yes	5.00E-10	0.01	5	7.08E-08
6.77E-13	Yes	5.00E-10	0.01	5	6.57E-08
6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08
6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08
6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08
6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08
6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08
6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08
6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08
6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08
6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08
6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08
6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08
6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08
6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08
6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08
6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08
6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08

Figure C.14: Detail for Model “Cracked Baseline 2” inputs for structural slab cracking

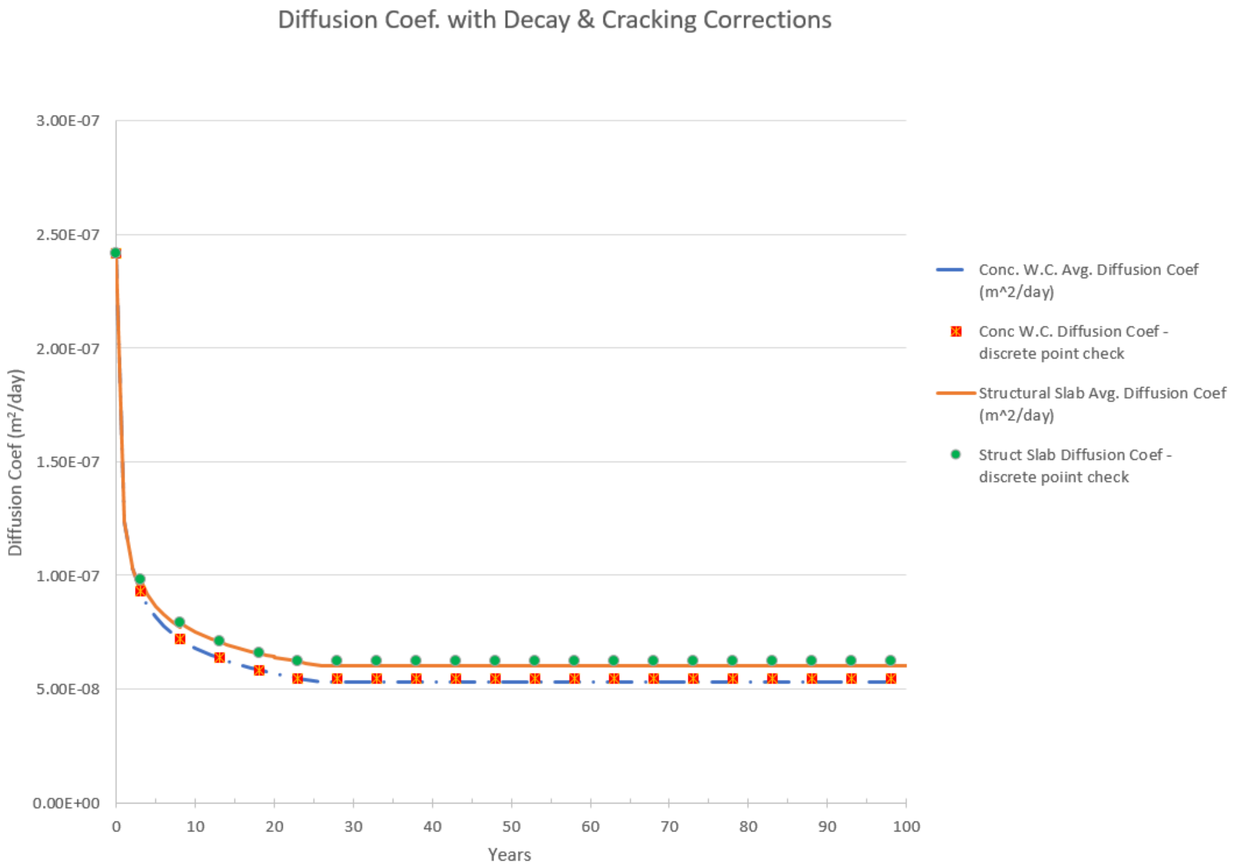
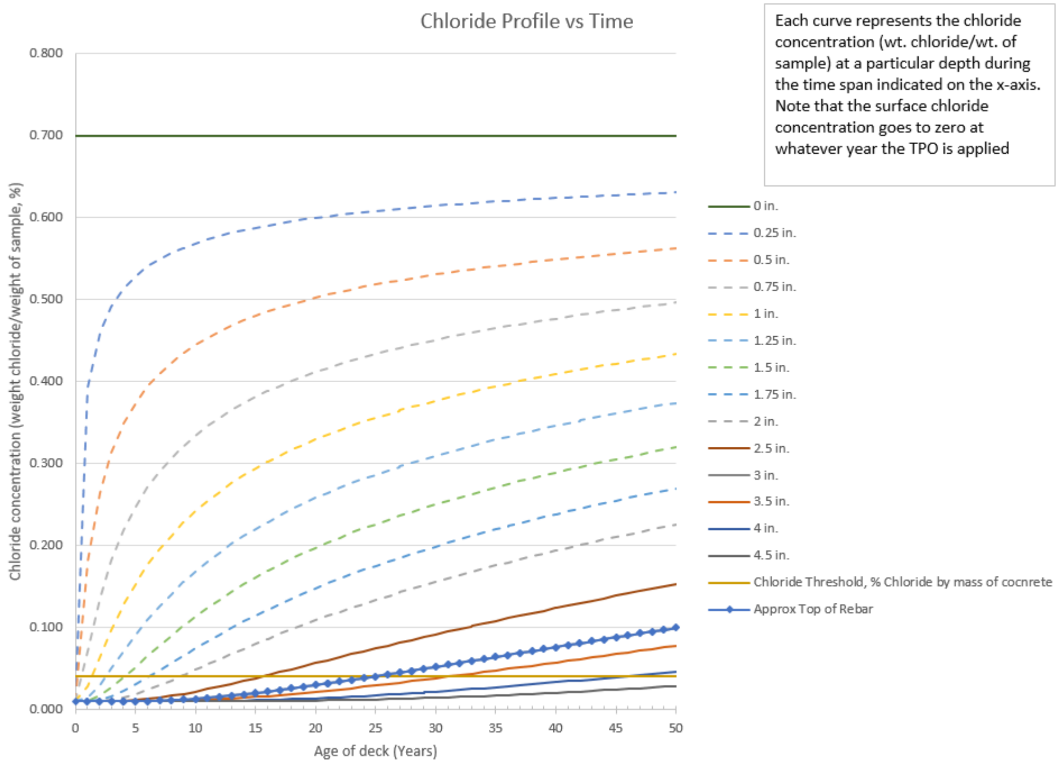


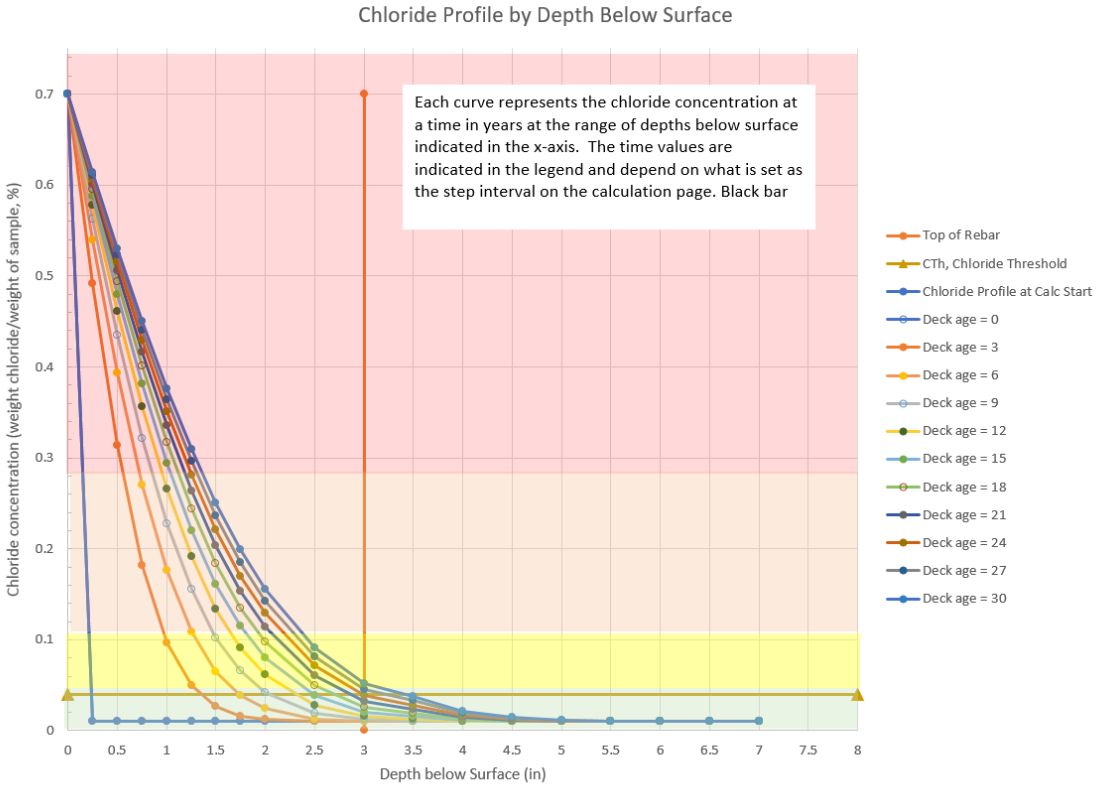
Figure C.15: Resultant diffusion coefficient computed in program over time. The sawtooth jumps in years 3 and 8 represent the smear formula application with changes in cracking input. Note the cracking has moved the diffusion coefficient to a higher value than the concrete wearing course diffusion coefficient that does not have cracking activated. In these models there is no concrete wearing course thickness, however, so there concrete wearing course diffusion coefficient is not used in the chloride penetration calculations.

Two plots were created by Model Cracked Baseline 2: “C Profiles Time” and “C Profiles Depth”. Figure C.16 illustrates the chloride concentration in the deck (wt. chloride/wt. of sample) at multiple depths from 0 to 50 years. The model calculated the chloride ingress out to 100 years, but the plot view was limited to show more detail between 0-50 years.



Each curve represents the chloride concentration (wt. chloride/wt. of sample) at a particular depth during the time span indicated on the x-axis. Note that the surface chloride concentration goes to zero at whatever year the TPO is applied

Figure C.16: "C Profiles Time" plot from model Cracked Baseline 2



Each curve represents the chloride concentration at a time in years at the range of depths below surface indicated in the x-axis. The time values are indicated in the legend and depend on what is set as the step interval on the calculation page. Black bar

Figure C.17: "C Profiles Depth" plot from model Cracked Baseline 2

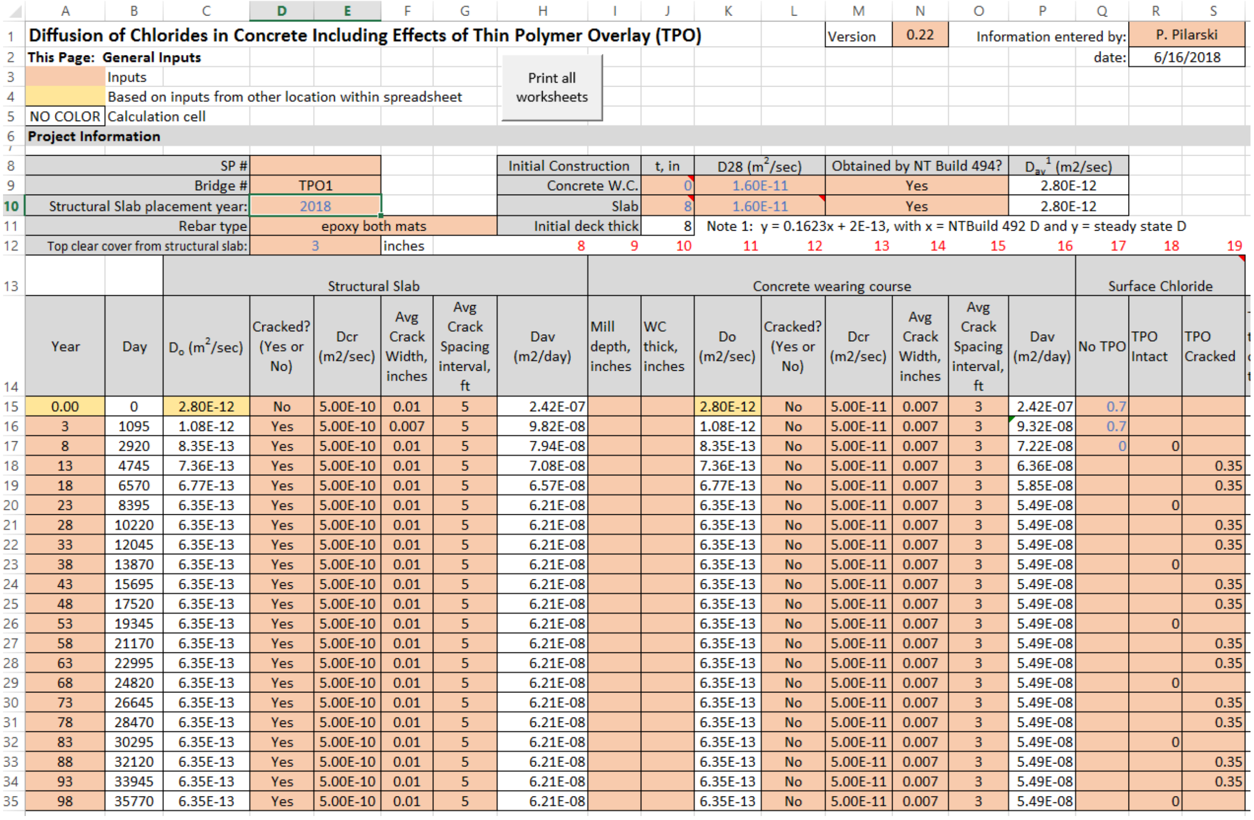
Each curve in Figure C.16 (“C Profiles Depth”) represents the chloride concentration at a time in years through the thickness of the deck. The depth of rebar is indicated by the straight vertical line at 3 in. While the model calculated chloride ingress to 100 years, the plots were limited to snapshots of the chloride profile projection at years 0, 6, 12, 18, 24, and 30.

Figures C.16 and C.17 show that the chloride threshold at the level of the reinforcing steel is reached at about 20 years for a 0.030%CH/sample threshold and 25 years for a 0.040% CH/sample. Comparing the Baseline 2, the chloride threshold is reached 2 years earlier with the level of cracking indicated.

C.1.4 Case Study Scenario 4: TPO 1

Model “TPO 1” will show how the chloride profile changes when a TPO is applied and serviced throughout the life of the deck. In “TPO 1”, all inputs remain the same as “Cracked Baseline 2” except for the inputs in the Surface Chloride columns on the General Inputs tab. After 8 years, a TPO is applied effectively cutting off surface chloride. The TPO remains in service without cracks for 5 years, after which some cracking is observed. To recognize cracking, the model uses half the surface chloride loading. When the TPO is replaced after 15 years of service, the cycle repeats. The user can adjust the discrete years to any desired interval and have immediate results. It is recommended, however, to space the years as regularly as possible.

The year and surface chloride inputs are shown in Figures C.18 and C.19. In the model, the TPO is “applied” by adjusting the surface chloride concentration. When a TPO is applied, it cuts off the source of chlorides from the rest of the deck so the surface chloride concentration is effectively 0. After some time, the TPO will likely develop cracks and other distresses allowing some quantity of chlorides through to the deck. In TPO 1, years 13 through 23 assume a cracked TPO represented by a surface chloride concentration adjusted to half (0.35%) that of the original surface chloride concentration (0.7%).



Diffusion of Chlorides in Concrete Including Effects of Thin Polymer Overlay (TPO)

Version 0.22

Information entered by: P. Pilarski

date: 6/16/2018

This Page: General Inputs

Inputs

Based on inputs from other location within spreadsheet

NO COLOR Calculation cell

Project Information

SP #:

Bridge #: TPO1

Structural Slab placement year: 2018

Rebar type: epoxy both mats

Top clear cover from structural slab: 3 inches

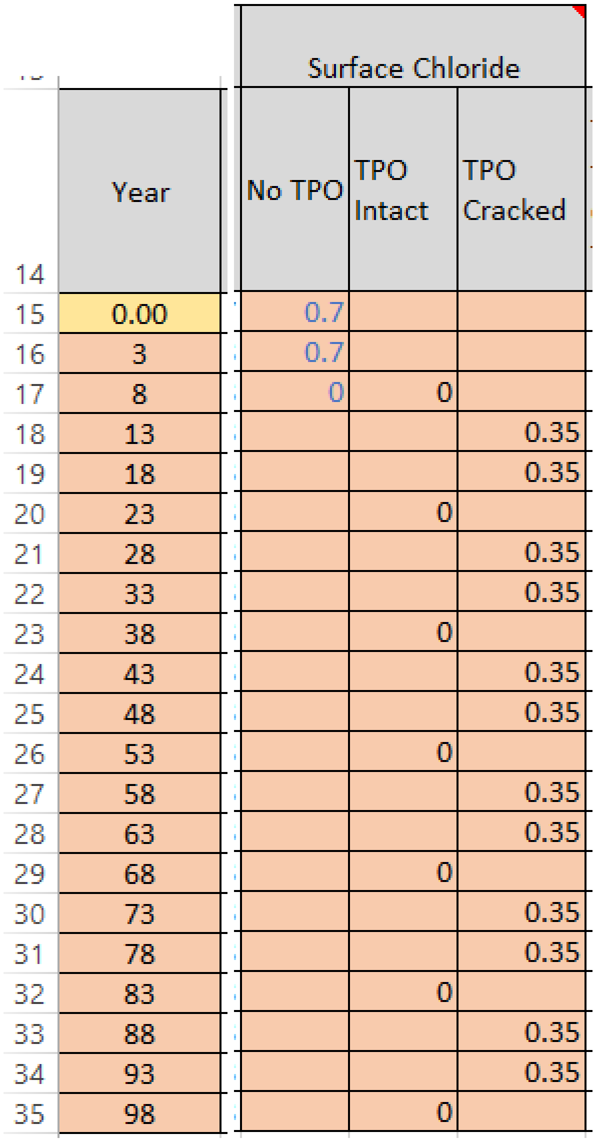
Initial Construction	t, in	D28 (m^2/sec)	Obtained by NT Build 494?	D_{av}^1 (m2/sec)
Concrete W.C.	0	1.60E-11	Yes	2.80E-12
Slab	8	1.60E-11	Yes	2.80E-12
Initial deck thick	8			

Note 1: y = 0.1623x + 2E-13, with x = NTBuild 492 D and y = steady state D

8 9 10 11 12 13 14 15 16 17 18 19

		Structural Slab						Concrete wearing course								Surface Chloride		
Year	Day	D_o (m^2/sec)	Cracked? (Yes or No)	Dcr (m2/sec)	Avg Crack Width, inches	Avg Crack Spacing interval, ft	Dav (m2/day)	Mill depth, inches	WC thick, inches	Do (m2/sec)	Cracked? (Yes or No)	Dcr (m2/sec)	Avg Crack Width, inches	Avg Crack Spacing interval, ft	Dav (m2/day)	No TPO	TPO Intact	TPO Cracked
0.00	0	2.80E-12	No	5.00E-10	0.01	5	2.42E-07			2.80E-12	No	5.00E-11	0.007	3	2.42E-07	0.7		
3	1095	1.08E-12	Yes	5.00E-10	0.007	5	9.82E-08			1.08E-12	No	5.00E-11	0.007	3	9.32E-08	0.7		
8	2920	8.35E-13	Yes	5.00E-10	0.01	5	7.94E-08			8.35E-13	No	5.00E-11	0.007	3	7.22E-08	0	0	
13	4745	7.36E-13	Yes	5.00E-10	0.01	5	7.08E-08			7.36E-13	No	5.00E-11	0.007	3	6.36E-08			0.35
18	6570	6.77E-13	Yes	5.00E-10	0.01	5	6.57E-08			6.77E-13	No	5.00E-11	0.007	3	5.85E-08			0.35
23	8395	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08		0	
28	10220	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08			0.35
33	12045	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08			0.35
38	13870	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08		0	
43	15695	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08			0.35
48	17520	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08			0.35
53	19345	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08		0	
58	21170	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08			0.35
63	22995	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08			0.35
68	24820	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08		0	
73	26645	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08			0.35
78	28470	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08			0.35
83	30295	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08		0	
88	32120	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08			0.35
93	33945	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08			0.35
98	35770	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08		0	

Figure C.18: Year and surface chloride inputs in the General Inputs tab for model TPO 1



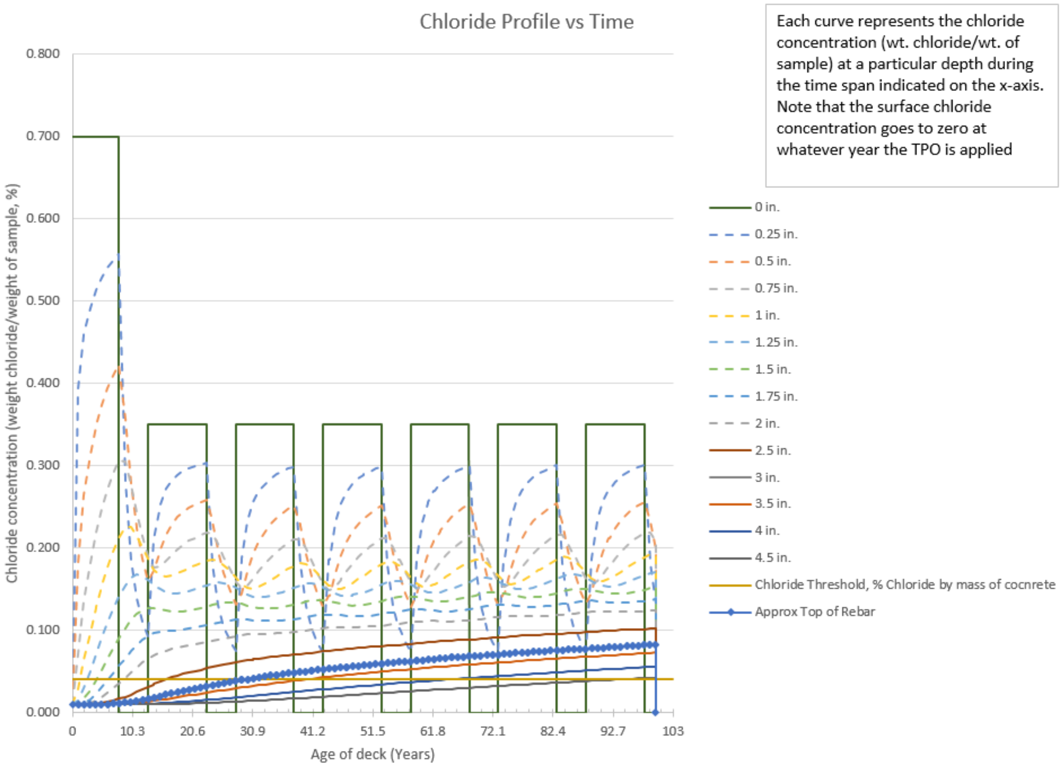
	Year	Surface Chloride		
14		No TPO	TPO Intact	TPO Cracked
15	0.00	0.7		
16	3	0.7		
17	8	0	0	
18	13			0.35
19	18			0.35
20	23		0	
21	28			0.35
22	33			0.35
23	38		0	
24	43			0.35
25	48			0.35
26	53		0	
27	58			0.35
28	63			0.35
29	68		0	
30	73			0.35
31	78			0.35
32	83		0	
33	88			0.35
34	93			0.35
35	98		0	

Figure C.19: Year and surface chloride inputs in the General Inputs tab for model TPO 1

It is important to point out some nuances with this case study. Recall that “Cracked Baseline 2” scenario increased the diffusion coefficient in the slab to account for cracking levels. This case scenario builds on the Cracked Baseline 2 model and simply changes in the surface chloride loading, which effectively models the TPO presence. However, using a diffusion coefficient increased to account for cracks is subject to debate. Many DOT’s use crack penetrating sealers such as low viscosity epoxy or high molecular weight methyl methacrylate ahead of TPO application. In these cases, it may be appropriate to remove the presence of cracks in the model once the TPO is applied and intact. This is because the model uses the modified (cracked) diffusion coefficient to predict existing chloride movement. If the cracked diffusion coefficient is being used within a slab that is insulated from new moisture ingress, diffusion of existing chlorides may be overestimated.

As with the other case scenarios, plots “C Profiles Time” and “C Profiles Depth” were created for Model TPO 1. Figure C.20 (“C Profiles Time”) illustrates the chloride concentration in the deck (wt. chloride/wt. of sample) at multiple depths from 0 to 100 years. Notice how the surface chloride concentration changes when the TPO is added, when it becomes cracked, and when it is renewed. This plot illustrates how the concrete closest to the surface changes more rapidly with changing surface chloride concentration compared to concrete at greater depths.

In Figure C.21, the predicted chloride profile is given for discrete years at years 0, 6, 12, 18, 24, and 30. The depth of rebar is indicated by the straight vertical line at 3 in. Figure C.21 may appear confusing when inputting variable surface chloride loading cases. This is especially true reviewing the upper 2-inches of each chloride profile year because the surface loading dramatically changes the gradient of the chloride profile near the surface. To avoid confusion, one can review Figure C.20 and focus on both the surface chloride level and the chloride level at the rebar horizon. The surface chloride level presents a step-like loading which mimics the input of either cutting chlorides off completely by a TPO less than 5 years old or seeing a partial chloride loading. This approach may be simplistic but captures the needs of most agencies in seeing the benefit of maintaining good condition of applied polymer overlays.



Each curve represents the chloride concentration (wt. chloride/wt. of sample) at a particular depth during the time span indicated on the x-axis. Note that the surface chloride concentration goes to zero at whatever year the TPO is applied

Figure C.21: “C Profiles Time” plot from Model “TPO 1” where a TPO is placed in year 8 and re-applied every 15 years. Note the block-step pattern is the result of surface chlorides being first cut off by the TPO, and then subsequently working through the TPO when it cracks 5 years into the service life. The repeated block pattern is due to re-application of the TPO and cutting off surface chlorides for half the TPO life.

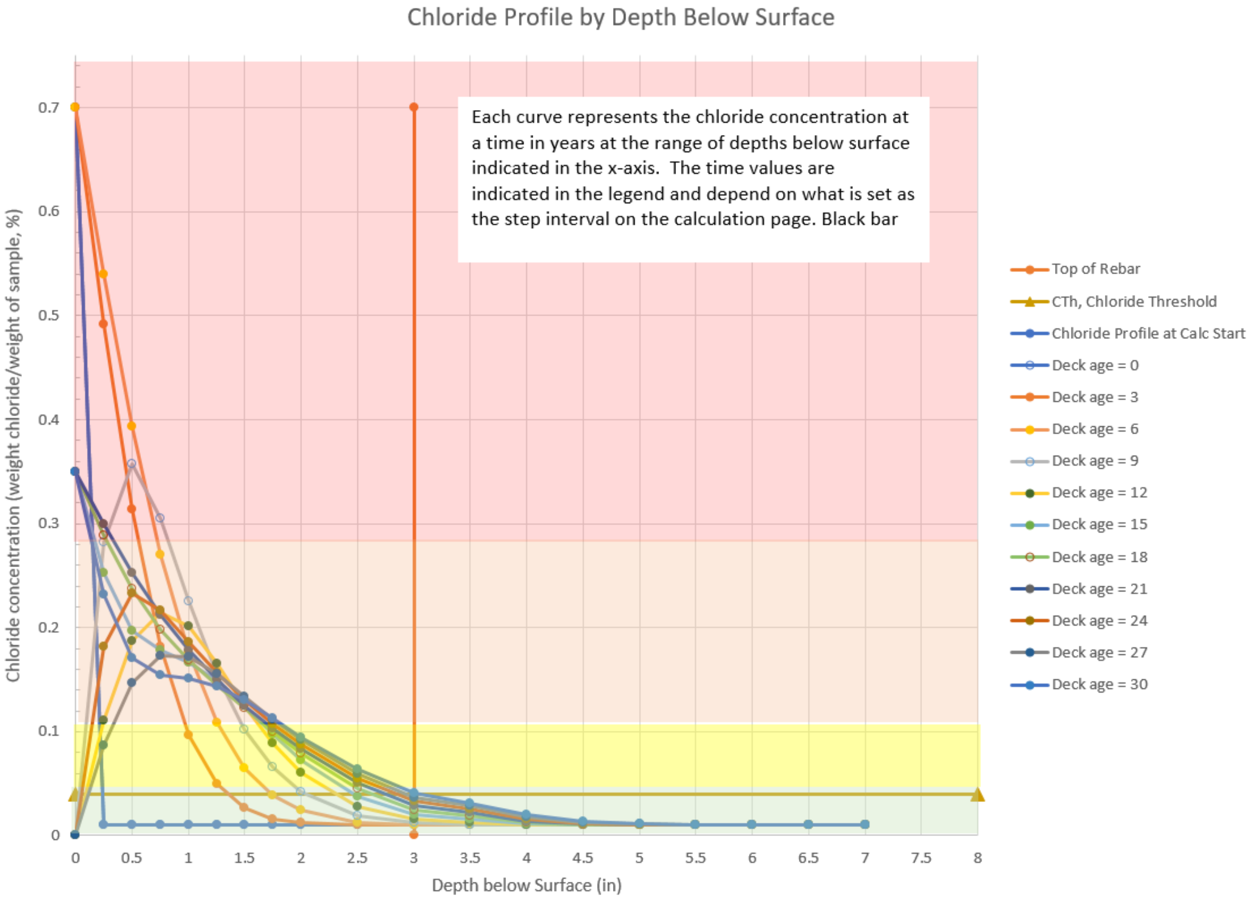
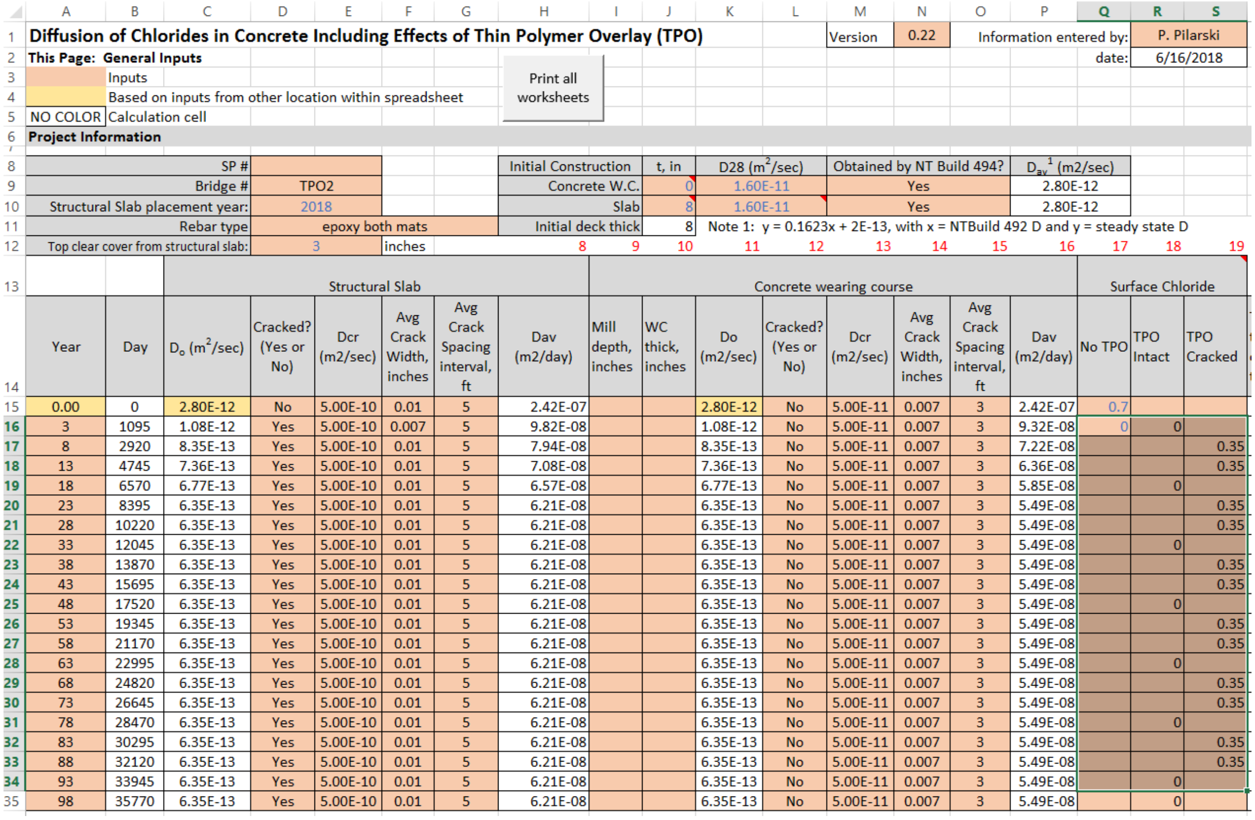


Figure C.22: "C Profiles Depth" plot from TPO 1. Note that depending on the year plotted, the surface chloride is either present, 0, or partially applied. This surface chloride loading is entered by the user to mimic the condition of the TPO.

When the TPO is applied at 8 years, the chloride concentration threshold is reached at the level of the reinforcing steel at 27 years. This is a very short gain in life if the threshold value were the sole determining influence of service life. The next case study will illustrate application in the same approach with TPO application in year 3. One will see that applying the TPO in year 3 gains 15 years additional time until chlorides have reached the level of topmost steel reinforcement.

C.1.5 Case Study Scenario 5: TPO 2

Model "TPO 2" will build on TPO but show the effects of applying a TPO in year 3. All other inputs are the same except for the surface loading. After 3 years, a TPO is applied effectively cutting off surface chloride. The TPO remains in service without cracks for 5 years, after which some cracking is observed. To recognize cracking, the model uses half the surface chloride loading. When the TPO is replaced after 15 years of service, the cycle repeats. The year and surface chloride inputs are shown in Figure C.23.



Diffusion of Chlorides in Concrete Including Effects of Thin Polymer Overlay (TPO)

Version 0.22

Information entered by: P. Pilarski

date: 6/16/2018

This Page: General Inputs

Inputs

Based on inputs from other location within spreadsheet

NO COLOR Calculation cell

Project Information

SP #	
Bridge #	TPO2
Structural Slab placement year:	2018
Rebar type	epoxy both mats
Top clear cover from structural slab:	3 inches

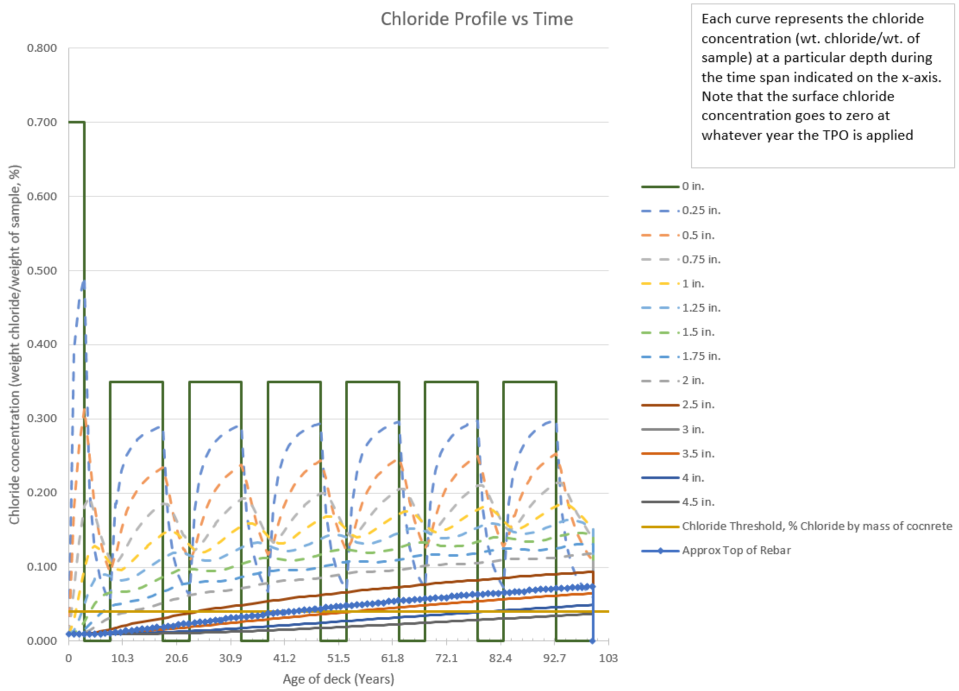
Initial Construction	t, in	D28 (m^2/sec)	Obtained by NT Build 494?	D_{av} [1] (m2/sec)
Concrete W.C.	0	1.60E-11	Yes	2.80E-12
Slab	8	1.60E-11	Yes	2.80E-12
Initial deck thick	8			

Note 1: y = 0.1623x + 2E-13, with x = NTBuild 492 D and y = steady state D

8 9 10 11 12 13 14 15 16 17 18 19

		Structural Slab						Concrete wearing course								Surface Chloride		
Year	Day	D_o (m^2/sec)	Cracked? (Yes or No)	Dcr (m2/sec)	Avg Crack Width, inches	Avg Crack Spacing interval, ft	Dav (m2/day)	Mill depth, inches	WC thick, inches	Do (m2/sec)	Cracked? (Yes or No)	Dcr (m2/sec)	Avg Crack Width, inches	Avg Crack Spacing interval, ft	Dav (m2/day)	No TPO	TPO Intact	TPO Cracked
0.00	0	2.80E-12	No	5.00E-10	0.01	5	2.42E-07			2.80E-12	No	5.00E-11	0.007	3	2.42E-07	0.7		
3	1095	1.08E-12	Yes	5.00E-10	0.007	5	9.82E-08			1.08E-12	No	5.00E-11	0.007	3	9.32E-08	0	0	
8	2920	8.35E-13	Yes	5.00E-10	0.01	5	7.94E-08			8.35E-13	No	5.00E-11	0.007	3	7.22E-08			0.35
13	4745	7.36E-13	Yes	5.00E-10	0.01	5	7.08E-08			7.36E-13	No	5.00E-11	0.007	3	6.36E-08			0.35
18	6570	6.77E-13	Yes	5.00E-10	0.01	5	6.57E-08			6.77E-13	No	5.00E-11	0.007	3	5.85E-08		0	
23	8395	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08			0.35
28	10220	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08			0.35
33	12045	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08		0	
38	13870	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08			0.35
43	15695	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08			0.35
48	17520	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08		0	
53	19345	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08			0.35
58	21170	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08			0.35
63	22995	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08		0	
68	24820	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08			0.35
73	26645	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08			0.35
78	28470	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08		0	
83	30295	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08			0.35
88	32120	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08			0.35
93	33945	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08		0	
98	35770	6.35E-13	Yes	5.00E-10	0.01	5	6.21E-08			6.35E-13	No	5.00E-11	0.007	3	5.49E-08		0	

Figure C.23: Year and surface chloride inputs in the General Inputs tab for model TPO 2



Each curve represents the chloride concentration (wt. chloride/wt. of sample) at a particular depth during the time span indicated on the x-axis. Note that the surface chloride concentration goes to zero at whatever year the TPO is applied

Figure C.24: "C Profiles Time" plot from Model "TPO 2" where a TPO is placed in year 3 and re-applied every 15 years.

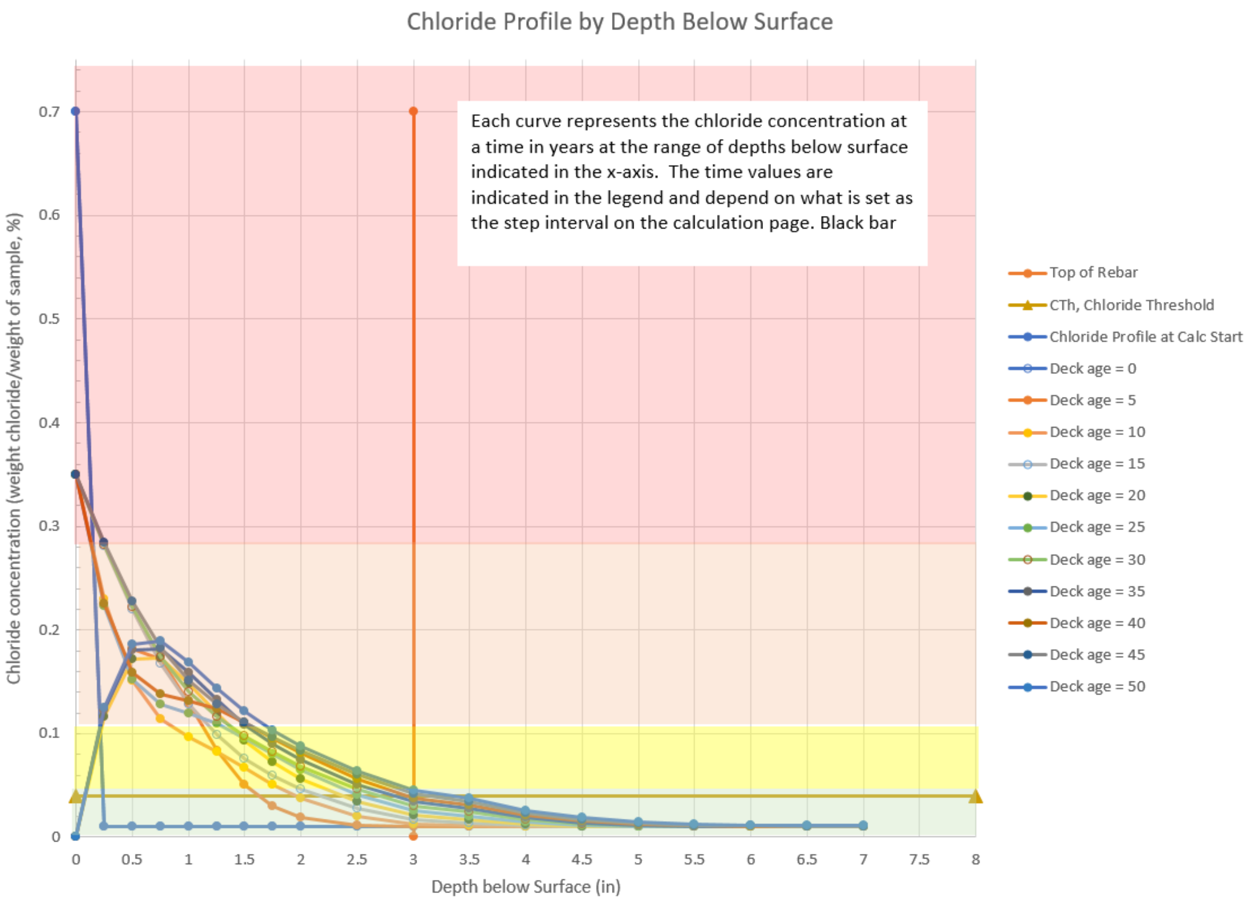


Figure C.25: “C Profiles Depth” plot from Model “TPO 2” where a TPO is placed in year 3 and re-applied every 15 years. Chloride threshold at the top rebar level is reached in year 42.

Reviewing Figures C.24 and C.25 it is found that a 0.040% CH/sample threshold is reached in year 42. Numerous scenarios may be run by the user for optimal timing of the TPO for use in life cycle cost models.

It is important to illustrate that this is a hypothetical case, but may be close to reality which can be reviewed with further use of the model and further case study review (for which the authors are still processing). As mentioned earlier in Baseline 2, the model accounted for cracks increasing in width through the first 10 years of life and remaining unsealed except when topped by a TPO. Unless a deck is left unsealed by maintenance for an extended period of time it is likely modern HPC decks with fly ash could delay TPO application with minimal risk. In addition, the chloride threshold of 0.40 has been used in this model despite incorporating epoxy coated reinforcement in both reinforcement steel mats. Corrosion of epoxy reinforcing steel is highly variable, most often local to cracks, and depends on holiday or defect rates. The chloride threshold should be evaluated for individual owner construction practice.

C.2 SUMMARY

For a new, 8 in. bridge deck that contains 600 lbs cementitious with 30% fly ash replacement for Portland cement, the TPO model predicts that the chloride concentration at the level of the top mat of reinforcing steel in an uncracked deck will not reach a chloride level of 0.040% CH/sample until 123 years and the uncoated reinforcement threshold level (0.03%) as late as 101 years (Baseline 1 model). When the concrete mix only uses Portland cement, a decay coefficient of 0.26 is used. Model Baseline 2 shows this effect and results in chlorides reaching a 0.030% CH/sample level in year 22, and at a 0.040% CH/sample in year 27. Once cracks are considered with a mix without flyash or slag, the threshold chloride concentration is reached 2 years earlier.

When a TPO is added 8 years after the Baseline 2 deck is poured, the 0.040% CH/sample threshold is predicted to be reached at 27 years. Applying the TPO in year 3 instead of year 8 results in the 0.040% CH/sample threshold being met in year 42. Both of these TPO predictions assumes cracks within the TPO after 5 years of service, and a TPO renewal cycle of 15 years. When the TPO cracks the surface chloride is changed to half the value of the surface chloride loading without TPO.

An important observation from development of these models is the great influence of the first year in a concrete decks life. If the decay coefficient behaviour shown in models Baseline 1 and Baseline 2 is assumed correct, the first year from construcion is when the chloride absorption is greatest. It would be prudent to consider the following actions during initial construciotn to greatly enhance deck life:

1. Forego any diamond grinding for texture
2. Place silanes or siloxane sealers with initial construction
3. Use Poly-Alpha Methylsytrene (AMS) membrane curing compound in a high doasage to lengthen concrete cure and provide an additional chloride barrier during first salting season

Modeling bridge specific conditions by the relatively simple method presented in this paper will present quick assessments on the chloride implications. In addition, through this program the user could model concrete wearing course replacement effects, as well as use of penetrating sealers if the diffusion coefficient modifications were known.

APPENDIX D: CASE STUDIES USING THE MODEL DEVELOPED FOR GENERAL CHLORIDE DIFFUSION MODELING

D.1 BRIDGE DECK PRESERVATION MODELING

The case studies contained herein were developed by MnDOT staff as the modeling spreadsheet program finished development. The intent is to illustrate the use of the spreadsheet with some real-world examples. The case studies will illustrate user inputs, potential errors, adjustments and observations. Further study and research is needed to determine the full potential of the model for deck preservation modeling. Service life modeling is divided into two periods: initiation and propagation time. Propagation time estimates have been reported to be less than 10 years, but these estimates may not necessarily represent real world conditions for Minnesota environment, chloride exposures, concrete cover, rebar coatings, rebar spacing and density. Modeling bridges and checking against actual project deck patching quantities will enable better predictions of propagation time, deck patching levels, and service expectations for future asset management.

Case Study 1: Advanced deterioration of Bridge 6347 deck, TH 243 over St. Croix River

This bridge is a MnDOT deck truss bridge constructed in 1952 and redecked in 1980. The bridge consists of two trusses with the monolithic bridge 7" thick deck supported by steel stringers at 4'-9" on center. The top reinforcement mat utilizes epoxy-coated reinforcement, with 2 1/2" concrete cover, and the bottom mat was uncoated. This study will examine the chloride ingress over time and compare the modeling results to the chloride profiles obtained in 2010, as well as deck repair results from two preservation projects in 2010 and in 2017. Illustrating modeling at end of life and reviewing corrosion tolerance in Minnesota environments and salting will enable better patching estimates for asset management near end of life.

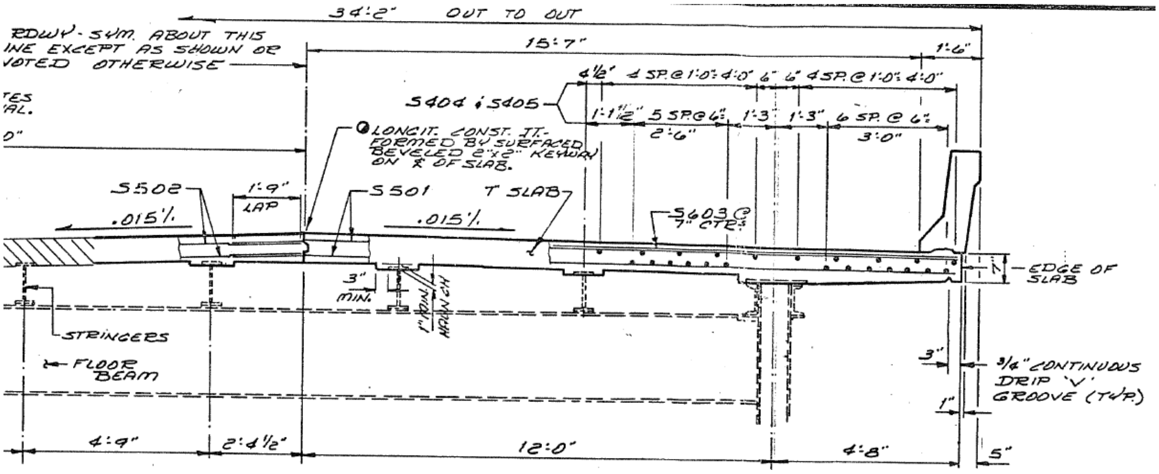


Figure D.1.1: 1980 deck cross section with 7" slab thickness.

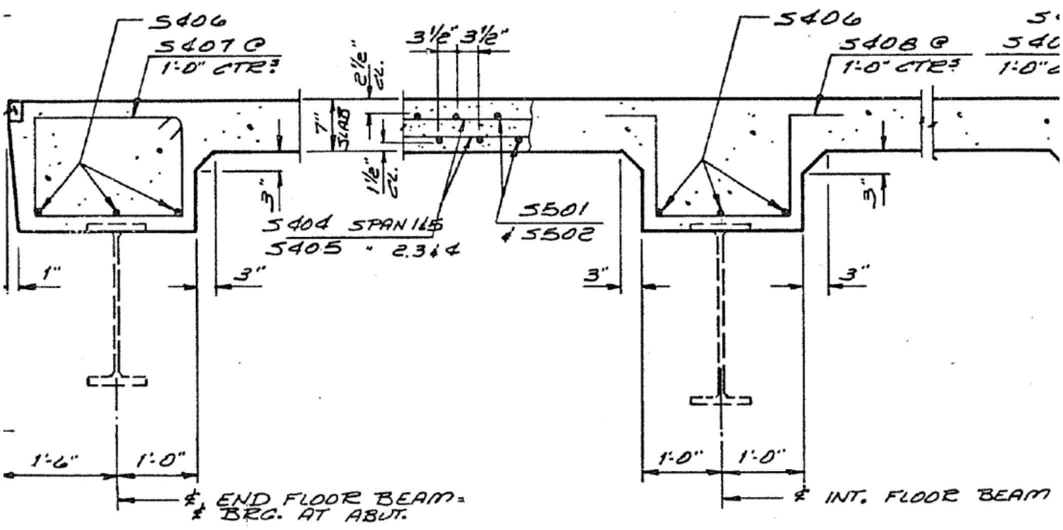
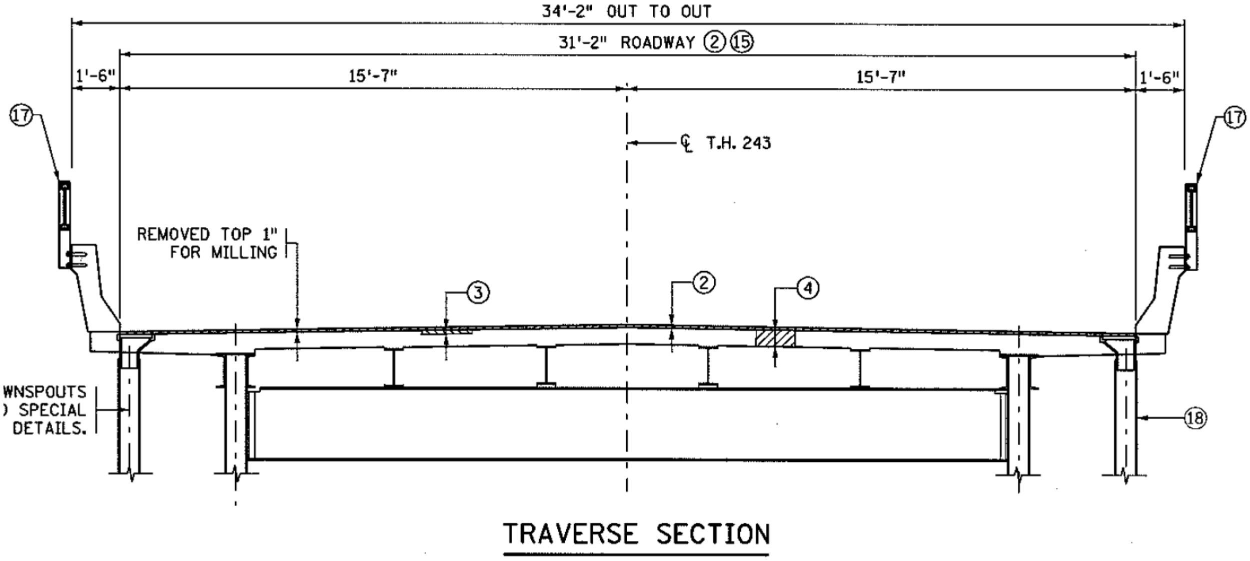


Figure D.1.2: 1980 deck cross section with 2 ½" reinforcement cover to top bars.



NOTES

① "RECONSTRUCT EXP. JT. TYPE C" @ ABUTMENTS.
SEE SHEET NO. 4 & SPECIAL PROVISIONS FOR DETAILS.

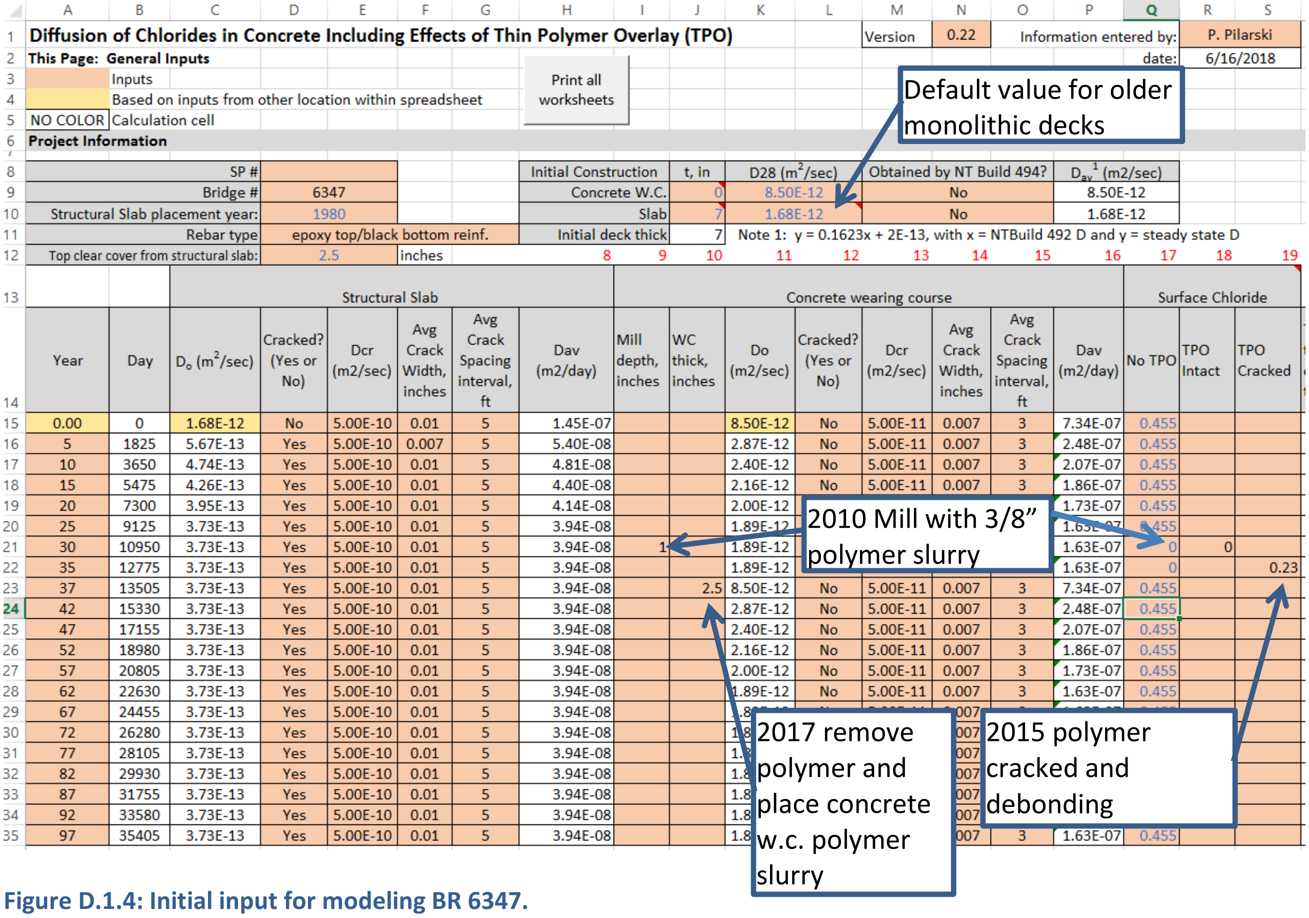
② NEW ⅜" MIN. EPOXY CHIP OVERLAY "CONCRETE CHIPSEAL".
SEE SPECIAL PROVISIONS.

③ CONCRETE SLAB REMOVAL TYPE 1.
SEE SHEET NO. 2 & SPECIAL PROVISIONS FOR DETAILS.

④ CONCRETE SLAB REMOVAL TYPE 3.
SEE SHEET NO. 2 & SPECIAL PROVISIONS FOR DETAILS.

Figure D.1.3: 2010 bridge preservation work with 3/8" polymer overlay. Transpo T48 slurry was used.

The diffusion coefficient and diffusion coefficient decay factor will be first input as the default for older or unknown monolithic decks at 1.68E-12 m^2/sec. Figure D.1.4 shows the General Inputs tab parameters.



Diffusion of Chlorides in Concrete Including Effects of Thin Polymer Overlay (TPO)

Version 0.22

Information entered by: P. Pilarski

date: 6/16/2018

This Page: General Inputs

Inputs

Based on inputs from other location within spreadsheet

NO COLOR Calculation cell

Project Information

SP #		Initial Construction	t, in	D28 (m^2/sec)	Obtained by NT Build 494?	D_{av}^{1} (m2/sec)
Bridge #	6347	Concrete W.C.	0	8.50E-12	No	8.50E-12
Structural Slab placement year:	1980	Slab	7	1.68E-12	No	1.68E-12
Rebar type	epoxy top/black bottom reinf.	Initial deck thick	7			
Top clear cover from structural slab:	2.5 inches					

Note 1: y = 0.1623x + 2E-13, with x = NTBuild 492 D and y = steady state D

Default value for older monolithic decks

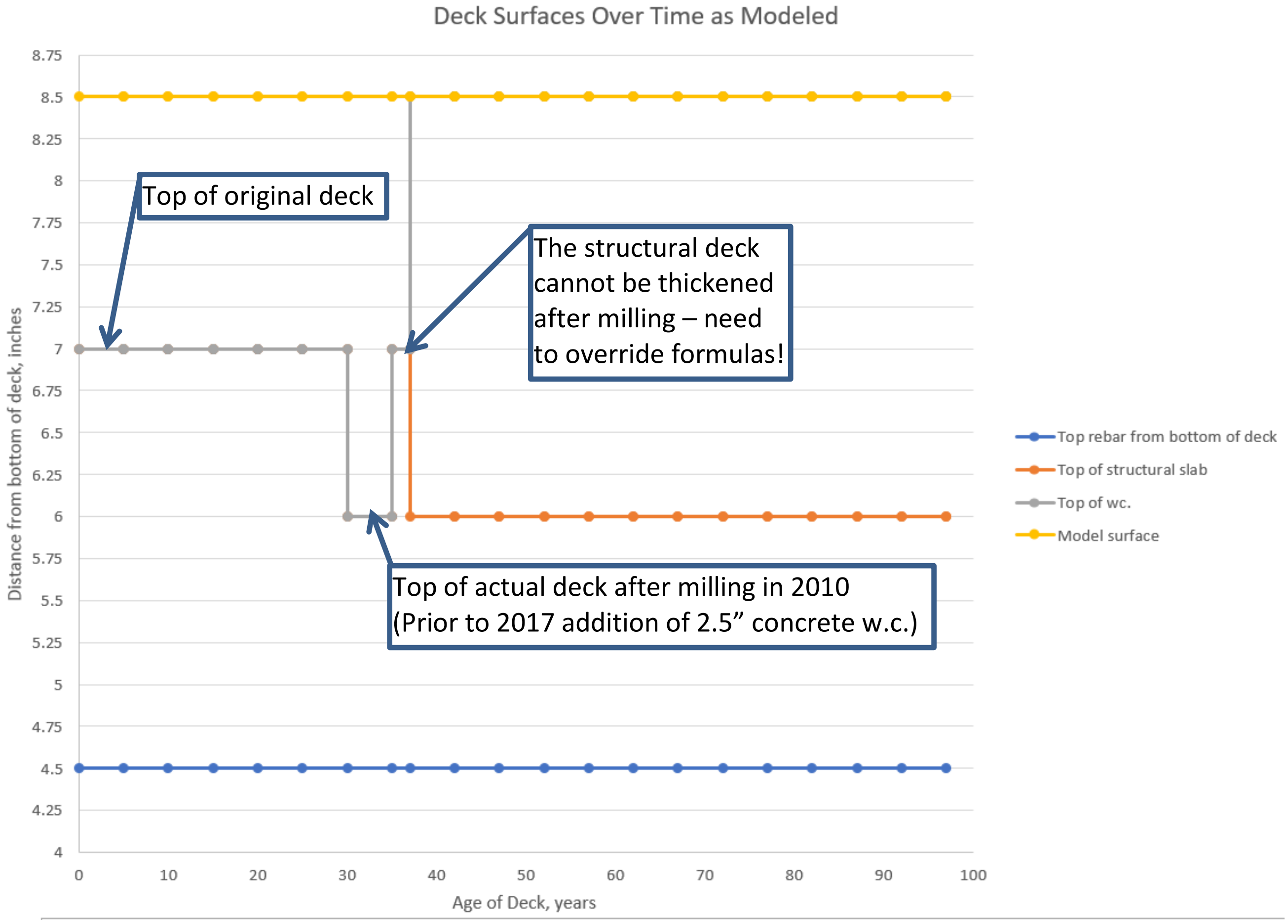
		Structural Slab								Concrete wearing course						Surface Chloride		
							8	9	10	11	12	13	14	15	16	17	18	19
Year	Day	D_o (m^2/sec)	Cracked? (Yes or No)	Dcr (m2/sec)	Avg Crack Width, inches	Avg Crack Spacing interval, ft	Dav (m2/day)	Mill depth, inches	WC thick, inches	Do (m2/sec)	Cracked? (Yes or No)	Dcr (m2/sec)	Avg Crack Width, inches	Avg Crack Spacing interval, ft	Dav (m2/day)	No TPO	TPO Intact	TPO Cracked
0.00	0	1.68E-12	No	5.00E-10	0.01	5	1.45E-07			8.50E-12	No	5.00E-11	0.007	3	7.34E-07	0.455		
5	1825	5.67E-13	Yes	5.00E-10	0.007	5	5.40E-08			2.87E-12	No	5.00E-11	0.007	3	2.48E-07	0.455		
10	3650	4.74E-13	Yes	5.00E-10	0.01	5	4.81E-08			2.40E-12	No	5.00E-11	0.007	3	2.07E-07	0.455		
15	5475	4.26E-13	Yes	5.00E-10	0.01	5	4.40E-08			2.16E-12	No	5.00E-11	0.007	3	1.86E-07	0.455		
20	7300	3.95E-13	Yes	5.00E-10	0.01	5	4.14E-08			2.00E-12	[illegible]	[illegible]	[illegible]	[illegible]	1.73E-07	0.455		
25	9125	3.73E-13	Yes	5.00E-10	0.01	5	3.94E-08			1.89E-12	[illegible]	[illegible]	[illegible]	[illegible]	1.63E-07	0.455		
30	10950	3.73E-13	Yes	5.00E-10	0.01	5	3.94E-08	1		1.89E-12	[illegible]	[illegible]	[illegible]	[illegible]	1.63E-07	0	0	
35	12775	3.73E-13	Yes	5.00E-10	0.01	5	3.94E-08			1.89E-12	[illegible]	[illegible]	[illegible]	[illegible]	1.63E-07	0		0.23
37	13505	3.73E-13	Yes	5.00E-10	0.01	5	3.94E-08		2.5	8.50E-12	No	5.00E-11	0.007	3	7.34E-07	0.455		
42	15330	3.73E-13	Yes	5.00E-10	0.01	5	3.94E-08			2.87E-12	No	5.00E-11	0.007	3	2.48E-07	0.455		
47	17155	3.73E-13	Yes	5.00E-10	0.01	5	3.94E-08			2.40E-12	No	5.00E-11	0.007	3	2.07E-07	0.455		
52	18980	3.73E-13	Yes	5.00E-10	0.01	5	3.94E-08			2.16E-12	No	5.00E-11	0.007	3	1.86E-07	0.455		
57	20805	3.73E-13	Yes	5.00E-10	0.01	5	3.94E-08			2.00E-12	No	5.00E-11	0.007	3	1.73E-07	0.455		
62	22630	3.73E-13	Yes	5.00E-10	0.01	5	3.94E-08			1.89E-12	No	5.00E-11	0.007	3	1.63E-07	0.455		
67	24455	3.73E-13	Yes	5.00E-10	0.01	5	3.94E-08			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		
72	26280	3.73E-13	Yes	5.00E-10	0.01	5	3.94E-08			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
77	28105	3.73E-13	Yes	5.00E-10	0.01	5	3.94E-08			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
82	29930	3.73E-13	Yes	5.00E-10	0.01	5	3.94E-08			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
87	31755	3.73E-13	Yes	5.00E-10	0.01	5	3.94E-08			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
92	33580	3.73E-13	Yes	5.00E-10	0.01	5	3.94E-08			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
97	35405	3.73E-13	Yes	5.00E-10	0.01	5	3.94E-08			[illegible]	[illegible]	[illegible]	[illegible]	3	1.63E-07	0.455		

2010 Mill with 3/8" polymer slurry

2017 remove polymer and place concrete w.c. polymer slurry

2015 polymer cracked and debonding

Figure D.1.4: Initial input for modeling BR 6347.

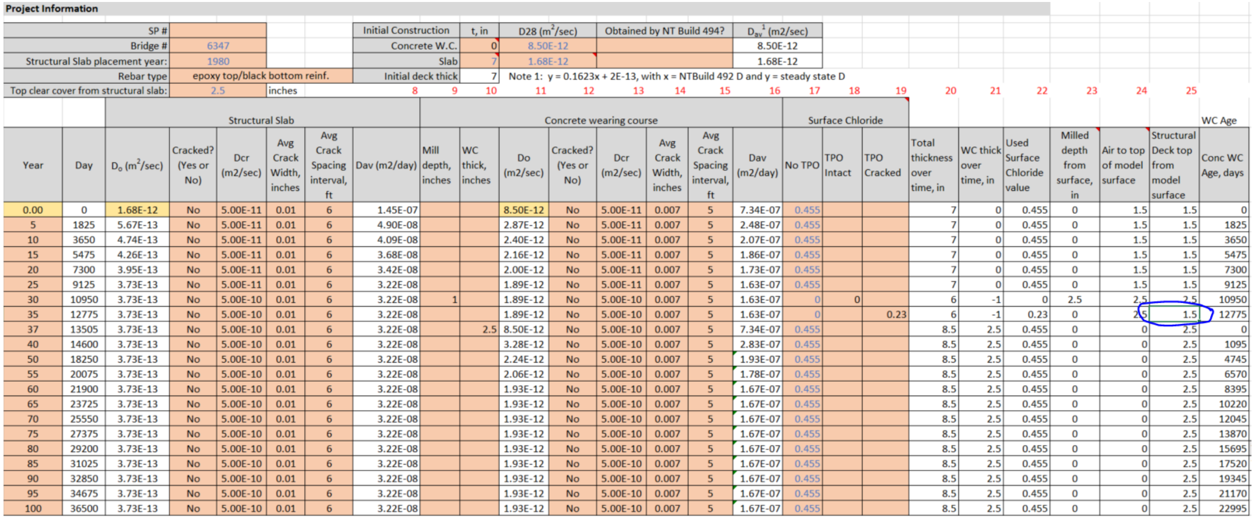


Top of original deck

The structural deck cannot be thickened after milling – need to override formulas!

Top of actual deck after milling in 2010 (Prior to 2017 addition of 2.5" concrete w.c.)

Figure D.1.4: Model geometry reflected from inputs. Note an error in the model was observed when the polymer was placed and it was caught by checking the depth to top of structural slab.



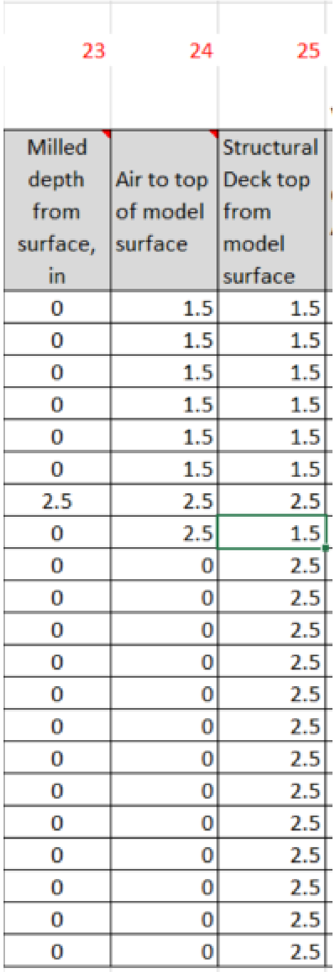
Project Information

SP #			Initial Construction	t, in	D28 (m^2/sec)	Obtained by NT Build 494?	D_{av}[1] (m2/sec)
Bridge #	6347		Concrete W.C.	0	8.50E-12		8.50E-12
Structural Slab placement year:	1980		Slab	7	1.68E-12		1.68E-12
Rebar type	epoxy top/black bottom reinf.		Initial deck thick	7	Note 1: y = 0.1623x + 2E-13, with x = NTBuild 492 D and y = steady state D		
Top clear cover from structural slab:	2.5	inches					

		Structural Slab								Concrete wearing course						Surface Chloride									WC Age
							8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	
Year	Day	D_o (m^2/sec)	Cracked? (Yes or No)	Dcr (m2/sec)	Avg Crack Width, inches	Avg Crack Spacing interval, ft	Dav (m2/day)	Mill depth, inches	WC thick, inches	Do (m2/sec)	Cracked? (Yes or No)	Dcr (m2/sec)	Avg Crack Width, inches	Avg Crack Spacing interval, ft	Dav (m2/day)	No TPO	TPO Intact	TPO Cracked	Total thickness over time, in	WC thick over time, in	Used Surface Chloride value	Milled depth from surface, in	Air to top of model surface	Structural Deck top from model surface	Conc WC Age, days
0.00	0	1.68E-12	No	5.00E-11	0.01	6	1.45E-07			8.50E-12	No	5.00E-11	0.007	5	7.34E-07	0.455			7	0	0.455	0	1.5	1.5	0
5	1825	5.67E-13	No	5.00E-11	0.01	6	4.90E-08			2.87E-12	No	5.00E-11	0.007	5	2.48E-07	0.455			7	0	0.455	0	1.5	1.5	1825
10	3650	4.74E-13	No	5.00E-11	0.01	6	4.09E-08			2.40E-12	No	5.00E-11	0.007	5	2.07E-07	0.455			7	0	0.455	0	1.5	1.5	3650
15	5475	4.26E-13	No	5.00E-11	0.01	6	3.68E-08			2.16E-12	No	5.00E-11	0.007	5	1.86E-07	0.455			7	0	0.455	0	1.5	1.5	5475
20	7300	3.95E-13	No	5.00E-11	0.01	6	3.42E-08			2.00E-12	No	5.00E-11	0.007	5	1.73E-07	0.455			7	0	0.455	0	1.5	1.5	7300
25	9125	3.73E-13	No	5.00E-11	0.01	6	3.22E-08			1.89E-12	No	5.00E-11	0.007	5	1.63E-07	0.455			7	0	0.455	0	1.5	1.5	9125
30	10950	3.73E-13	No	5.00E-10	0.01	6	3.22E-08	1		1.89E-12	No	5.00E-10	0.007	5	1.63E-07	0	0		6	-1	0	2.5	2.5	2.5	10950
35	12775	3.73E-13	No	5.00E-10	0.01	6	3.22E-08			1.89E-12	No	5.00E-10	0.007	5	1.63E-07	0		0.23	6	-1	0.23	0	2.5	1.5	12775
37	13505	3.73E-13	No	5.00E-10	0.01	6	3.22E-08		2.5	8.50E-12	No	5.00E-10	0.007	5	7.34E-07	0.455			8.5	2.5	0.455	0	0	2.5	0
40	14600	3.73E-13	No	5.00E-10	0.01	6	3.22E-08			3.28E-12	No	5.00E-10	0.007	5	2.83E-07	0.455			8.5	2.5	0.455	0	0	2.5	1095
50	18250	3.73E-13	No	5.00E-10	0.01	6	3.22E-08			2.24E-12	No	5.00E-10	0.007	5	1.93E-07	0.455			8.5	2.5	0.455	0	0	2.5	4745
55	20075	3.73E-13	No	5.00E-10	0.01	6	3.22E-08			2.06E-12	No	5.00E-10	0.007	5	1.78E-07	0.455			8.5	2.5	0.455	0	0	2.5	6570
60	21900	3.73E-13	No	5.00E-10	0.01	6	3.22E-08			1.93E-12	No	5.00E-10	0.007	5	1.67E-07	0.455			8.5	2.5	0.455	0	0	2.5	8395
65	23725	3.73E-13	No	5.00E-10	0.01	6	3.22E-08			1.93E-12	No	5.00E-10	0.007	5	1.67E-07	0.455			8.5	2.5	0.455	0	0	2.5	10220
70	25550	3.73E-13	No	5.00E-10	0.01	6	3.22E-08			1.93E-12	No	5.00E-10	0.007	5	1.67E-07	0.455			8.5	2.5	0.455	0	0	2.5	12045
75	27375	3.73E-13	No	5.00E-10	0.01	6	3.22E-08			1.93E-12	No	5.00E-10	0.007	5	1.67E-07	0.455			8.5	2.5	0.455	0	0	2.5	13870
80	29200	3.73E-13	No	5.00E-10	0.01	6	3.22E-08			1.93E-12	No	5.00E-10	0.007	5	1.67E-07	0.455			8.5	2.5	0.455	0	0	2.5	15695
85	31025	3.73E-13	No	5.00E-10	0.01	6	3.22E-08			1.93E-12	No	5.00E-10	0.007	5	1.67E-07	0.455			8.5	2.5	0.455	0	0	2.5	17520
90	32850	3.73E-13	No	5.00E-10	0.01	6	3.22E-08			1.93E-12	No	5.00E-10	0.007	5	1.67E-07	0.455			8.5	2.5	0.455	0	0	2.5	19345
95	34675	3.73E-13	No	5.00E-10	0.01	6	3.22E-08			1.93E-12	No	5.00E-10	0.007	5	1.67E-07	0.455			8.5	2.5	0.455	0	0	2.5	21170
100	36500	3.73E-13	No	5.00E-10	0.01	6	3.22E-08			1.93E-12	No	5.00E-10	0.007	5	1.67E-07	0.455			8.5	2.5	0.455	0	0	2.5	22995

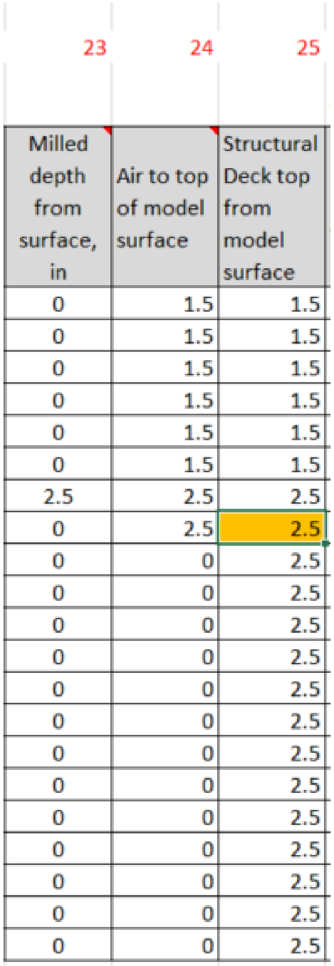
Figure D.1.5: Model formula cells that would suggest the structural slab gained thickness over time.

Error Identified:



23	24	25
Milled depth from surface, in	Air to top of model surface	Structural Deck top from model surface
0	1.5	1.5
0	1.5	1.5
0	1.5	1.5
0	1.5	1.5
0	1.5	1.5
0	1.5	1.5
2.5	2.5	2.5
0	2.5	1.5
0	0	2.5
0	0	2.5
0	0	2.5
0	0	2.5
0	0	2.5
0	0	2.5
0	0	2.5
0	0	2.5
0	0	2.5
0	0	2.5
0	0	2.5
0	0	2.5
0	0	2.5

Corrected:



23	24	25
Milled depth from surface, in	Air to top of model surface	Structural Deck top from model surface
0	1.5	1.5
0	1.5	1.5
0	1.5	1.5
0	1.5	1.5
0	1.5	1.5
0	1.5	1.5
2.5	2.5	2.5
0	2.5	2.5
0	0	2.5
0	0	2.5
0	0	2.5
0	0	2.5
0	0	2.5
0	0	2.5
0	0	2.5
0	0	2.5
0	0	2.5
0	0	2.5
0	0	2.5
0	0	2.5
0	0	2.5

Figure D.1.6: Model formula cells that are overridden for correct calculation.

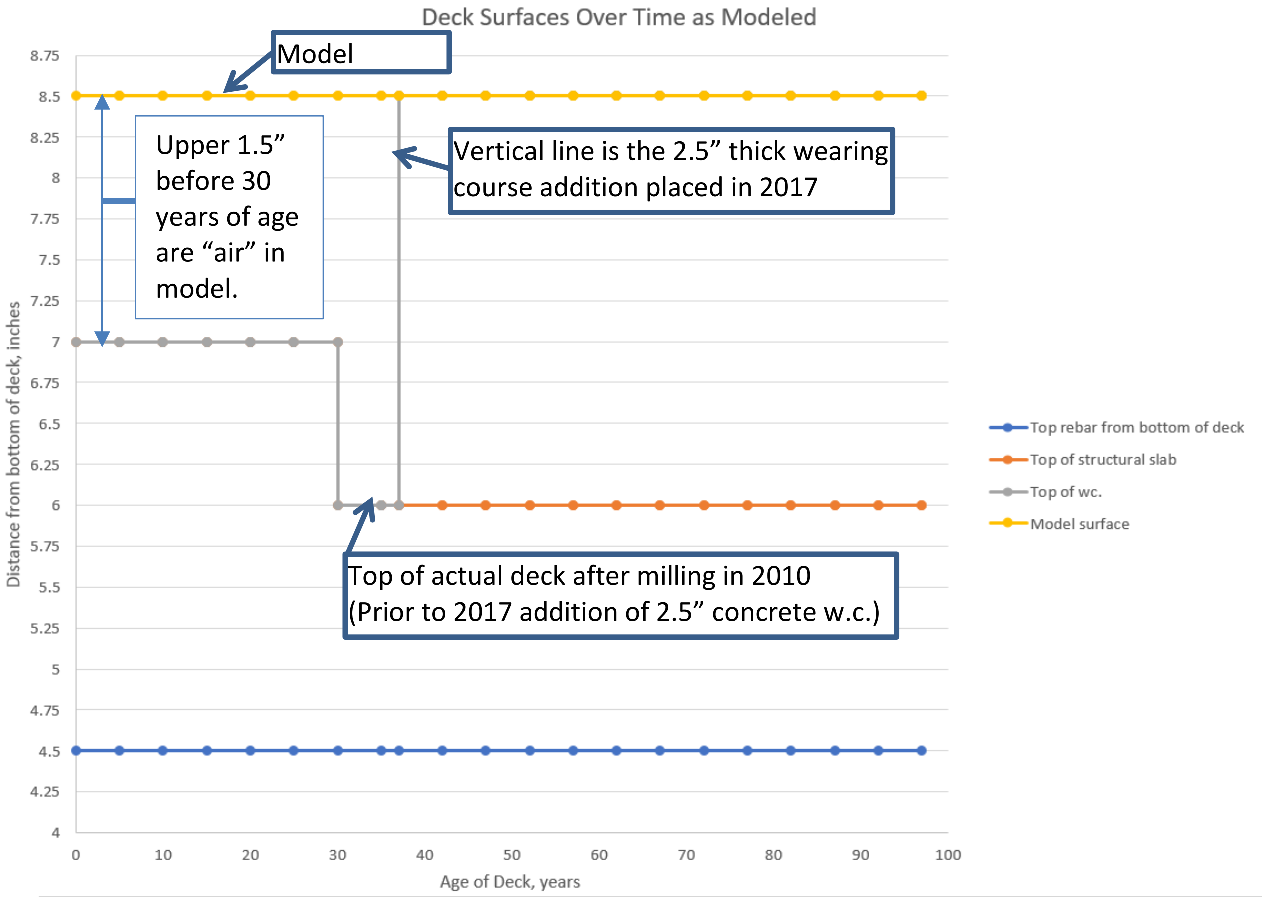
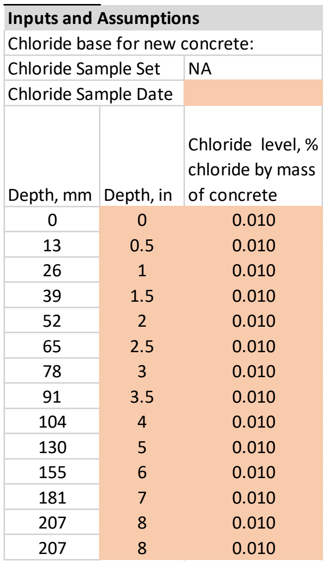


Figure D.1.7: Model overrides properly reflected to correctly show the structural slab history.

Figure D.1.8 shows the inputs for starting chloride profile. The values reflect the background chloride in the concrete, which was selected as 0.01%.



Inputs and Assumptions		
Chloride base for new concrete:		
Chloride Sample Set		NA
Chloride Sample Date		
Depth, mm	Depth, in	Chloride level, % chloride by mass of concrete
0	0	0.010
13	0.5	0.010
26	1	0.010
39	1.5	0.010
52	2	0.010
65	2.5	0.010
78	3	0.010
91	3.5	0.010
104	4	0.010
130	5	0.010
155	6	0.010
181	7	0.010
207	8	0.010
207	8	0.010

Figure D.1.8: Model Inputs on the Chloride Profile tab

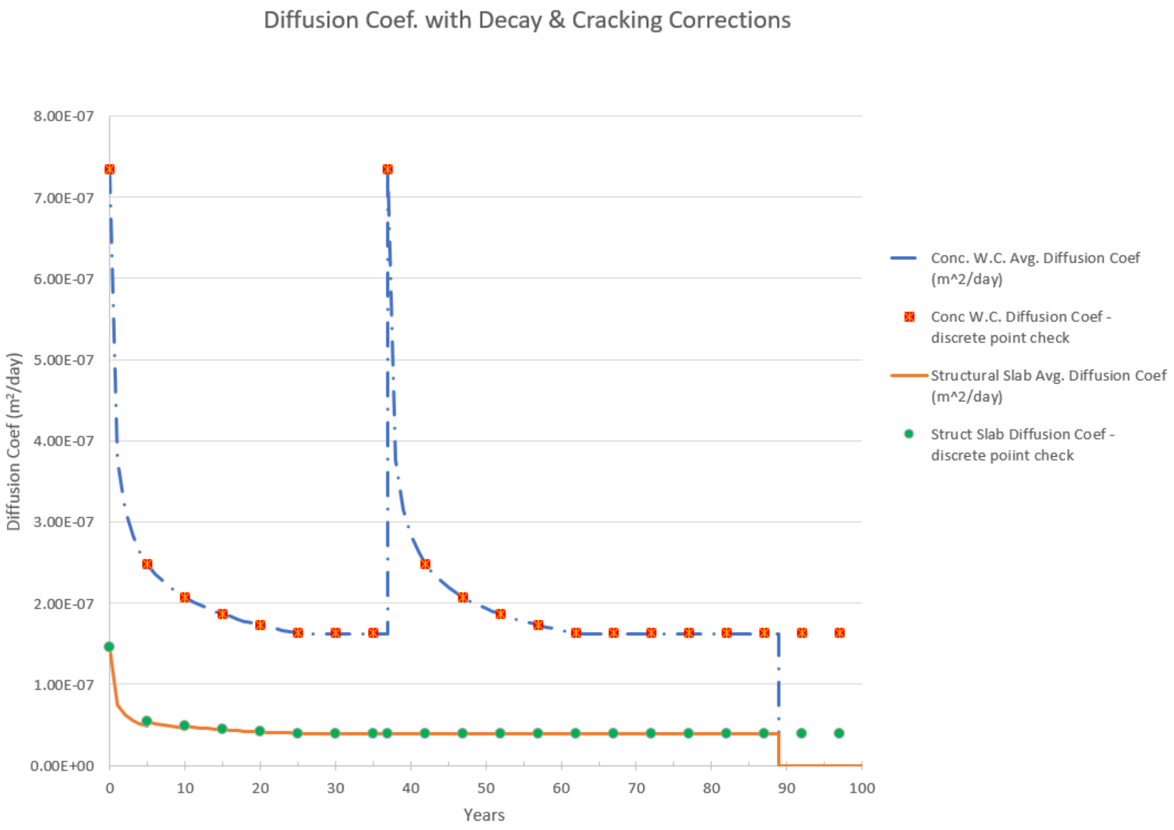
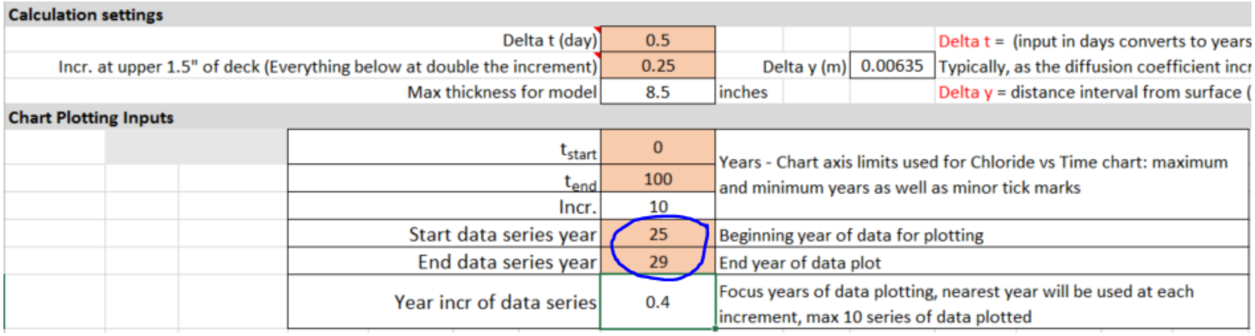


Figure D.1.9: Resultant diffusion coefficient the program calculates over time. The concrete wearing course was placed in year 37.

Two plots were created as is usual for this spreadsheet model: “C Profiles Time” and “C Profiles Depth”. Figure D.1.11 illustrates the chloride concentration in the deck (wt. chloride/wt. of sample) at multiple depths from 25 to 29 years using the default diffusion coefficient of 1.68E-12. The age range for plotting was selected because chloride profile cores were taken in 2010 at 30 years of age. The model calculated chloride concentration through the deck from 0-100 years, but the plot was truncated to show more detail between 0-30 years. This truncation is achieved by modifying the inputs shown in Figure D.1.10.



Calculation settings				
Delta t (day)	0.5			Delta t = (input in days converts to years
Incr. at upper 1.5" of deck (Everything below at double the increment)	0.25	Delta y (m)	0.00635	Typically, as the diffusion coefficient incr
Max thickness for model	8.5	inches		Delta y = distance interval from surface (
Chart Plotting Inputs				
t_{start}	0	Years - Chart axis limits used for Chloride vs Time chart: maximum and minimum years as well as minor tick marks		
t_{end}	100			
Incr.	10			
Start data series year	25	Beginning year of data for plotting		
End data series year	29	End year of data plot		
Year incr of data series	0.4	Focus years of data plotting, nearest year will be used at each increment, max 10 series of data plotted		

Figure D.1.10: Model Inputs on the Chloride Profile tab

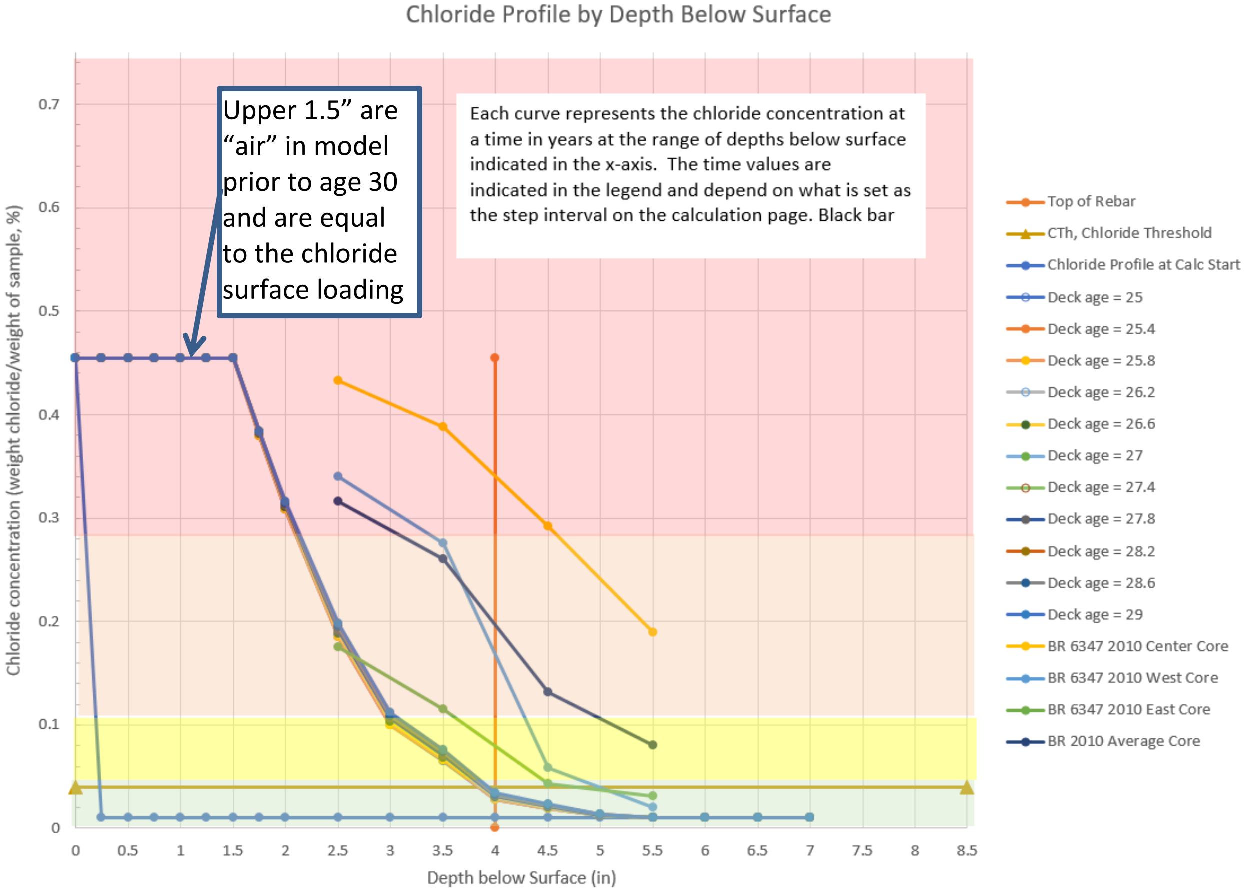
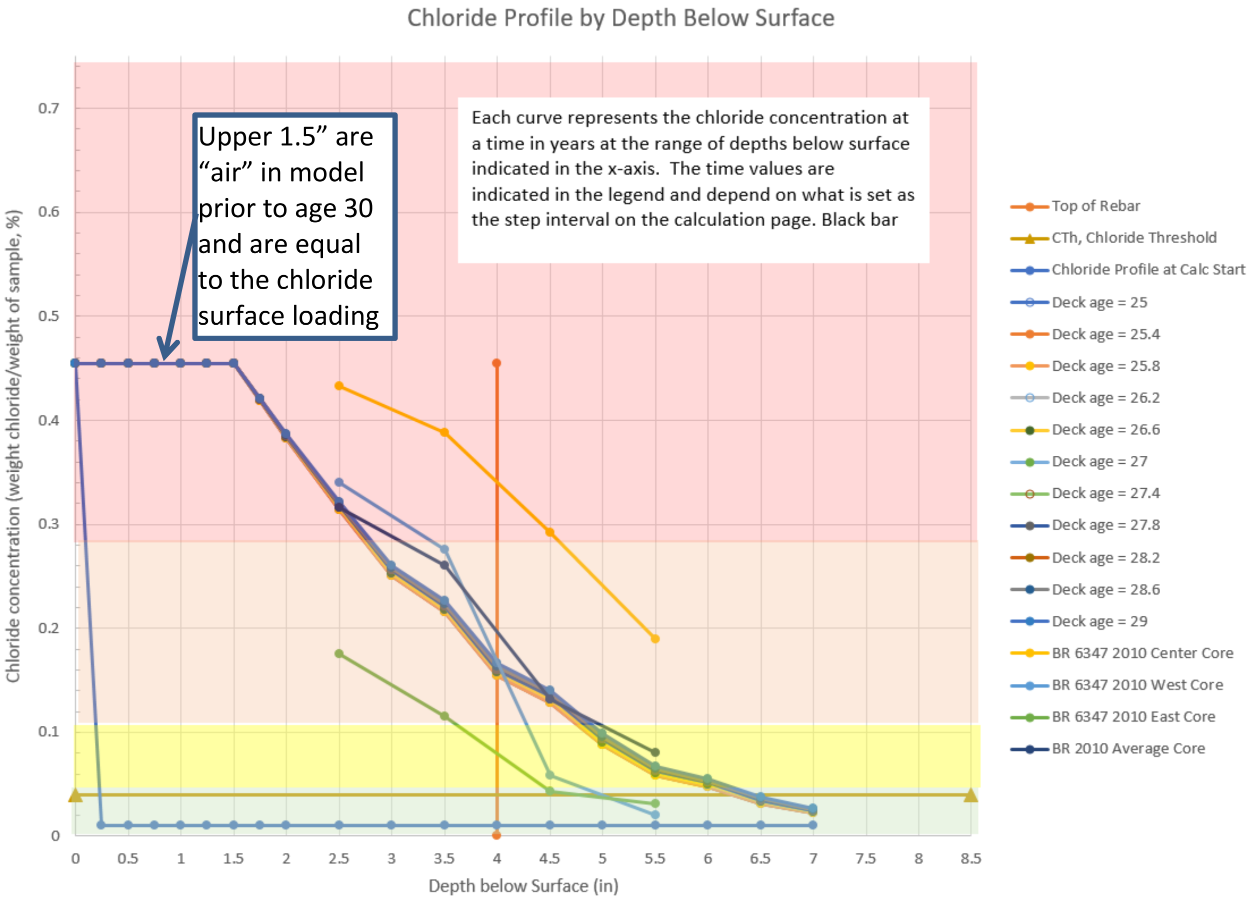


Figure D.1.11: Chloride versus Depth Plot: Results of initial inputs using default diffusion coefficient of 1.68E-12 m^2/sec and chloride surface loading of 0.455. The year range plotted is between 25 and 29 years to focus results to the chloride profile sampling date for model calibration.

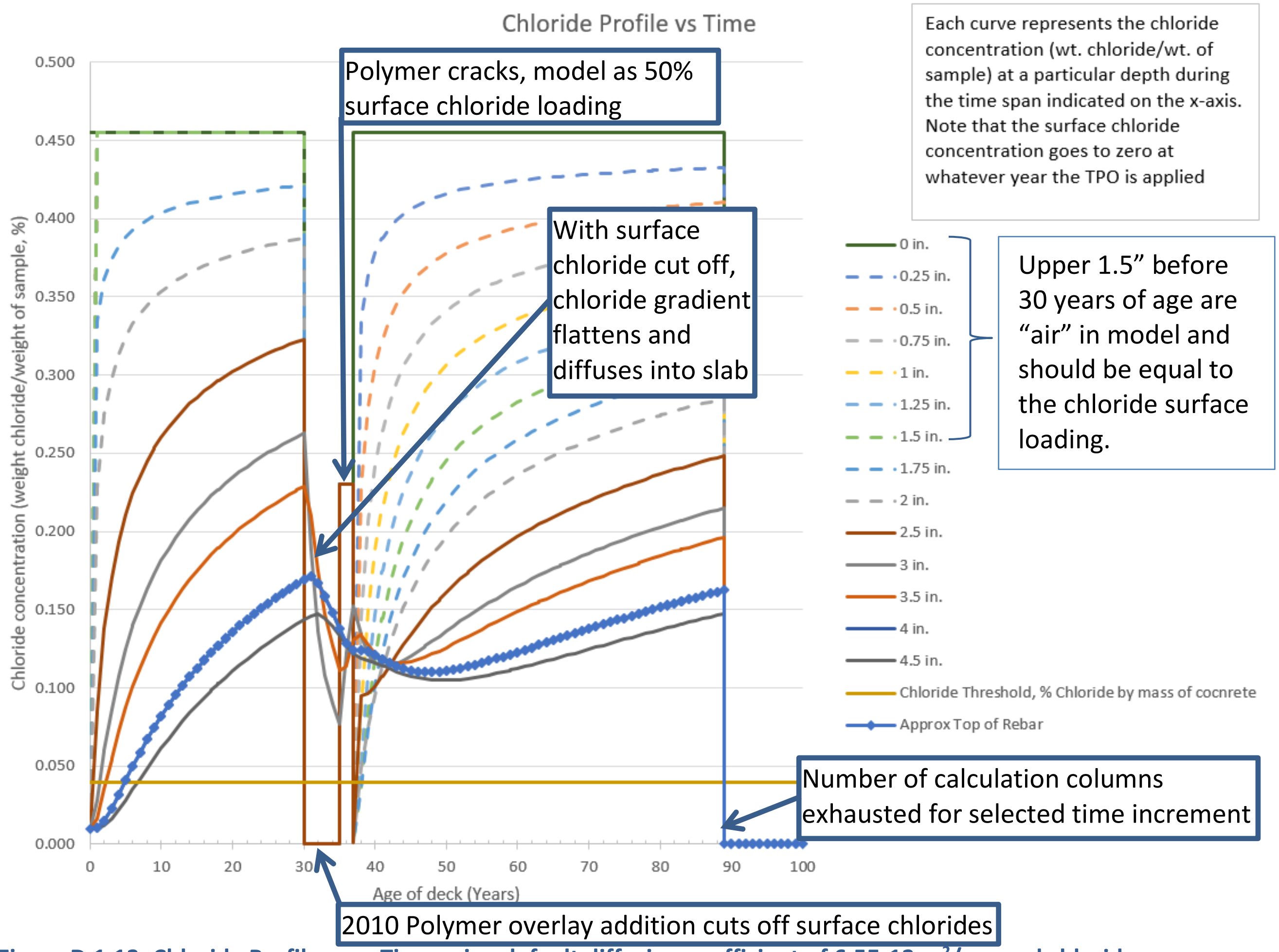
As can be seen, there is relatively poor correlation with either the average chloride profile or the majority of chloride profiles. It seems that the shape of the chloride profile is fair, though, so it will be attempted to increase the diffusion coefficient and see the results. Several trials on the diffusion coefficient (not shown) shows a good match at 8.0E-12, the results of which are revealed in Figure D.1.12. A plot of chloride over time with these values is shown in Figure D.1.13.



Upper 1.5" are "air" in model prior to age 30 and are equal to the chloride surface loading

Each curve represents the chloride concentration at a time in years at the range of depths below surface indicated in the x-axis. The time values are indicated in the legend and depend on what is set as the step interval on the calculation page. Black bar

Figure D.1.12: results of initial inputs using default diffusion coefficient of 8.0E-12 m^2/sec and chloride surface loading of 0.455. The year range plotted is between 25 and 29 years to focus results to the chloride profile sampling date for model calibration.



Each curve represents the chloride concentration (wt. chloride/wt. of sample) at a particular depth during the time span indicated on the x-axis. Note that the surface chloride concentration goes to zero at whatever year the TPO is applied

Polymer cracks, model as 50% surface chloride loading

With surface chloride cut off, chloride gradient flattens and diffuses into slab

Upper 1.5” before 30 years of age are “air” in model and should be equal to the chloride surface loading.

Number of calculation columns exhausted for selected time increment

2010 Polymer overlay addition cuts off surface chlorides

Figure D.1.13: Chloride Profile over Time using default diffusion coefficient of 6.5E-12 m^2/sec and chloride surface loading of 0.455 when no polymer wearing course is present. Note the chloride levels at the level of rebar remain high but drop when the overlay is present due to diffusion deeper within the slab.

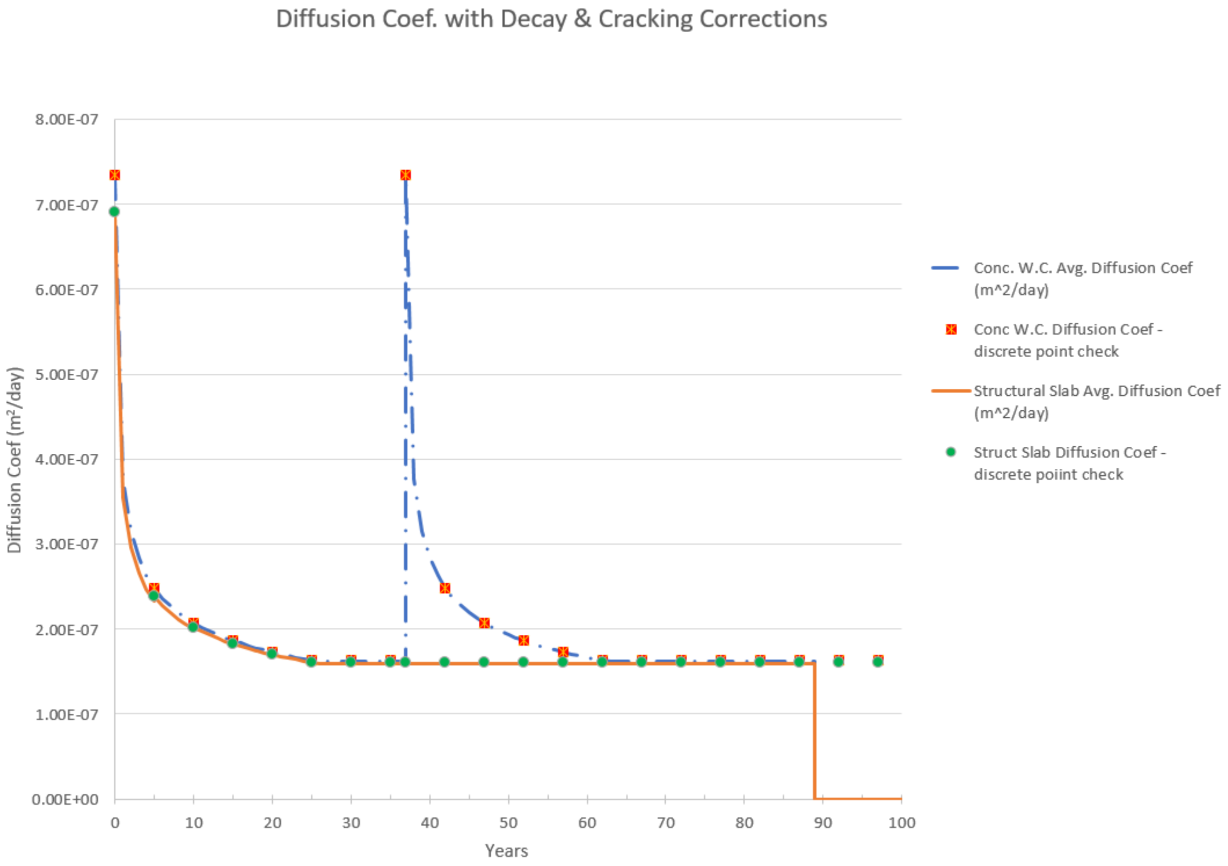
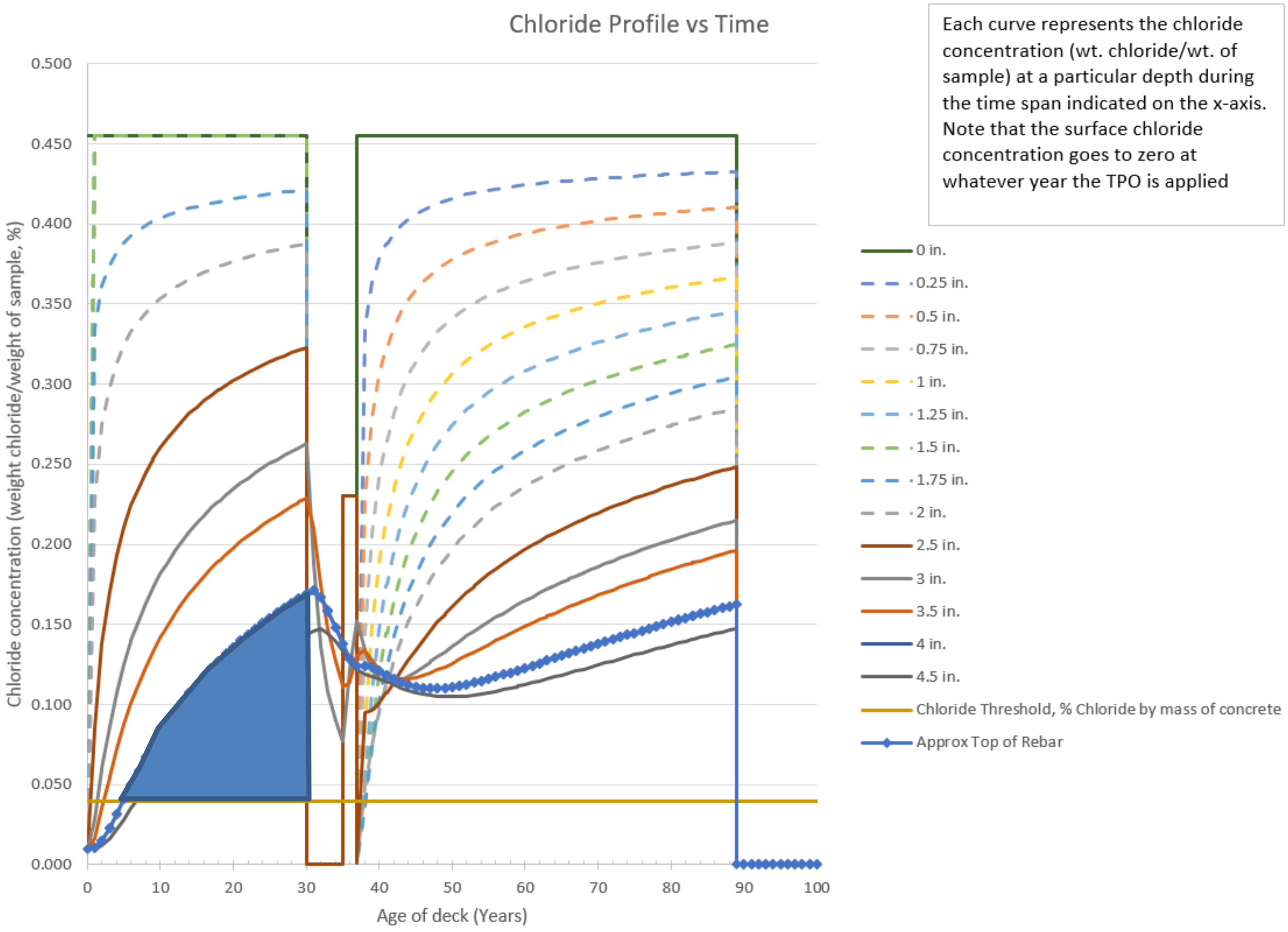


Figure D.1.14: Resultant diffusion coefficient after iteration to match "Chloride Profile versus Depth" plot (Figure D.1.13) to average 2010 chloride profiles. No change was made to the concrete wearing course diffusion coefficient.

Since the diffusion coefficient and surface loading is fairly calibrated based on the 2010 chloride profiles, it will be assumed that the diffusion coefficient remained constant after the first 10 years. With this assumption, one may review the actual repair quantities incurred in the 2010 and 2017 contracts to see how chloride levels translated to repair quantities in the Minnesota climate and salting practices.

In 2010 the deck was milled 1", repaired with shallow and full-depth patches, and subsequently placing a ⅜" - ½" thick Transpo T48 slurry style epoxy chip seal. This approach was taken to remove the load restriction in place on the structure. The 2010 project estimated 700 SF shallow deck repairs with 991 SF actually encountered during construction. Similarly, 70 Sf of full-depth repair were estimated with 274 SF actually encountered. Combined, the areas represent 6% of the roadway area and technically these areas could overlap and represent the same locations, but there is evidence within in the project closeout finals that the areas were considered as separate areas not overlapping areas. Reviewing the Chloride Profile over Time plot, it appears the reinforcement had been exposed to chlorides exceeding the 0.03 % threshold for 27 years before 6% patching was encountered. A chloride threshold of 0.03% by weight of concrete is the generally accepted corrosion threshold for uncoated reinforcement. Realizing the top mat is epoxy-coated, it is suggested a higher chloride threshold of 0.05% to 0.11% by weight of concrete would be rational (Moderate risk of corrosion). It can be postulated that there may be some method of calibrating the propagation time to known patching quantities. With a predicted chloride level at the level of rebar over time, the model could be used to explore correlations between chloride exposure duration and patching levels. One approach would be to determine the time-chloride area above the chloride threshold. The next exercise will attempt to explore such a patching relationship by using the chloride exposure time above both 0.03% chloride/sample and 0.08% chloride/sample.

Ignoring values less than 0.03%, the time and chloride exposure area is determined by summing the time increment x chloride level for the rebar horizon. See Figure D.1.15 for this area of integration. The result is 2.15 year-% Chloride exposure in 2010 (Neglecting chloride exposure below 0.03%) and 1.01 year-% Chloride if using 0.08% chloride as the onset threshold.



Each curve represents the chloride concentration (wt. chloride/wt. of sample) at a particular depth during the time span indicated on the x-axis. Note that the surface chloride concentration goes to zero at whatever year the TPO is applied

Figure D.1.15: Chloride Profile over Time integration for time of 2010 contract as an trial to quantify chloride exposure and duration.

The addition of the TPO in year 30 was programmed without the appreciation for both the short chloride propagation period and the effects of reduced rebar cover on the deck flexibility. The TPO debonded between 2012 and 2015 escalating to a repair contract being scheduled in 2017. The TPO delamination was attributed to not only corrosion related spalling, but also due to areas of poor surface preparation. At the time of scoping the preservation project in 2015 it was recognized that the bridge deck should be replaced, but due to load rating and conveyance needs the entire river crossing needed replacement. Funding and project delivery challenges including multi-agency coordination required that the bridge be kept in service to the extent possible for as long as could be safely permitted.

By 2017 the polymer wearing course had substantially delaminated. Figures D.1.16 through D.1.20 show delamination and spall mappings ahead of the project. The project goal was to maintain serviceability for up to 8 years, and the method of achieving such a duration included repairing delamination in combination with an overlay that would cut off moisture ingress. In 2015 and 2016 it was believed that a Novachip asphalt based product, which had been cost effective and very good at sealing bridge decks in other locations, would be the most economical solution for a short term life extension.

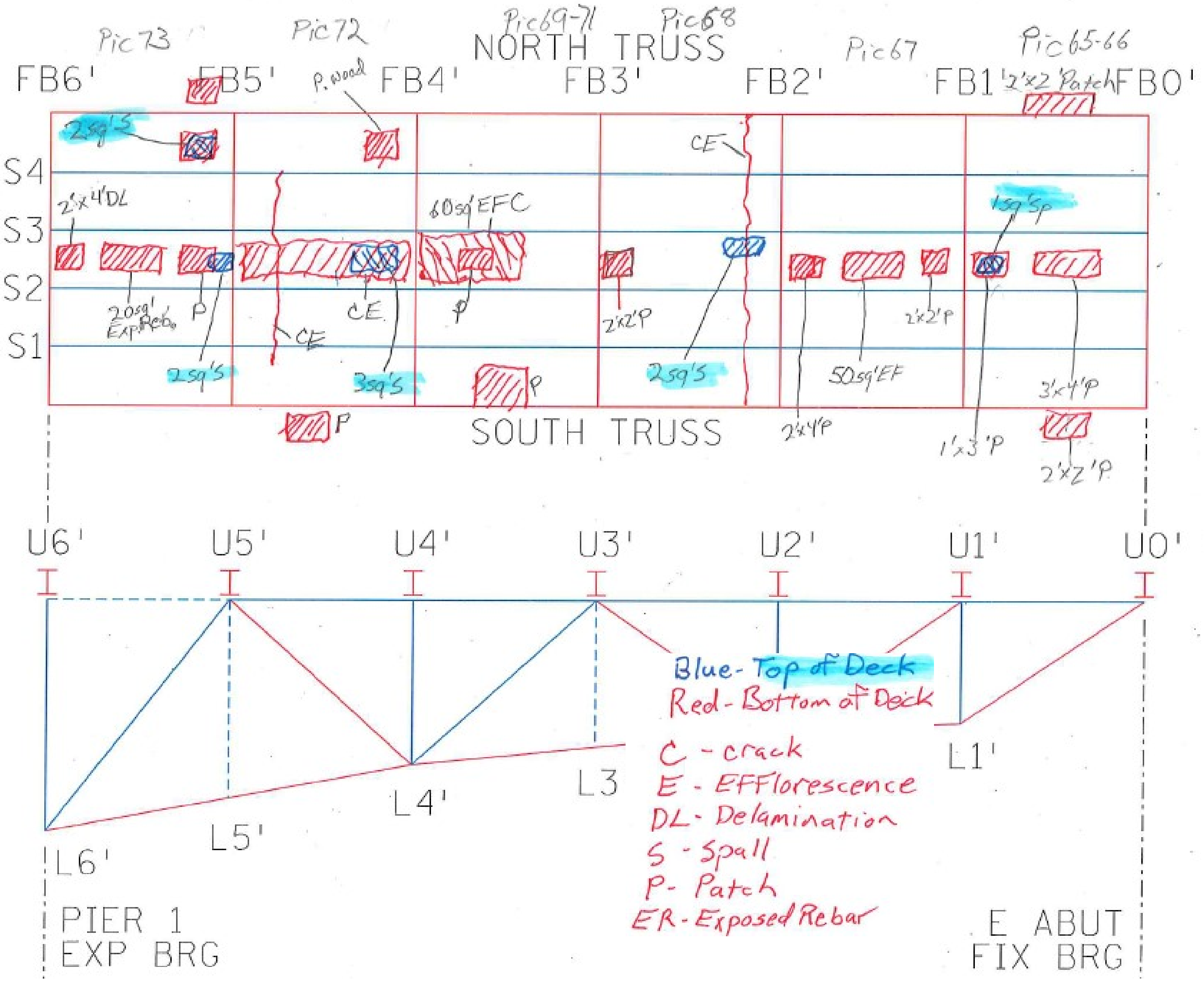


Figure D.1.16: Underdeck and topside sounding performed in February 2017 (Span 5).

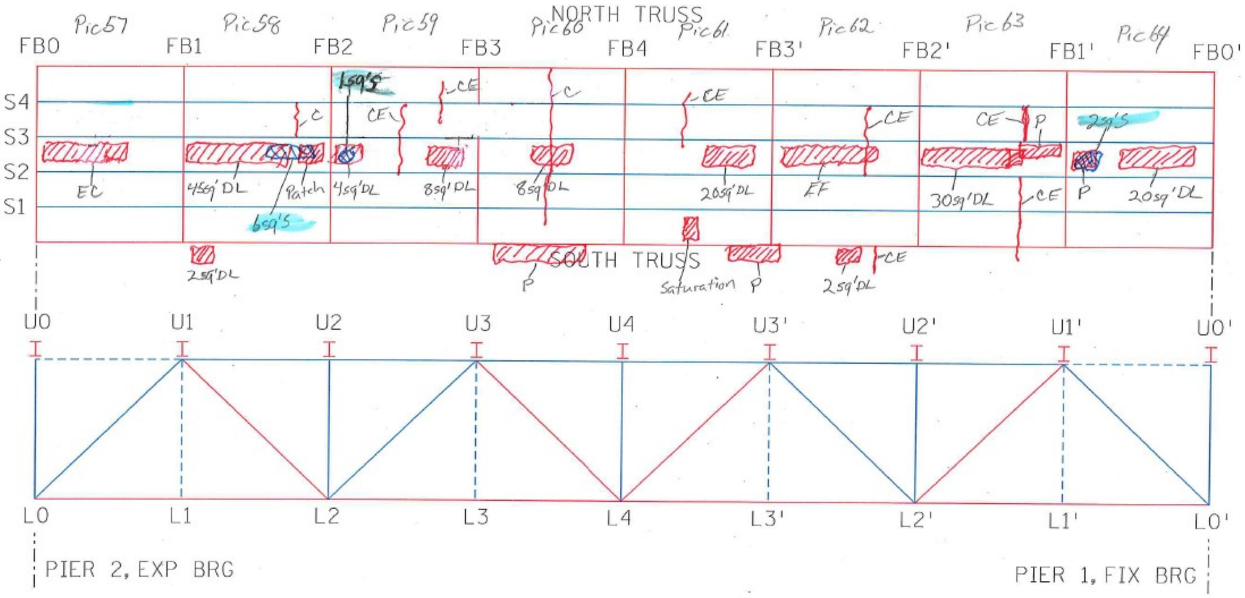


Figure D.1.17: Underdeck and topside sounding performed in February 2017 (Span 4).

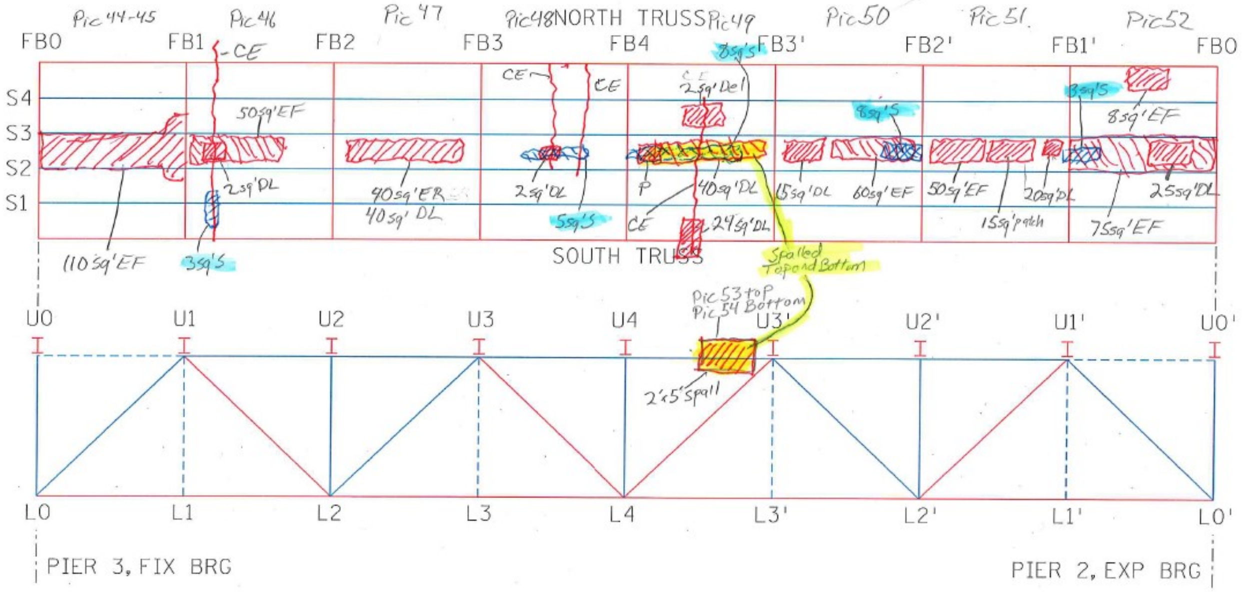


Figure D.1.18: Underdeck and topside sounding performed in February 2017 (Span 3).

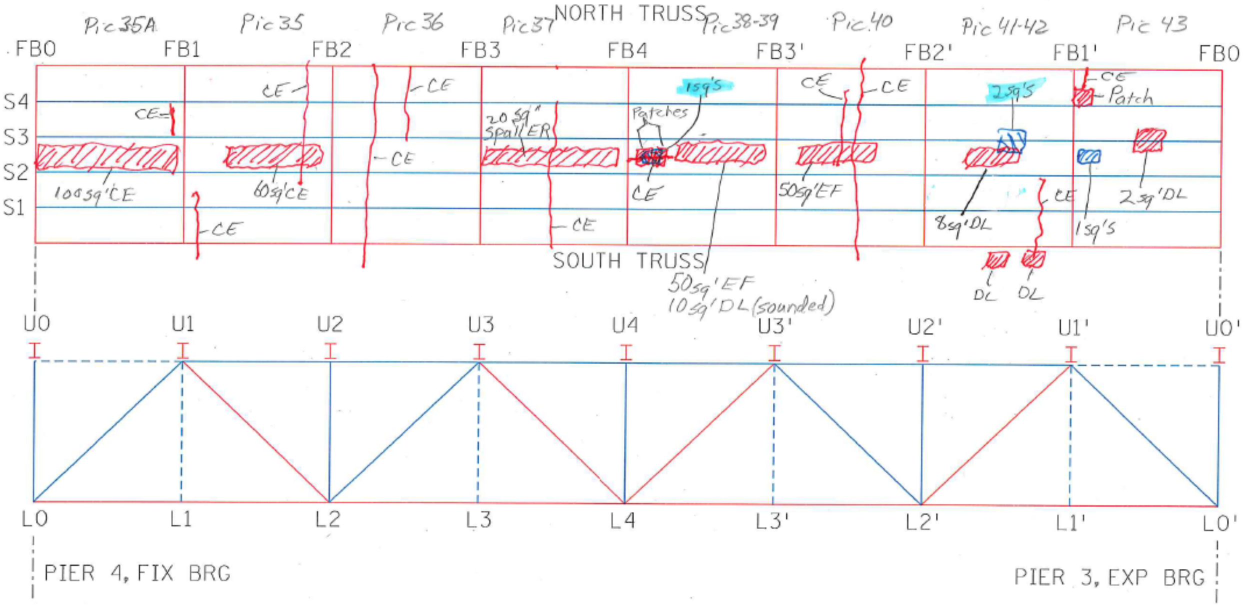


Figure D.1.19: Underdeck and topside sounding performed in February 2017 (Span 2).

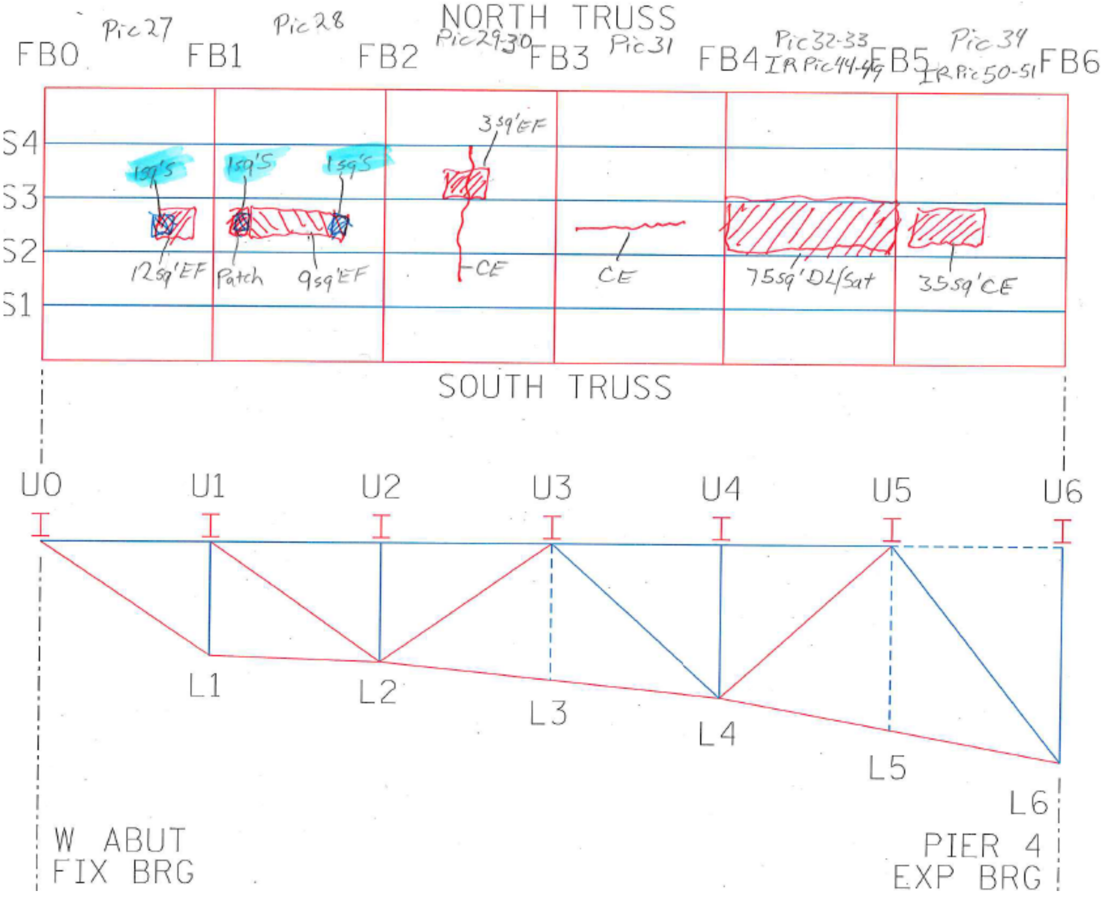


Figure D.1.20: Underdeck and topside sounding performed in February 2017 (Span 1).

Immediately prior to award, a hole was encountered in the bridge deck indicating the severity of corrosion at the 1980 centerline slab construction joint. See Figure D.1.20 for hole images.

Figure D.1.21: Punch-through deck failure at 1980 centerline construction joint that occurred in July 2017.

During September 2017 construction the deck condition was discovered to be quite poor from the duration the deck had been exposed to a delaminated polymer and with reduced concrete cover thickness. Limitations were placed on the full-depth patches and to salvage the deck, a reinforced overlay was placed. The patching encountered was 1071 square feet of shallow deck repairs and 17 square feet of full-depth repairs during contract. This represents 4.8% of the roadway area but fails to capture the areas of uncoated bottom mat spalling that were left with underside delamination due to corrosion.

Much of the issue in this bridge deck was the very shallow deck thickness and rebar mats that had very little separation due to the thin slab. To clarify, the original 7” thick deck used 2.5” top cover and 1” bottom cover leaving only 3.5” for four layers of reinforcement. The design created a reinforced slab where reinforcement is located near the core and away from the extreme fibers where tensile resistance is needed to stop crack formation. Once cracked, the thin slab becomes a fairly flexible element.

Overall, this case study is meant to illustrate modeling chloride diffusion and illustrate some of the real world challenges for predicting bridge deck end of life. The modeling of chlorides is critical to assessing the viability of a TPO overlay. More research is needed to understand the propagation period for various environments and coated rebar.

Figure D.1.22: Polymer overlay with debonding and concrete spalling progression.

Figure D.1.23: In September 2017 the polymer overlay removed and patching was initiated. Photo on right shows epoxy-coated reinforcement corrosion at local defects that had spread. was Older epoxy coating processes were more susceptible to the coating debonding from the rebar.

Figure D.1.24: Uncoated bottom reinforcement has corroded more rapidly and spalled off underside concrete cover, resulting in a slab that was prone to punch-through failure.

Figure D.1.25: A 2.5" thick low-slump concrete wearing course was placed to extend deck life until replacement. The center 12-foot wide pass consisted of a reinforced. The bridge was permanently load posted to reduce heavy truck loads.

As a side note, observations with mixed bar decks (epoxy coated top mat, uncoated reinforcement in bottom mat) show accelerated corrosion of the bottom mat while the top mat experienced high localized corrosion near cracks. A picture of such phenomenon is included in Figure D.1.26 (Provided by Wisconsin DOT from Bridge 6566 taken during repair project (Taylors Falls, MN).

Figure D.1.26: Accelerated bottom mat (uncoated reinforcement) with localized corrosion in top mat (Epoxy-coated reinforcement).

D.2.1 Bridge 2440 deck life extension predictions, TH 65 over Mississippi River

The 3rd Avenue Bridge (Bridge 2440) is a historic arch structure MnDOT bridge constructed in in 1918. It is 1,888-foot long and conveys four lanes of traffic over the Mississippi River. The top reinforcement mat utilizes epoxy-coated reinforcement, with 1” concrete cover, and the bottom mat is uncoated. This study will examine the chloride ingress and compare the modeling results to the chloride profiles obtained in a 2017 Bridge Inspection and Condition Evaluation Report. Once the diffusion coefficient is calibrated to the coring data, the model will forecast the effects of milling off the existing concrete wearing course and replacing it in-kind.

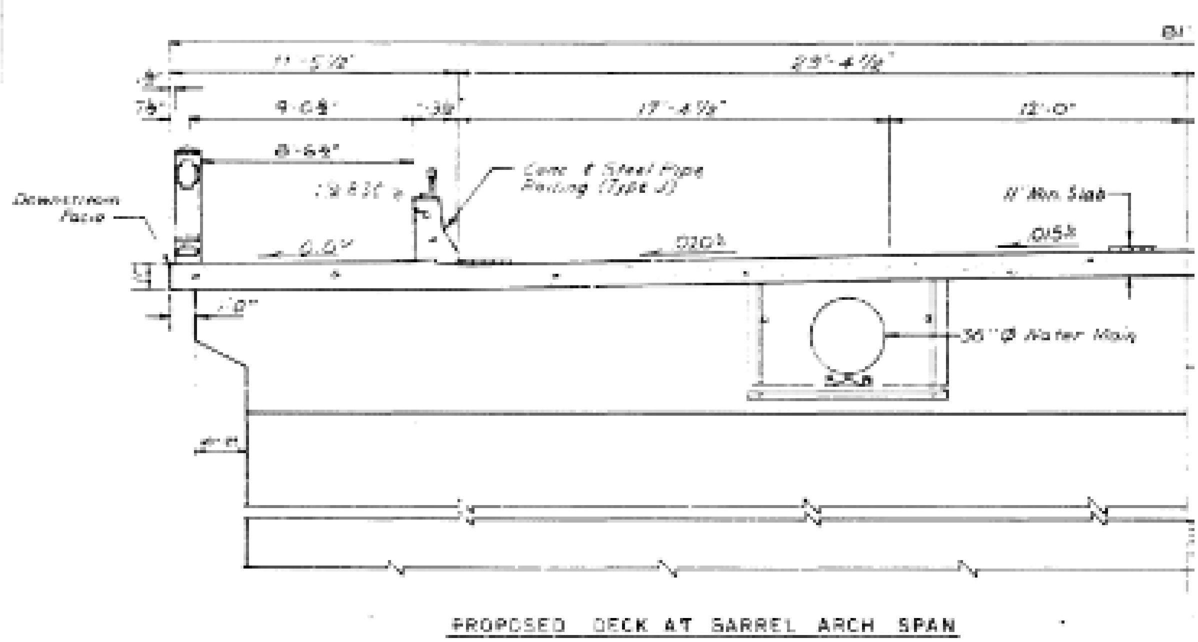


Figure D.2.1. 1979 deck cross section with 11” slab thickness.

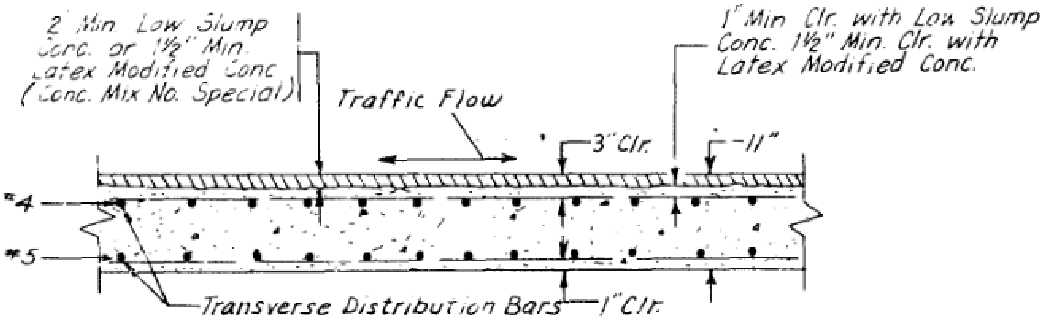
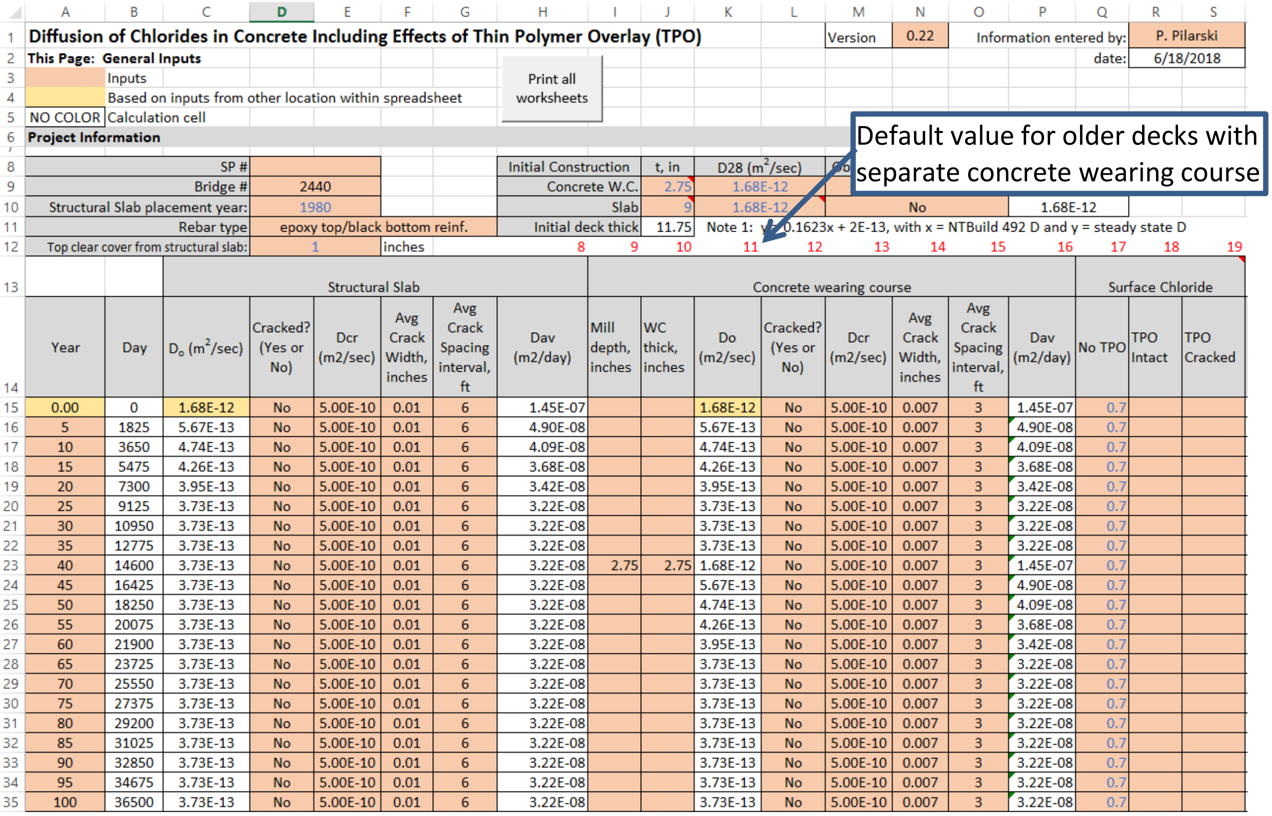


Figure D.2.2. 1979 deck cross section with 3” reinforcement cover to top bars. A 2017 concrete cover survey found 3.75” average concrete cover revealing that the concrete wearing course was much thicker than originally planned. This construction phenomenon is actually quite common.

When MnDOT places a concrete deck with separate concrete wearing course in initial construction, the strike-off is most often achieved by use of a Morrison screed or vibrating A-frame style air screed. This equipment rides on skis on top of the top rebar mat with 1” concrete cover. Because of this, the concrete cover over the topmost rebar in a structural slab placement can almost always be assumed to be 1” concrete cover. The remainder of the required 3” concrete cover over topmost rebar is achieved through the concrete wearing course. Since the Wiss Janey Elsner rebar conver survey revealed 3.75” average concrete cover, it can be assumed that the concrete wearing course is 2.75” thick.

The diffusion coefficient and diffusion coefficient decay factor will be first input as the default for older or unknown monolithic decks at 1.68E-12 m^2/seD.2. Figure 6.2.3 shows the General Inputs tab at the start of modeling. The mill and overlay input in year 40, as a preservation strategy, will not be relevant until diffusion input calibration is performed on the 2017 chloride profile data.

Once the initial input is made the user can review the deck thickness plot to verify the thickness and rebar depth input is correct. This can be seen in Figure D.2.4. Figure D.2.5 shows baseline chlorides assumed to be in the concrete mix itself. The author’s prior experience suggests that up to 0.01% chloride by mass of sample may exist in the initial mix itself. The initial chloride is used throughout the thickness of the deck as a baseline. For wider applicability, the user could modify this input to represent a starting chloride profile for subsequent service life evaluation.



Diffusion of Chlorides in Concrete Including Effects of Thin Polymer Overlay (TPO)

Version 0.22

Information entered by: P. Pilarski

date: 6/18/2018

This Page: General Inputs

Inputs

Based on inputs from other location within spreadsheet

NO COLOR Calculation cell

Print all worksheets

Project Information

SP #:

Bridge #: 2440

Structural Slab placement year: 1980

Rebar type: epoxy top/black bottom reinf.

Top clear cover from structural slab: 1 inches

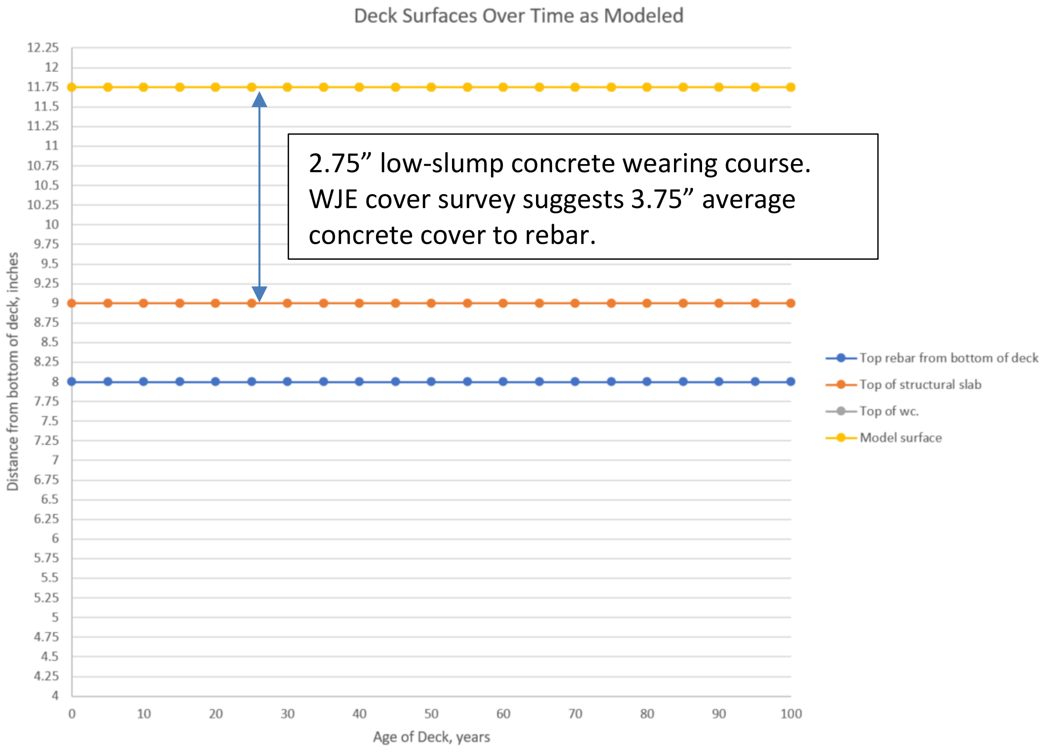
Initial Construction	t, in	D28 (m^2/sec)	Ob	
Concrete W.C.	2.75	1.68E-12		
Slab	9	1.68E-12	No	1.68E-12
Initial deck thick	11.75			

Note 1: y = 0.1623x + 2E-13, with x = NTBuild 492 D and y = steady state D

Default value for older decks with separate concrete wearing course

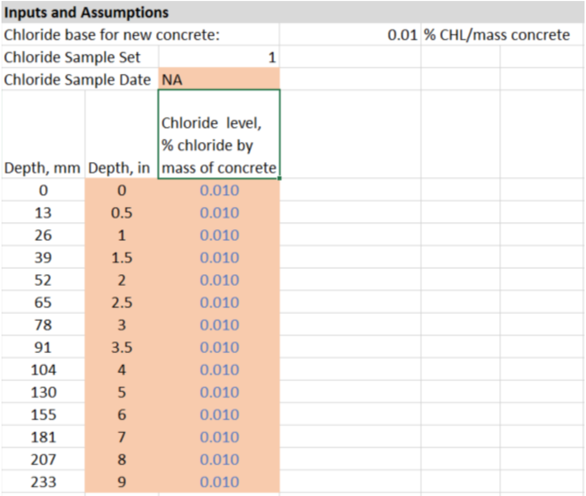
		Structural Slab						Concrete wearing course								Surface Chloride		
							8	9	10	11	12	13	14	15	16	17	18	19
Year	Day	D_o (m^2/sec)	Cracked? (Yes or No)	Dcr (m2/sec)	Avg Crack Width, inches	Avg Crack Spacing interval, ft	Dav (m2/day)	Mill depth, inches	WC thick, inches	Do (m2/sec)	Cracked? (Yes or No)	Dcr (m2/sec)	Avg Crack Width, inches	Avg Crack Spacing interval, ft	Dav (m2/day)	No TPO	TPO Intact	TPO Cracked
0.00	0	1.68E-12	No	5.00E-10	0.01	6	1.45E-07			1.68E-12	No	5.00E-10	0.007	3	1.45E-07	0.7		
5	1825	5.67E-13	No	5.00E-10	0.01	6	4.90E-08			5.67E-13	No	5.00E-10	0.007	3	4.90E-08	0.7		
10	3650	4.74E-13	No	5.00E-10	0.01	6	4.09E-08			4.74E-13	No	5.00E-10	0.007	3	4.09E-08	0.7		
15	5475	4.26E-13	No	5.00E-10	0.01	6	3.68E-08			4.26E-13	No	5.00E-10	0.007	3	3.68E-08	0.7		
20	7300	3.95E-13	No	5.00E-10	0.01	6	3.42E-08			3.95E-13	No	5.00E-10	0.007	3	3.42E-08	0.7		
25	9125	3.73E-13	No	5.00E-10	0.01	6	3.22E-08			3.73E-13	No	5.00E-10	0.007	3	3.22E-08	0.7		
30	10950	3.73E-13	No	5.00E-10	0.01	6	3.22E-08			3.73E-13	No	5.00E-10	0.007	3	3.22E-08	0.7		
35	12775	3.73E-13	No	5.00E-10	0.01	6	3.22E-08			3.73E-13	No	5.00E-10	0.007	3	3.22E-08	0.7		
40	14600	3.73E-13	No	5.00E-10	0.01	6	3.22E-08	2.75	2.75	1.68E-12	No	5.00E-10	0.007	3	1.45E-07	0.7		
45	16425	3.73E-13	No	5.00E-10	0.01	6	3.22E-08			5.67E-13	No	5.00E-10	0.007	3	4.90E-08	0.7		
50	18250	3.73E-13	No	5.00E-10	0.01	6	3.22E-08			4.74E-13	No	5.00E-10	0.007	3	4.09E-08	0.7		
55	20075	3.73E-13	No	5.00E-10	0.01	6	3.22E-08			4.26E-13	No	5.00E-10	0.007	3	3.68E-08	0.7		
60	21900	3.73E-13	No	5.00E-10	0.01	6	3.22E-08			3.95E-13	No	5.00E-10	0.007	3	3.42E-08	0.7		
65	23725	3.73E-13	No	5.00E-10	0.01	6	3.22E-08			3.73E-13	No	5.00E-10	0.007	3	3.22E-08	0.7		
70	25550	3.73E-13	No	5.00E-10	0.01	6	3.22E-08			3.73E-13	No	5.00E-10	0.007	3	3.22E-08	0.7		
75	27375	3.73E-13	No	5.00E-10	0.01	6	3.22E-08			3.73E-13	No	5.00E-10	0.007	3	3.22E-08	0.7		
80	29200	3.73E-13	No	5.00E-10	0.01	6	3.22E-08			3.73E-13	No	5.00E-10	0.007	3	3.22E-08	0.7		
85	31025	3.73E-13	No	5.00E-10	0.01	6	3.22E-08			3.73E-13	No	5.00E-10	0.007	3	3.22E-08	0.7		
90	32850	3.73E-13	No	5.00E-10	0.01	6	3.22E-08			3.73E-13	No	5.00E-10	0.007	3	3.22E-08	0.7		
95	34675	3.73E-13	No	5.00E-10	0.01	6	3.22E-08			3.73E-13	No	5.00E-10	0.007	3	3.22E-08	0.7		
100	36500	3.73E-13	No	5.00E-10	0.01	6	3.22E-08			3.73E-13	No	5.00E-10	0.007	3	3.22E-08	0.7		

Figure D.2.3. Initial input for modeling BR 2440.



2.75” low-slump concrete wearing course. WJE cover survey suggests 3.75” average concrete cover to rebar.

Figure D.2.4 Model geometry reflected from inputs.

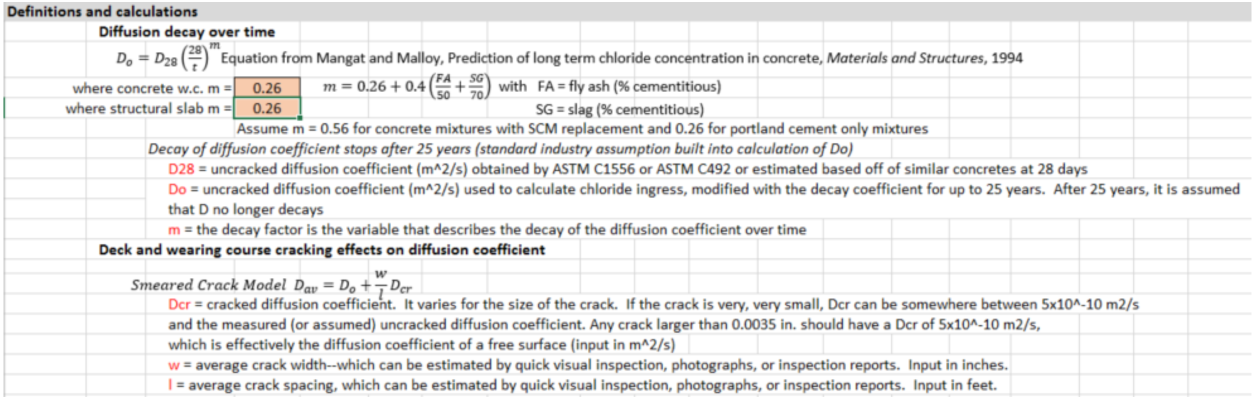


Inputs and Assumptions				
Chloride base for new concrete:			0.01	% CHL/mass concrete
Chloride Sample Set		1		
Chloride Sample Date		NA		
Depth, mm	Depth, in	Chloride level, % chloride by mass of concrete		
0	0	0.010		
13	0.5	0.010		
26	1	0.010		
39	1.5	0.010		
52	2	0.010		
65	2.5	0.010		
78	3	0.010		
91	3.5	0.010		
104	4	0.010		
130	5	0.010		
155	6	0.010		
181	7	0.010		
207	8	0.010		
233	9	0.010		

Figure D.2.5 Default input on the Chloride Profile tab for inputting chloride levels inherent to the 1980 mix placement.

Along with the General Input, the decay coefficient is reviewed (See Figure D.2.6). By default a 0.26 decay coefficient is used to illustrate the refinement in concrete pore structure with age. Finer void structure developed through cement hydration and lengthened curing improves the resistance to chlorides and other chemicals. The user may evaluate the mix properties and modify the decay coefficient based on slag and fly ash substitutions.

Below the diffusion decay input is a section for plotting parameters, also seen in Figure D.2.7. The user enters a year range and other plotting parameters relevant to the objective. At this point calibration to 2017 chloride profiles is desired, so a narrow plotting range is selected around year 37.



Definitions and calculations

Diffusion decay over time

$D_o = D_{28}\left(\frac{28}{t}\right)^m$ Equation from Mangat and Malloy, Prediction of long term chloride concentration in concrete, *Materials and Structures*, 1994

where concrete w.c. m = 0.26 $m = 0.26 + 0.4\left(\frac{FA}{50} + \frac{SG}{70}\right)$ with FA = fly ash (% cementitious)

where structural slab m = 0.26 SG = slag (% cementitious)

Assume m = 0.56 for concrete mixtures with SCM replacement and 0.26 for portland cement only mixtures

Decay of diffusion coefficient stops after 25 years (standard industry assumption built into calculation of Do)

D28 = uncracked diffusion coefficient (m^2/s) obtained by ASTM C1556 or ASTM C492 or estimated based off of similar concretes at 28 days

Do = uncracked diffusion coefficient (m^2/s) used to calculate chloride ingress, modified with the decay coefficient for up to 25 years. After 25 years, it is assumed that D no longer decays

m = the decay factor is the variable that describes the decay of the diffusion coefficient over time

Deck and wearing course cracking effects on diffusion coefficient

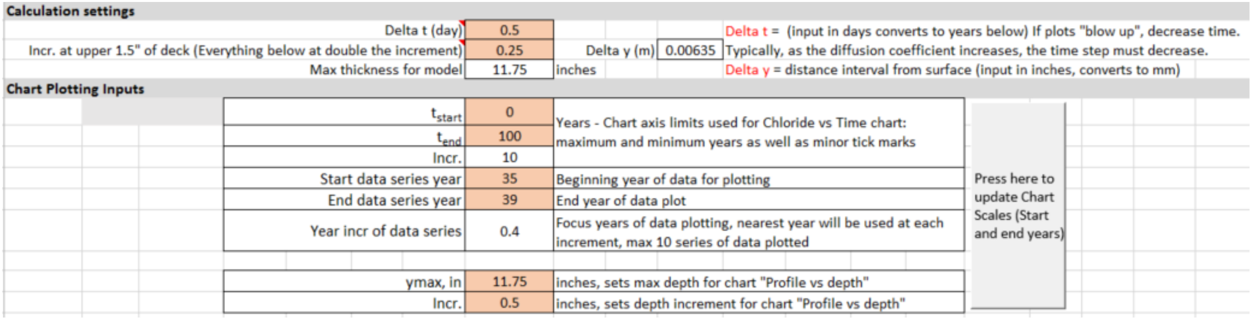
Smeared Crack Model $D_{av} = D_o + \frac{w}{l}D_{cr}$

Dcr = cracked diffusion coefficient. It varies for the size of the crack. If the crack is very, very small, Dcr can be somewhere between 5x10^-10 m2/s and the measured (or assumed) uncracked diffusion coefficient. Any crack larger than 0.0035 in. should have a Dcr of 5x10^-10 m2/s, which is effectively the diffusion coefficient of a free surface (input in m^2/s)

w = average crack width--which can be estimated by quick visual inspection, photographs, or inspection reports. Input in inches.

l = average crack spacing, which can be estimated by quick visual inspection, photographs, or inspection reports. Input in feet.

Figure D.2.6 Decay coefficient input at start of modeling.



Calculation settings

Delta t (day)	0.5			Delta t = (input in days converts to years below) If plots "blow up", decrease time.
Incr. at upper 1.5" of deck (Everything below at double the increment)	0.25	Delta y (m)	0.00635	Typically, as the diffusion coefficient increases, the time step must decrease.
Max thickness for model	11.75	inches		Delta y = distance interval from surface (input in inches, converts to mm)

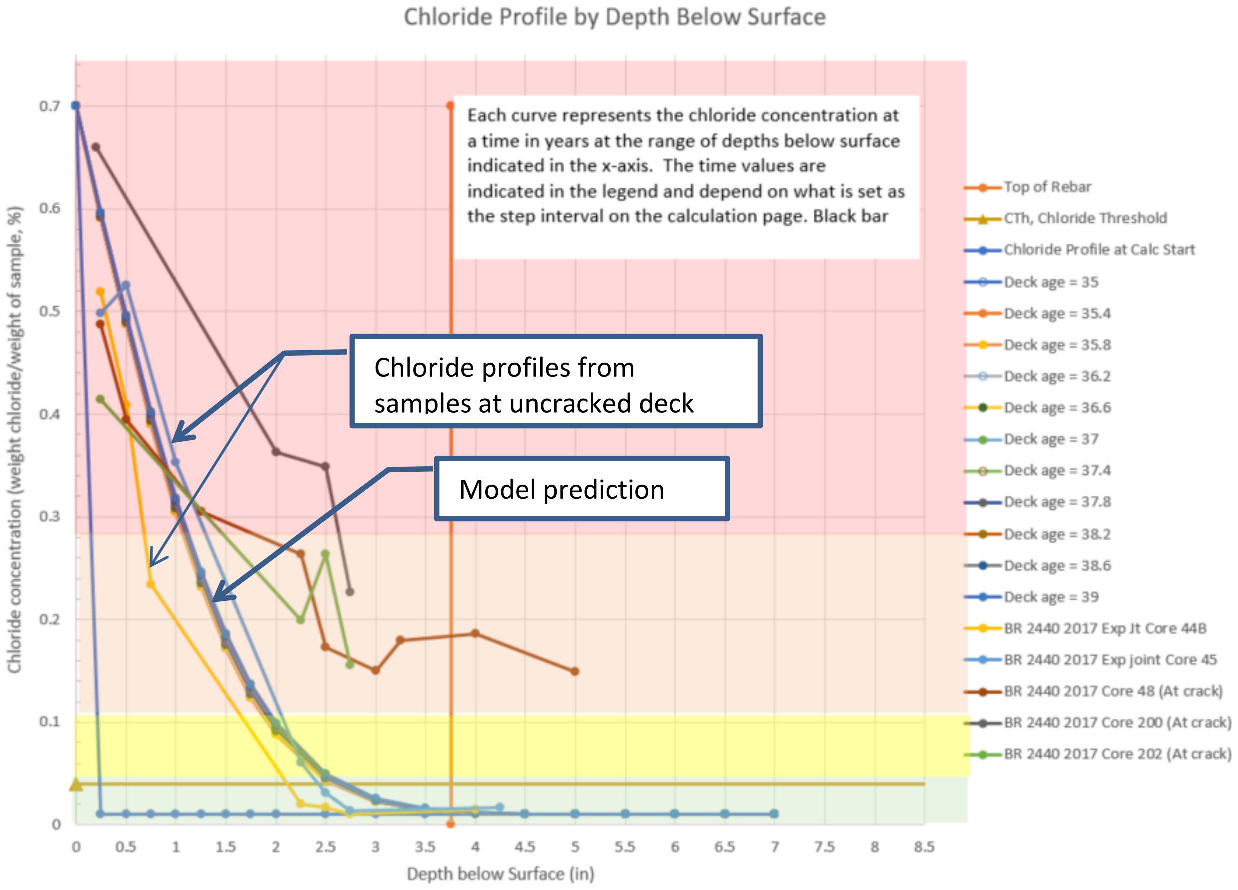
Chart Plotting Inputs

t_{start}	0	Years - Chart axis limits used for Chloride vs Time chart: maximum and minimum years as well as minor tick marks
t_{end}	100	
Incr.	10	
Start data series year	35	Beginning year of data for plotting
End data series year	39	End year of data plot
Year incr of data series	0.4	Focus years of data plotting, nearest year will be used at each increment, max 10 series of data plotted
ymax, in	11.75	inches, sets max depth for chart "Profile vs depth"
Incr.	0.5	inches, sets depth increment for chart "Profile vs depth"

Figure D.2.7 Model plotting range selection. The data series years for generating chloride versus depth plots was centered on the 2017 date (37 years) of coring and sample analysis.

Figure D.2.8 illustrates the effects of the above inputs on a chloride profile plot that already includes chloride profiles obtained from the 2017 sample analyses. There are five samples plotted, three of which represent chloride profiles at crack locations. The uncracked chloride profiles, samples 44B and 45, will be used in order to calibrate to the concrete properties. The plot shows fair correlation with the chloride samples, but near the structural slab interface it appears the model overpredicts the chloride penetration. The predictions were made using the default diffusion coefficient of 1.68E-12 m^2/sec with a surface chloride loading of 0.70 % Chl/weight of concrete. The initial surface chloride for Trunk Highway bridges with high ADT appears to be in the range of 0.6 to 0.7 % chloride in the Twin Cities Metro area. Further research and calibration may suggest other values for overpasses and outstate bridges.

To improve correlation, the user may change the diffusion coefficient or the decay coefficient in either the concrete wearing course or the structural slab. The effects of these changes are instantaneous, allowing the quick calibration evaluation to a known chloride profile. The following iterations are presented to illustrate the effects of changing the different variables.

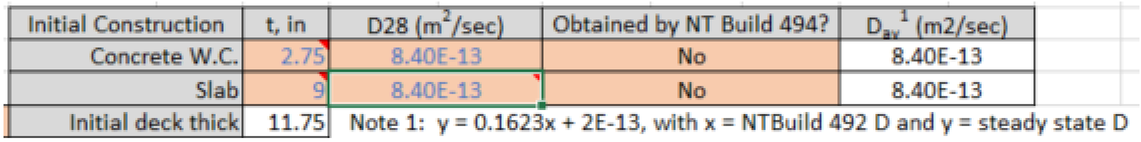


Each curve represents the chloride concentration at a time in years at the range of depths below surface indicated in the x-axis. The time values are indicated in the legend and depend on what is set as the step interval on the calculation page. Black bar

Chloride profiles from samples at uncracked deck

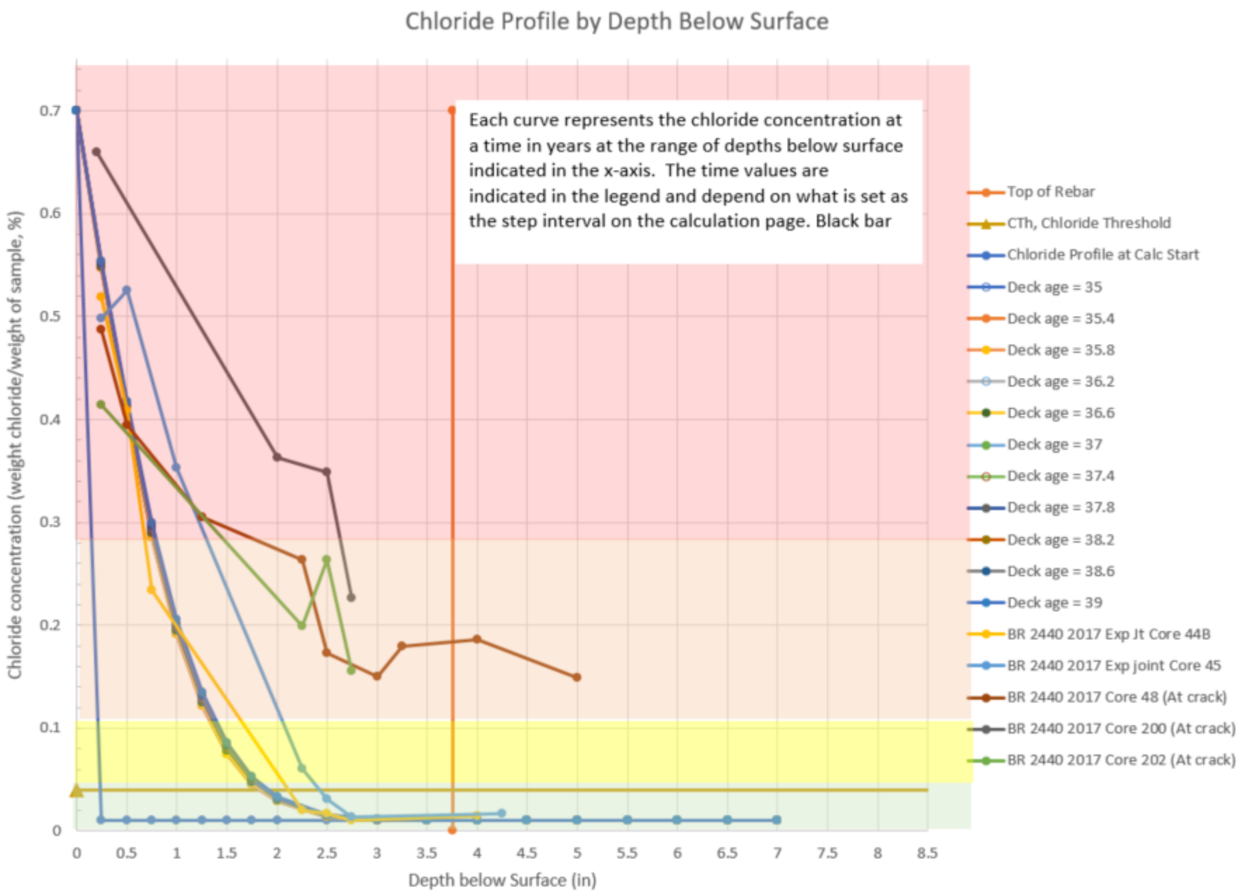
Model prediction

Figure D.2.10: Chloride versus Depth Plot: Results of initial inputs using default diffusion coefficient of 1.68E-12 m^2/sec for concrete overlay, 1.68E-12 m^2/sec for structural slab, and chloride surface loading of 0.7. The year range plotted is between 35 and 39 years to focus results to the 2017 chloride profile sampling date. It appears that chlorides deeper than 2.25" are not aligning well. The user should either change the diffusion coefficient for the structural slab or the structural slab decay factor.



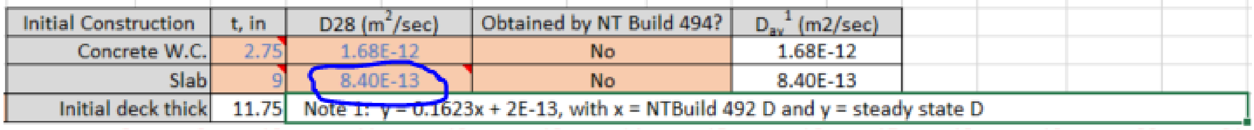
Initial Construction	t, in	D28 (m^2/sec)	Obtained by NT Build 494?	$D_{av}{}^1$ (m2/sec)
Concrete W.C.	2.75	8.40E-13	No	8.40E-13
Slab	9	8.40E-13	No	8.40E-13
Initial deck thick	11.75	Note 1: y = 0.1623x + 2E-13, with x = NTBuild 492 D and y = steady state D		

Figure D.2.11: Change of diffusion coefficient to half of default diffusion coefficient for unknown slabs with separate concrete wearing course. The effects are shown in Figure D.2.12.



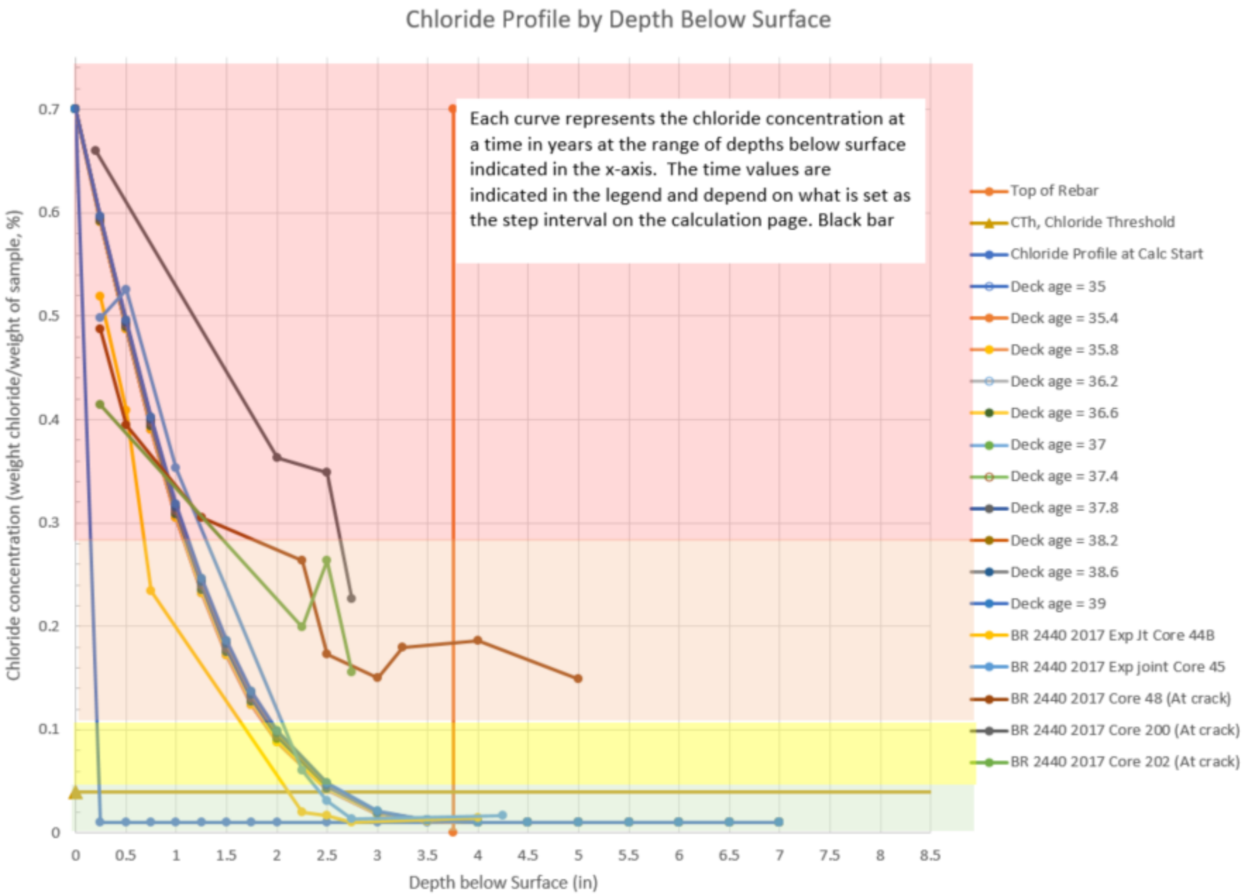
Each curve represents the chloride concentration at a time in years at the range of depths below surface indicated in the x-axis. The time values are indicated in the legend and depend on what is set as the step interval on the calculation page. Black bar

Figure D.2.12: Chloride versus Depth plot: Results of using default diffusion coefficient of 0.84E-12 m^2/sec for concrete overlay, 0.84E-12 m^2/sec for structural slab, and chloride surface loading of 0.7 % Chl/mass of sample. The resultant penetration of predicted chlorides is unconservative and not aligning with the cores.



Initial Construction	t, in	D28 (m^2/sec)	Obtained by NT Build 494?	D_{av}^{1} (m2/sec)
Concrete W.C.	2.75	1.68E-12	No	1.68E-12
Slab	9	8.40E-13	No	8.40E-13
Initial deck thick	11.75	Note 1: y = 0.1623x + 2E-13, with x = NTBuild 492 D and y = steady state D		

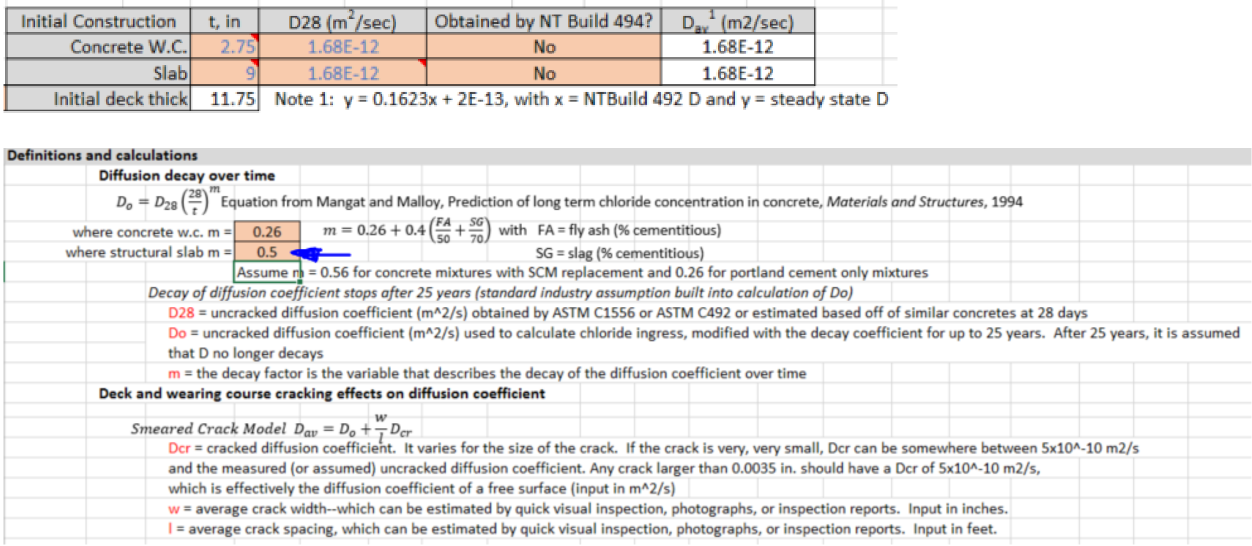
Figure D.2.13: Change of diffusion coefficient to half of default diffusion coefficient for structural slab only.



Each curve represents the chloride concentration at a time in years at the range of depths below surface indicated in the x-axis. The time values are indicated in the legend and depend on what is set as the step interval on the calculation page. Black bar

Figure D.2.14: Chloride versus Depth Plot: Results of initial inputs using default diffusion coefficient of 1.68E-12 m²/sec for concrete overlay, 0.83E-12 m²/sec for structural slab, and chloride surface loading of 0.7. The year range plotted is between 35 and 39 years to focus results to the chloride profile sampling date for model calibration.

Reviewing figures D.2.10, D.12, and D.2.14 one can see that changing the wearing course diffusion coefficient from the default of 1.68 m²/sec does not dramatically improve the correlation. Changing the structural slab diffusion coefficient improves the deeper chloride level alignment with the cores, although there are limitations. It is also likely the levels are so low there is error in the accuracy of the sample or in the finite difference depth increment to accurately get a match. A last opportunity to improve correlation would be to change the structural slab decay coefficient. Bridge 2440 deck was constructed in 1979 with an unknown concrete deck mix, and there is potential that fly ash substitutions were made. In the next iteration the structural slab and concrete wearing course diffusion coefficients will be reset to the default diffusion coefficient of 1.68 m2/sec, but the structural slab decay coefficient will be increased to 0.5 to account for fly ash substitution. Figures D.2.15 through D.2.17 show the input and results.



Initial Construction	t, in	D28 (m^2/sec)	Obtained by NT Build 494?	$D_{av}{}^1$ (m2/sec)
Concrete W.C.	2.75	1.68E-12	No	1.68E-12
Slab	9	1.68E-12	No	1.68E-12
Initial deck thick	11.75	Note 1: y = 0.1623x + 2E-13, with x = NTBuild 492 D and y = steady state D		

Definitions and calculations

Diffusion decay over time

$D_o = D_{28}\left(\frac{28}{t}\right)^m$ Equation from Mangat and Malloy, Prediction of long term chloride concentration in concrete, *Materials and Structures*, 1994

where concrete w.c. m = 0.26 $m = 0.26 + 0.4\left(\frac{FA}{50} + \frac{SG}{70}\right)$ with FA = fly ash (% cementitious)

where structural slab m = 0.5 SG = slag (% cementitious)

Assume m = 0.56 for concrete mixtures with SCM replacement and 0.26 for portland cement only mixtures

Decay of diffusion coefficient stops after 25 years (standard industry assumption built into calculation of Do)

D28 = uncracked diffusion coefficient (m^2/s) obtained by ASTM C1556 or ASTM C492 or estimated based off of similar concretes at 28 days

Do = uncracked diffusion coefficient (m^2/s) used to calculate chloride ingress, modified with the decay coefficient for up to 25 years. After 25 years, it is assumed that D no longer decays

m = the decay factor is the variable that describes the decay of the diffusion coefficient over time

Deck and wearing course cracking effects on diffusion coefficient

Smeared Crack Model $D_{av} = D_o + \frac{w}{l} D_{cr}$

Dcr = cracked diffusion coefficient. It varies for the size of the crack. If the crack is very, very small, Dcr can be somewhere between 5x10^-10 m2/s and the measured (or assumed) uncracked diffusion coefficient. Any crack larger than 0.0035 in. should have a Dcr of 5x10^-10 m2/s, which is effectively the diffusion coefficient of a free surface (input in m^2/s)

w = average crack width--which can be estimated by quick visual inspection, photographs, or inspection reports. Input in inches.

l = average crack spacing, which can be estimated by quick visual inspection, photographs, or inspection reports. Input in feet.

Figure D.2.15 Last iteration inputs, changing the slab and wearing course diffusion coefficients to 1.68 m2/sec while trying a higher decay coefficient for the structural slab.

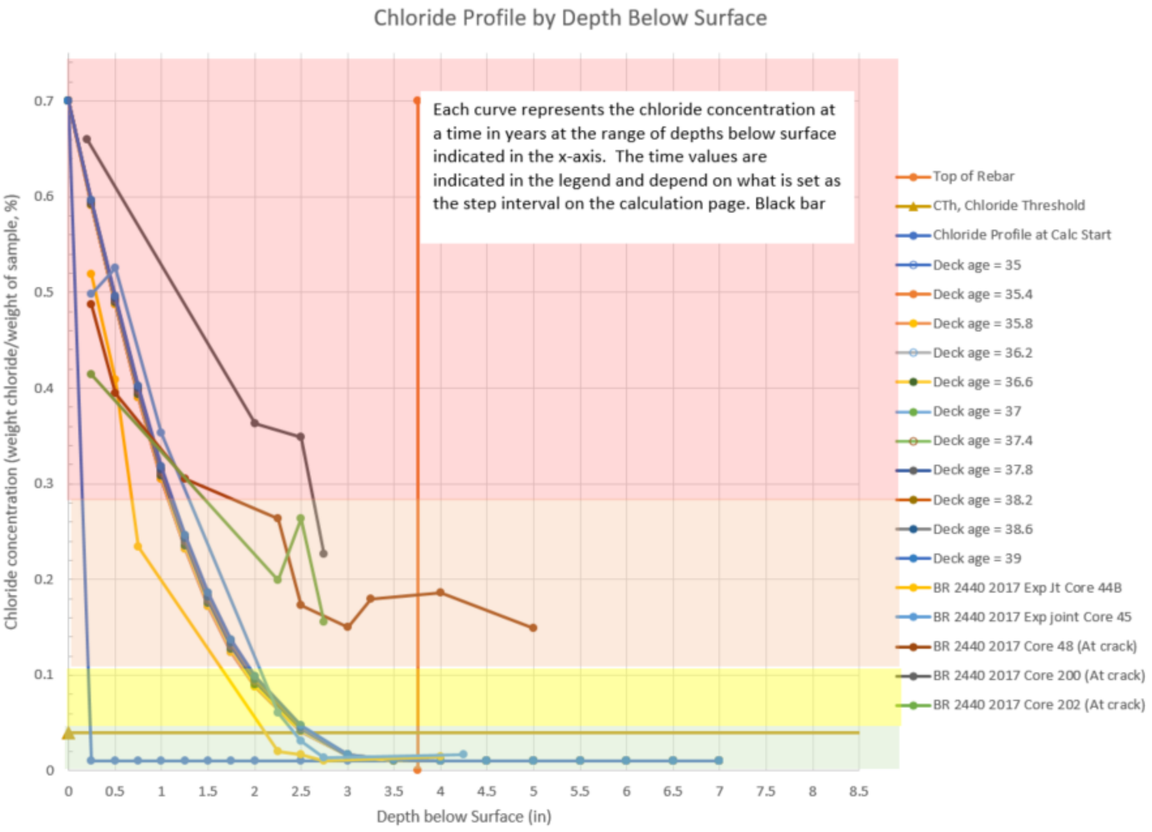


Figure D.2.16: Chloride versus Depth Plot: Results of initial inputs using default diffusion coefficient of 1.68E-12 m2/sec for concrete overlay, 1.68E-12 for structural slab, and chloride surface loading of 0.7. The decay factor for the structural slab has been increased to 0.50 to represent a large fly ash substitution. The parameters and resultant plot best matches the chloride sample profiles away from cracks.

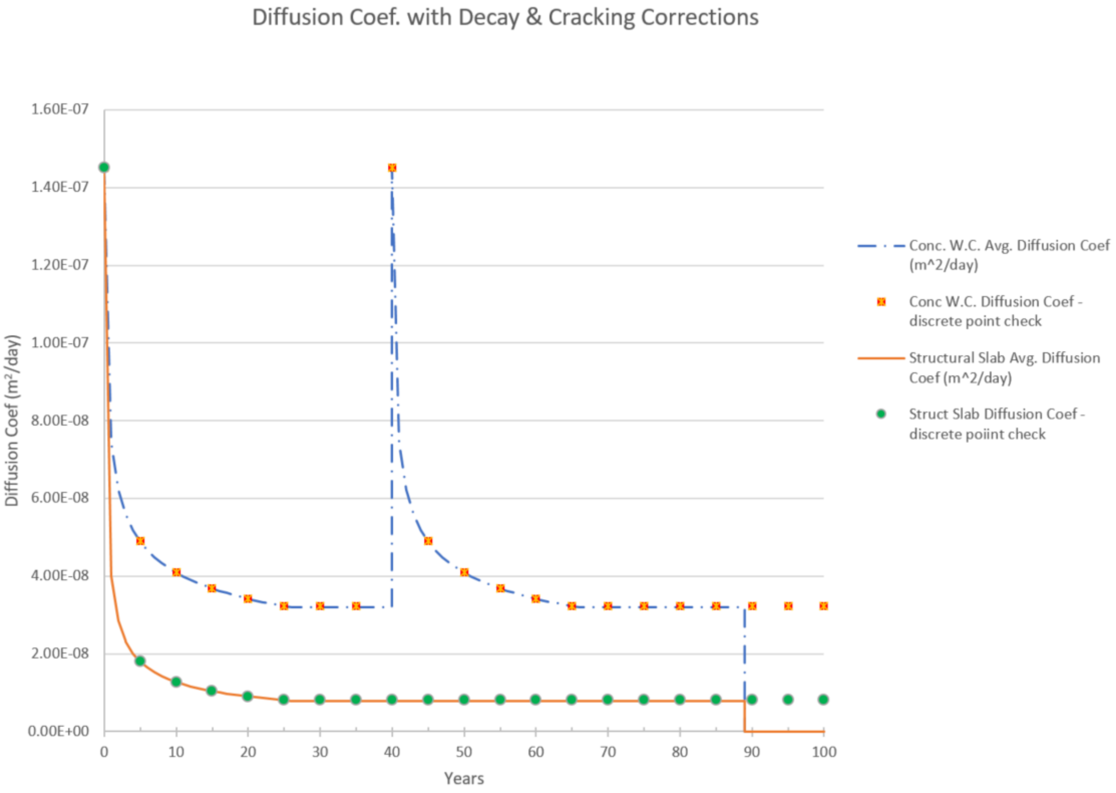
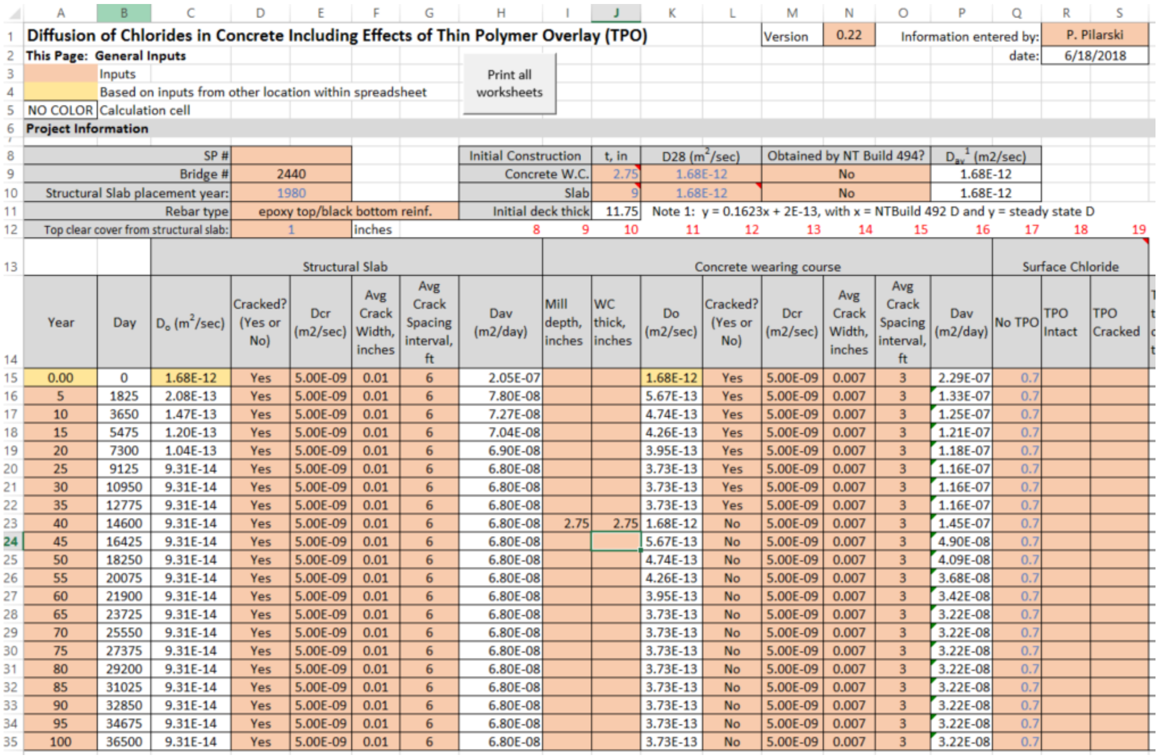


Figure D.2.17: Resultant diffusion coefficient for best match to cores in uncracked areas of the deck.

Calibration of the inputs have been made to chloride profiles obtained from cores taken away from cracks. With the parameters held constant, it will be attempted to match chloride profiles at core samples taken over the cracks. Several iterations not shown here were tried with various crack widths, crack spacings, and crack diffusion coefficient input. At the end the default cracked diffusion coefficient, D_{cr}, of 5E-10 m^2/sec was raised by a factor of 10 to 5E-9 m^2/sec, and the crack width for the structural slab set at 0.01-inches at 6-foot spacing while the wearing course cracking was set to 0.007-inches at 3-foot spacing. These inputs are shown in Figure D.2.18. The crack inputs would be a fairly severe level of cracking, and does not match the field observations of the 9” structural slab. However, for illustration it brings the predicted chloride profile more inline with the measured chloride profiles as shown in D.2.19. It is reasoned that cores directly over a crack will show erratic chloride levels because of the large surface area within the core subject to chloride ingress. The large surface areas of the crack faces are not necessarily appropriate for making judgments on the whole deck. They would, however, present a large risk of diffusion into the concrete horizontally and elevated risk of localized corrosion. Interpreting the risk level to be associated with localized corrosion is beyond the scope of this paper.

Figure D.2.20 shows the resultant diffusion coefficients taking into account the cracking level inputs. One may also notice the effect of replacing the low-slump wearing course in year 40 on the wearing course diffusion coefficient. The effects of replacing the concrete wearing course on the chloride levels at the top of rebar are illustrated in the Chloride versus Time plot, Figure D.2.21



Diffusion of Chlorides in Concrete Including Effects of Thin Polymer Overlay (TPO) | Version 0.22 | Information entered by: P. Pilarski

This Page: General Inputs | date: 6/18/2018

Inputs

Based on inputs from other location within spreadsheet

NO COLOR Calculation cell

Print all worksheets

Project Information

SP #		Initial Construction	t, in	D28 (m²/sec)	Obtained by NT Build 494?	D_{av} ¹ (m2/sec)
Bridge #	2440	Concrete W.C.	2.75	1.68E-12	No	1.68E-12
Structural Slab placement year:	1980	Slab	9	1.68E-12	No	1.68E-12
Rebar type	epoxy top/black bottom reinf.	Initial deck thick	11.75			
Top clear cover from structural slab:	1 inches					

Note 1: y = 0.1623x + 2E-13, with x = NTBuild 492 D and y = steady state D

							8	9	10	11	12	13	14	15	16	17	18	19
		Structural Slab						Concrete wearing course								Surface Chloride		
Year	Day	D_o (m²/sec)	Cracked? (Yes or No)	Dcr (m2/sec)	Avg Crack Width, inches	Avg Crack Spacing interval, ft	Dav (m2/day)	Mill depth, inches	WC thick, inches	Do (m2/sec)	Cracked? (Yes or No)	Dcr (m2/sec)	Avg Crack Width, inches	Avg Crack Spacing interval, ft	Dav (m2/day)	No TPO	TPO Intact	TPO Cracked
0.00	0	1.68E-12	Yes	5.00E-09	0.01	6	2.05E-07			1.68E-12	Yes	5.00E-09	0.007	3	2.29E-07	0.7		
5	1825	2.08E-13	Yes	5.00E-09	0.01	6	7.80E-08			5.67E-13	Yes	5.00E-09	0.007	3	1.33E-07	0.7		
10	3650	1.47E-13	Yes	5.00E-09	0.01	6	7.27E-08			4.74E-13	Yes	5.00E-09	0.007	3	1.25E-07	0.7		
15	5475	1.20E-13	Yes	5.00E-09	0.01	6	7.04E-08			4.26E-13	Yes	5.00E-09	0.007	3	1.21E-07	0.7		
20	7300	1.04E-13	Yes	5.00E-09	0.01	6	6.90E-08			3.95E-13	Yes	5.00E-09	0.007	3	1.18E-07	0.7		
25	9125	9.31E-14	Yes	5.00E-09	0.01	6	6.80E-08			3.73E-13	Yes	5.00E-09	0.007	3	1.16E-07	0.7		
30	10950	9.31E-14	Yes	5.00E-09	0.01	6	6.80E-08			3.73E-13	Yes	5.00E-09	0.007	3	1.16E-07	0.7		
35	12775	9.31E-14	Yes	5.00E-09	0.01	6	6.80E-08			3.73E-13	Yes	5.00E-09	0.007	3	1.16E-07	0.7		
40	14600	9.31E-14	Yes	5.00E-09	0.01	6	6.80E-08	2.75	2.75	1.68E-12	No	5.00E-09	0.007	3	1.45E-07	0.7		
45	16425	9.31E-14	Yes	5.00E-09	0.01	6	6.80E-08			5.67E-13	No	5.00E-09	0.007	3	4.90E-08	0.7		
50	18250	9.31E-14	Yes	5.00E-09	0.01	6	6.80E-08			4.74E-13	No	5.00E-09	0.007	3	4.09E-08	0.7		
55	20075	9.31E-14	Yes	5.00E-09	0.01	6	6.80E-08			4.26E-13	No	5.00E-09	0.007	3	3.68E-08	0.7		
60	21900	9.31E-14	Yes	5.00E-09	0.01	6	6.80E-08			3.95E-13	No	5.00E-09	0.007	3	3.42E-08	0.7		
65	23725	9.31E-14	Yes	5.00E-09	0.01	6	6.80E-08			3.73E-13	No	5.00E-09	0.007	3	3.22E-08	0.7		
70	25550	9.31E-14	Yes	5.00E-09	0.01	6	6.80E-08			3.73E-13	No	5.00E-09	0.007	3	3.22E-08	0.7		
75	27375	9.31E-14	Yes	5.00E-09	0.01	6	6.80E-08			3.73E-13	No	5.00E-09	0.007	3	3.22E-08	0.7		
80	29200	9.31E-14	Yes	5.00E-09	0.01	6	6.80E-08			3.73E-13	No	5.00E-09	0.007	3	3.22E-08	0.7		
85	31025	9.31E-14	Yes	5.00E-09	0.01	6	6.80E-08			3.73E-13	No	5.00E-09	0.007	3	3.22E-08	0.7		
90	32850	9.31E-14	Yes	5.00E-09	0.01	6	6.80E-08			3.73E-13	No	5.00E-09	0.007	3	3.22E-08	0.7		
95	34675	9.31E-14	Yes	5.00E-09	0.01	6	6.80E-08			3.73E-13	No	5.00E-09	0.007	3	3.22E-08	0.7		
100	36500	9.31E-14	Yes	5.00E-09	0.01	6	6.80E-08			3.73E-13	No	5.00E-09	0.007	3	3.22E-08	0.7		

Figure D.2.18: Final inputs for model calibrated to cracked core chloride profiles. Note that the Dcr value was changed to 5.0E-09 based after iteration to better match cracked core samples. The deck is currently being evaluated for years 40 and beyond where milling the old wearing course off and placing a new concrete wearing course is being contemplated.

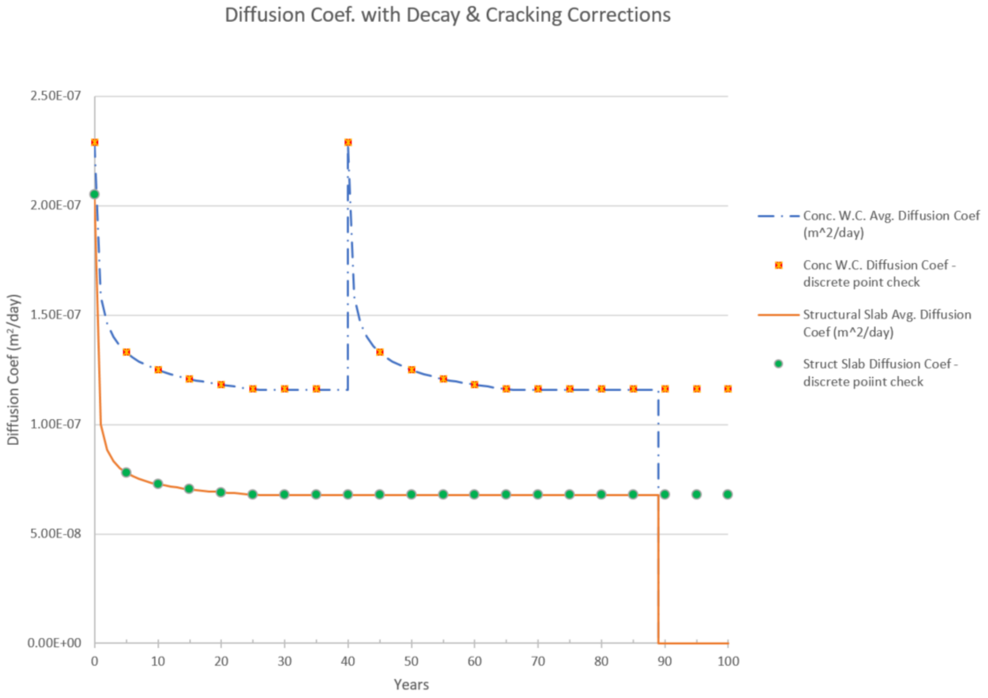
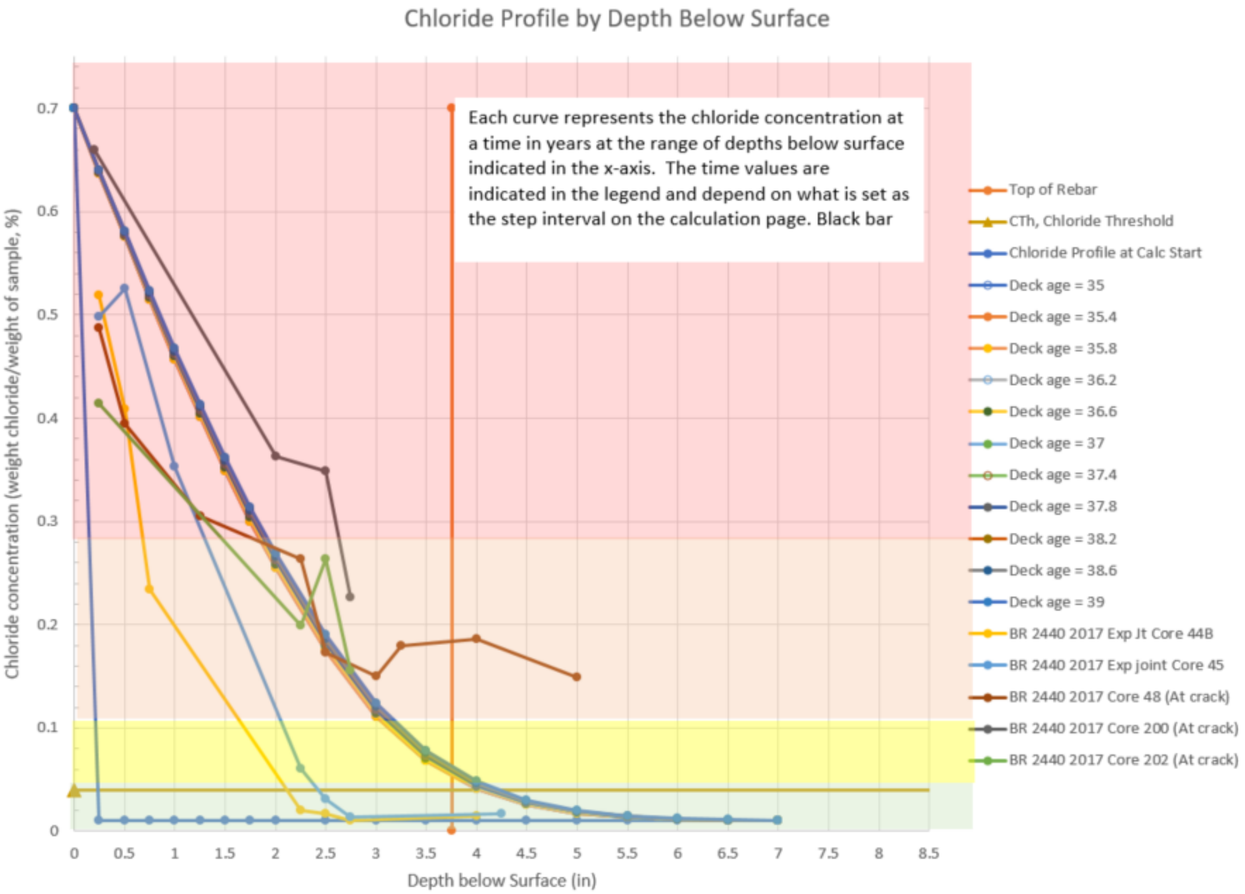


Figure D.2.19: Diffusion coefficients used based on cracked input.



Each curve represents the chloride concentration at a time in years at the range of depths below surface indicated in the x-axis. The time values are indicated in the legend and depend on what is set as the step interval on the calculation page. Black bar

Figure D.2.20: Chloride profile prediction for calibration to cracked cores. Cracked cores were especially erratic and difficult to calibrate with the diffusion model.

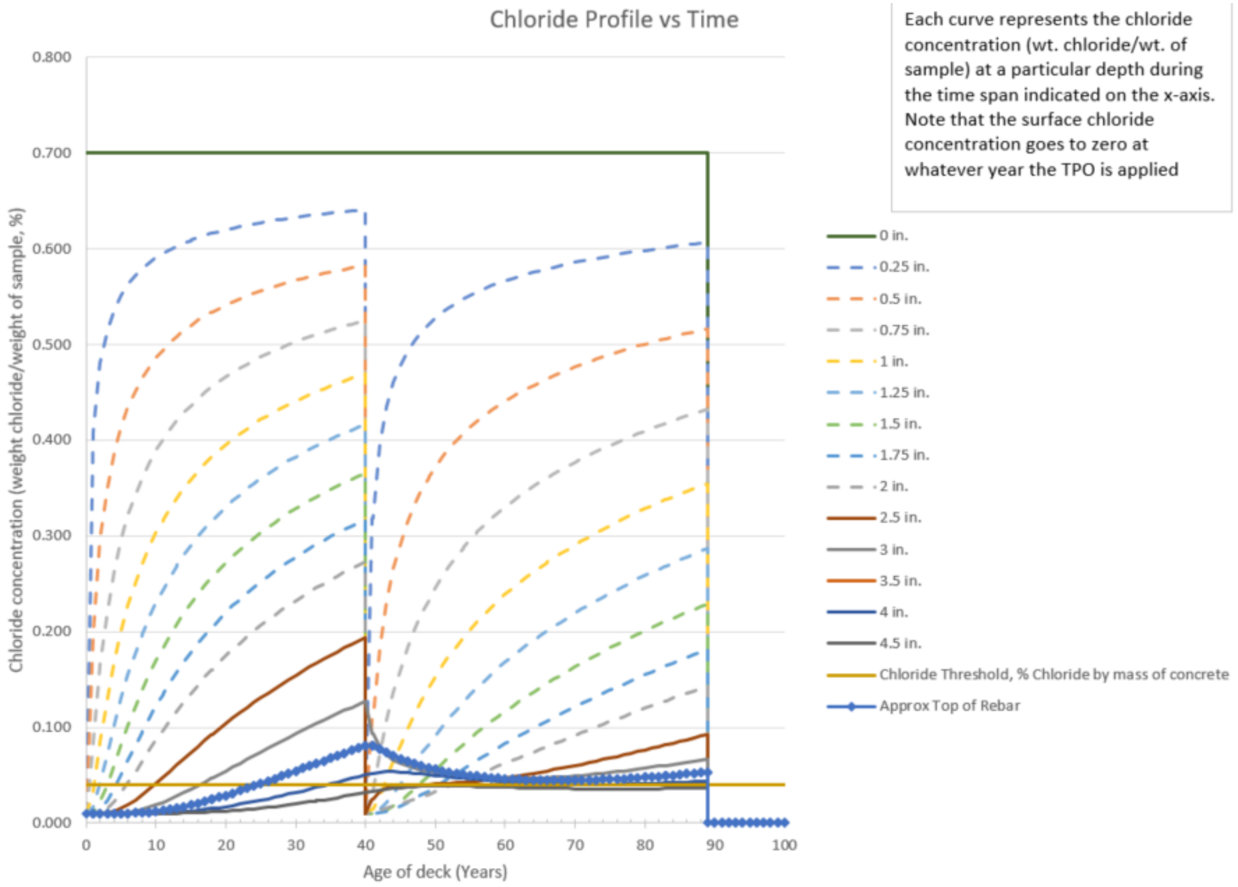
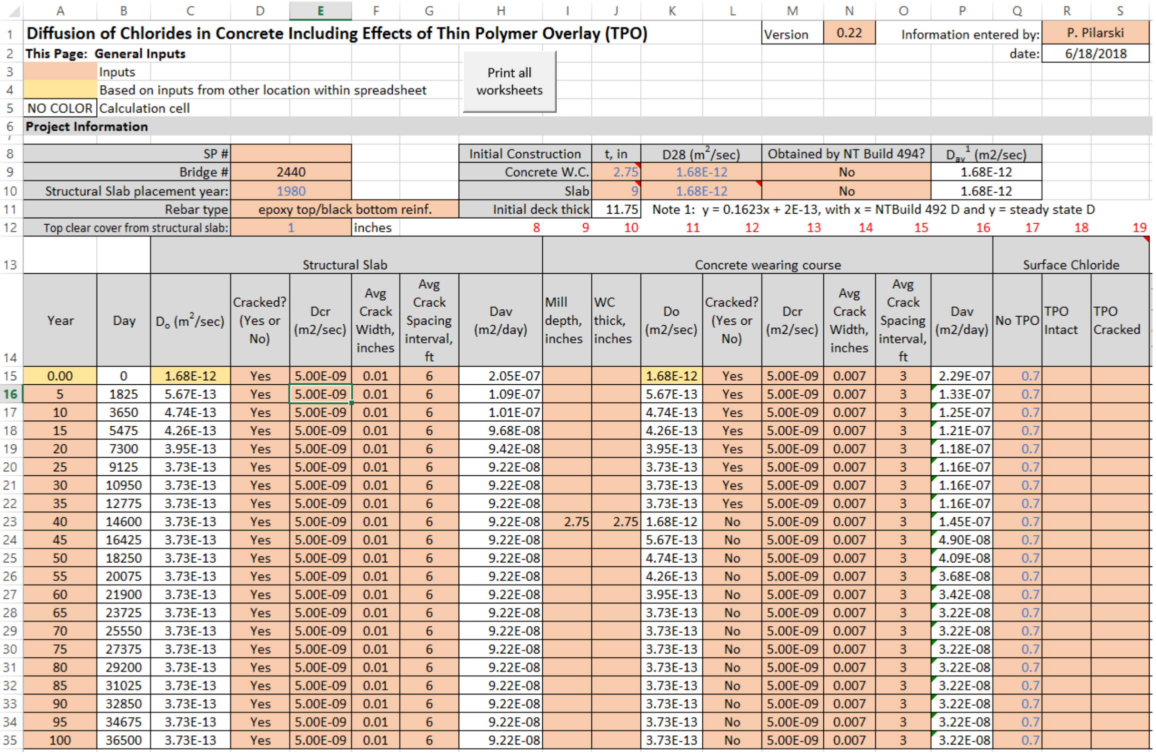


Figure D.2.21: Chloride prediction over time using model incorporating cracked diffusion coefficients. Chloride levels at level of rebar are likely to be much higher local to the crack, but away from a crack the chloride profiles would be much lower. The dark blue line is the top rebar level.

A comparative analysis can also be shown on the concrete wearing course replacement alternative if the uncracked model parameters are used. In other words, simple changing the input column asking if cracking were present to a “No” response. The input and effects are shown in figures D.2.22 and D.2.22, respectively. Figure D.2.22 show that the existing structural deck is capable of remaining in service for over 40 additional years should the high chlorides in the old concrete wearing course be removed and an equivalent thickness concrete overlay is placed. The new concrete wearing course would have to have any cracks sealed to achieve this result, or possibly have a Methylmethcrylate flood seal applied at routine intervals to prevent chloride penetration into any cracks.



Diffusion of Chlorides in Concrete Including Effects of Thin Polymer Overlay (TPO)

Version 0.22

Information entered by: P. Pilarski

date: 6/18/2018

This Page: General Inputs

	Inputs
	Based on inputs from other location within spreadsheet
NO COLOR	Calculation cell

Project Information

SP #	
Bridge #	2440
Structural Slab placement year:	1980
Rebar type	epoxy top/black bottom reinf.
Top clear cover from structural slab:	1 inches

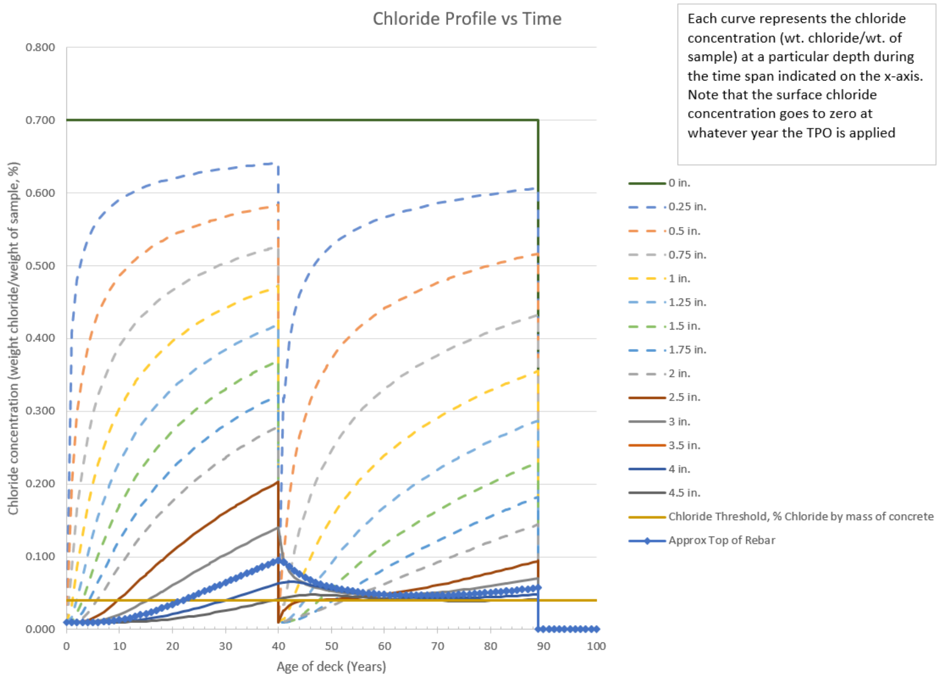
Initial Construction	t, in	D28 (m^2/sec)	Obtained by NT Build 494?	D_{av} ^{1} (m2/sec)
Concrete W.C.	2.75	1.68E-12	No	1.68E-12
Slab	9	1.68E-12	No	1.68E-12
Initial deck thick	11.75			

Note 1: y = 0.1623x + 2E-13, with x = NTBuild 492 D and y = steady state D

8 9 10 11 12 13 14 15 16 17 18 19

		Structural Slab						Concrete wearing course								Surface Chloride		
Year	Day	D_o (m^2/sec)	Cracked? (Yes or No)	Dcr (m2/sec)	Avg Crack Width, inches	Avg Crack Spacing interval, ft	Dav (m2/day)	Mill depth, inches	WC thick, inches	Do (m2/sec)	Cracked? (Yes or No)	Dcr (m2/sec)	Avg Crack Width, inches	Avg Crack Spacing interval, ft	Dav (m2/day)	No TPO	TPO Intact	TPO Cracked
0.00	0	1.68E-12	Yes	5.00E-09	0.01	6	2.05E-07			1.68E-12	Yes	5.00E-09	0.007	3	2.29E-07	0.7		
5	1825	5.67E-13	Yes	5.00E-09	0.01	6	1.09E-07			5.67E-13	Yes	5.00E-09	0.007	3	1.33E-07	0.7		
10	3650	4.74E-13	Yes	5.00E-09	0.01	6	1.01E-07			4.74E-13	Yes	5.00E-09	0.007	3	1.25E-07	0.7		
15	5475	4.26E-13	Yes	5.00E-09	0.01	6	9.68E-08			4.26E-13	Yes	5.00E-09	0.007	3	1.21E-07	0.7		
20	7300	3.95E-13	Yes	5.00E-09	0.01	6	9.42E-08			3.95E-13	Yes	5.00E-09	0.007	3	1.18E-07	0.7		
25	9125	3.73E-13	Yes	5.00E-09	0.01	6	9.22E-08			3.73E-13	Yes	5.00E-09	0.007	3	1.16E-07	0.7		
30	10950	3.73E-13	Yes	5.00E-09	0.01	6	9.22E-08			3.73E-13	Yes	5.00E-09	0.007	3	1.16E-07	0.7		
35	12775	3.73E-13	Yes	5.00E-09	0.01	6	9.22E-08			3.73E-13	Yes	5.00E-09	0.007	3	1.16E-07	0.7		
40	14600	3.73E-13	Yes	5.00E-09	0.01	6	9.22E-08	2.75	2.75	1.68E-12	No	5.00E-09	0.007	3	1.45E-07	0.7		
45	16425	3.73E-13	Yes	5.00E-09	0.01	6	9.22E-08			5.67E-13	No	5.00E-09	0.007	3	4.90E-08	0.7		
50	18250	3.73E-13	Yes	5.00E-09	0.01	6	9.22E-08			4.74E-13	No	5.00E-09	0.007	3	4.09E-08	0.7		
55	20075	3.73E-13	Yes	5.00E-09	0.01	6	9.22E-08			4.26E-13	No	5.00E-09	0.007	3	3.68E-08	0.7		
60	21900	3.73E-13	Yes	5.00E-09	0.01	6	9.22E-08			3.95E-13	No	5.00E-09	0.007	3	3.42E-08	0.7		
65	23725	3.73E-13	Yes	5.00E-09	0.01	6	9.22E-08			3.73E-13	No	5.00E-09	0.007	3	3.22E-08	0.7		
70	25550	3.73E-13	Yes	5.00E-09	0.01	6	9.22E-08			3.73E-13	No	5.00E-09	0.007	3	3.22E-08	0.7		
75	27375	3.73E-13	Yes	5.00E-09	0.01	6	9.22E-08			3.73E-13	No	5.00E-09	0.007	3	3.22E-08	0.7		
80	29200	3.73E-13	Yes	5.00E-09	0.01	6	9.22E-08			3.73E-13	No	5.00E-09	0.007	3	3.22E-08	0.7		
85	31025	3.73E-13	Yes	5.00E-09	0.01	6	9.22E-08			3.73E-13	No	5.00E-09	0.007	3	3.22E-08	0.7		
90	32850	3.73E-13	Yes	5.00E-09	0.01	6	9.22E-08			3.73E-13	No	5.00E-09	0.007	3	3.22E-08	0.7		
95	34675	3.73E-13	Yes	5.00E-09	0.01	6	9.22E-08			3.73E-13	No	5.00E-09	0.007	3	3.22E-08	0.7		
100	36500	3.73E-13	Yes	5.00E-09	0.01	6	9.22E-08			3.73E-13	No	5.00E-09	0.007	3	3.22E-08	0.7		

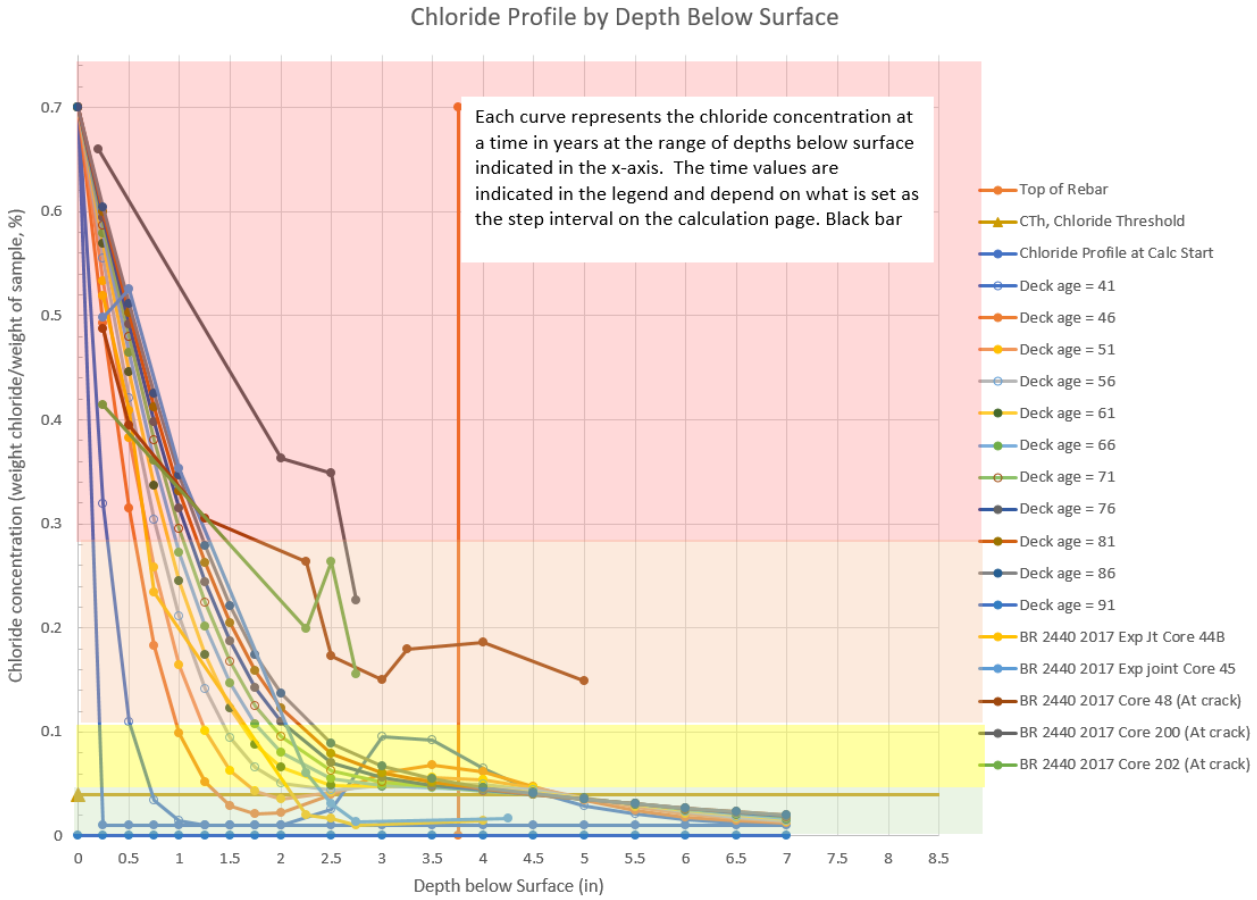
Figure D.2.22: Uncracked core model using all the same diffusion parameters as in the earlier cracked model but no new cracking in proposed concrete wearing course. The deck is being evaluated for years 40 and beyond where milling the old wearing course off and placing a new concrete wearing course is being contemplated.



Each curve represents the chloride concentration (wt. chloride/wt. of sample) at a particular depth during the time span indicated on the x-axis. Note that the surface chloride concentration goes to zero at whatever year the TPO is applied

Figure D.2.23: Resultant chloride concentration over time with structural slab cracked at 6-feet on center, and wearing course uncracked. Notice the predicted diffusion effect shows the new concrete wearing course can also reduce chloride levels in the upper structural slab.

Figure D.2.24 illustrates the chloride versus depth profile prediction beyond year 40 in 5-year increments as a result of the new concrete wearing course. Similar to a TPO timing study, concrete wearing courses can be effectively managed and replaced using this modeling spreadsheet if chloride sampling and calibration is performed. Once a state has sufficient data on diffusion coefficients, assumptions may be refined to be applied on a more systematic level for asset management.



Each curve represents the chloride concentration at a time in years at the range of depths below surface indicated in the x-axis. The time values are indicated in the legend and depend on what is set as the step interval on the calculation page. Black bar

Figure D.2.24: Resultant chloride profile predictions forecast in 5-year increments beyond year 40 as a result of the new concrete wearing course.

This case study illustrated the input and iteration on a bridge slab and concrete wearing course nearing 40-years of age. It represented one method of bridge preservation evaluation that involves removing high chloride levels in the upper levels of the slab and replacing it with a new concrete wearing course. Applying the model to additional bridges will enhance the general knowledge of chloride diffusion patterns, generate best practice for making model adjustments, and open the path for further uses.

D.3: Bridge 09823 TPO addition, I 35 SB over CSAH 61

The I35 Bridge (Bridge 09823) is a MnDOT bridge constructed in in 1965. It is 320-foot long and conveys two lanes of interstate traffic over County Road 61. The original construction reinforcement in uses uncoated reinforcement with 1 1/2" concrete cover. In 1982 the bridge was widened and utilized epoxy-coated top reinforcement in the widened portion while the bottom mat remained uncoated. This study will examine the chloride ingress and compare the modeling results to the chloride profiles obtained in a 2010, 2011, and 2014.

Figure D.3.1: Bridge overhead view from Google Maps in 2018. North is toward left of photo. BR 09823 conveys SB I35 at bottom of picture, sister bridge BR09824 conveys NB I35 and was redecked in 2018. Both bridges utilize an anti-icing system.

Figure D.3.2: Bridge Elevation from west

Figure D.3.3: Bridge deck photo from August 2014 (Obtained from Google Streetview)

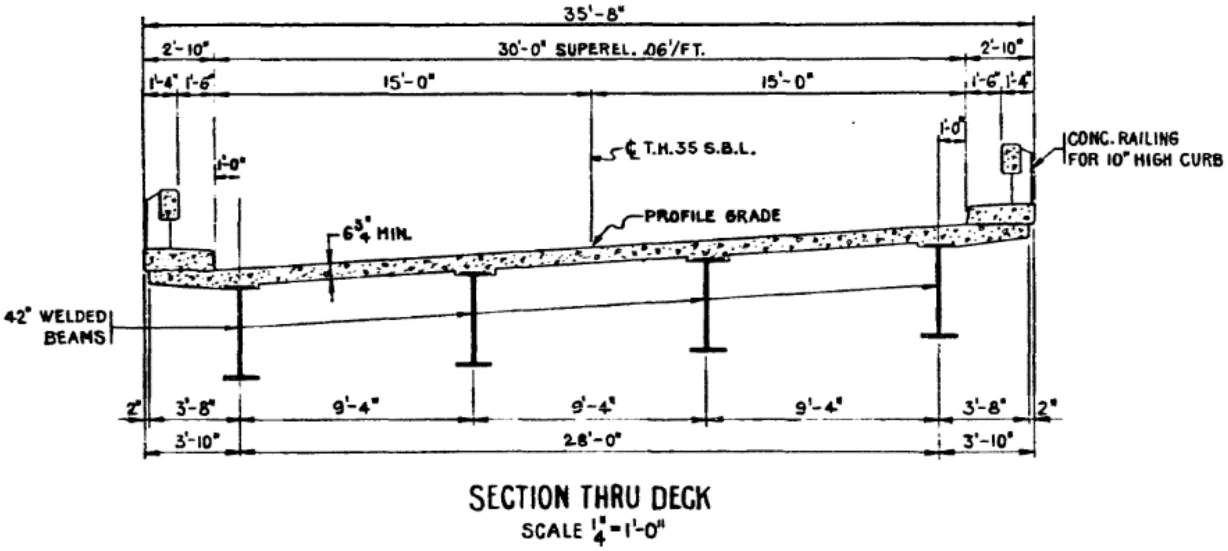


Figure D.3.4: 1965 deck cross section with 6 3/4" slab thickness.

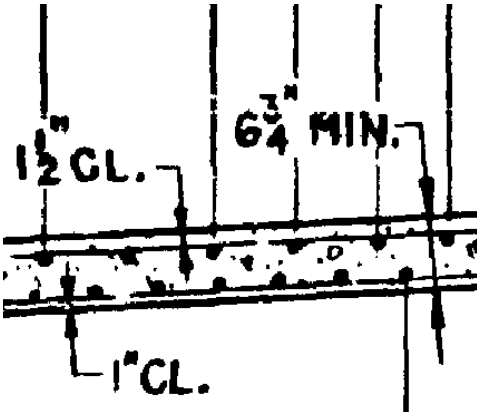


Figure D.3.5: 1965 reinforcement cover.

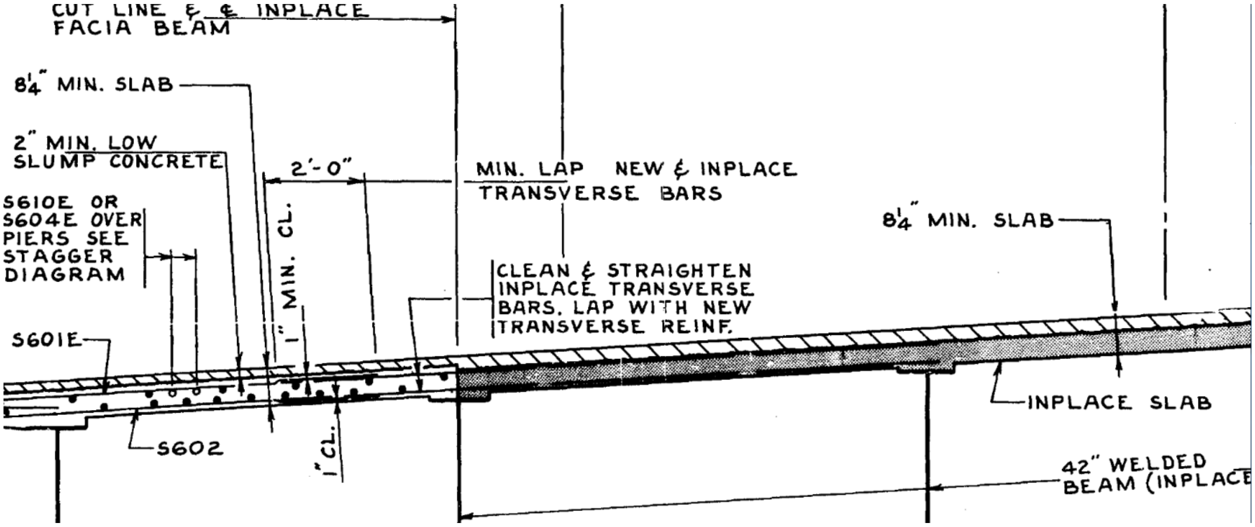
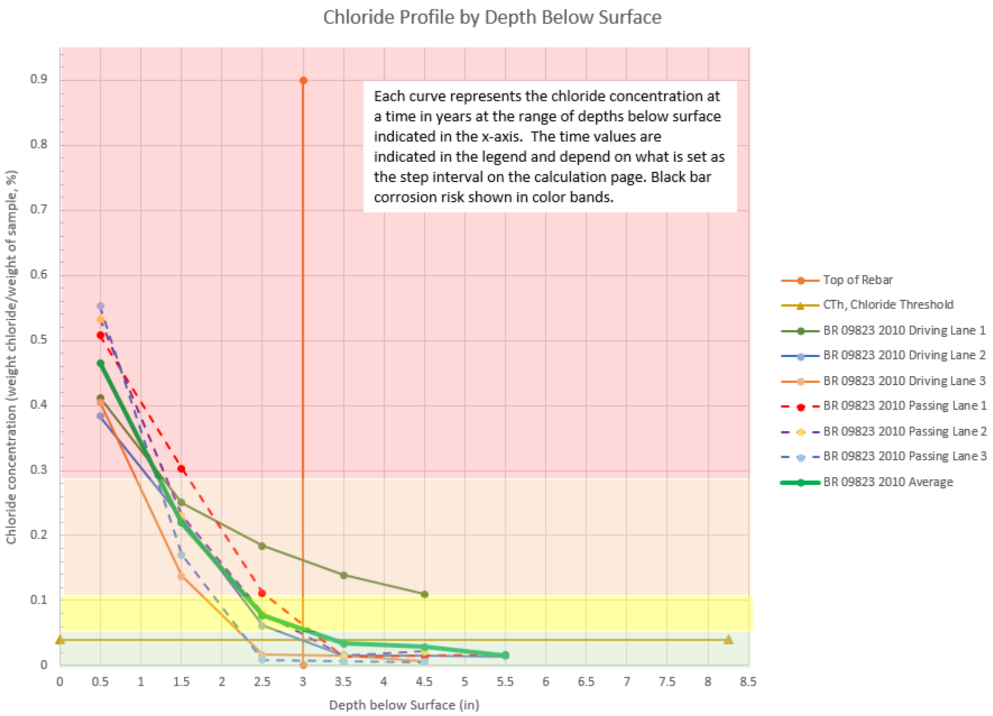


Figure D.3.6: 1982 deck cross section where the bridge was widened. The existing slab was milled 1 ½" to the top of the transverse bars, and a 3" low-slump wearing course was placed over the milled areas over old deck while 2" low slump wearing course topped the widened portion of deck.

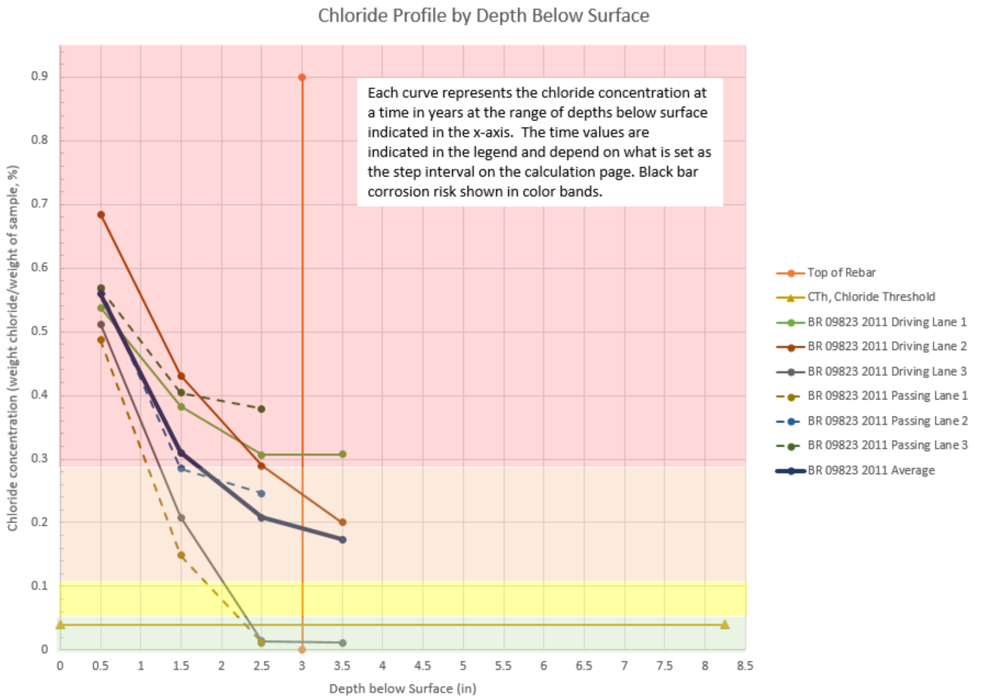
In 2010 Bridge 09823 was included in a prior study on the effectiveness of epoxy chip seals or TPOs. The research was never published, but the data was made available to this research effort. The TPO had been applied in 2009 and researchers sampled the deck through the TPO to obtain chloride profiles in 2010, 2011 and 2014. Cores from both passing lanes and driving lanes were obtained, with a total count of 14 over the three sampled years. The generated chloride profiles are seen in Figures D.3.7 through D.3.11. There appears to be little evidence to suggest a difference between the chloride concentrations between the driving lanes and the passing lanes for bridge 09823. Figure D.3.10 shows the average of all 14 chloride profiles in the three sample years. This average will be used as representative for modeling calibration. The reason to take the average for all three years is because the wide scatter in the data obtained within a given year as well as the short timeframe for chloride diffusion between years.

As can be seen in Figure D.3.11, there is no strong trend that can be observed after the TPO was in service. The 2014 chloride profiles show a blunting of chloride concentrations near the surface, which may be indicative of gradual distribution in the lower depths. However, between 2010 and 2011 the average chloride profiles appear to increase. This behavior is attributed to the natural variation in data. It also is indicative of the research need for further field sampling of TPO-covered decks. It could be Regardless of the trends, it appears that the behavior of chloride profiles once the TPO is applied may be too slow to properly model as was one original desire of this research. In other words, any diffusion prediction made once the TPO is applied may be very conservative at least at the rebar level. This conservatism, however, may still yield value because an asset manager making predictions can be confident that the predictions are showing worst case chloride penetration at the rebar level once the TPO had been applied.



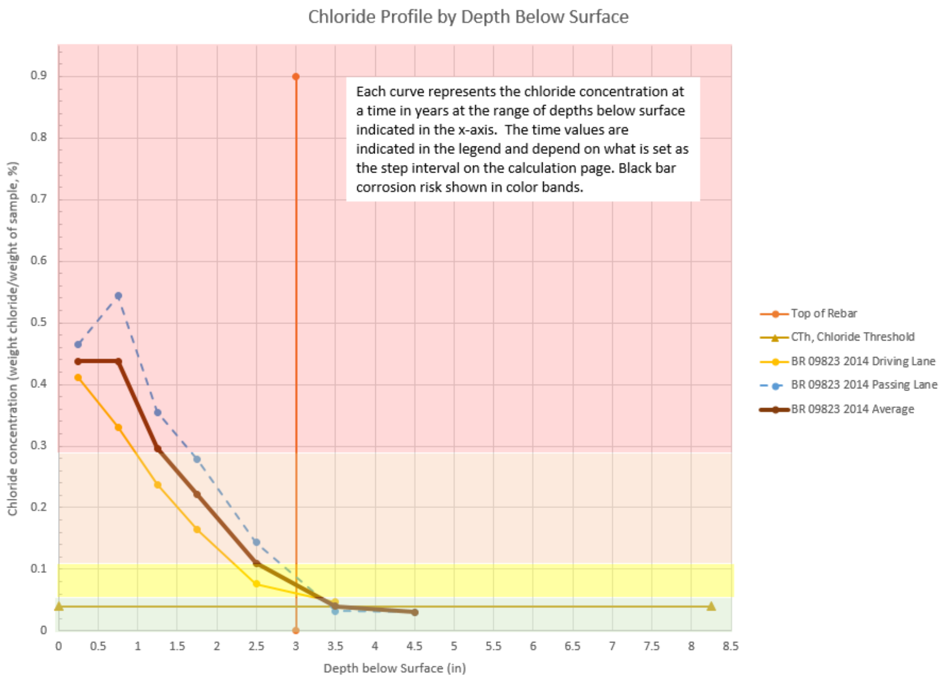
Each curve represents the chloride concentration at a time in years at the range of depths below surface indicated in the x-axis. The time values are indicated in the legend and depend on what is set as the step interval on the calculation page. Black bar corrosion risk shown in color bands.

Figure D.3.7: Chloride versus Depth Plot: 2010 passing lanes versus the driving lanes are plotted against the average for the year. Within the concrete wear course there is wider chloride data variation than at deeper levels. Driving Lane 1 chloride profile is at a crack within the slab and will be excluded from modeling.



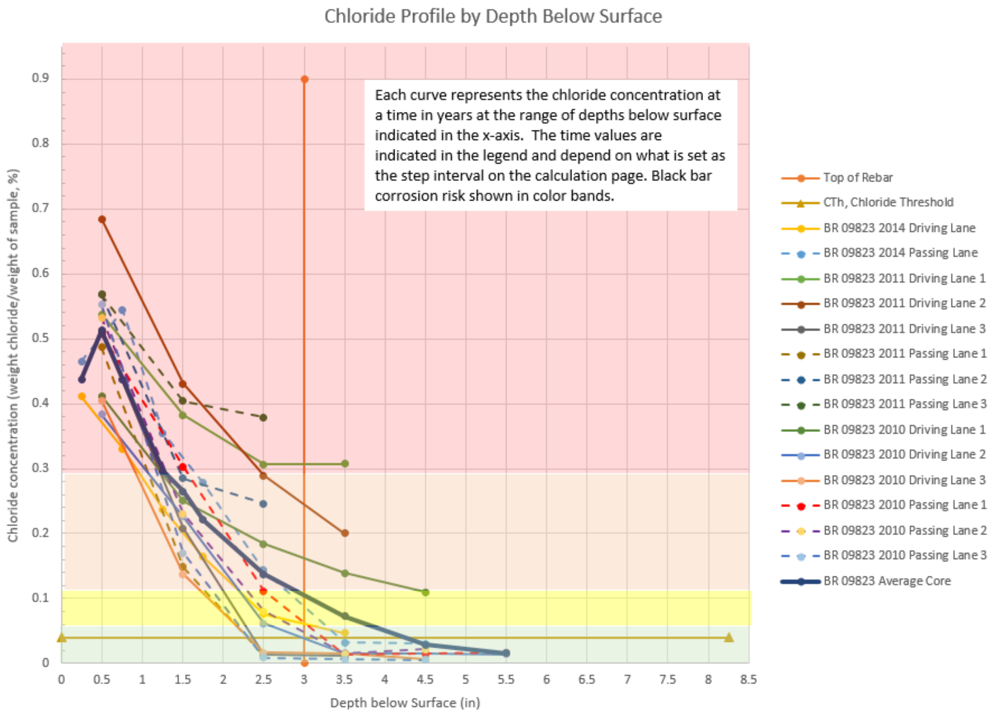
Each curve represents the chloride concentration at a time in years at the range of depths below surface indicated in the x-axis. The time values are indicated in the legend and depend on what is set as the step interval on the calculation page. Black bar corrosion risk shown in color bands.

Figure D.3.8: Chloride versus Depth Plot: 2011 passing lanes versus the driving lanes are plotted against the average for the year.



Each curve represents the chloride concentration at a time in years at the range of depths below surface indicated in the x-axis. The time values are indicated in the legend and depend on what is set as the step interval on the calculation page. Black bar corrosion risk shown in color bands.

Figure D.3.9: Chloride versus Depth Plot: 2014 passing lanes versus the driving lanes are plotted against the average for the year. There were only two profiles taken in 2014. The limited data limits the ability to draw reasonable conclusions.



Each curve represents the chloride concentration at a time in years at the range of depths below surface indicated in the x-axis. The time values are indicated in the legend and depend on what is set as the step interval on the calculation page. Black bar corrosion risk shown in color bands.

Figure D.3.10: Chloride versus Depth Plot: The 14 cores collected from 2010 to 2014 are plotted with the average of all cores collected. The passing lane cores are denoted with dotted lines and the driving lanes are denoted with solid lines. 2010 Driving Lane 1 is excluded from the average due to presence of a crack.

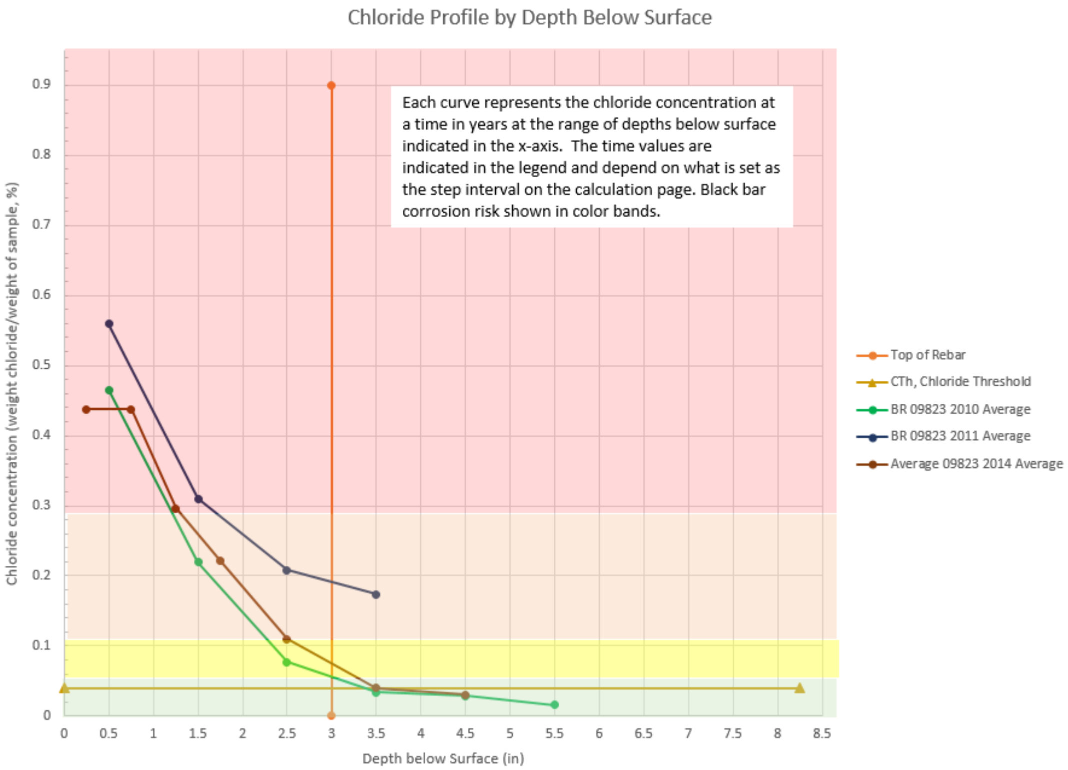
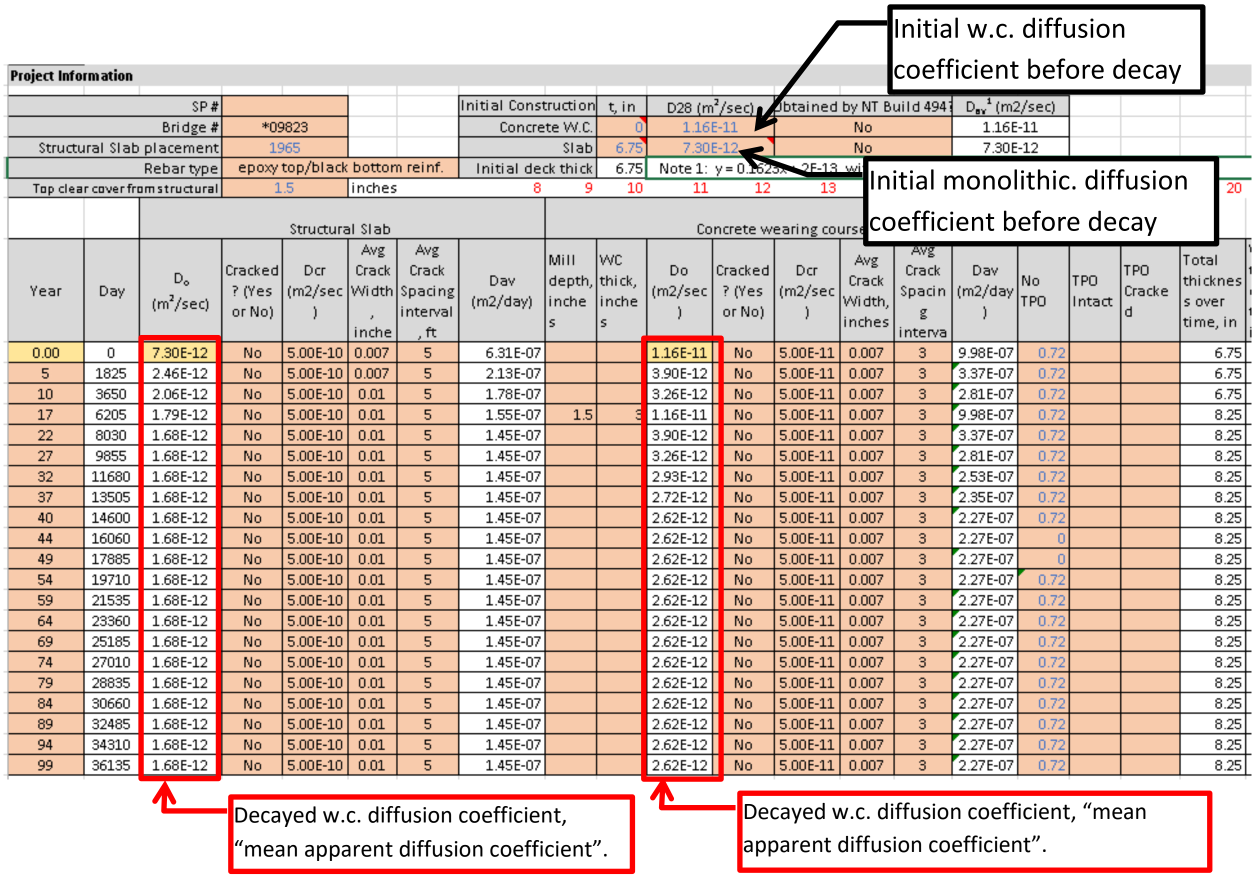


Figure D.3.11: Chloride versus Depth Plot: The average of the three of years of cores are plotted. The data is pulled from widely varying profile data and trends may not be conclusive.

Refer to Figure 6.2.9 for the General Inputs tab at the start of modeling. Because there is no initial concrete wearing course, the initial thickness is set to 0-inches. The mill and overlay is input in year 17. The TPO was applied in year 44 and is modeled by setting the surface chloride equal to 0 once the TPO is applied. When the TPO is not present, a surface chloride input was found by iteration to be 0.72 % by weight of sample. This finding was established by visual examination of the trajectory of the obtained chloride profiles with the surface in the Chloride versus depth chart.

The diffusion coefficient for older or unknown monolithic decks has been recommended at 1.68E-12 m^2/sec. The 1.68E-12 m^2/sec value reflects decay that would have already happened because it had been obtained from sampling many older decks. In other words, decay has largely already occurred from a higher initial value to decrease to this value. Using m=0.26 in Equation 5.2 and iterating to solve for an initial diffusion coefficient, a value of 7.3E-12 m^2/sec was found as an appropriate starting value to eventually decay to the recommended value of 1.68E-12 m/s^2 for mean apparent diffusion coefficient on unknown or monolithic decks. Similarly, a value of 11.55E-12 m^2/sec would be required to result in a decayed mean apparent diffusion coefficient of 2.62E-12 m^2/sec for decks with a low slump wearing course. These initial inputs are shown in Figure D.3.12 as well as the decay over time, which is illustrated in Figure D.3.15. In this example these non-decayed coefficients are being used to demonstrate the correlation with report recommendations. Note that Figure D.3.15 shows the diffusion coefficient over time based on these inputs, but the plotting has been converted from m^2/sec to m^2/day.

For a deck with no initial concrete wearing course, the program will use the input diffusion coefficient for the structural slab. Only when the concrete wearing course is input as a thickness greater than 0 inches will the input concrete wearing course diffusion coefficient be used. This is illustrated in Figure D.3.15 by observing that the concrete wearing course diffusion coefficient jumps to the initial value in year 17 and restarts decay. Prior to year 17 the concrete wearing course diffusion coefficient had seen a decay period, but since the wearing course thickness was 0 inches during this time period it inherently played no role in finite difference diffusion calculations. Figure 6.2.10 shows the slab thickness and wearing course inputs as reflected in the model.



Initial w.c. diffusion coefficient before decay

Initial monolithic. diffusion coefficient before decay

Project Information

SP #		Initial Construction	t, in	D28 (m^2/sec)	btained by NT Build 494	D_{av}^{1} (m2/sec)
Bridge #	*09823	Concrete W.C.	0	1.16E-11	No	1.16E-11
Structural Slab placement	1965	Slab	6.75	7.30E-12	No	7.30E-12
Rebar type	epoxy top/black bottom reinf.	Initial deck thick	6.75	Note 1: y = 0.1625x 2E-13 wi		
Top clear cover from structural	1.5	inches				

8 9 10 11 12 13 20

		Structural Slab						Concrete wearing course											
Year	Day	D_o (m^2/sec)	Cracked? (Yes or No)	Dcr (m2/sec)	Avg Crack Width, inche	Avg Crack Spacing interval, ft	Dav (m2/day)	Mill depth, inches	WC thick, inches	Do (m2/sec)	Cracked? (Yes or No)	Dcr (m2/sec)	Avg Crack Width, inches	Avg Crack Spacing interva	Dav (m2/day)	No TPO	TPO Intact	TPO Cracked	Total thickness over time, in
0.00	0	7.30E-12	No	5.00E-10	0.007	5	6.31E-07			1.16E-11	No	5.00E-11	0.007	3	9.98E-07	0.72			6.75
5	1825	2.46E-12	No	5.00E-10	0.007	5	2.13E-07			3.90E-12	No	5.00E-11	0.007	3	3.37E-07	0.72			6.75
10	3650	2.06E-12	No	5.00E-10	0.01	5	1.78E-07			3.26E-12	No	5.00E-11	0.007	3	2.81E-07	0.72			6.75
17	6205	1.79E-12	No	5.00E-10	0.01	5	1.55E-07	1.5	3	1.16E-11	No	5.00E-11	0.007	3	9.98E-07	0.72			8.25
22	8030	1.68E-12	No	5.00E-10	0.01	5	1.45E-07			3.90E-12	No	5.00E-11	0.007	3	3.37E-07	0.72			8.25
27	9855	1.68E-12	No	5.00E-10	0.01	5	1.45E-07			3.26E-12	No	5.00E-11	0.007	3	2.81E-07	0.72			8.25
32	11680	1.68E-12	No	5.00E-10	0.01	5	1.45E-07			2.93E-12	No	5.00E-11	0.007	3	2.53E-07	0.72			8.25
37	13505	1.68E-12	No	5.00E-10	0.01	5	1.45E-07			2.72E-12	No	5.00E-11	0.007	3	2.35E-07	0.72			8.25
40	14600	1.68E-12	No	5.00E-10	0.01	5	1.45E-07			2.62E-12	No	5.00E-11	0.007	3	2.27E-07	0.72			8.25
44	16060	1.68E-12	No	5.00E-10	0.01	5	1.45E-07			2.62E-12	No	5.00E-11	0.007	3	2.27E-07	0			8.25
49	17885	1.68E-12	No	5.00E-10	0.01	5	1.45E-07			2.62E-12	No	5.00E-11	0.007	3	2.27E-07	0			8.25
54	19710	1.68E-12	No	5.00E-10	0.01	5	1.45E-07			2.62E-12	No	5.00E-11	0.007	3	2.27E-07	0.72			8.25
59	21535	1.68E-12	No	5.00E-10	0.01	5	1.45E-07			2.62E-12	No	5.00E-11	0.007	3	2.27E-07	0.72			8.25
64	23360	1.68E-12	No	5.00E-10	0.01	5	1.45E-07			2.62E-12	No	5.00E-11	0.007	3	2.27E-07	0.72			8.25
69	25185	1.68E-12	No	5.00E-10	0.01	5	1.45E-07			2.62E-12	No	5.00E-11	0.007	3	2.27E-07	0.72			8.25
74	27010	1.68E-12	No	5.00E-10	0.01	5	1.45E-07			2.62E-12	No	5.00E-11	0.007	3	2.27E-07	0.72			8.25
79	28835	1.68E-12	No	5.00E-10	0.01	5	1.45E-07			2.62E-12	No	5.00E-11	0.007	3	2.27E-07	0.72			8.25
84	30660	1.68E-12	No	5.00E-10	0.01	5	1.45E-07			2.62E-12	No	5.00E-11	0.007	3	2.27E-07	0.72			8.25
89	32485	1.68E-12	No	5.00E-10	0.01	5	1.45E-07			2.62E-12	No	5.00E-11	0.007	3	2.27E-07	0.72			8.25
94	34310	1.68E-12	No	5.00E-10	0.01	5	1.45E-07			2.62E-12	No	5.00E-11	0.007	3	2.27E-07	0.72			8.25
99	36135	1.68E-12	No	5.00E-10	0.01	5	1.45E-07			2.62E-12	No	5.00E-11	0.007	3	2.27E-07	0.72			8.25

Decayed w.c. diffusion coefficient, "mean apparent diffusion coefficient".

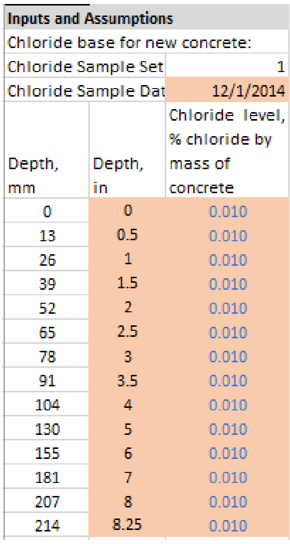
Decayed w.c. diffusion coefficient, "mean apparent diffusion coefficient".

Figure D.3.12: Initial input for chloride modeling. Note the concrete wearing course application after milling the monolithic slab in year 17.

3” low slump concrete wearing course.

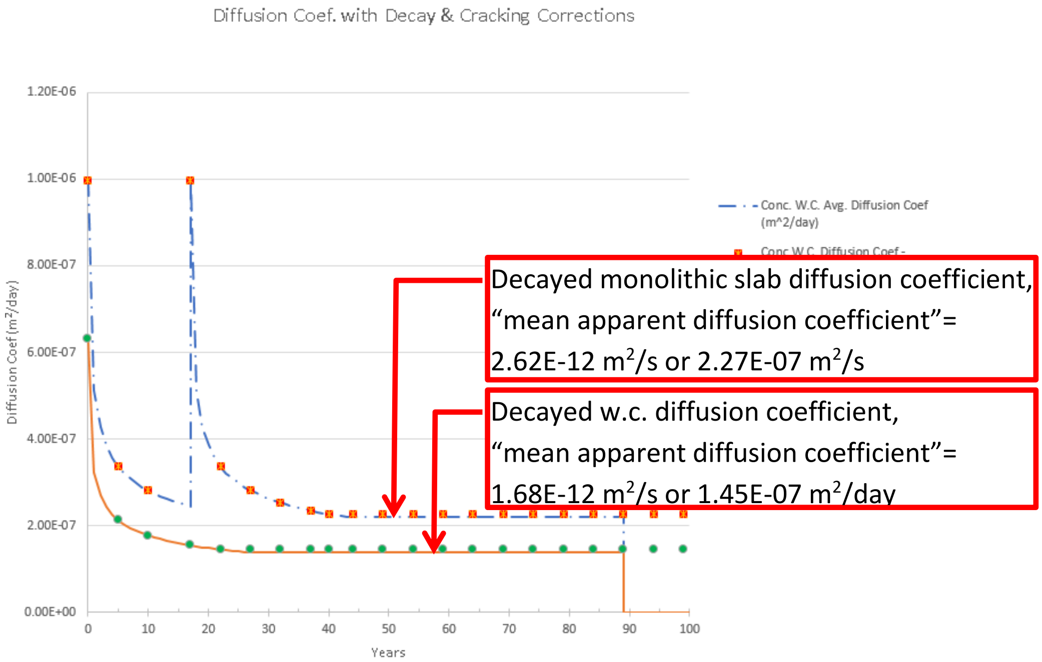
1 1/2” concrete surface milling

Figure D.3.13: Model geometry reflected from inputs including effects of milling and placing low slump wearing course.



Inputs and Assumptions		
Chloride base for new concrete:		
Chloride Sample Set		1
Chloride Sample Dat		12/1/2014
Depth, mm	Depth, in	Chloride level, % chloride by mass of concrete
0	0	0.010
13	0.5	0.010
26	1	0.010
39	1.5	0.010
52	2	0.010
65	2.5	0.010
78	3	0.010
91	3.5	0.010
104	4	0.010
130	5	0.010
155	6	0.010
181	7	0.010
207	8	0.010
214	8.25	0.010

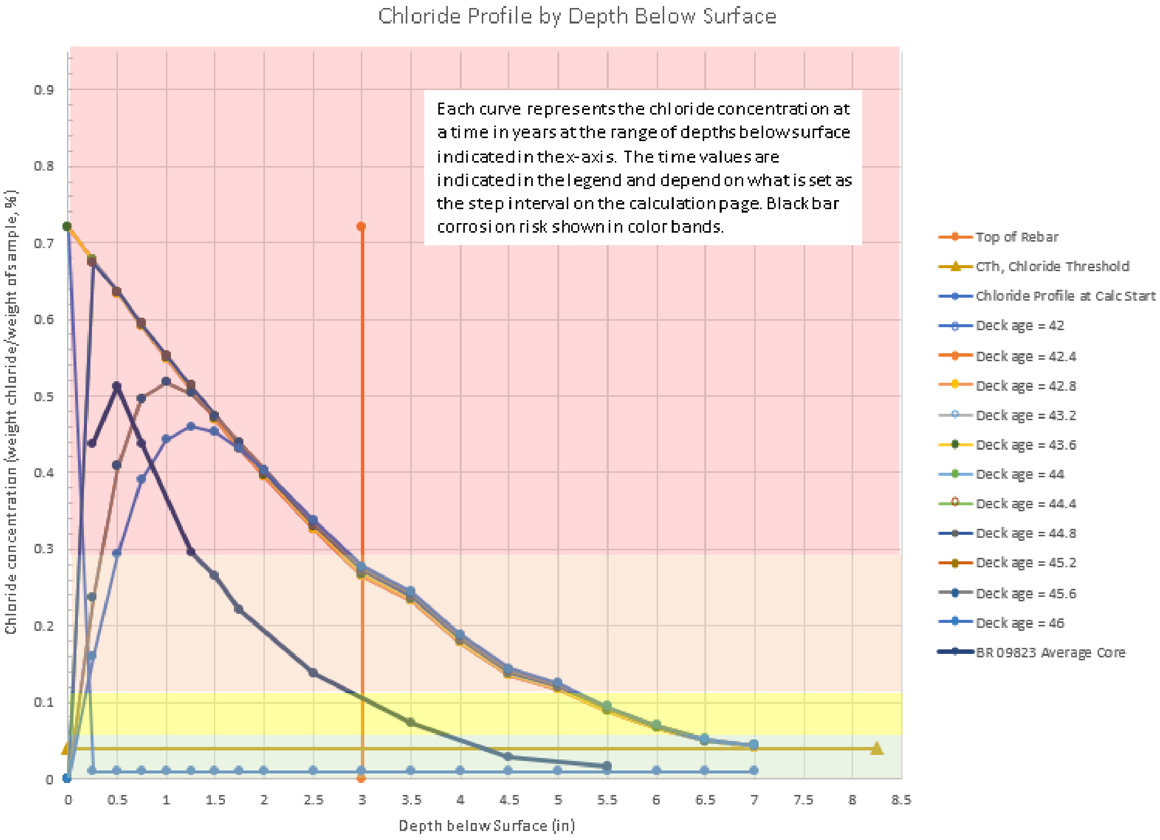
Figure D.3.14: Default input on the Chloride Profile tab for inputting chloride levels inherent to the 1965 mix placement.



Decayed monolithic slab diffusion coefficient, “mean apparent diffusion coefficient”= 2.62E-12 m^2/s or 2.27E-07 m^2/s

Decayed w.c. diffusion coefficient, “mean apparent diffusion coefficient”= 1.68E-12 m^2/s or 1.45E-07 m^2/day

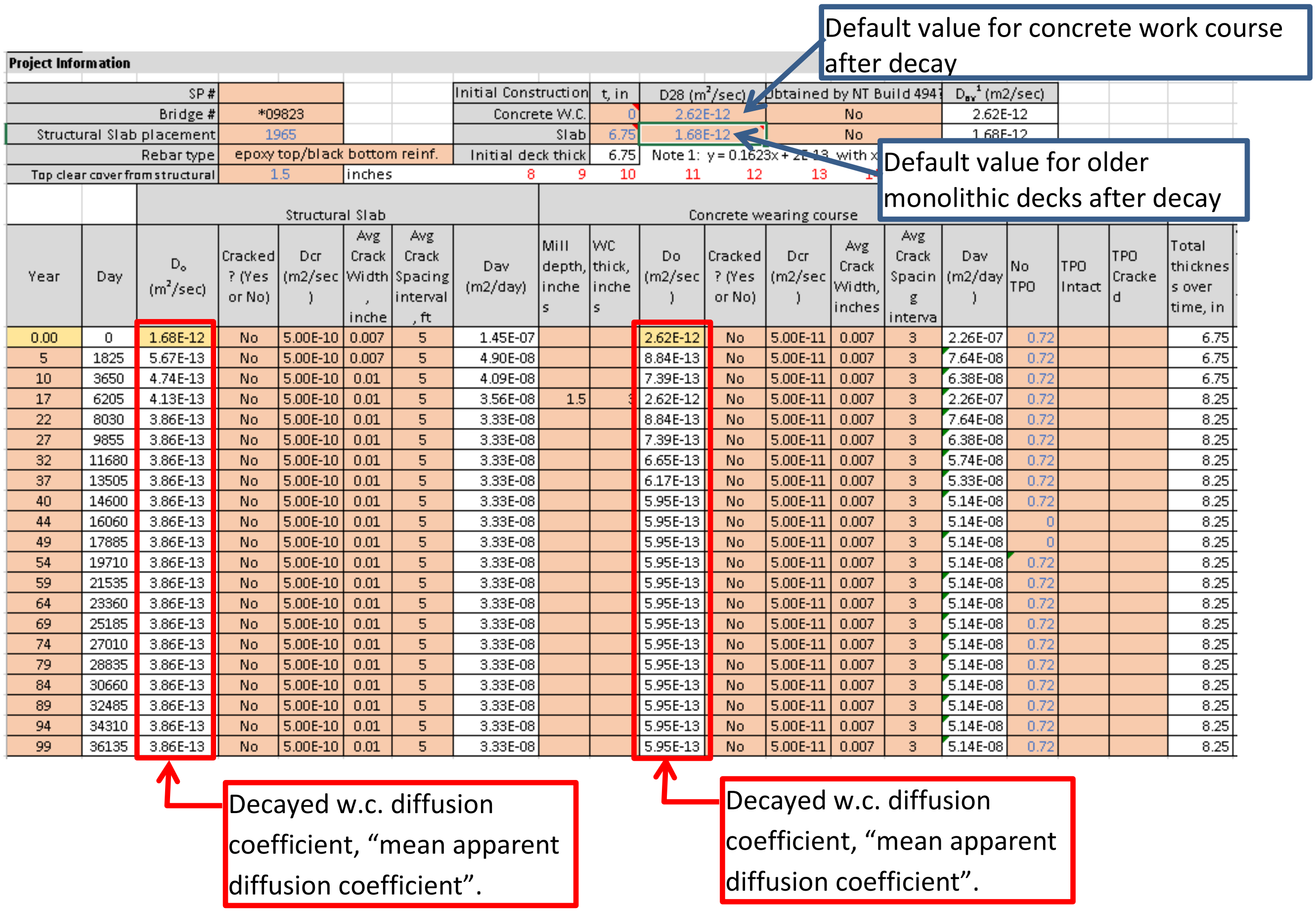
Figure D.3.15: Diffusion coefficient assuming decay over time to the recommended values.



Each curve represents the chloride concentration at a time in years at the range of depths below surface indicated in the x-axis. The time values are indicated in the legend and depend on what is set as the step interval on the calculation page. Black bar corrosion risk shown in color bands.

Figure D.3.16: Diffusion coefficient assuming decay over time to the recommended diffusion coefficient values.

The General Inputs of Figure D.3.12 results in a predicted chloride profile shown in Figure D.3.16. As can be seen, using high initial diffusion coefficients that eventually decay to the recommended diffusion coefficient values yields a poor correlation to chloride profile averages obtained at year 45. The next Figure (Figure D.3.17) shows input of the recommended values as starting values, with decay subsequently occurring on those values. This input will be used to demonstrate the other extreme of diffusion coefficient input. Figure D.3.15 shows the predicted chloride profile versus depth in year 45 as a result.



Default value for concrete work course after decay

Default value for older monolithic decks after decay

Project Information

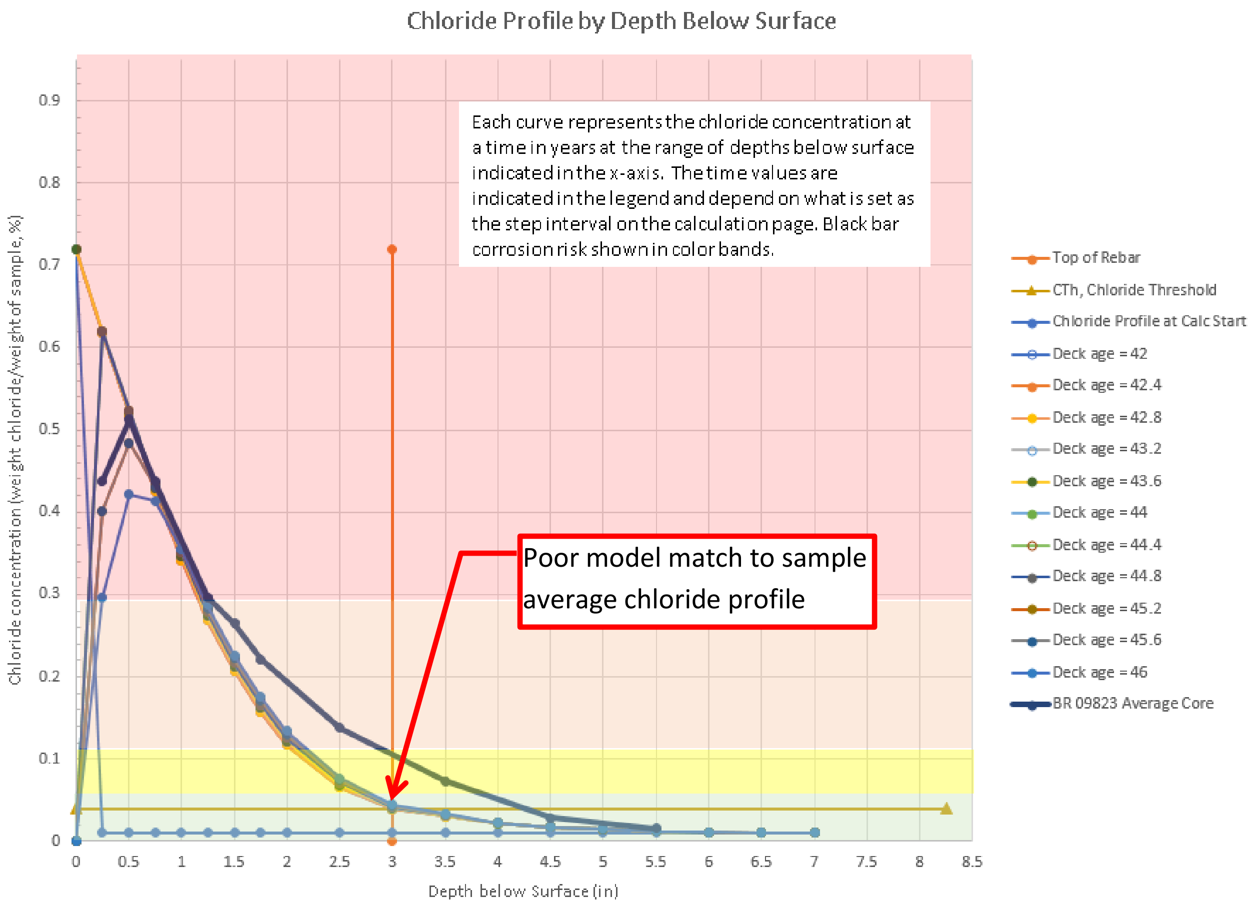
SP #			Initial Construction	t, in	D28 (m^2/sec)	Obtained by NT Build 494?	D_{av}^1 (m2/sec)
Bridge #	*09823		Concrete W.C.	0	2.62E-12	No	2.62E-12
Structural Slab placement	1965		Slab	6.75	1.68E-12	No	1.68E-12
Rebar type	epoxy top/black bottom reinf.		Initial deck thick	6.75	Note 1: y = 0.1623x + 2E-13 with x		
Top clear cover from structural	1.5	inches	8 9	10	11	12	13

		Structural Slab						Concrete wearing course											
Year	Day	D_o (m^2/sec)	Cracked ? (Yes or No)	Dcr (m2/sec)	Avg Crack Width , inche	Avg Crack Spacing interval , ft	Dav (m2/day)	Mill depth, inches	WC thick, inches	Do (m2/sec)	Cracked ? (Yes or No)	Dcr (m2/sec)	Avg Crack Width, inches	Avg Crack Spacing interva	Dav (m2/day)	No TPO	TPO Intact	TPO Cracked	Total thickness over time, in
0.00	0	1.68E-12	No	5.00E-10	0.007	5	1.45E-07			2.62E-12	No	5.00E-11	0.007	3	2.26E-07	0.72			6.75
5	1825	5.67E-13	No	5.00E-10	0.007	5	4.90E-08			8.84E-13	No	5.00E-11	0.007	3	7.64E-08	0.72			6.75
10	3650	4.74E-13	No	5.00E-10	0.01	5	4.09E-08			7.39E-13	No	5.00E-11	0.007	3	6.38E-08	0.72			6.75
17	6205	4.13E-13	No	5.00E-10	0.01	5	3.56E-08	1.5	3	2.62E-12	No	5.00E-11	0.007	3	2.26E-07	0.72			8.25
22	8030	3.86E-13	No	5.00E-10	0.01	5	3.33E-08			8.84E-13	No	5.00E-11	0.007	3	7.64E-08	0.72			8.25
27	9855	3.86E-13	No	5.00E-10	0.01	5	3.33E-08			7.39E-13	No	5.00E-11	0.007	3	6.38E-08	0.72			8.25
32	11680	3.86E-13	No	5.00E-10	0.01	5	3.33E-08			6.65E-13	No	5.00E-11	0.007	3	5.74E-08	0.72			8.25
37	13505	3.86E-13	No	5.00E-10	0.01	5	3.33E-08			6.17E-13	No	5.00E-11	0.007	3	5.33E-08	0.72			8.25
40	14600	3.86E-13	No	5.00E-10	0.01	5	3.33E-08			5.95E-13	No	5.00E-11	0.007	3	5.14E-08	0.72			8.25
44	16060	3.86E-13	No	5.00E-10	0.01	5	3.33E-08			5.95E-13	No	5.00E-11	0.007	3	5.14E-08	0			8.25
49	17885	3.86E-13	No	5.00E-10	0.01	5	3.33E-08			5.95E-13	No	5.00E-11	0.007	3	5.14E-08	0			8.25
54	19710	3.86E-13	No	5.00E-10	0.01	5	3.33E-08			5.95E-13	No	5.00E-11	0.007	3	5.14E-08	0.72			8.25
59	21535	3.86E-13	No	5.00E-10	0.01	5	3.33E-08			5.95E-13	No	5.00E-11	0.007	3	5.14E-08	0.72			8.25
64	23360	3.86E-13	No	5.00E-10	0.01	5	3.33E-08			5.95E-13	No	5.00E-11	0.007	3	5.14E-08	0.72			8.25
69	25185	3.86E-13	No	5.00E-10	0.01	5	3.33E-08			5.95E-13	No	5.00E-11	0.007	3	5.14E-08	0.72			8.25
74	27010	3.86E-13	No	5.00E-10	0.01	5	3.33E-08			5.95E-13	No	5.00E-11	0.007	3	5.14E-08	0.72			8.25
79	28835	3.86E-13	No	5.00E-10	0.01	5	3.33E-08			5.95E-13	No	5.00E-11	0.007	3	5.14E-08	0.72			8.25
84	30660	3.86E-13	No	5.00E-10	0.01	5	3.33E-08			5.95E-13	No	5.00E-11	0.007	3	5.14E-08	0.72			8.25
89	32485	3.86E-13	No	5.00E-10	0.01	5	3.33E-08			5.95E-13	No	5.00E-11	0.007	3	5.14E-08	0.72			8.25
94	34310	3.86E-13	No	5.00E-10	0.01	5	3.33E-08			5.95E-13	No	5.00E-11	0.007	3	5.14E-08	0.72			8.25
99	36135	3.86E-13	No	5.00E-10	0.01	5	3.33E-08			5.95E-13	No	5.00E-11	0.007	3	5.14E-08	0.72			8.25

Decayed w.c. diffusion coefficient, “mean apparent diffusion coefficient”.

Decayed w.c. diffusion coefficient, “mean apparent diffusion coefficient”.

Figure D.3.17: Trial using the recommended diffusion coefficient values as the initial diffusion coefficients.

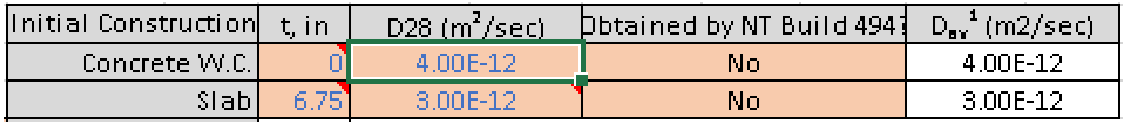


Each curve represents the chloride concentration at a time in years at the range of depths below surface indicated in the x-axis. The time values are indicated in the legend and depend on what is set as the step interval on the calculation page. Black bar corrosion risk shown in color bands.

Poor model match to sample average chloride profile

Figure D.3.18: Chloride profile prediction using recommended diffusion coefficient values as starting diffusion coefficient values.

Reviewing Figure D.3.18, the prediction shows less penetration and lower chloride profile as compared to the sampling. Therefore the input coefficients are incorrect and unconservative. Some iteration is required to achieve a match. It can be seen that at depths greater than 1.5-inches there is too low a chloride concentration. Deeper chloride profile correlation requires changing both the concrete wearing course and structural slab diffusion coefficients. An increase structural slab diffusion coefficient alone will result in higher levels of deeper chlorides but the shape of the chloride profile may not always provide a good match. After several iterations, the chloride profile was best matched by the coefficients given in Figure D.3.19 and modeling results shown in Figure D.3.20.



Initial Construction	t, in	D28 (m^2/sec)	Obtained by NT Build 494	D_{av}^{1} (m2/sec)
Concrete W.C.	0	4.00E-12	No	4.00E-12
Slab	6.75	3.00E-12	No	3.00E-12

Figure D.3.19: Final coefficients determined from trial and error, matching the chloride prediction to the average chloride profile. The effects are shown in Figure D.3.13.

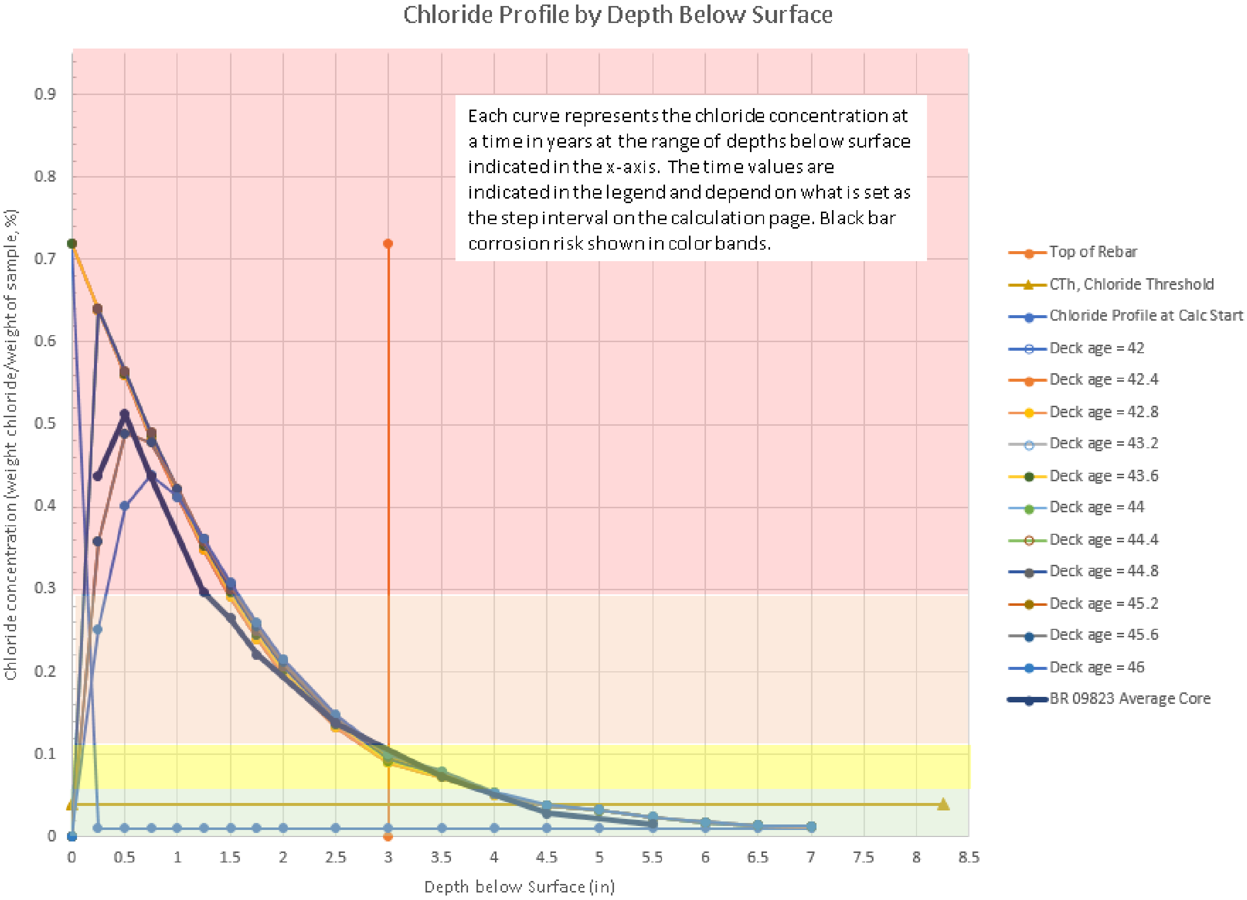
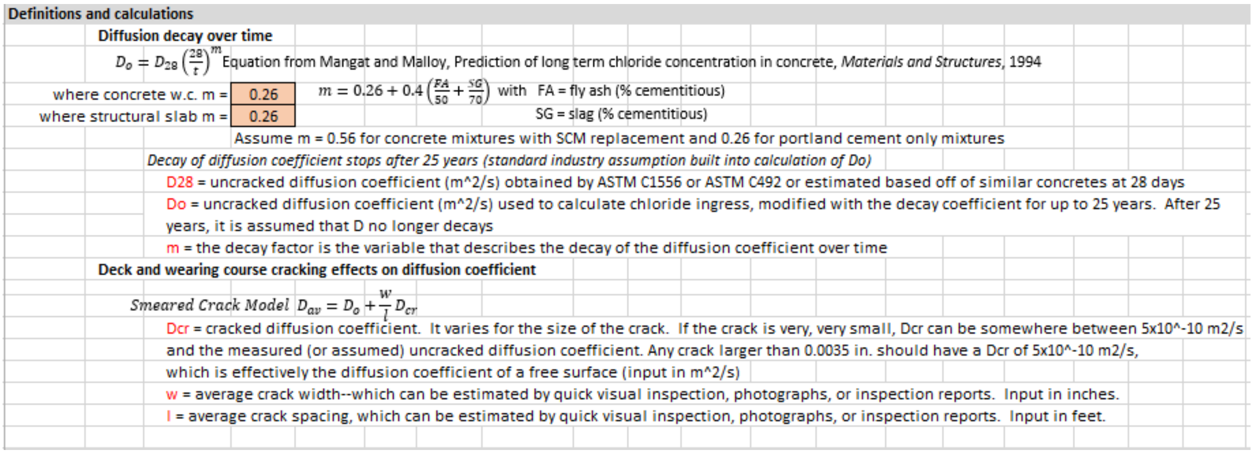


Figure D.3.20: Chloride profile prediction to the average chloride profile using coefficients from Figure D.3.16.

The model prediction was determined to be the best match because of the similarity in curve shape at the deeper levels as well as the match at the rebar level. Within the upper 2" of depth, there is deviation. However, this is deemed conservative and yields the best correlation at the rebar level which is of primary importance. Note that there is some uncertainty at this time on the right value to use for initial low slump concrete wearing course placements. It is thought that an initial value of 2.62E-12 m^2/s should be used for the concrete wearing course 28-day diffusion coefficient but sampling in late 2018 may reveal different recommendations. Having best determined a match, one can predict forward for future preservation activities.

Throughout this example the standard decay coefficient of m=0.26 was used, as seen in Figure D.3.21. Figure D.3.22 shows the plot parameters of year input and thickness increment used in order to create model-predicted chloride profiles near the time of the chloride profile sampling. Calibration from 2010 to 2014 chloride profiles is desired, so a narrow plotting range is selected around year 47.



Definitions and calculations

Diffusion decay over time

$D_o = D_{28}\left(\frac{28}{t}\right)^m$ Equation from Mangat and Malloy, Prediction of long term chloride concentration in concrete, *Materials and Structures*, 1994

where concrete w.c. m = 0.26 $m = 0.26 + 0.4\left(\frac{FA}{50} + \frac{SG}{70}\right)$ with FA = fly ash (% cementitious)

where structural slab m = 0.26 SG = slag (% cementitious)

Assume m = 0.56 for concrete mixtures with SCM replacement and 0.26 for portland cement only mixtures

Decay of diffusion coefficient stops after 25 years (standard industry assumption built into calculation of Do)

D28 = uncracked diffusion coefficient (m^2/s) obtained by ASTM C1556 or ASTM C492 or estimated based off of similar concretes at 28 days

Do = uncracked diffusion coefficient (m^2/s) used to calculate chloride ingress, modified with the decay coefficient for up to 25 years. After 25 years, it is assumed that D no longer decays

m = the decay factor is the variable that describes the decay of the diffusion coefficient over time

Deck and wearing course cracking effects on diffusion coefficient

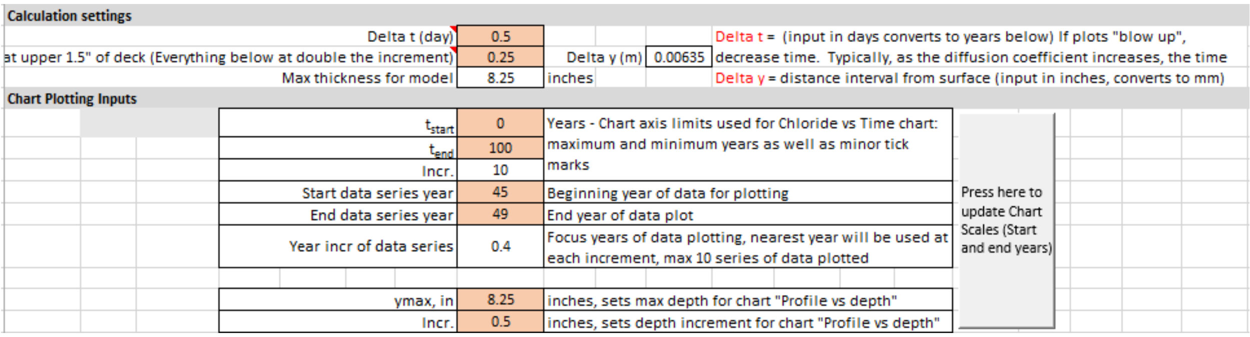
Smeared Crack Model $D_{av} = D_o + \frac{w}{l} D_{cr}$

Dcr = cracked diffusion coefficient. It varies for the size of the crack. If the crack is very, very small, Dcr can be somewhere between 5x10^-10 m2/s and the measured (or assumed) uncracked diffusion coefficient. Any crack larger than 0.0035 in. should have a Dcr of 5x10^-10 m2/s, which is effectively the diffusion coefficient of a free surface (input in m^2/s)

w = average crack width--which can be estimated by quick visual inspection, photographs, or inspection reports. Input in inches.

l = average crack spacing, which can be estimated by quick visual inspection, photographs, or inspection reports. Input in feet.

Figure D.3.21: Decay coefficient input at start of modeling.



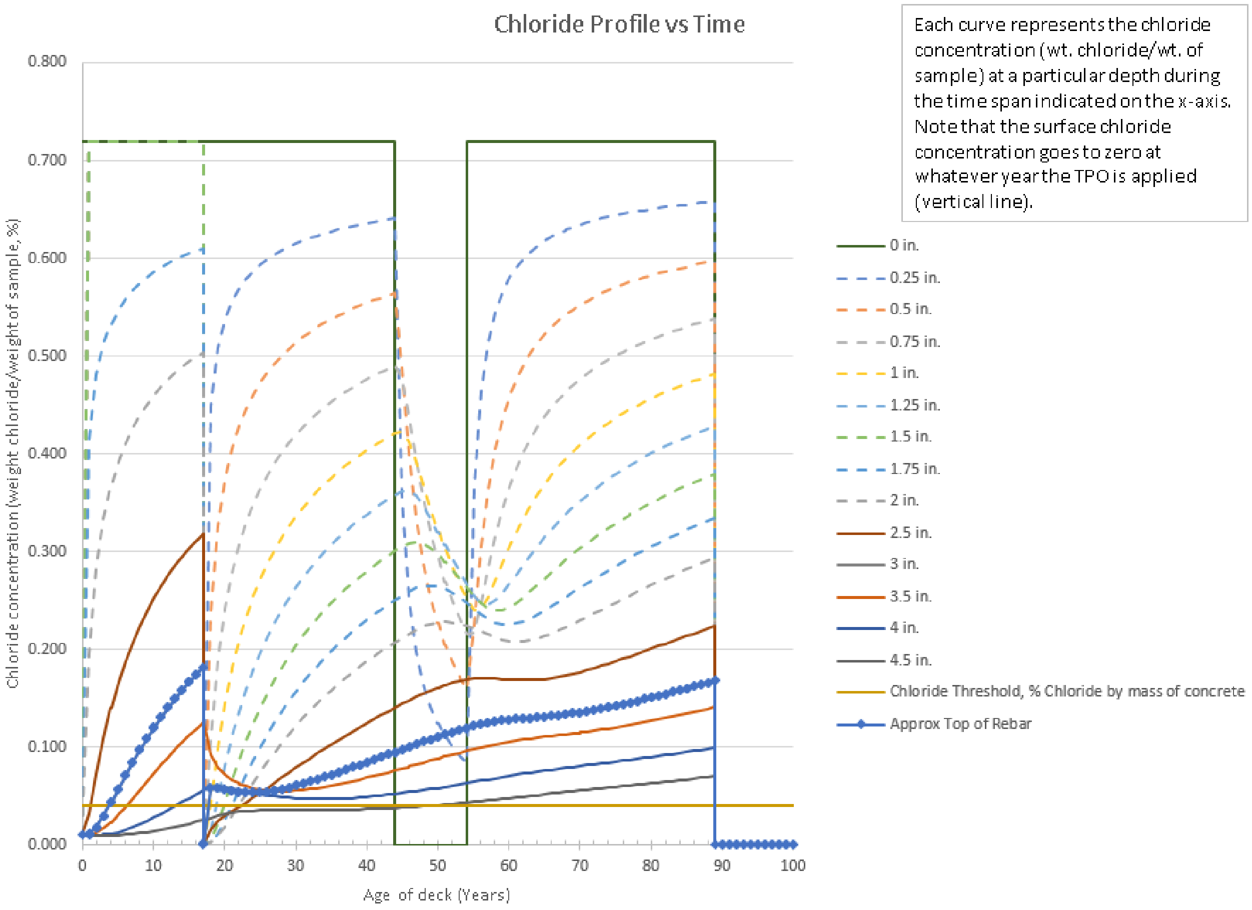
Calculation settings

Delta t (day)	0.5			Delta t = (input in days converts to years below) If plots "blow up",
at upper 1.5" of deck (Everything below at double the increment)	0.25	Delta y (m)	0.00635	decrease time. Typically, as the diffusion coefficient increases, the time
Max thickness for model	8.25	inches		Delta y = distance interval from surface (input in inches, converts to mm)

Chart Plotting Inputs

t_{start}	0	Years - Chart axis limits used for Chloride vs Time chart: maximum and minimum years as well as minor tick marks
t_{end}	100	
Incr.	10	
Start data series year	45	Beginning year of data for plotting
End data series year	49	End year of data plot
Year incr of data series	0.4	Focus years of data plotting, nearest year will be used at each increment, max 10 series of data plotted
ymax, in	8.25	inches, sets max depth for chart "Profile vs depth"
Incr.	0.5	inches, sets depth increment for chart "Profile vs depth"

Figure D.3.22: Model plotting range selection. The data series years for generating chloride versus depth plots was centered on the 2012 date (47 years) of coring and sample analysis.



Each curve represents the chloride concentration (wt. chloride/wt. of sample) at a particular depth during the time span indicated on the x-axis. Note that the surface chloride concentration goes to zero at whatever year the TPO is applied (vertical line).

Figure D.3.23: Chloride prediction over time using calibrated diffusion coefficients. The sharp cutoff in year 17 is due to the mill that occurred in that year. The 10 year gap around year 44 shows the TPO that was added. The dark blue line is the top rebar level.

Looking at the chloride versus time plot we can see that the chloride concentration for the rebar passes through the chloride threshold within the first ten years. This is due to the apparent high surface chloride loading and the relatively shallow 1.5-inch top concrete cover with original construction. It may be confusing to discuss 1.5-inch rebar cover but be observing the rebar at 3-inches horizon. Recall that the 1.5-inch rebar cover does not necessarily equate to 1.5-inch in the model. The 1.5-inch milling and addition of the 3-inch concrete wearing course places the rebar depth at 3” through the life of the model. During the first 17 years when there is only 1.5-inch concrete cover, the upper 1.5-inches is considered air and equivalent to the surface chloride loading.

The 1.5-inch milling at year 17 strips the chlorides to the top of the rebar level. The resultant chloride plot at top of rebar may not be realistic since the plot appears to be capturing the exact bottom of milling as equal to the top of rebar. Much of the chlorides would still be trapped around the rebar after the milling. One can observe the deeper 3.5-inch horizon to see the general trend in chloride profile. The chloride level at the rebar seems to be ever increasing after the milling and wearing course placement. This behavior is realistic because the embedded chlorides were never removed at the level of the rebar.

Based on the model chloride predictions and 2010 – 2014 chloride profiles, adding the TPO in 2009 would not be a good programmatic decision for long-term perpetuation of the bridge deck. The logic is that a TPO may blunt the chlorides, but the levels are already too high to prevent widespread corrosion even with reduced moisture in the deck. Such dire predictions are based on traditional interpretation of the chloride levels. This bridge remains in service as of this 2018 report and the TPO, although showing 9% delamination in 2012, has remained unchanged as of the 2016 inspection report. There is light staining on the underside, and some cracks in the TPO, but generally the bridge remains serviceable. The District as an asset owner is starting to consider replacing the deck within 10 years. Had the TPO not been applied, the deterioration may have progressed more rapidly but the rate would be difficult to predict.

Figure D.3.24: Photos of TPO surface taken July 2018.

Figure D.3.25: Photos of deck underside (1965 deck) taken in July 2018.

Figure D.3.26: Photos of deck underside (1965 deck) taken in July 2018.

Eight cores are planned to be obtained this fall to review the chloride redistribution within the deck after 9 years with the TPO. These cores and corresponding chloride profiles may also provide good data on the corrosion rate in northern climates and after surface moisture is cutoff. It is believed that the good performance of the TPO is due to the 3-inch low slump wearing course, which is a very dense high-cement mix. The low-slump wearing course provides a solid load distribution slab and may not show the effects of reinforcement corrosion below.

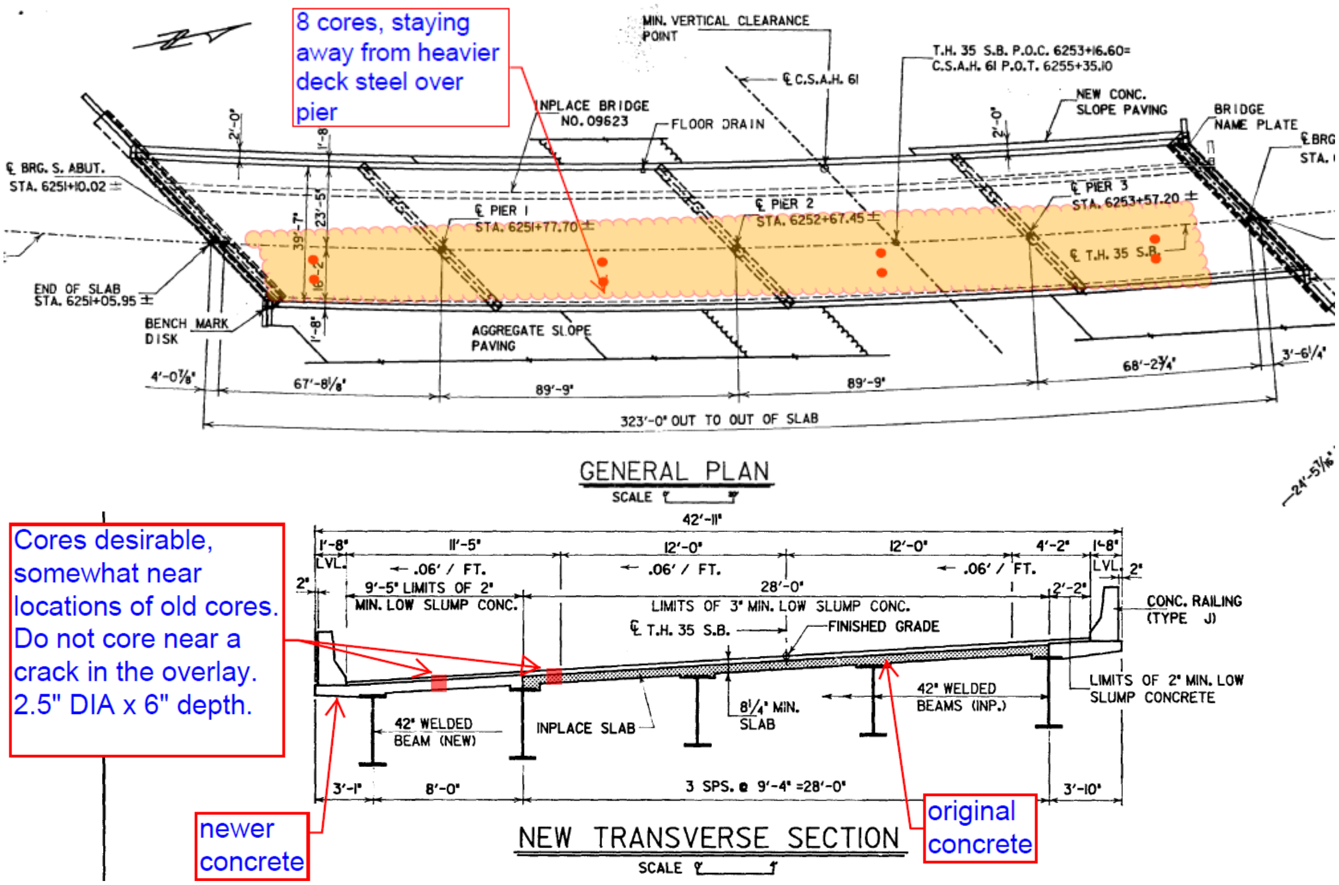


Figure D.3.27: Proposed 2018 coring locations.