Bridge Deck Chloride Testing Guide

AASHTO TSP-2 Program

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Executive Summary

This guide was developed by the Bridge Deck Chloride Testing Working Group as part of the Bridge Preservation Partnership under the AASHTO TSP-2 Program. The working group was composed of members from the 4 regional partnerships which have contributions from Industry, Academia, FHWA and State Department of Transportation members. The guide is intended to assist both owners and industry as a means of providing consistency in how concrete bridge decks are sampled for chloride contamination.

Owners are constantly challenged to identify cost effective actions to maximize the benefit of limited budgets to maintain an aging infrastructure. The Bridge Preservation Partnership identified the deck as the highest risk component of the structure for deterioration. As such, owners are placing an emphasis on preservation projects to maximize the service life and delay costly rehabilitation projects. Detecting chloride contamination is a key component of deciding when a preservation action for the deck should take place.

Although it is widely accepted that chloride testing is a valuable component of bridge deck preservation, there is little consistency throughout the United States in how bridges are selected for sampling or how the sampling is performed. The Bridge Deck Chloride Working Group was specifically formed to address this issue.

The report is setup to help assist owners with developing a chloride testing program. The first chapter covers background in preservation vs. rehabilitation and an overview of factors that impact chloride induce corrosion.

The second chapter covers network level screening where bridges are strategically identified for testing. Emphasis is placed on structures of high value and obtaining information when preservation can still be effective. Because it isn't economical to test the entire inventory, guidance is provided on how to extrapolate test information to other structures.

The third chapter introduces project level considerations. Project level decisions include how many samples are to be collected and how those samples are obtained. A discussion of different sampling techniques, frequency and locations is presented along with the associated risks.

The final chapter gives an overview of ASTM and AASHTO testing methods for obtaining the chloride diffusion profile and some general guidance on how to proceed with the test results. Linking specific actions to results was beyond the scope of work and is left to the judgement of the owner.

The user is directed to the Appendices for example projects, a boiler plate statement of work for chloride sample collection and testing, and a method for quantify the relative risk for chloride sampling for use at then network level.

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1.0 Overview

The primary concern with chloride exposure of reinforced and prestressed concrete elements is the occurrence of reinforcement corrosion. However, chlorides can also contribute to other forms of deterioration, such as freezing-and-thawing damage to concrete. The purpose of this guide is to provide a general review of bridge deck chloride sampling strategies and methods, and provide basic guidance on interpretation and use of the resulting information. The reader is provided a general understanding of how chlorides cause deck deterioration and impact service life

1.1 Preservation vs Rehabilitation

Bridge projects fall within three categories; replacement, rehabilitation, and preservation. Limited funding levels and performance measures focused on structurally deficient bridges have historically pushed agencies to focus on the worst bridges in the inventory. This has been coined the “Worst-First” asset management strategy. Although a worst-first strategy is understandable, it is also highly inefficient. This was recognized by the Federal Highway Agency (FHWA) in the Moving Ahead for Progress in the 21st Century Act (MAP-21) and the Fixing America’s Surface Transportation (FAST) Act. These Acts recognized the benefit of preservation and made many preservation actions eligible for federal funding.

Bridge replacements and rehabilitations are the most expensive actions. However, these actions do result in significant improvements in the bridge condition ratings. Owners that want to show increasing bridge conditions will be tempted to focus funding on poor condition bridges in an effort to highlight the immediate improvements in the inventory. Preservation actions are low cost and cause low impact to the traveling public. Although the preservation actions have been shown to extend the service life of bridges, it doesn’t usually result in an improvement in the bridge condition. This is a real challenge as owners try to quantify the benefit of preservation. The benefit of preservation is easy to grasp, but quantifying it can be a challenge.

The bridge deck is typically the highest value component of a bridge. It is also subjected to the most destructive conditions as it is not only exposed to the environment (rain, snow and ice, deicers) but it also exposed to vehicles which cause impact and wear. The bridge deck is also the most visible bridge component to the traveling public.

Deck rehabilitation is the only option if deterioration is allowed to reach significant levels. The bridge deck shown in Figure 1 is an example of one that has reached the stage of needing major rehabilitation. Rehabilitation projects require long term traffic disruption leading to staging expenses and additional costs to the public (congestion, local businesses, etc.). It is common for half the total project cost to go traffic staging. The high cost of deck rehabilitation will often push a project to a full bridge replacement. Historically, chloride sampling has been focused on bridge decks that resemble the ones in Figure 1. For rehabilitation projects it is useful to know what the chloride concentration vs. depth profile looks like. But regardless of the results, a rehabilitation is still required.

Figure 1: Damage in a Bridge Deck

Deck preservation projects should focus on bridge decks in good condition. Normally, these decks wouldn't be considered in a worst-first asset management plan and historically haven't been a focus for additional condition investigation. Realizing the benefits of preservation, agencies are shifting their focus towards bridges in good condition where they are able to get better returns on investments. Figure 2 is an example of a deck that, although shows signs of cracking, is still categorized as being in good condition. Decks like the one shown in Figure 2 are great candidates for preservation.

Figure 2: Deck with minor cracking

Chlorides are a major factor that cause decks to deteriorate to the point of requiring rehabilitation. If chloride levels are allowed to reach the threshold for corrosion at the surface of reinforcement (conventional and prestress) or other embedded ferrous materials, then repair options become limited. If an owner can identify when chloride levels are nearing threshold concentrations at the steel depth, then corrective and preventative measures can be taken to extend a deck's service life.

1.2 Factors that Impact Chloride Corrosion

1.2.1 Introduction:

Steel embedded in high-pH concrete is typically protected from corrosion due to the formation of a passive oxide film around the steel. However, this passive film can be compromised if pH of the cement is lowered, or if sufficient chloride content accumulates around the reinforcement. Once the film breaks down, corrosion of the steel initiates. In addition to section losses of the reinforcement, corrosion product typically expands 4 to 6 times the volume of the original steel, leading to internal stresses in the concrete. Once sufficient corrosion product has accumulated, the concrete cracks, delaminates, and eventually spalls. Chloride-induced corrosion and resulting concrete damage is the most common form of deterioration in reinforced concrete structures exposed to deicing salts or marine environments. Most deicing materials contain chloride; the most common forms being calcium chloride ($CaCl_2$), sodium chloride (NaCl) or magnesium chloride ($MgCl_2$).

When a bridge deck is exposed to a source of chlorides (cyclic or constant exposure), the chlorides will diffuse into the concrete over time. There are actually several physical mechanisms of chloride transport through the cement paste portion of concrete, including flow of solution into cracks, capillary action within the paste's pore structure, and other modes of moisture movement. However, over the long term, the mechanism that most closely reflects transport of chloride through concrete is diffusion caused by concentration gradients, wherein physics drives toward achieving equilibrium, or equal concentration, through the depth of the concrete. A significant degree of concrete saturation (>50%) is necessary to support continued diffusion but concrete is rarely dry enough in exterior deck exposures to prevent it, unless completely sealed by a membrane.

The concentration increases first at the surface, moving deeper over time. As chlorides diffuse through the deck, the chloride concentration at the reinforcement level increases. Once a critical threshold is reached, corrosion can initiate, leading to reinforcement section losses and attendant concrete damage. A number of factors impact the rate of chloride diffusion, time to corrosion initiation, and the rate of corrosion/concrete damage once corrosion initiates. It is important to consider each factor when evaluating bridge decks, as a change in one or more of them can significantly impact the life of the bridge deck.

1.2.2 Environmental:

The chloride concentration at the surface of the concrete and the time and frequency of exposure drive the diffusion of chlorides into the concrete. For a fixed concrete quality, a higher surface concentration will lead to a higher rate of diffusion.

There are different types of exposures that may affect chloride contamination levels in concrete. Bridges may be exposed to salt/brackish water (submerged, tidal zone, splash zone), salt spray, liquid deicing salts (salt brine), pre-wet sodium chloride, or dry deicing salt (rock salt). Anti-icing liquids, such as magnesium chloride solution, may readily soak into concrete and significantly increase the chloride concentrations. Thus, bridges can have varying levels of chloride contamination even within the same region, or different areas of the same structure. Cyclic exposure actually leads to greater rate of penetration than constant exposure because of the capillary action that occurs when salt-laden water comes into contact with concrete after a dry period. Therefore, liquid applications could pose greater risk to bridge decks than dry deicers.

For a structure in a marine environment, the chloride exposure may be relatively constant. For decks exposed to deicing salts, chloride exposure may be limited to the winter months. Deicing salt application will vary from year to year, but chloride concentration just below the surface (approximately ½ inch) will increase relatively steadily and eventually become relatively constant over a longer time period (i.e., after the first 5 to 10 years).

The average temperature, quantity of frozen precipitation, and number of days below freezing are surrogate indicators for the amount of deicing salts applied to a bridge. For example, in colder upper Midwestern climates, significantly greater salt loading can occur each year compared to the lower Mid-Atlantic regions. Temperature and humidity will also affect the rate of corrosion once chloride concentrations at the reinforcing steel exceed the critical threshold.

1.2.3 Physical:

One of the most important factors that affects the time to corrosion is reinforcement cover. Increasing the concrete clear cover over the reinforcing steel increases the time to corrosion initiation since the chlorides must diffuse through more concrete. This is one of the easiest factors that a designer can control to meet the specified design life. However, it should be noted that many factors can result in concrete cracking which compromises the benefit of additional reinforcement cover. Common causes of concrete cracking include; subsidence, restrained concrete shrinkage, and negative moment in the deck, or other structurally-induced stresses. Minimum cover is critical, but having too much cover-depth can allow for more cracking due to shrinkage, which negates the benefits of the deeper cover-depth.

Another way to prevent corrosion is to create a barrier between chlorides and steel. Epoxy-Coated Rebar (ECR) attempts to do this by providing a layer of fusion-bonded epoxy to the outer surface of the reinforcing steel that is meant to serve as both a physical barrier to salts and an electrical barrier to electrochemical current flow. In an ideal scenario, the coating prevents contact between the steel and chloride-contaminated concrete. However, manufacturing defects and damage during handling or installation frequently create isolated holes in the coating where corrosion can initiate. At defects or holidays, corrosion occurs at the same chloride concentration threshold as uncoated black bar. However, the coating may prevent or slow widespread corrosion, thereby delaying the onset of corrosion-related concrete damage by several years. If using a corrosion initiation limit state (i.e., predicting the time to corrosion initiation, but not the subsequent propagation phase), ECR is considered by some engineers to have no effect on the service life. This is often done because no validated mechanistic model exists to predict the time of propagation from corrosion initiation to damage sufficient to cause end of useful service life.

The prevention of water and chlorides from entering the concrete can also greatly extend the time to, or prevent, corrosion initiation. Waterproofing membranes, thin epoxy overlays, sealers, and the like prevent or slow water from entering the concrete. Their efficacy and service life depend on the quality of materials and application. These types of membranes eventually develop localized defects that allow the intrusion of chlorides. Various wearing surface overlays may not be waterproof, but may still reduce the exposure of the substrate concrete to chlorides and water, thereby extending the service life. (Oregon has experience with membranes for bridge decks that have a few applications of deicer per year; Virginia routinely applies thin epoxy overlays to relatively young decks to prevent chloride ingress for 15 years or more).

In areas subject to snow and icy weather, runoff water from the deck carries deicing salts in the winter. It is important to carefully control drainage and direct away from substructure elements. If drain pipes or expansion joints allow deck runoff water to leak onto the substructure, this will lead to chloride-induced corrosion in these areas as well. This greatly reduces the life of substructure elements. By simply diverting drain water effectively, the chloride exposure of the substructure can be greatly reduced.

It should be noted that stay-in-place forms on the underside of decks serve as a trap for moisture in the deck. This can influence the rate of diffusion and the subsequent rate of corrosion by ensuring relatively high moisture levels in the concrete during all seasons. Stay-in-place forms may also serve to mask corrosion damage that may be occurring at the bottom layer of reinforcement.

Cracks in the surface of the concrete (due to shrinkage, ASR, settlement, or other causes) provide a more direct path for chlorides to reach the reinforcement. Any surface-opening crack will reduce the life of concrete elements exposed to chlorides, unless sealed. The service life of cracked members depends on the prevalence, width and depth of cracking. Cracks greater than about 0.005 inch in width should be sealed. Moving structural cracks may be more difficult to address, as sealants may not remain intact, unless they are made up of highly flexible materials, such as silicone. Surface treatments, such as a low viscosity, high molecular weight methyl methacrylate (MMA) have been used effectively to treat large areas of fine cracks, but these material can wear over time and may require periodic retreatment.

1.2.4 Materials:

One of the most influential factors that impact bridge service life is the constituent material properties of both the reinforcement and the concrete. Some materials have a very high resistance to corrosion (e.g., stainless steel or fiber-reinforced polymer reinforcement) or slow/prevent the exposure to deleterious chemicals (e.g., high-performance concrete), as discussed below. Typically, these materials are more expensive than standard construction materials, so they must be used appropriately to balance cost and service life requirements.

1.2.4.1 Reinforcement:

When standard black reinforcing steel (e.g., ASTM A615) is embedded in concrete, it is protected from corrosion by the high alkalinity (pH) of the surrounding cement paste. This high pH forms a stable protective oxide film over the steel surface. This protective film is broken down in the presence of sufficient chloride concentration at the depth of reinforcement. Sacrificial metallic-coated (ASTM A676) or protective organic-coated (ASTM A775) reinforcement may be used to slow the initiation and propagation of corrosion, but the underlying material is typically still mild steel, which will corrode once the barrier coatings are breached. Certain types of reinforcement materials can tolerate high levels of chloride contamination in concrete before experiencing corrosion. Micro-alloyed steel (e.g., ASTM

A1035) and stainless steel (e.g., ASTM A955) of various types can tolerate significantly higher chloride concentrations than mild steel reinforcement, and thus can provide significantly more service life for a given exposure. Alternatively, carbon-fiber, glass-fiber reinforced polymers, basalt, and other non-metallic materials may be used in place of steel in certain applications. Owners must consider the mechanical properties and cost versus the service life of each material and select the combination of reinforcement and concrete that provides the required service life at the least life-cycle cost.

1.2.4.2 Concrete:

It is primarily the high alkalinity (pH) of the cement paste that protects steel from corrosion. If the pH is reduced (due to carbonation, for example), the concentration of chloride required to initiate corrosion is also reduced. If the pH drops below a minimum threshold (approximately 9), corrosion can occur even in the absence of chlorides. Carbonation of concrete is typically not a problem for U.S. bridge decks. However, over a 100-year service life, areas of low cover may experience corrosion due to carbonation of the concrete.

The concrete's pH has the largest impact on the concentration of chlorides required to break the passivity and allow for the initiation of corrosion. Older concrete may have lower pH which could result in corrosion initiation at lower chloride levels.

The diffusion rate of chloride through concrete controls the time for chloride concentrations to reach the critical threshold at the depth of the reinforcement. The lower the rate of diffusion, the longer the time to corrosion initiation in a given exposure condition. The following factors affect chloride diffusion rate through concrete by altering the pore structure and formation of the concrete:

- Supplementary Cementitious Materials (SCMs), such as slag, silica fume, or fly ash
- water-cement ratio (or water-cementitious materials ratio where SCMs are used)
- inclusion of latex
- polymer additives
- air entrainment

An indication of relative rates of diffusion of concrete mixtures can be measured by accelerated testing using NT Build 492, ASTM C1556, or similar testing standards. With appropriate planning, designers can adjust the concrete mix design to achieve a specified diffusion rate.

In addition to chlorides that diffuse into the concrete over time, the original concrete mix typically contains a small amount of free chloride in the cement, aggregate, and/or water. Although typically minimal, these chlorides contribute toward reaching the critical chloride threshold at the reinforcement level and should be considered when designing a concrete mix for 100-year service life. In addition, the aggregates can contain bound chlorides that may not have any effect on reaching the critical chloride threshold.

Concrete may be susceptible to other sources of cracking in the form of alkali-silica reactivity (ASR), freeze-thaw (F/T) damage, and delayed ettringite formation (DEF). Cracking provides a shorter path for chloride to reach the reinforcement. This type of deterioration can be avoided by testing aggregate for reactivity before use, selection of appropriate cementitious materials (e.g., low-alkali cements or combinations of SCMs) and ensuring proper air content and curing of the concrete. Mitigation once in service can be more challenging and is beyond the scope of this guide.

2.0 Network Level Chloride Program

It may be desirable for an agency to establish a program of screening their inventory for chloride contamination to aid in service life projection and planning. Screening is necessary to avoid the cost and resources required to sample the entire inventory. A network level sampling program should consider two selection methods; condition-based and importance-based.

If the environment and the salt loading are expected to be the same for a given corridor of bridges, one can select a few bridges of similar design, traffic exposure and vintage (spread throughout the corridor) for in-depth evaluation and then conduct minimal sampling on the other bridges to confirm the findings from the in-depth evaluations. This information, along with the age of the bridges, can be used to develop a matrix of recommendations based on the data collected in the field, results of laboratory analysis, and service life analysis. The repair recommendations can be further ranked based on life-cycle cost of viable repair options that will provide the desired service life. This approach assists owners in managing their assets by supporting informed planning, scheduling, and arranging of budgets for repairs.

2.1 Condition-Based Selection

This methodology focuses on identifying bridge decks that are most likely to have chloride issues based on deck condition and exposure to deicing.

If a bridge deck is showing severe visual defects due to chloride-induced corrosion, especially if the soffit is affected (map cracking, efflorescence, water staining), then conventional patching, sealing, or overlay preservation techniques may no longer be effective. Essentially the problem wasn't caught soon enough. Some level of damage, however, may be effectively addressed through rehabilitation and the use of more invasive and costly preservation treatments (cathodic protection, etc.).

It is not necessary to screen and test bridges that have not been in service for long enough periods to accumulate significant chloride contamination. Depending upon the climate and local winter maintenance policies, it may not be necessary or fruitful to test decks that have been in service for less than 10 to 15 years. Another consideration would be whether or not the bridges in question were constructed with, or had applied shortly after construction, protective systems such as low-slump dense concrete wearing courses, protective polymer overlays or membranes. Such systems may provide 20 years or more of service before being compromised. If any overlay or sacrificial wearing surface shows signs of localized failure due to cracking or loss of bond, then they would be good candidates for evaluation.

Reference Appendix C for a methodology that attempts to develop a qualitative approach to determining if the bridge deck is a good candidate for chloride sampling. The method includes many of the factors discussed below with the goal of separating the population of bridge decks into High, Medium, and Low Risk for deck corrosion.

2.1.1 Current Deck Condition

At the network level it is best to focus on bridge decks that are still candidates for preservation activities. Sampling bridge decks in poor condition is necessary at the project level, but the deck has likely already passed the point of preservation.

The FHWA Bridge Preservation Guide provides useful tools for using condition to identify bridges as candidates for preservation. Sampling bridges in good condition can help time preservation actions to extend the service life before the condition drops requiring rehabilitation. While sampling bridges in fair or poor condition will only help verify the deterioration mechanism but won’t likely change the type of project required.

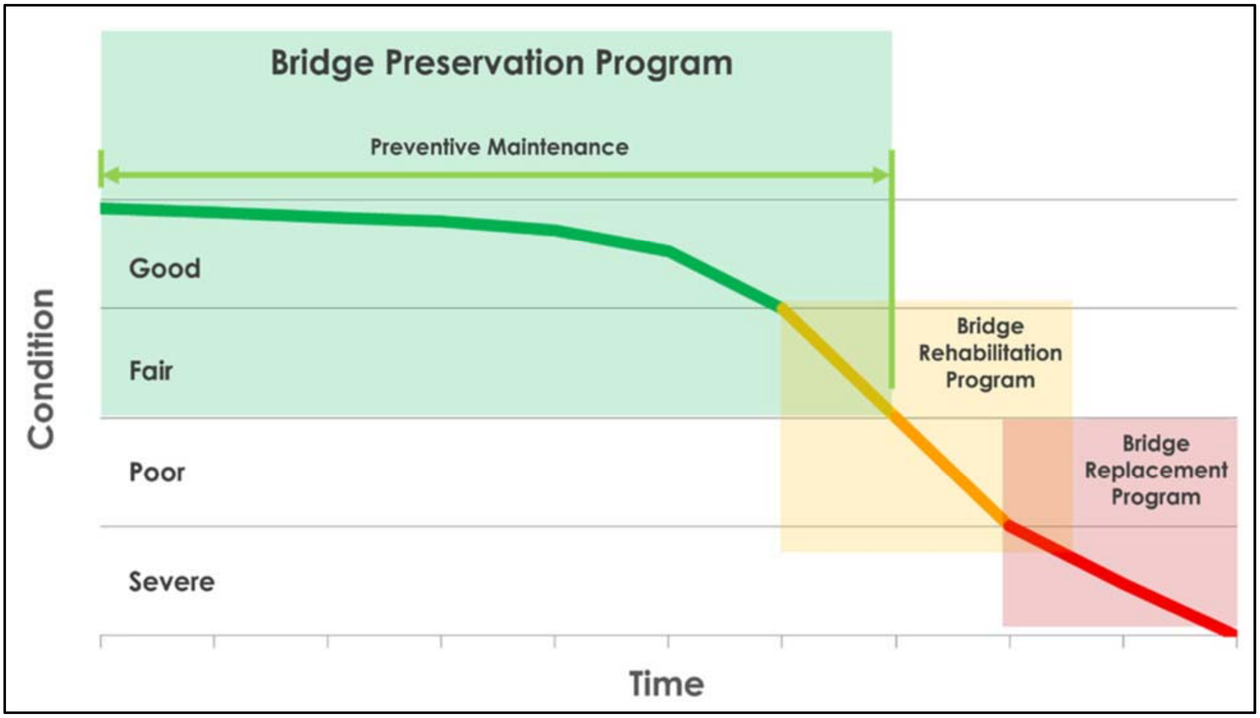


Figure 3: Condition vs Action Graph (Source FHWA Bridge Preservation Guide)

2.1.2 Environment Factors

The environment impacts the bridge deck both directly and indirectly as maintenance practices change in different exposures. Freeze-thaw climates will not only expose the bridge deck to the physical deterioration of those cycles (cracking), but are also likely to be exposed to high levels of salting as maintenance attempts to keep the deck from icing over. Atmospheric deposits are another possible source of chloride contamination. The map in Figure 4 shows that these deposits aren't just limited to the coast. This can be an explanation for minor deck chloride concentrations in locations that don't use deicing salts. It should be noted that atmospheric deposits aren't generally in high enough concentrations to significantly impact the performance of the bridge deck. Bridges that are directly exposed to salt water or ocean spray can have very high chloride exposure and should be carefully considered for monitoring.

When developing a network level sampling program is it important to consider the regional climates and how that climate will vary natural and manmade contaminates.

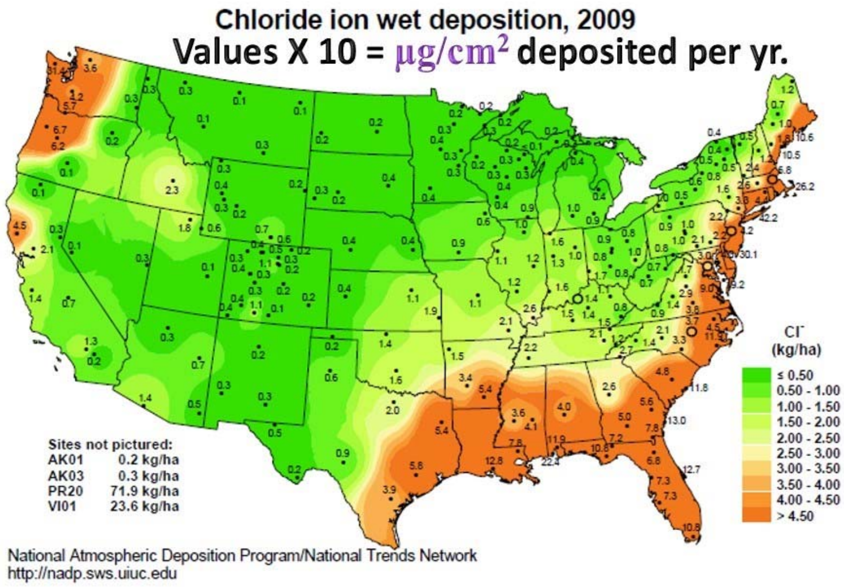


Figure 4: Atmospheric deposition map (http://nadp.sws.uiuc.edu)

2.1.3 Maintenance and Project History Impact:

Maintenance practices can have a large impact on the risk of chloride ingress. For example; regular bridge cleaning and crack sealing will significantly decrease the rate that chlorides will reach the reinforcement level.

When identifying bridges to sample it is important to consider the decks maintenance and project history. Bridges with recent deck rehabilitations are low risk for chloride damage. But sampling should begin before the deck condition starts to deteriorate and preserving the deck is no longer an option.

Care should also be taken in extrapolating results across regions with significantly different maintenance practices. Even bridges in similar climates, details, and age could have significantly different chloride profiles if one region performs regular deck cleaning and sealing while the other does not.

2.2 Importance-Based Selection

System asset management includes consideration of importance. Importance may be separated into functional importance and structural sensitivity to deterioration. Structural sensitivity should consider the following:

- Deck structural importance. The deck is an integral component of concrete box girders and should be given a higher importance for monitoring and protection than girder bridge types.
- Policy implications: Bridge owners may have in place policies that defer load rating and barrier upgrades for bridge preservation activities, but require upgrades should a rehabilitation be implemented. Other policies such as geometric improvements might also be required of a rehabilitation level investment, where the bridge life is expected to be extended beyond 30 years. These upgrades can add significant cost and/or even require bridge replacement.
- Reinforcement type and cover. Corrosion resistant rebar will defer some importance with respect to monitoring chloride levels. Higher cover will enable longer time prior to chlorides reaching the reinforcement.
- Other deck protection measures. Existing membranes and low permeability overlays decrease the need for more frequent chloride monitoring.
- Ability to stage traffic in rehabilitation. If the roadway width does not allow for adequate staging, and significant investment would be required to enable construction, stronger importance is attributed to preservation.
- Ability to detour traffic and average daily traffic per lane. Long detours can be deemed intolerable, forcing heavier expenditures in accelerated construction.

As may be noticed from the above list, there are many parallels between preservation importance and establishing good sites for accelerated bridge construction techniques. Many states have developed screening formulas for identifying bridges that would benefit from accelerated bridge construction. With the addition of concrete box girder bridges, these sites are also sites that would be candidates for establishing higher preservation importance and for which chloride sampling makes the most sense. In short, it is important to invest more heavily in regular preservation intervals for these bridges.

2.2.1 Daily Vehicle Operating Cost

Daily vehicle operating costs is a function of bridge length, Average Daily Traffic (AADT) and Heavy Commercial Average Annual Daily Traffic (HCAADT). In Minnesota, for instance, the formula is stated as follows:

User Cost Formula = (AADT x $0.31/mile + HCAADT x $0.64/mile) x Detour Length x Br Length Factor

Such a user cost can be segmented into a single scalar value for use in ranking bridges that should be weighted more heavily for preservation timing and assessments. In effect, using user costs identifies bridges that comprise important road segments or corridors.

2.2.2 Traffic Factors

AADT and HCAADT information is readily available. Dividing these traffic counts by the available number of lanes, or the roadway width, can signify how heavily relied upon the bridge is for operation. In other words, it signifies the traffic density on the bridge.

In addition to traffic density, the detour length can be determined and given weight. The owner agency would have to assign a weighting to place on detour length and thus the relational importance to the other factors mentioned above.

2.2.3 Bridge Significance

Decks of significant size can drive up deck rehabilitation cost to the point where many agencies simply can't afford to program rehabilitation. Smaller infusions of cost-effective preservative actions should therefore be considered. The timing of preservative actions is important in order to maintain low chloride levels at the level of rebar because once threshold values have been reached there are few cost effective preservation options. It is important, therefore, to not only sample chloride levels in large decks, but also to identify high susceptibility locations and focus efforts. Such sampling will help level budgetary needs in long term asset management.

2.2.4 Key Structural Features:

Concrete box girder bridges are typically supported on falsework until the deck is cured and minimum strength attained. Consequently, deck repairs conducted in the absence of structural support shift internal forces to remaining cross section. Deck patching in minor amounts may be tolerable but should be checked in a structural analysis. Larger sections of deck removals, in particular transverse, can result in stress redistribution, cracking and deformation. Some owners have mandated that concrete box girder repairs be done in longitudinal strips to maintain integrity. While this may be effective from a strain compatibility perspective, a sequential redistribution of stress will nonetheless occur with each strip of deck repairs.

Bridges with negative moment steel in the deck present unique challenges for deck rehabilitations as concrete removal can require falsework. Box girder bridges are of particular challenge as the negative moment steel in the deck may be required to support just the dead load of the adjacent span. Therefore, removal of contaminated deck concrete may cause stability concerns. Because of this staging challenge, these structure types should rank high on a chloride monitoring program

Other structures with similar concerns all have one attribute in common: Some sequence in construction was required to exert an internal stress critical to the deck function. Examples of this concept are post-tensioned decks, prestressed decks or deck panels, and closures pours made while segments had been jacked apart. All of these decks would require some level of care in repair in order to maintain the original design. All of those decks should have an elevated monitoring ranking.

A final but less common structural feature would include its historic classification. Historic bridges traditionally cost more to repair in contract than traditional structures. There is additional defect review time, plan review time, and greater oversight of the entire process through construction. Although historians have generally observed that decks are equivalent to roofs and a maintenance item, the barrier/railings and light features that perch on the deck becomes a point of focus. Barriers and railings can be very difficult to replace in conformance with modern design standards while also maintaining the historic look of the bridge the public observes. Consequently, an agency would be best served to invest more in regular deck preservation activities and chloride monitoring on historic bridges.

2.2.5 Bridge Age and Concrete Quality

In the absence of cracking, concrete quality and overlay permeability hold the key attributes to control chloride penetration. The chloride path begins at the deck surface. If a low permeability overlay is present, very little chlorides may penetrate into the concrete. Membranes, Thin Polymer Overlays (TPOs), and Polyester Polymer Concrete Overlays are amongst the many solutions aimed at creating impenetrable surfaces. With membrane systems such as a spray-applied waterproofing membrane and asphalt topping, it is important that the membrane remain watertight. Moisture accumulates on top of the membrane and must have extended periods of drying in order to evaporate. If and when the membrane is breached, moisture accumulates within the concrete and has a very difficult time escaping which leads to increased rate of chloride transport and corrosion activity.

Once chlorides enter the concrete from the surface the penetration mechanics is governed by the pore structure, the capillaries between the pores, and the moisture levels in the pores. Moisture also increases corrosion activity at the level of rebar. Because of these relationships, decks in relatively dry areas will see lower chloride penetration and lower corrosion while decks in humid environments will see increased chloride penetration rates and corrosion activity. Bridge age and concrete wearing course/overlay age are important attributes for chloride modeling. An owner can establish either steady-state diffusion coefficients (obtained by real-world sampling and back-calculating the diffusion coefficient) or use concrete mix properties and computer software to estimate the diffusion coefficient. Generally concrete pore structure refines with age, slowing the rate of chloride penetration (Lower diffusion coefficient). However, this diffusion coefficient reduction has been shown to largely occur within the first 5 years and reaches its lowest coefficient after 26 years.

2.2.6 Miscellaneous Structural Features:

There are many other features that would elevate the chloride penetration of a deck. Many of these features are harder to identify in a systematic way via inventory data:

- Flat or sag profile
- Poor drainage

- Existence of scaling
- Rain or freezing damage during construction
- Flat cross slope, or single cross slope on wide curved bridges that drain to one side
- Deck drains, deck drain configuration, susceptibility of clogging such as shallow sloped drain pans

2.3 Program Management

Identifying candidates for sampling is just one component of incorporating chloride sampling into an asset management plan. The data must be recorded in a consistent manner that will facilitate comparing the data across the bridge inventory. Since it isn't feasible to sample the entire inventory, a method of extrapolating the data will also be required to make network level decisions.

2.3.1 Tools for Managing System Level Chloride Data

In order to manage chloride testing of a large number of structures, it is beneficial to develop a record of deck conditions and chloride test results for each bridge. This allows owners to compare chloride contamination over time and to develop testing frequencies based on deck condition and significance. Figure 5 is an example matrix for categorizing chloride testing frequencies in this manner. Additional factors such as overlay material, rebar type, level of testing (in-depth vs. limited), etc. should be taken into account in order to refine inspection frequencies further.

Inspection Frequency (Years)				
	Bridge Significance			
Deck Condition		High	Med.	Low
	Poor	2	4	6
	Fair	4	8	12
	Good	6	12	12

Figure 5: Inspection Frequency Matrix

2.3.2 Extrapolating Chloride Data

If the owner determines that a group of bridges are exposed to similar environments (based on local weather conditions and deicing salt applications), it may be possible to combine data from multiple bridges in order to minimize the amount of testing/sampling per bridge. The owner can perform in-depth evaluations of several bridge decks along a corridor, collecting sufficient data from each deck to develop individual data-driven repair/preservation options. Sufficient data includes age, overlay type/depth, rebar type and cover statistics, chloride profiles, and corrosion-related concrete damage at a minimum. Non-destructive testing (NDT), including infrared thermography, ground penetrating radar, impact-echo, or others, may be appropriate on a case-by-case basis.

Bridges selected for In-Depth (ID) evaluation should cover the full range of conditions along the corridor from good to poor. It is important that a range of conditions are evaluated so that the owner has a reference point for other deck evaluations.

Repair/preservation options identified for each ID bridge should address the present condition of the deck as well as future deterioration based on service life modeling. Life cycle costs of viable preservation options can be compared to identify the most cost-effective option for each bridge. The owner may identify a few different preservation options (e.g. re-evaluate in 10 years, scarify chloride-contaminated concrete and place a new overlay, install cathodic protection, or replace the deck) based on the condition of each deck. This list of preservation options can be applied to other bridge decks along the corridor based on reduced testing.

At the same time as the ID evaluations, Reduced Testing (RT) is performed on nearby bridges along the same corridor. Results can be compared to ID bridge results to select appropriate preservation strategies for each deck. Since preservation options would be selected based on comparison with ID bridge decks, service life modeling or life cycle cost analysis are not required for RT decks. Thus, fewer data points per bridge are required to evaluate each deck.

The same data that was collected for ID bridges (age, overlay type/depth, rebar type, cover statistics, chloride profiles, and corrosion-related concrete damage) is required for RT bridges. However, the owner may reduce the number samples/readings for each deck. For example, testing for an RT deck may be performed on 25% of the deck rather than 100% of an ID deck. Additionally, instead of full chloride profiles (7 to 10 sample depths per chloride core), the owner could test four sample depths per chloride core (one at the surface, one between the surface and rebar depth, one at the rebar depth, and one behind the rebar depth) in order to categorize the level of chloride contamination and level of deterioration.

When comparing RT and ID bridges, it is important to only compare bridges with similar construction (overlay vs. no overlay, black vs. epoxy-coated bar, etc.). Comparing dissimilar bridges may lead either selecting preservation options that fail to address chloride-induced corrosion or implementing options are much more expensive than required to address corrosion activity.

3.0 Project Level Sampling and Testing Procedures

NCHRP Report 558 will be a useful resource for this section. It is good to address the various sampling/testing techniques, but work towards a recommended method.

Chloride concentrations in concrete are usually determined via physical sampling followed by laboratory testing. Field collection typically includes the collection of either a concrete core or powder sample that is then brought to a laboratory for testing. The standardized methods of chloride concentration testing involve electrochemical titration of solution containing the chloride that has been leached or digested from a known sample of powdered concrete.

3.1 Deck Sampling

The following section provides a detailed discussion regarding the actual collection and preparation of concrete samples from the field so that a determination of chloride concentration can be obtained.

3.1.1 Sampling Methods

The first step in the analysis of a bridge deck's chloride concentration is to collect a physical concrete sample. Laboratory analysis of concrete for chloride requires a ground sample that will pass an 850-μm (No. 20) sieve, typically referred to as a powdered sample. The most common practices to obtain concrete powdered samples at controlled depth increments are by: a) collecting powdered concrete while drilling a hole into the concrete with a rotary hammer or b) obtaining a core from the concrete surface and then subdividing the sample in the laboratory by saw-cutting and pulverizing or by grinding. Both methods have been used successfully, but there are precautions that need to be taken with each approach.

An advantage of powder sampling is that the final powder sample is produced in the field. On decks, powder sampling is typically more time-consuming than core collection. Capturing the powdered concrete sample can be difficult to conduct especially in vertical or overhead sampling and under windy or rainy conditions. In addition, controlling sampling depths with a rotary hammer and limiting cross-sample contamination can be difficult.

Concrete samples may also be collected by extracting a core to be cut into slices (along the depth of the core). The advantage of coring is the speed of sampling in the field and the reduced possibility of sample contamination. The coring process can be completed more quickly in the field (reducing closure times), is less influenced by weather, and samples can be more carefully subsampled in a laboratory setting. However, there is more labor involved in the laboratory phase with cores. Note that coring is typically only faster than powder collection when working on top of a deck. Concrete sample collection in vertical and overhead situations typical is quicker with powder collection than coring. This is due to the increased difficulty of handling a core drill.

When collecting a concrete sample for chloride analysis, consider the following factors:

- Diameter of the collection tool
- Depth increments of sampling
- Captured sample volume
- Effect of cross contamination

3.1.1.1 Sample Diameter

Concerning the size of core or drill bit to be used, it is important to obtain concrete samples that are uniform and representative of the concrete. Since the majority of diffused chloride resides within the pore structure of the cement paste, the ratio of aggregate to paste in the sample will have significant effects on the accuracy and repeatability of the testing. The diameter of the sample (core or bit) should be no less than 1.5 times and preferably 2.5 times the nominal maximum aggregate size in the concrete. If the diameter is too small, there is an increased risk that the sample may be concentrated within cement paste or within large aggregate particles, resulting in overestimation or underestimation of chloride concentration, respectively. Consider Figure 6 which is a highlighted photograph of the cross-section of a 4-inch diameter concrete core with various diameter increments indicated on it. The smaller diameter increments contain higher concentrations of aggregate and less paste, which would most likely underestimate the chloride concentration. The larger diameter provides a more representative balance between the aggregate and paste.

In Figure 7, near the top, coarse aggregate particles have been traced out in black to differentiate them from the cement paste. If samples are drilled at three depth increments with a small diameter (say 0.5 to 0.75 in.) bit, then the yellow and red lines show comparison of two areas of potential sampling. Note that the red sample area would contain significantly greater proportion of paste, whereas the yellow area would contain more coarse aggregate. The resulting chloride profiles for the same concrete would be vastly different. Thus, to obtain an “average” sample of the concrete composite material, it is necessary to have large enough sample volume to be representative.

Figure 6: 4 Inch Core with 1 Inch Cross-Section Rings.

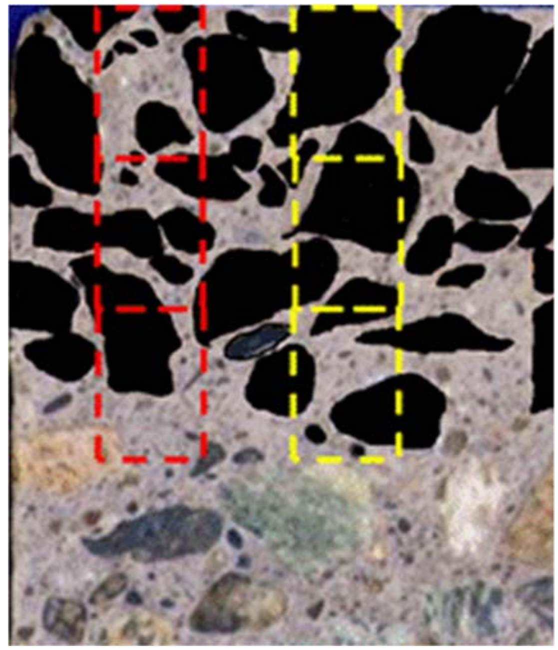


Figure 7: Small Sample Diameter Effects on Sample Composition

3.1.1.2 Sample Depth Increments

Depth increments for the concrete samples vary in practice, and are generally determined based on the objectives of the practitioner. Some practitioners have taken 2 or more inches in depth as a single sample and tested from the combined powder to determine an overall "average". Others have drilled to near the reinforcement depth and sampled approximately ½ to 1 inch of material to determine the chloride concentration at bar depth. Depending on the user's objective these methods may or may not be applicable.

With regards to the context of this document, the authors recommend that the most useful information can be determined by creating a profile comprised of depth increments extending from the surface to the depth of the reinforcement and beyond (Figure 8). Such profiles can be taken at increments of a few millimeters to up to an inch. Not only does this type of sampling provide the chloride concentration at the bar depth but it can also be used to determine the rate at which chlorides are progressing in the deck. When conducting service life projections and programing future deck repairs, understanding the level of chloride exposure over time on a bridge can be extremely useful.

To strike a balance between number of subsamples to titrate (the cost of testing is usually charged per titration) and sufficient depth increments and range to create a representative profile, it is generally recommended to test in ½-inch depth increments. A minimum of 3, but preferably 5 depth increments are recommended to create a profile from which a diffusion model can be fitted. A typical range of chloride samples for a profile (for nominal 2" cover reinforcement) might be ¼" - ¾", ¾"-1¼", 1¼" -1¾", 1¾"-2¼", and 2¼" -2¾" (samples centered at ½", 1", 1½", 2", and 2½", respectively). This sample range will provide the near surface concentration, an indication of the exposure, and a range of samples around the expected cover-depth. It is important to note that cover-depth will vary in a bridge deck, and just sampling at the design specified cover-depth will not provide a true representation of the deck.

The first 1/4" of concrete is not recommended for sampling as this surface concentration is highly variable due to seasonal weather conditions. If a rain event occurs prior to sampling it can wash chloride from the surface layer and not provide a true representation of the exposure. Conversely, if salting of the deck had just occurred, the surface concentration would be extremely high. At ¼" the daily environmental changes will not widely change the sample concentration, therefore, it is an indication of what is truly starting to diffuse into the concrete matrix.

If the practitioner is conducting an acid soluble titration (ASTM 1152) for the analysis of the chloride concentration, it is important to understand the "background" chloride level. The "background" chloride concentration is inherent to the concrete constituents before the structure was opened to service. Typically, this is done by taking a sample at a depth beyond which chloride diffusion is expected to have occurred, a sample below the top mat reinforcement at 3 or more inches from the concrete surface. This depth may need to be adjusted based on the time and severity of exposure to chloride sources.

It is not necessary that the sample increments be contiguous to develop a chloride profile that can be used in a diffusion analysis. For example, it is possible to space the samples to represent distributed ranges of depths such as ¼" - ¾", 1¼" -1¾", 2¼" -2¾", etc. (centered at ½", 1½", 2½", etc.). This can help to reduce laboratory costs, while still providing information regarding the chloride profile.

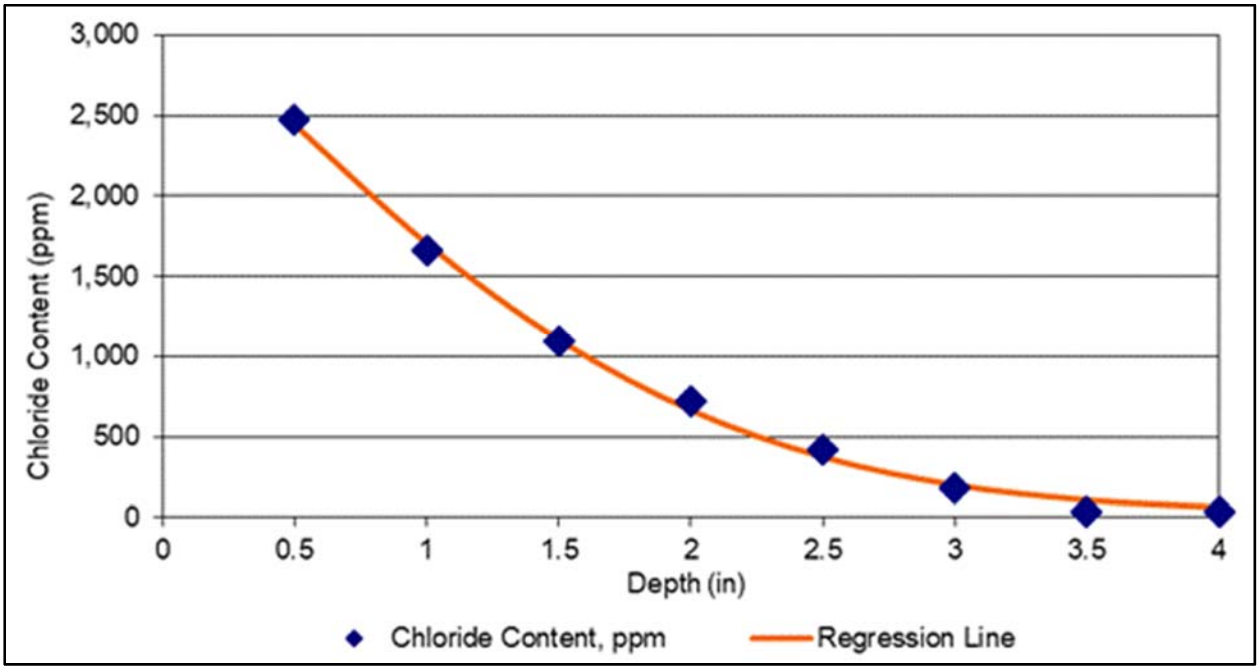


Figure 8: Chloride Profile from a Bridge Deck

3.1.1.3 Sample Volume

The most commonly cited standards for chloride testing are AASHTO T260 and ASTM C1152 or C1218. With regard to sample volume, the minimum sample necessary for a single test is 3 grams of material for AASHTO and 10 grams for ASTM. It is preferred sampled volumes be at least twice that needed to conduct the test, both to be representative and to allow for re-test if a test fault occurs. Generally, it is recommended that each sample increment to be tested produce no less than 20 grams of powdered concrete.

3.1.1.2 Potential Sample Contamination Sources

Two considerations that should be made when sampling and sub-sampling of concrete for chloride concentration testing are to avoid cross-contamination and to prevent leaching of chlorides. Cross-contamination occurs when the sampling, handling and storage of the powdered concrete allows chloride or concrete from another source to be introduced into powder sample. With drilled powder sampling (Figure 9), this can occur by a few different means, most notably the abrasion of concrete from the upper (presumably more contaminated) portions of a drilled hole while drilling samples from the deeper (presumably less contaminated) concrete. Concrete and any chloride contaminated within it, may contaminate the deeper sample, falsely increasing or even decrease the measured chloride concentration. Also, if powder sample is retrieved from the drilled hole with a sampling spoon, contaminated material may be inadvertently scraped from the sides of the upper portion.

It is also necessary to clean the sampling equipment between uses, typically with alcohol which rinses contaminants but air-dries quickly. This could include but is not limited to the drill bit, sample collection receptacles, or suction devices. For a suction collection device, like a vacuum and filter method, it is important to minimize the potential for cross-contamination from the sampling tube.

Core sampling (Figure 10), is typically conducted using wet coring with a diamond-impregnated core bit. The wet coring process exposes the outer perimeter of the core to water, which may wash away (leach) chloride near the core surface. Therefore, it is important that the sample be sufficiently large and subsampling be structured to minimize this effect. Once a core is returned to the laboratory for subsampling, dry methods are recommended, such as dry-cutting and crushing/pulverizing, or dry grinding and capture of powder. As with drilling in the field, it is important during these laboratory subsampling steps that possibility of cross-contamination be minimized by cleaning tools between operations.

Figure 9: Drilled Powder Sampling on a Bridge Deck.

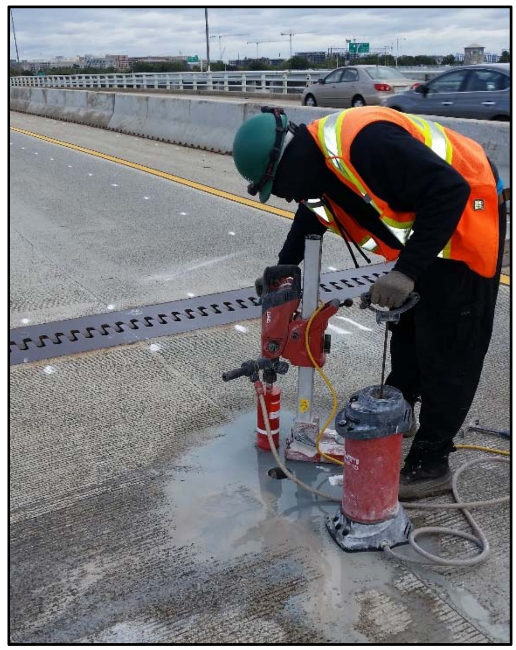


Figure 10: Core Sampling on a Bridge Deck

The type of sample method may also be related to the bridge deck risk exposure category. Low or medium risk decks, those that are relatively early in their service life or have limited apparent exposure to chloride in their service environment, may warrant lower frequency and lower cost for prescribed sampling and testing methods. As deck exposure risk increases, justification exists to use greater sampling frequency and there may be less pressure to minimize the cost of testing in favor of obtaining more critical useful information that will impact the service life assessment. It may be possible to optimize both the methods used and the frequency, temporal and spatial, of sampling based on the perceived importance of the structure or network and the risk and consequences of corrosion damage.

3.1.2 Number of Samples to Take

Chloride concentrations are the defining factor in chloride corrosion and resultant concrete deterioration. Use of sound sampling techniques, number and size of sampling, are key to run service life modeling and making data driven decisions.

When testing an existing bridge for chloride contamination, it is important to consider the number and distribution of samples. Various elements (shoulder verses travel lanes) will have different exposure conditions. Therefore, it is necessary to collect samples from each type of exposure condition if evaluating the whole bridge deck. The number of samples required from each element/exposure condition depends on the size of the structure and the type of analysis required.

There are many approaches to selection of the number of cores to be collected from a bridge deck. NCHRP 558 *Manual on Service Life of Corrosion-Damaged Reinforced Concrete Bridge Superstructure Elements* states a minimum level of sampling that is required to obtain reliable results. A minimum sampling rate of 1 chloride profile core per 1000 square feet of deck area is specified. Practitioners have also used rules of thumb like, at least 4 cores per span. For a large bridge, the sampling rate may be reduced, but still a minimum number of cores are required.

The cores must be distributed throughout all the lanes of traffic. A minimum sampling is important to maintain the integrity of service life modeling that predicts future concrete deterioration, as this would affect repair/rehabilitation decisions.

At each core location, the number of depths/samples per core may vary as well. For service life analysis, the chloride diffusion coefficient must be calculated from the chloride profile. For an acceptable curve fit through the chloride profile, five samples per core is suggested.

3.1.3 Sample Location

When selecting the location of where to collect samples, there are many factors to consider;

- Exposure
    - Is it a shoulder or traffic lane?
    - Wheel path?
    - Near or away from drainage
    - Joints
- Current condition
    - Presence of cracks, delamination, spall
    - Pooling water

        - Patched areas
- Accessibility
    - Impact to traffic
        - Collection only from shoulder to minimize traffic impact?

3.1.3.1 Exposure

There are several different localized environments on a bridge deck and understanding chloride exposure in each is important in understanding the condition of the bridge and its exposure to chlorides. Practitioners often find it important to sample from each lane and shoulder of the structure, near and away from joints and near and away from drainage elements.

Wheel paths are likely to contain the most at-risk portions of chloride penetration due to potential for rutting, ponding, cracking and pumping action. Pumping action is illustrated in Figure 11. Consideration should be given to include some limited core samples from the wheel path and nearby adjacent shoulder areas to show the chloride profile escalation that might exist due to dominant wheel position. This is important because the wheel path controls the deck service level.

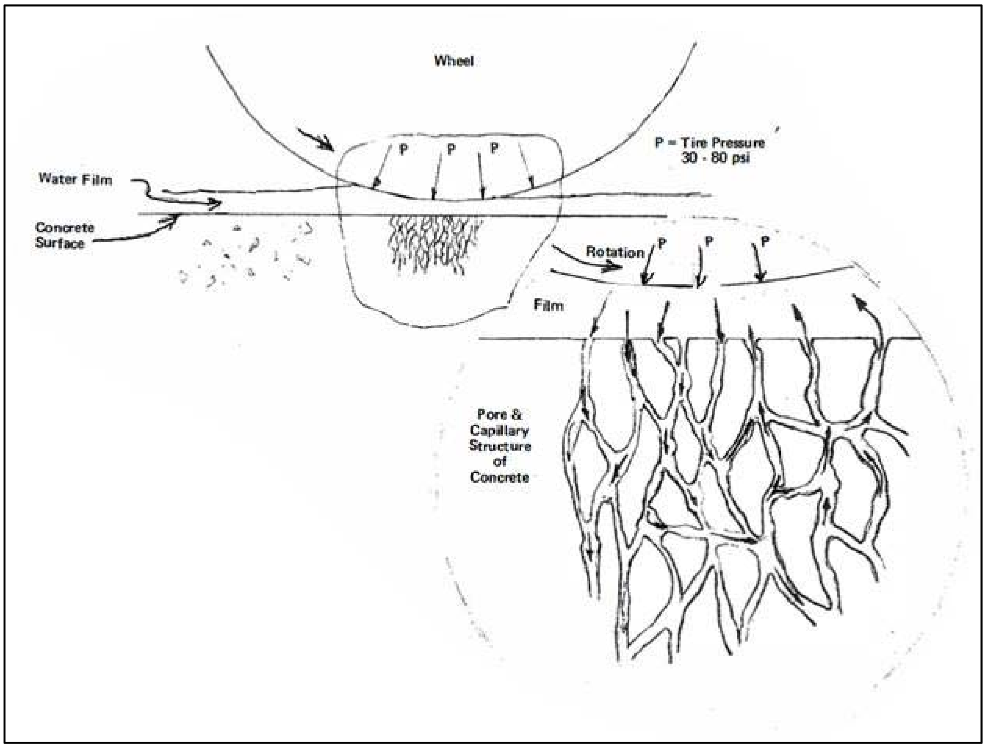


Figure 11: Wheel Path Pumping Action Diagram

3.1.3.2 Current Condition

Depending on the objective of the work, it is not always necessary to sample at cracks, delaminations and spalls. Cores collected at these locations cannot be analyzed through a diffusion curve analysis as the chloride exposure is no longer governed by the diffusion mechanism. These conditions will allow chlorides to progress into the concrete at high rates, therefore, it is not always necessary to sample at them because it is typically known that the chloride concentration at the steel in these areas will be high enough to initiate corrosion. However, it is critical to the service life assessment of a bridge to understand the concentration and distribution of cracks, delaminations and spalls, it may not be necessary to measure the chloride there.

3.1.3.3 Accessibility

In some instances, cores are only collected from the shoulder as to lessen the impact to traffic and save money. While this is cost-effective because of reduced maintenance of traffic (MOT) requirements, typically the shoulder has a higher exposure to chloride due to it being a runoff drainage path, areas of piling snow in winter months, and receives less maintenance and care than the travel lanes. As a result, cores when only collected from the shoulder may overestimate the chloride exposure and shorten the expected service life. It is recommended that whenever possible to collect cores from all bridge lanes and shoulders to understand the full scope of the chloride exposure.

3.1.3.4 Random Sampling

One approach is to break down the bridge deck into (x,y) coordinates, or some other means, and randomly select the sample locations. This can be done by using a random number generator to select the (x,y) coordinates for the required number of cores. While random sampling is very effective from a statistics point of view, from a practical point of view it can result in certain important areas being under or over sampled. For example, randomly selecting core locations could end up missing a bridge span, or under sample a specific lane.

3.1.3.5 Semi-Random Sampling

Others take the approach of randomly sampling from distinct areas. For example, a practitioner may dictate that 3 cores are to be collected from each shoulder, travel lane and passing lane (12 total cores). Each of the 3 cores are focused to a specific area but then randomly collected within that area. While this is not true random sampling, it provides a random sampling within each of these unique exposure areas.

3.1.3.6 Focused Sampling

Focused sampling is the practitioner selecting the exact location of each core. Typically, the location of the cores is based on the practitioner’s experience and project objectives. Focused sampling can be biased and as a result may not provide a truly representative sampling of the bridge.

3.1.4 Traffic Control Requirements

When performing the collection and testing of concrete there are many safety precautions that should be taken to ensure the welfare of the people and equipment involved. It is the responsibility of the employer and employees to ensure that proper workplace safety is being conducting at all times. It is not within the scope of this document to detail each safety concern to be encountered throughout the collection and testing of concrete. However, the sample collection phase presents a unique and highly dangerous activity that the authors felt was important to highlight. Sample collection typically occurs on an active bridge deck, in which the personnel collecting the samples are on the deck while cars are still actively driving across. There is significant risk to the workers and drivers during this work and it is critical that the work is conducted in a safe manner. The following provides considerations with regards to working on an active bridge deck that anyone collecting concrete samples should be aware of;

- Proper maintenance of traffic (MOT).
    - This is the workers first and most important line of defense. MOT will provide a barrier between the workers and vehicles and also alert drivers to the workers presence so that they can be more alert.
    - MOT requirements will be dictated by
        - Bridge owner's policies
        - Average annual daily traffic (AADT) of a bridge
        - Speed limit
        - If on/off ramps are present
    - MOT will typically include
        - Proper barriers or traffic control devices between workers and traffic
        - Attenuation vehicles
        - Police escort
        - Proper signage
        - Flaggers
- Proper personal protective equipment (PPE) like
    - Highly visible clothing
    - Eye and ear protection
    - Hard hat
- Alert to one's location within the closure
    - It is easy to be engaged in a task and take a step in the wrong direction which could be into active traffic. Being constantly aware of your location in relationship to vehicles is critical to a safe work environment.

Prior to doing any work on a bridge deck it is recommended that the practitioner discuss safety with the bridge owner's local maintenance staff. The maintenance staff will typically have an extensive knowledge of the area and can provide the practitioner with safety policies and past experience for that bridge or a similar one in the area.

3.2 Chloride Testing

Once the concrete samples have been collected from the bridge deck they then need to be tested for the concentration of chloride. The following provides typical methods implemented for the testing of chloride concentration. This section is not fully encompassing of each method that exists and some practitioners may even choose to implement alternate procedures to these presented methods. However, the methods presented are considered standard practice and are in line with the ASTM and AASTHO methodology.

3.2.1 Field Test Kits

There are several in-field test kits that are able to provide a rapid assessment of chloride content from a collected concrete powder sample. Some of these tools implement a selective ion probe along extraction and calibration liquids. Other systems use paper strips placed in water digested samples to indicate the chloride content. All these systems rely on a powder sample being collected in the field. The pros and cons of collecting a powder sample have been discussed previously. The pros of these in-field concentration tools are that they are rapid and provide the user a value in the field. These are specifically useful on new structures to insure the new concrete being placed is free from chloride contamination. However, these systems may have significant drawbacks regarding accuracy and repeatability. Whenever conducting a laboratory like test in the field there are issues with controlling the process and insuring an exact procedure is conducted without cross-contamination.

If in-field kits are used it is recommended that extra samples are collected and the results of the in-field measurements are confirmed with laboratory tests.

3.2.2 Laboratory Tests

The preferred way to process concrete samples for chloride concentration are to return to the laboratory with the samples and process them in a controlled environment using procedures and guidelines that have been established by entities like ASTM and AASHTO to insure that consistent repeatable results are provided.

Florida DOT requires laboratory certifications. However, many DOTs do not require specific laboratory setups or verification testing. Caution should be used when selecting laboratories to ensure consistent and reliable results. At a minimum the laboratory QA/QC process should be reviewed to evaluate validity, accuracy, and error to achieve quality chloride testing data.

Methods of analysis affect evaluation of chloride content. Standards that measure acid-soluble chloride content, such as ASTM C1152 or AASHTO T-260, measure total chloride content in the concrete or grout material. However, methods that measure water-soluble chloride content, such as ASTM C1218, measure chlorides that are unbound and available for corrosion. While it may seem that the latter is the only type that may be of concern, it should be noted that measurement of water-soluble chlorides act only as a snapshot of the material at the time, and that bound chlorides can become unbound from hydrated cement products over time and can thus become available to participate in corrosion activities. Caution should be exercised between switching between water-soluble and acid-soluble during subsequent tests.

Regardless of the method that is chosen for laboratory testing, acid or water soluble, the following provides an overview of the typical process that is used to determine the chloride concentration of the concrete sample in the laboratory. It is important that for whatever methodology the practitioner chooses to follow that they be familiar with the procedure prior to commencing the work and follow the prescribed procedure accurately to insure a correct result.

Laboratory processing for a core begins by cutting and pulverizing the samples based on the preselect depth increments. If the sample was collected in a powder form, it may still require some pulverizing as the whole sample may not be smaller than an 850-μm (No. 20) sieve. Pulverizing can be conducted using a mortar and pestle (Figure 12 and Figure 13), or a pulverizing machine (Figure 14). When conducting the pulverizing it is critical that after and before each use the receptacles are thoroughly cleaned to prevent any cross contamination of the samples.

Figure 12: Pulverized Concrete Core

Figure 13: Concrete Core Wafer Prior to Pulverization

Figure 14: Mechanical Concrete Pulverization Machine and pulverized concrete sample

Figure 15 shows a sample being screened through the 850-µm (No. 20) sieve.

Figure 15: Sieving Powder Samples

Once the sample has been ground to a proper size the sample is accurately weighed (Figure 16).

Figure 16: Weighing Sample

Then the digestive solution is prepared and the concrete powder is placed in the solution and let to digest (Figure 17).

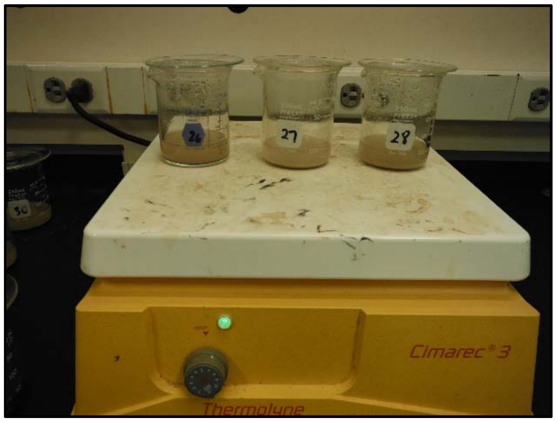


Figure 17: Sample Digestion

After a period of time the solution is filtered (Figure 18).

Figure 18: Filtering Sample

Finally the sample is tested for chloride content through titration (Figure 19).

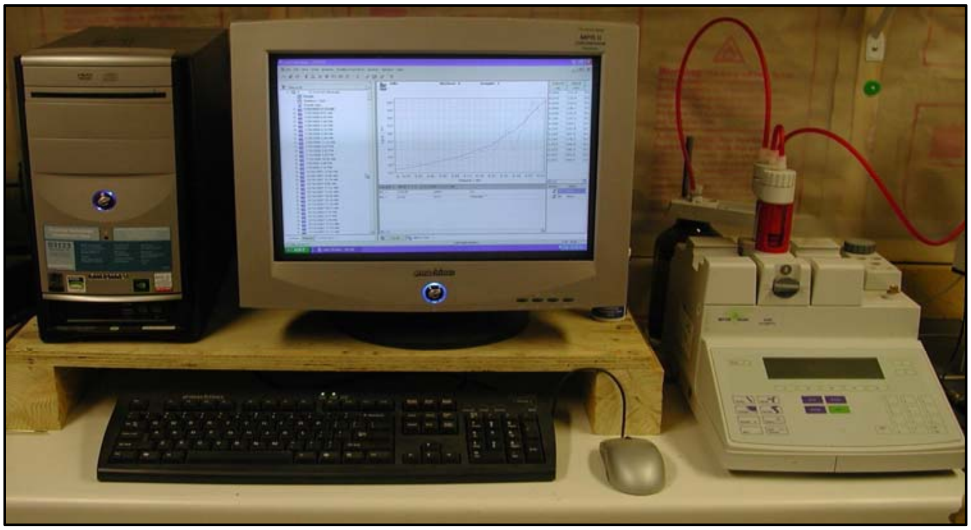


Figure 19: Titration of a Digested Concrete Sample

3.2.3 Units

The concentration of chloride in a concrete sample can be presented in various units and understanding those units is crucial in comparing data collected by other practitioners. The first break down in the units is whether the concentration is presented as chloride concentration by mass of cement or concrete. If this is not made clear when presenting data, vastly different conclusions regarding a chloride concentration can be made. Concrete is comprised of aggregate and therefore the concentration of chloride per concrete will be smaller than if reported by mass of cement. In addition, the threshold values as reported by mass of cement or mass of concrete are vastly different. Therefore it is critical when reporting chloride data that either by mass of cement or by mass of concrete is reported along with the data. The following provides the conversion of between the two entities.

$$Chloride\ Percent\ by\ Mass\ of\ Cement = Chloride\ Percent\ by\ Mass\ of\ Concrete * \frac{Density\ of\ Concrete}{Cement\ Content\ of\ Concrete}$$

If the density of concrete and cement content for the particular sample is unknown, reasonable approximations can be used. A reasonable approximation for these values for normal weight reinforced concrete typically used in bridge decks has a density of 3834 lbs/yd^3 and a cement content of 600 lbs/yd^3. It is important to note that these values vary depending on the materials used and the project's design factors.

In addition to the by mass of cement/concrete units there are various chloride concentration units that can be implemented. The most commonly used units are;

- Parts per million (ppm)

- Pounds (lbs)
- Percent (%)

The following provides conversions for ppm and lbs to percent.

$$Percent\ chloride\ by\ mass\ of\ concrete\ = \frac{ppm\ by\ mass\ of\ concrete}{1000000} * 100$$

$$Percent\ chloride\ by\ mass\ of\ concrete\ = \frac{lbs\ of\ chloride\ per\ yd^3\ of\ concrete}{Density\ of\ Concrete} * 100$$

3.3 Auxiliary factors to consider

In addition to chloride concentrations, there are other factors that will affect the in service performance. During sample it is prudent to consider the following.

3.3.1 Sulfate:

Presence of high sulfate concentrations can affect concrete in a few ways:

- Efflorescence - this is the fine powdery crystalline salt deposit found on concrete surfaces. Some efflorescence is typical. As moisture evaporates from concrete, it carries soluble salts to the surface. Excessive efflorescence results in a trace portion of the concrete dissolving away, thus increasing chloride penetration diffusion rates. These surface salts can contain sulfate.
- Sulfate attack results from excess sulfate which can react with concrete and weaken it due to gypsum and/or ettringite formation. This can increase chloride diffusion rates and lower concrete pH.
- Internal sulfate attack is the result of sulfate excesses present in the concrete mix. External sulfate attack occurs when sulfate penetrates the concrete from external sources. Sulfate is a known corrosive agent in low pH environments, such as old (carbonated) concrete or metal culvert pipe in soils containing sulfate.

3.3.2 Carbonation:

Carbonation occurs when carbon dioxide from the air penetrates the concrete and reaction with hydroxides to form calcium carbonate. The reaction reduces the pH of the pore structure of concrete which can jeopardize the passive film around the reinforcing steel. Fortunately carbonation of concrete is generally a very slow process in good quality concrete. For typical construction in the United States it can take 100 years for carbonation to impact the reinforcing steel.

Although carbonation alone isn't a significant cause of deterioration in the United States, it combination with chloride contamination can be detrimental to the concrete quality. Carbonation has been shown to result in the release of bound chlorides. This release of bound chlorides can expedite the ingress of chloride contamination. The increased rate of chloride ingress combined with the lowering of pH can result in corrosion of the reinforcing steel.

In particular, testing for carbonation should be considered in older structures that have insufficient concrete cover. Re-alkalization of concrete has become common in Europe to mitigate the effect of carbonation on older structures.

3.3.3 pH

It is primarily the high alkalinity (pH) of the cement paste that protects steel from corrosion. If the pH is reduced (due to carbonation, for example), the concentration of chloride required to initiate corrosion is also reduced. If the pH drops below a minimum threshold (approximately 9), corrosion can occur even in the absence of chlorides.

4.0 Modeling Test Results

After completion of the laboratory testing a user is typically provided a list of chloride concentrations for various locations and depths sampled. How one would process and analyze this data varies widely on the user's objectives and the type of data that is collected. In most cases there are two primary analysis methods that are conducted with regards to chloride concentration data. The first is an assessment of the chloride content at the depth of the reinforcement in the deck. Is the chloride above the threshold concentration at the depth of the reinforcement, indicating the risk for active corrosion in the deck. The second common analysis method, typically done when the concentrations at the reinforcement are still below the threshold, is to assess the rate at which chlorides are diffusing into the concrete so that an estimate when threshold is reached and be determined. This second analysis method frequently is a part of a service-life analysis.

4.1 Chloride Threshold Concentration

The concentration of chloride at the steel depth required to initiate corrosion is not an absolute values and various significantly based on the various factors previously presented in this paper. When assessing the risk for corrosion from chloride concentration data it is important to keep in mind that there is a range and that the type of environment and materials implemented will have a significant impact on this value. ACI 222 indicates that in the United States the threshold value typically used by practitioners falls between 1.0 to 1.5 lbs of chloride per yd^3 of concrete. Figure 20 is an example of various chloride ranges that have been used in practice to quantify the risk of deterioration due to chloride levels. It is up to each Agency to determine its level of risk tolerance with associated chloride levels.

Risk of chloride-induced corrosion	Uncoated (Black Bar) Reinforcement		Epoxy-Coated Reinforcement	
	Chloride concentration by weight of cement (% chloride by weight of cement)[1]	Chloride concentration in normal weight (140 pcf) concrete[2] (% chloride by weight of concrete)	Chloride concentration by weight of cement (% chloride by weight of cement)[3]	Chloride concentration in normal weight (140 pcf) concrete[2] (% chloride by weight of concrete)
Very Low	<0.2	<0.03	<0.3	< 0.05
Low	0.2-0.4	0.03-0.06	0.3-0.7	0.05- 0.11
Moderate	0.4-1.0	0.06-0.15	0.7-1.9	0.11-0.29
High	>1.0	>0.15	> 1.9	>0.29

[1] *From* (Broomfield, 2007)

[2] *Concentrations by weight of concrete assume cement content of 564 lbs/cu yd (i.e., a 6 bag mix)*

[3]*Based on previous work performed by WJE: "Statistical distributions for chloride threshold of carbon steel and epoxy coated reinforcing bars for probability service life modeling," John Lawler, et al.*

Figure 20: Chloride Risk Table

4.2 Chloride Content at Reinforcement Depth

Typically the chloride concentration data is processed by first assessing the concentration at the reinforcement depth. This can be done by using a plot to illustrate the sample depth versus chloride concentration as shown in Figure 21. Typically the vertical axis being the chloride concentration and the horizontal axis being the depth for which the sample was collected. To aid in the analysis it is recommended that the cover-depth be included as vertical lines on the plot.

It is important to note that the concrete cover-depth in a bridge deck is not consistent and will vary throughout a bridge deck. Tools like ground penetrating radar and cover-meters can help to determine the range of the cover-depth so that it can be plotted showing the variation. In the example plot the average measured in-place cover-depth is shown along with +/- a standard deviation. This aids in understanding how much of the bridge deck may be exposed to a chloride concentration that would initiate corrosion.

On the plot is a horizontal red line indicating the threshold value of 350 ppm. This is an approximate value and used by the practitioner to assess the data, but it is fully understood that the threshold in the bridge deck will vary and 350 ppm is only an approximation. That data is reviewed and the concentrations are analyzed based on their concentration and their depth in relation to the steel cover-depth. If the concentrations are above the threshold at the depth of steel the risk for corrosion is high. If the concentrations are below the threshold at the steel depth then the risk for corrosion is low. Using a statistical analysis one can estimate the amount of the bridge deck that is in a high risk for corrosion due to chloride exposure.

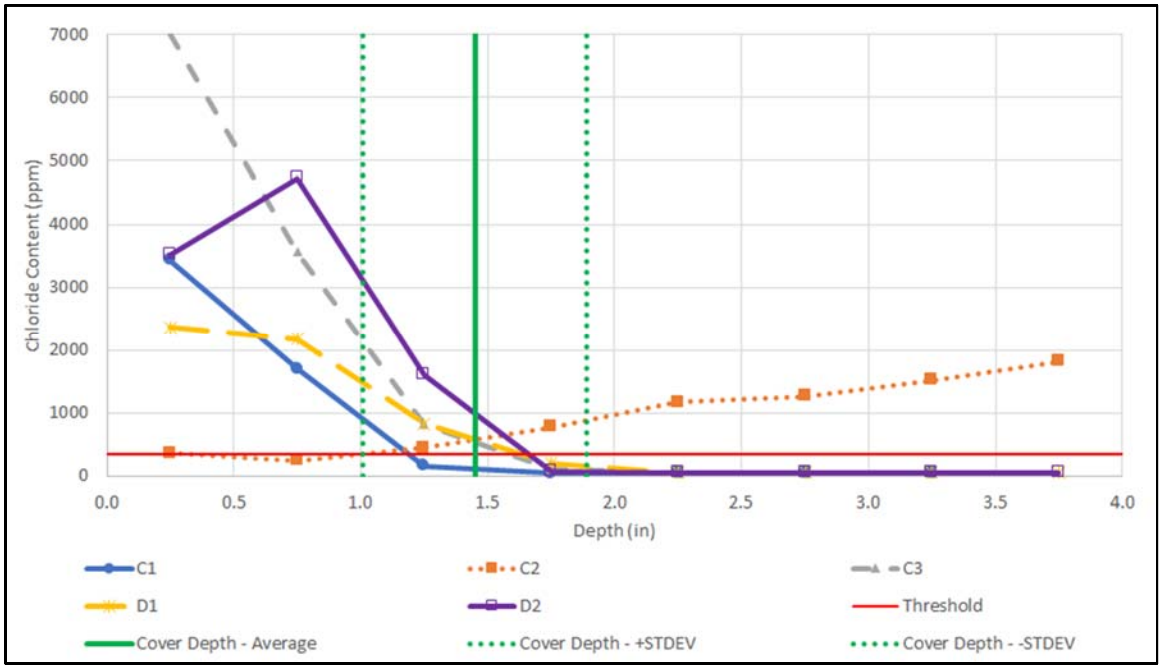


Figure 21: Examples Chloride Concentration Plot

4.3 Chloride Ion Transportation Methods

The most common modes of chloride transport are diffusion, permeation, migration, and convection (Poulsen, 2006). Diffusion is the main form of chloride transport, which occurs when chlorides move from areas of high concentration to areas of lower chloride concentration. Permeation is the transport of chlorides via hydraulic pressure, which moves chlorides into areas of lower pressure (Poulsen, 2006). Migration is the process whereby chloride ion is driven by differences in electrical potential; a location of more negative electrical potential will attract chlorides (Poulsen, 2006). Convection occurs as chlorides move toward areas of lower moisture content (Poulsen, 2006).

In bridge deck assessment diffusion is the primary process and the one that governs most modeling and service life analyses.

4.4 Fick's Laws of Diffusion

To model the transport of chloride into concrete with time Fick's Laws of Diffusion are used. Fick's laws are based on kinetic theory and the random motion of molecules. Fick's First Law of Diffusion (Equation 4.4-1) indicates that the rate at which chloride transports through concrete is proportional to the concentration per unit distance and a constant that is based on the concrete properties. This application of Fick's Law is based on the assumption that the concrete is a one-dimensional semi-infinite permeable solid (Funahashi, 1990).

Fick's First Law of Diffusion:

$$J = D_c \frac{dC}{dx} \qquad \text{(Equation 4.4-1)}$$

J = Rate of flow
Dc = Diffusion Coefficient
C = Concentration
x = Distance

Fick's Second Law of Diffusion (Equation 4.4-2) can be applied to model the concentration of chloride with a time dependency.

Fick's Second Law of Diffusion:

$$\frac{dC}{dt} = D_c \frac{d^2c}{dx^2} \qquad \text{(Equation 4.4-2)}$$

C = Concentration
t = Time
x = Distance

Using Fick's Laws, an equation for the chloride profile of a permeable solid element can be developed which gives the chloride concentration at specific depths and times. The chloride profile equation is based on several assumptions. 1) The concrete is first exposed to chlorides at t = 0, 2) the chloride concentration of the environment is constant, 3) the concrete is a quasi-homogeneous semi-infinite solid, and 4) the diffusion coefficient is constant (Poulsen, 2006).

Chloride Profile Equation:

$$C_{(x,t)} = C_0 \left(1 - erf \frac{c}{2\sqrt{D_c t}}\right) \qquad \text{(Equation 4.4-3)}$$

erf = Mathematical error function
C(x,t) = Chloride concentration at depth x after exposure time t
C0 = Constant chloride concentration near the surface

4.4 Diffusion Coefficient

Using Fick's laws of diffusion the diffusion coefficient provides the rate at which chloride ions are diffusing into the concrete. It is assumed that the diffusion rate is a constant for concrete. In newly placed concrete the diffusion rate actually changes with age. After 5 years the rate has substantially reduced and after approximately 25 years it has been found that the diffusion rate becomes effectively a constant for the remaining service life of the structure, as long as the structure is not substantially changed, i.e. an overlay is placed or cover concrete removed.

Using the curve provided in Figure 19 a regression analysis can be conducted on the collected chloride concentrations with depth to determine the Dc value for each core. It is important to note that Dc will vary throughout a single bridge deck. Also, samples collected at locations of damage or cracked concrete will not be governed by diffusion transportation and thus will violate the Fick's Laws of Diffusion. Therefore, it may not be possible to calculate a Dc value in these location or it may not be meaningful in the analysis of the data.

4.5 Service Life Prediction

Once the cover-depth and chloride concentration in the concrete have been measured a service life prediction model can be developed to estimate the time to corrosion initiation. From corrosion initiation the time to produce significant physical damage requiring repairs can be estimated. Many practitioners have built their own models based on their experience and preferred methodology to perform service life analyses. There are also products out on the market that are able to perform these analysis using a wide range of variables and user inputs. An example of these software packages is ACI Life 365 which is built on extensive laboratory testing of various concrete mixtures to determine their in-place properties and how they perform in a variety of exposure environments.

The advantage of these service life modeling tools is that it provides owners with an assessment of how the structure could perform in the future. This allows an owner to evaluate various rehabilitation strategies, understand future budgeting needs and coordinate future. The disadvantage with these modeling tools is that they are statistical, in that there are so many varying factors they are based on that the there is a range of service life predictions that could occur for a given structure. It is impossible to exactly determine the service life of a bridge deck. There may be localized areas that deteriorate very quickly while other areas will last for a very long time. Understanding that the data input into these models has significant variation will help to use the results of these models appropriately.

4.6 Programming Future Work

Providing specific recommendations for future work is beyond the scope of this document. Many factors will need to be considered before moving forward with a project. Owners will have to weigh the bridge importance, the impact to the public, and available funding before moving forward with a project. Obtaining consistent and good chloride information is just one component of the decision making process. A good asset management plan will focus on preserving structures that are in good condition.

Chloride contamination is a key indicator of the future bridge deck deterioration. Sampling before deterioration occurs enables programming preservation activities to maximize the longevity of the deck. Preservation actions (sealers and impermeable overlays) can certainly slow the rate of contamination but will have limited effect if applied to bridge decks that are close to the threshold. However, if funding for rehabilitation or replacement isn't available for the foreseeable future then these actions are relatively inexpensive and may be worth pursuing.

It is recommended to focus preservation actions on bridge decks that are in good condition and have low levels of chloride contamination. Sealing cracks with penetrating sealers will slow the rate of chloride ingress and significantly extend the service life of the bridge deck. Thin overlays, membranes and other impermeable overlays create a barrier for chloride ingress and should also be considered as part of the asset management plan.

If the chloride contamination is at or beyond the threshold and spalling is observed throughout the bridge deck then conventional preservation isn't as effective and the owner should start considering rehabilitation or replacement. The use of hydro-demolition can remove contaminated concrete that is at or below the reinforcement level and new concrete can be placed. This method of rehabilitation has been shown to be effective even when severe contamination has been documented.

5.0 References

Association, P. C. (2002). *Types and Causes of Concrete Deterioration.* Skokie: Portland Cemenet Association.

FHWA. (2018). *Bridge Preservation Guide.* US Department of Transportation.

Funashashi, M. (1990). Predicting Corrosion-Free Service Life of a Concrete Structure in a Chloride Environment. *ACI Materials Journal*, Vol. 87, No. 6.

L. Mejobro, E. P. (2006). *Diffusion of Chloride in Concrete.* New York: Taylor & Francis Inc.

Appendix A – Example Projects

Include a few example projects. Review existing work to ensure it doesn't contradict information provided in the report.

MnDOT Bridge 69816: Reinforced Concrete Box Girder

MnDOT bridge 69816 is an elevated concrete box girder serving as an overpass and interchange over Trunk Highway 35W in Duluth, Minnesota. The bridge was opened to traffic in 1984 and consists of a complex multi-cell reinforced box girder arrangement with 3" top concrete cover, of which 2" of the cover is provide by a low slump concrete wearing course (MnDOT specification mix 3U17A). The figures below show the general location and configuration. There are 9 box girder segments in four units, each separated by bridge expansion joints. The top slab was constructed in 1982 with epoxy coated top reinforcement and uncoated bottom reinforcement. Figure A1 shows a plan view excerpt of the bridge.

Figure A1: MnDOT Br 69816 in Duluth, MN

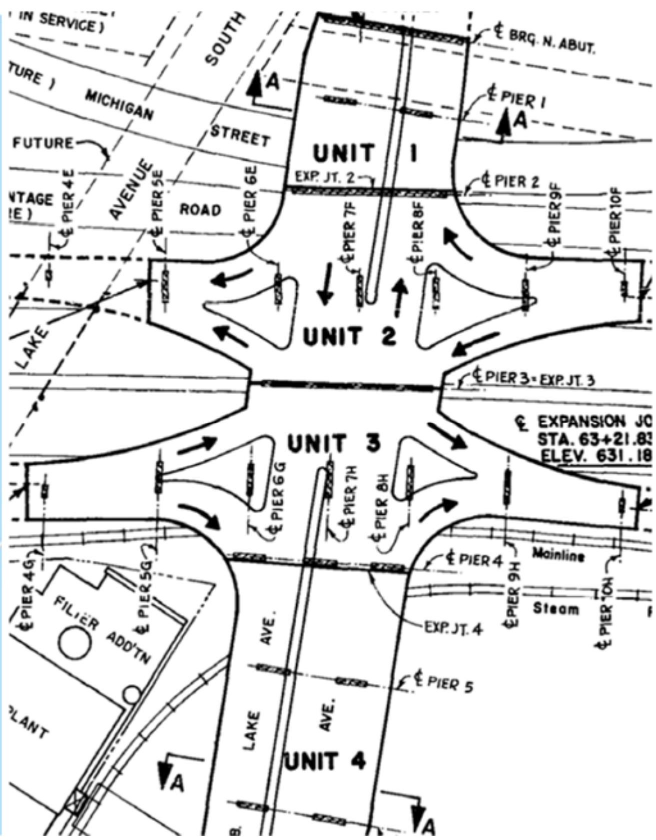


Figure A2: Box Girder units

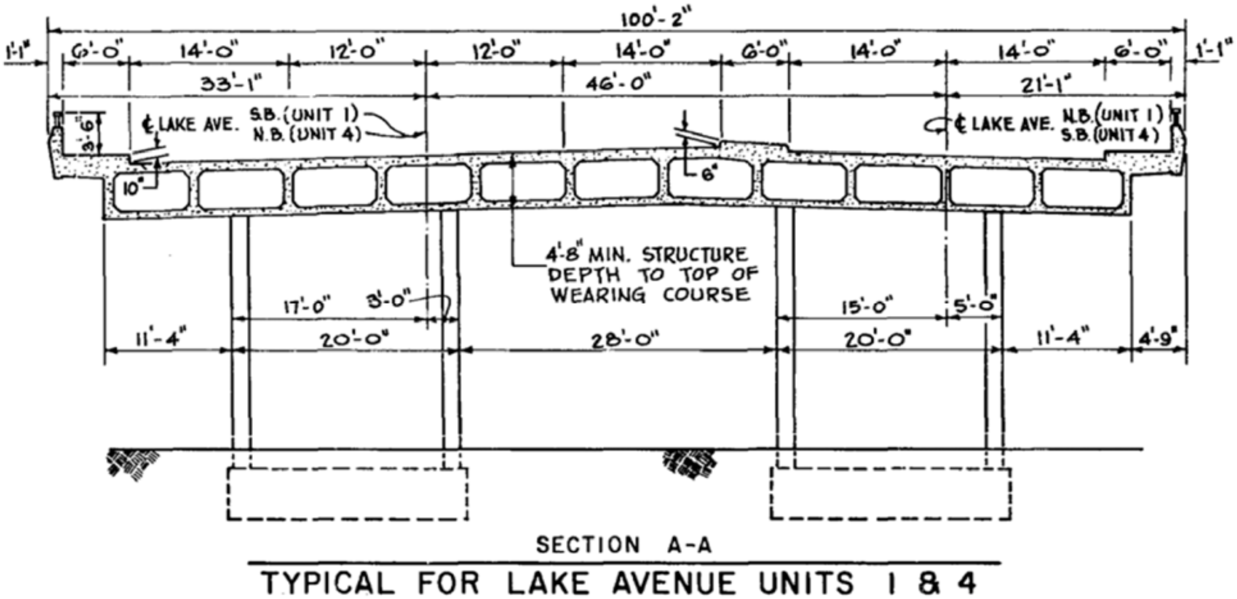


Figure A3: MnDOT Bridge 69816 general cross section

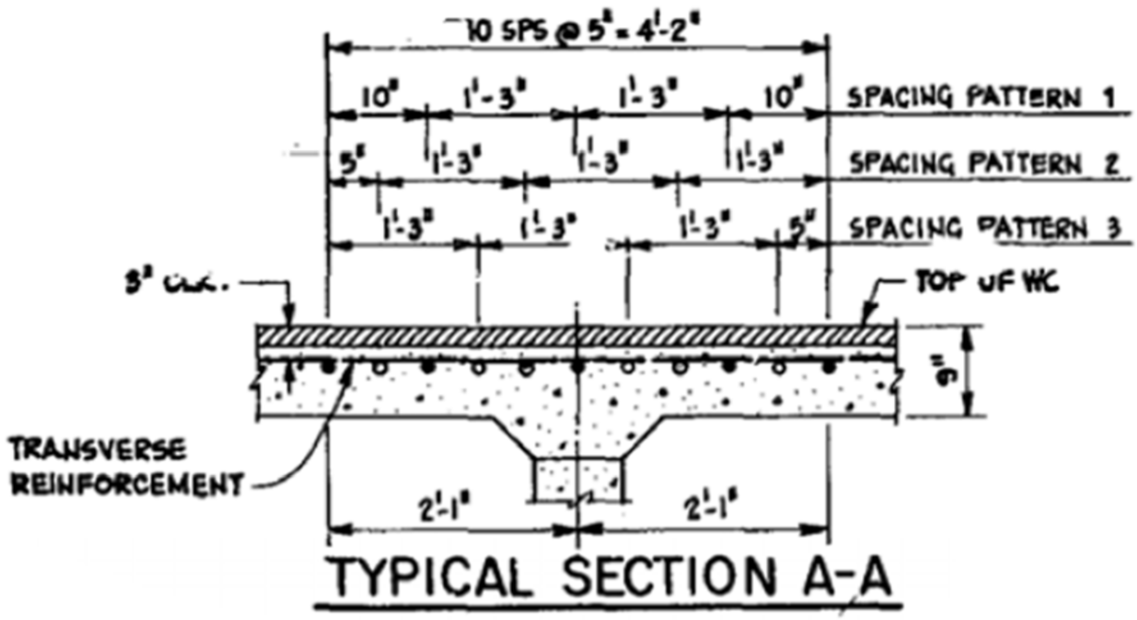


Figure A4: Showing top slab reinforcement and 3-inch top concrete cover (1" in structural slab and 2-inch additional provided by concrete wearing course). The top reinforcement is epoxy coated in accordance with 1982 specifications.

In 2017, MnDOT's District 1 and the centralized MnDOT Bridge Office identified the bridge as a candidate for major preservation. Major preservation often involves bridge expansion joint replacement and concrete wearing course replacement with deck patching. At the time, no chloride data was available but a recent chloride modeling and prediction research project was underway. A chloride coring plan was developed as shown in the following figure. The plan was developed to strike a balance between an abundance of cores and too small a statistical sample to be relevant. The MnDOT maintenance crews obtained the cores under the following guidance: Use two to three inch diameter cores (3-inch preferred) to a minimum depth of 6-inches, label each core as to location and number identified on the plan, and use handheld GPR to identify both reinforcement and top concrete cover prior to coring.

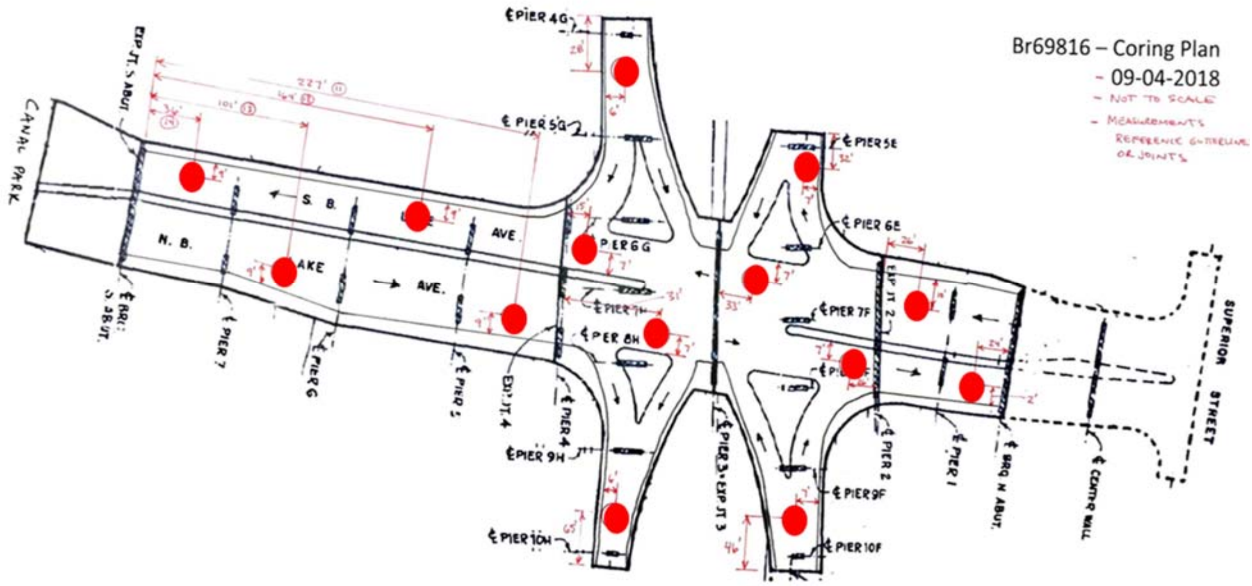


Figure A5: On September 2018, 14 cores were obtained as a representative sample based on the above coring plan.

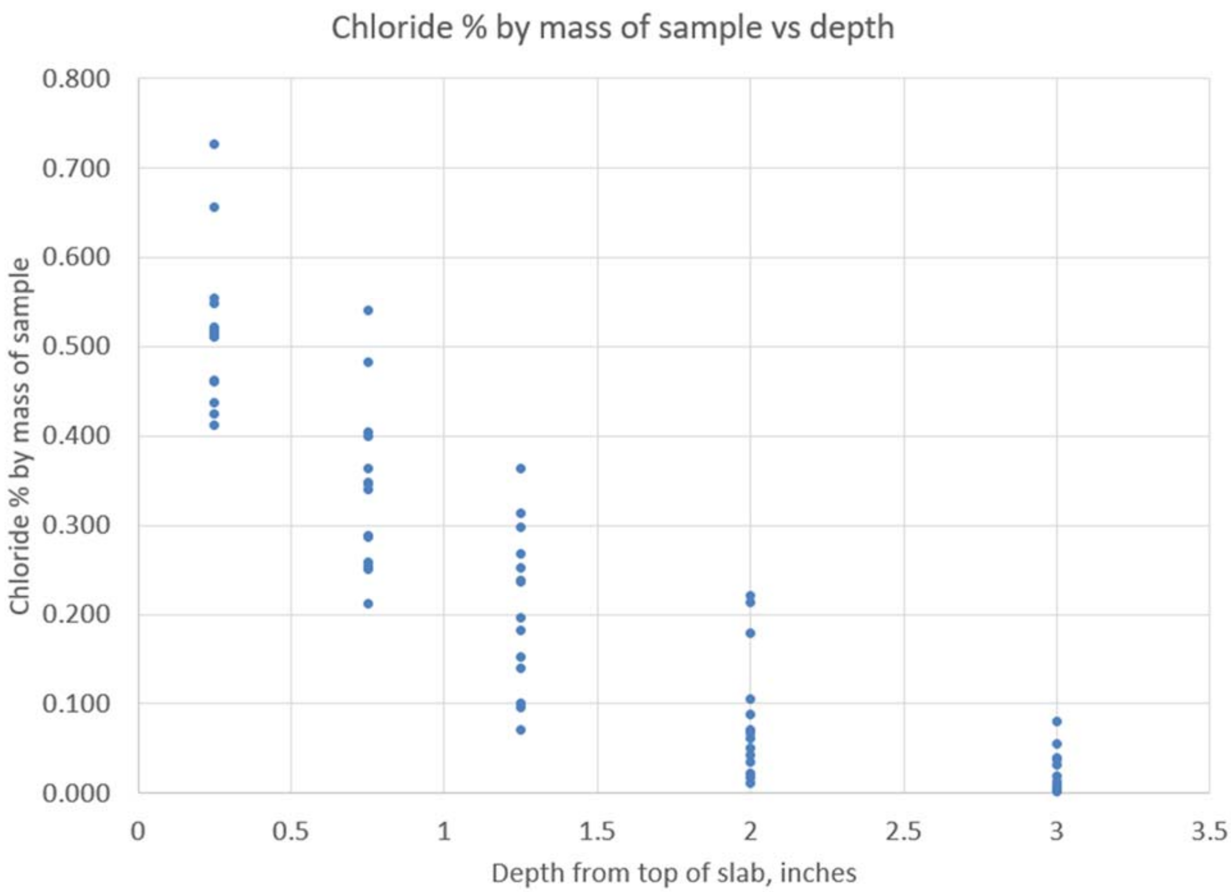


Figure A6: Resultant chloride profiles. At a rebar depth of 3-inches, 50% of chloride cores show chloride levels exceeding the traditional accepted chloride limit of 0.35% by mass of sample for uncoated reinforcement.

As mentioned earlier, MnDOT had been funding research into chloride modeling and as of May 2019 had completed its modeling software program. This software is an excel based spreadsheet that uses finite difference with Ficke's 2nd Law of diffusion. Although not unique on principle, the program conception is focused on many of the prediction activities a bridge deck preservation engineer would want to model. The excel program, called Chloride Diffusion Preservation Modeling (CDPM), and corresponding report is available on MnDOT's research website at:

Report 201824: http://dot.state.mn.us/research/reports/2018/201824.pdf
CDPM Program: http://www.dot.state.mn.us/research/reports/2019/CDPM_v0.92.xlsm
CDPM Program Instructions:
http://www.dot.state.mn.us/research/reports/2019/CDPM_Instructions.pdf

The chloride profiles were averaged amongst the 14 samples and plotted in the CDPM version 0.92 program in a chart of "Chloride versus Depth". The known chloride average plotted in this chart is used as a match point in the program. In other words, the user can iterate on diffusion coefficient to create a model prediction which closely aligns with the chloride profile obtained in the sample year. This is a general calibration of the apparent diffusion coefficient and surface chloride loading. Once the diffusion coefficient and surface chloride calibrations are made in the program, the user can enter in different preservation actions and instantly see the results in a plot of “Chloride versus Time”. The “Chloride versus Time” chart can plot chloride levels at the top-most rebar for up to 100 years of life.

Three different models were run using the program, resulting in a total of 13 different trial runs on the bridge. The first model was used to calibrate the diffusion coefficient and surface chloride loading to the known chlorides. Due to the scatter in chloride data, a range of +/- 50% on the diffusion coefficient was used to understand the best parameters to capture scatter in the chloride data. In addition, the surface chloride loading assumption was varied in 3 values: 0.90% Chl, 0.60% Chl, and 0.70% Chl. Figure A7 illustrates these variations in diffusion coefficient and surface chloride loading.

The CDPM program also generates a plot of “Chloride versus Time” which is shown in Figure A8. The depth at which the chloride is taken may be customized, but by default the chloride level versus time is plotted at the top level of rebar. Figure A8 shows the effect of chloride diffusion coefficient variation and surface chloride variation.

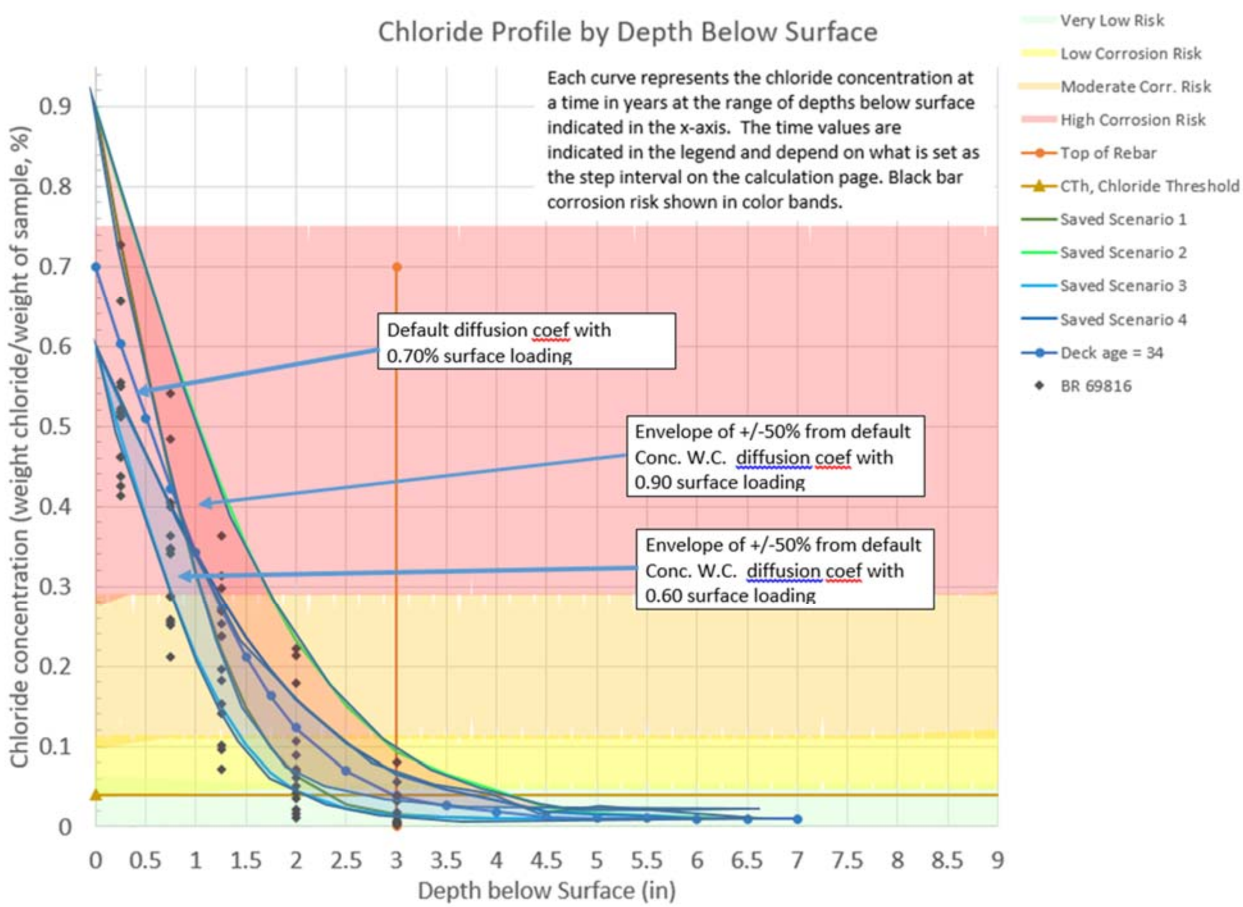


Figure A7: CDPM program prediction of chloride versus depth at 34 years after opening bridge to traffic. The black points represent the chloride data points gathered in 2018 (Year 34).

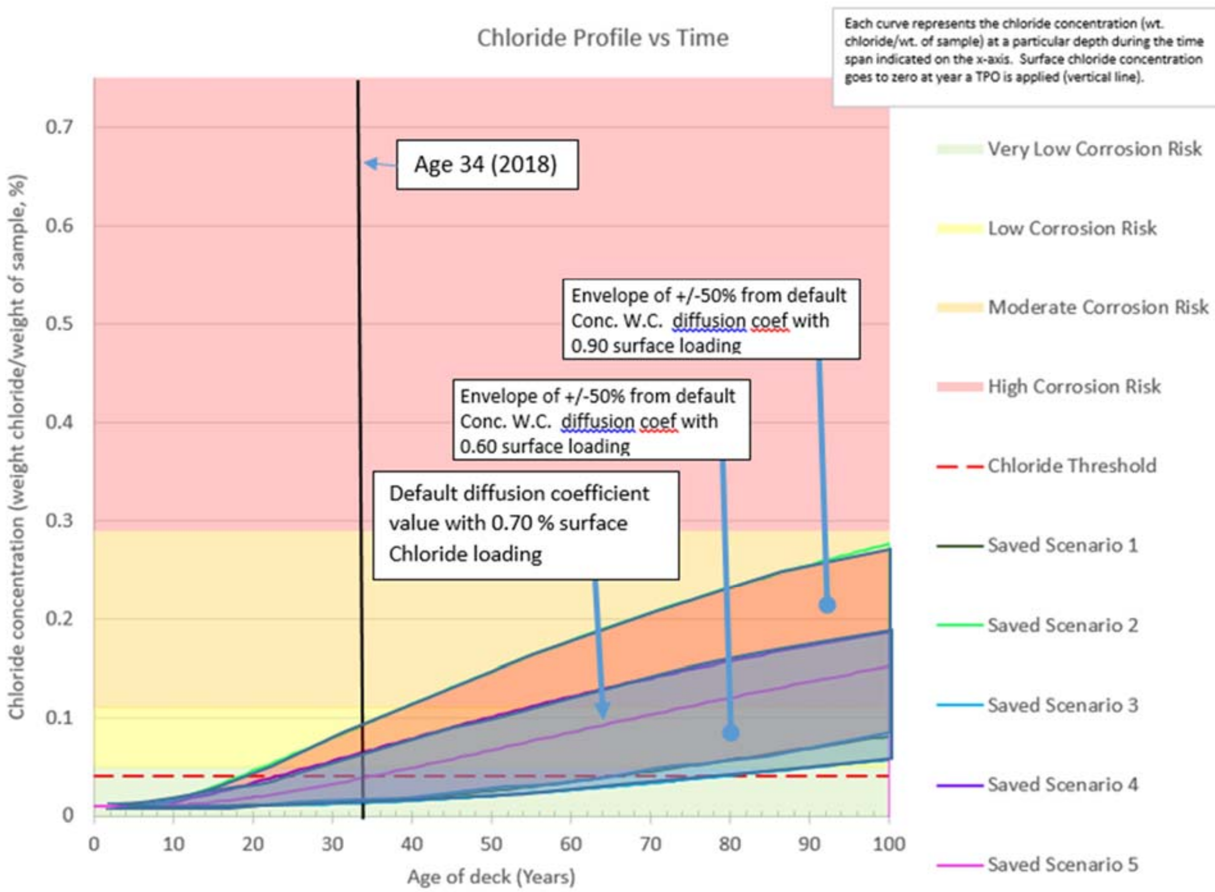


Figure A8: Chloride versus time at the top level of rebar based on CDPM predictions.

Based on the results shown in Figure A7, the default surface chloride loading of 0.70% and default diffusion coefficients were used moving forward with preservation modeling. The default diffusion coefficients were derived in the MnDOT research project by sampling and analysis of Minnesota bridge deck concrete. Modeling approaches by other methods may select the diffusion coefficient based on statistical analysis to ensure a 90% probability that the chlorides would not exceed the chloride threshold. MnDOT has not traditionally limited preservation actions based on chloride threshold. Instead, they have used it as a general guide as to when execute preservation actions of either a mill and overlay or localized patching only. MnDOT deck replacement decisions are often solely based on deck chaining data and prior patching history independent of chloride sampling.   Preservation timing analysis will be illustrated in the next few figures.

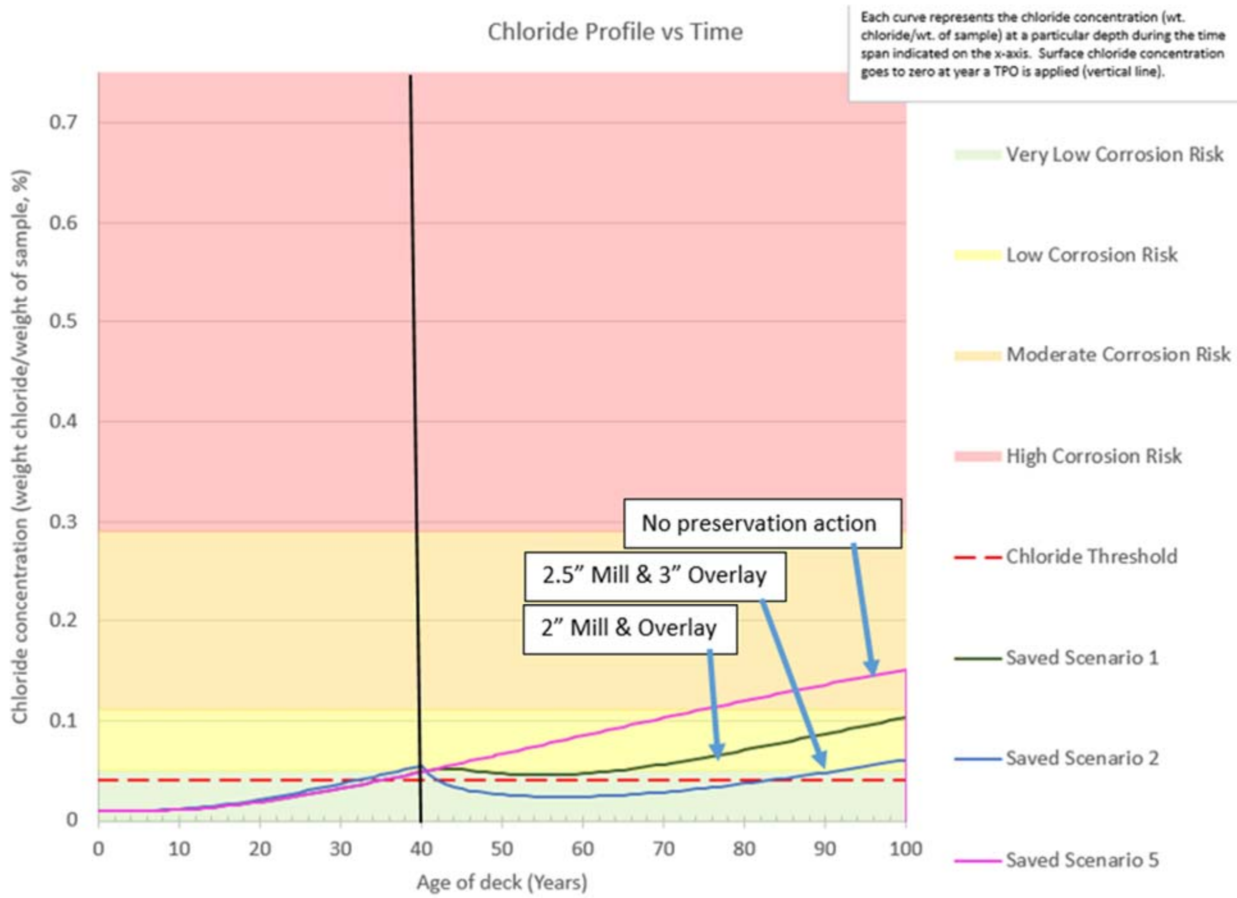


Figure A9: CDPM prediction of chloride at top of rebar.

Figure A9 illustrates the CDPM program predictions for chlorides at the top of rebar based on several scenarios. All scenarios assume the default diffusion coefficient and a surface chloride loading of 0.70% chloride. Scenario 5 illustrates the effect over time of taking no action. Scenario 1 illustrates the effect of milling off the existing 2-inch concrete wearing course and replacing in kind in year 2024 (40 years in service). It can be noticed that this preservation action blunts the rebar-level chlorides until it returns to original levels roughly around year 65.

Scenario 2 illustrates milling off not only the existing concrete wearing course, but also ½” of structural slab concrete, effectively removing more of the chloride concentrations in the top of the deck. For Scenario 2, the concrete overlay is placed back thicker than original at 3-inches for a ½” profile raise. This thicker concrete overlay would have greater rigidity and enable greater chloride buffer to the reinforcement for new chlorides. This action would, however, require load rating verification.

In addition to a new surface chloride buffer, further benefits can be seen for both mill and overlay scenarios. Recall that the depth of rebar is actually 3” prior to milling. The milling action modeled would have stopped above the rebar level. The effect of a new, chloride free concrete wearing course is clearly seen in Figure A9 to “wick up” chlorides and reduce the concentrations at the level of rebar for some time. In other words, chloride diffusion in the model is also occurring upwards into the new chloride-free wearing course.

This behavior is being tested on a MnDOT bridge in the coming years, but in industry discussions other states have observed this trend.

These scenarios can also be illustrated in a plot of Chloride versus Depth. This plot is presented in Figure A10 showing the predicted chloride profile in year 42 (2026) two years after the action of a 2-inch mill and 2-inch concrete wearing course replacement in year 2024. The mill and overlay prediction is shown alongside the predicted chloride profile if no preservation action is taken. One can also see the slight reduction in chlorides at the rebar level after 2 years due to the upwards diffusion of chlorides into the concrete wearing course.

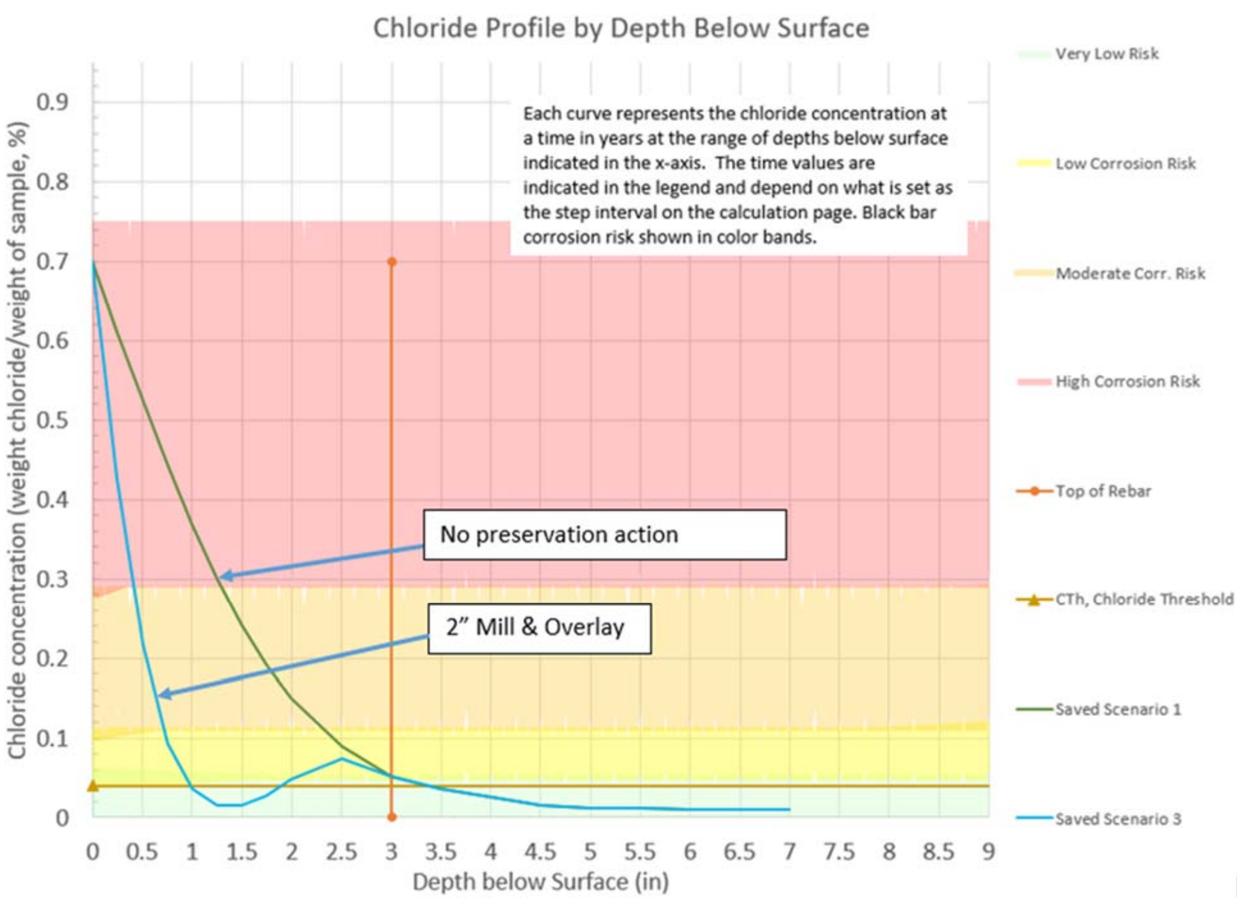


Figure A10: Chloride versus depth predictions in year 2026, 2 years after the proposed project execution.

The CDPM “Chloride versus Depth” plot may also be used to show changes in to predicted chloride profile over time. Focusing on the preferred action of a 2-inch mill and overlay, the change in chloride profile may be seen in Figure A11 at various years. In year 40 the existing 2-inch concrete wearing course is replaced. This reduces the chlorides slightly at the depth of rebar in the years following the preservation activity. The surface chloride loading remains constant because the bridge continues to be in service and in a salting environment. The high surface loading quickly starts to dominate the chloride levels in the new 2-inch concrete wearing course because diffusion is largely influenced by the gradient of chloride. For reference, the black data points represent the 2018 samples of chloride level in this figure.

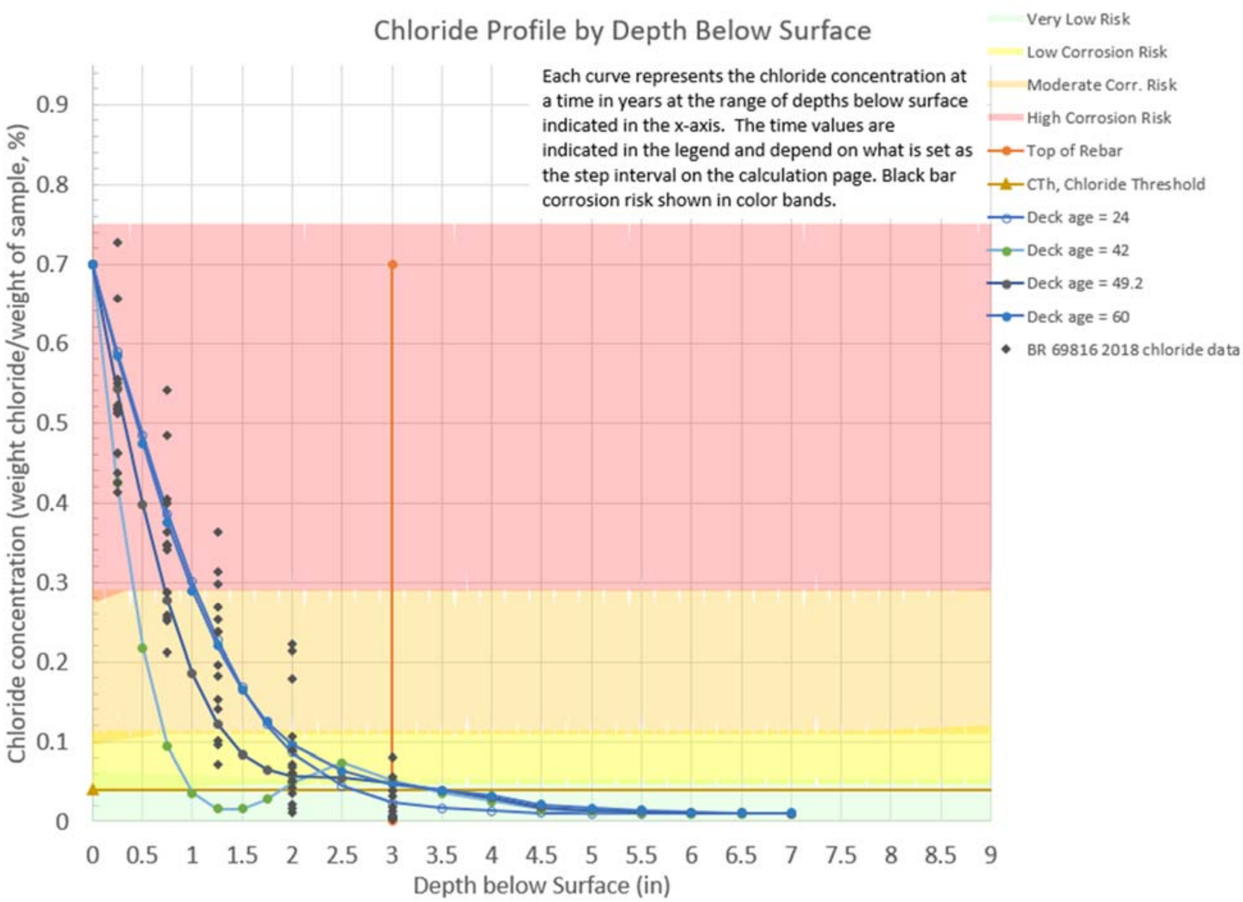


Figure A11: Chloride versus depth predictions based on a 2-inch mill and 2-inch concrete wearing course replacement in year 40.

This example illustrates an application of using chloride data. Variations in chloride profile, concrete cover, chloride surface loading, and salting levels will make all modeling efforts short of truly accurate predictions. While there are limitations to every assessment approach, MnDOT's CDPM program is a tool that offers a relatively simple way to incorporate chloride profile data and make better decisions on bridge deck preservation actions and timing.

Oregon DOT Salt Creek BR2071A

Background:

BR02071A at M.P. 42.93 on Hwy 18 (Route OR58N) was constructed in 1965 and is a combination RCBG and steel plate girder design. A unique design feature is the steel span bearing on a concrete cantilever approximately 15' off of each bent. An early application of post-tensioned rods is utilized to provide reinforcement where the steel bears on the cantilevers. Common to RCBG design of this era is a large amount of negative moment reinforcement in the top mat of the deck over the bents.

The deck has been having spalling issues for several years that the bridge crew has been chasing with patching efforts and a thin epoxy overlay that has continued to crack and spall as corrosion of the reinforcement continues. Chloride tests were conducted in September of 2015, but the results were inconclusive as not enough depths were tested to obtain a proper chloride profile and the powder sampling method was subject to inaccuracies.

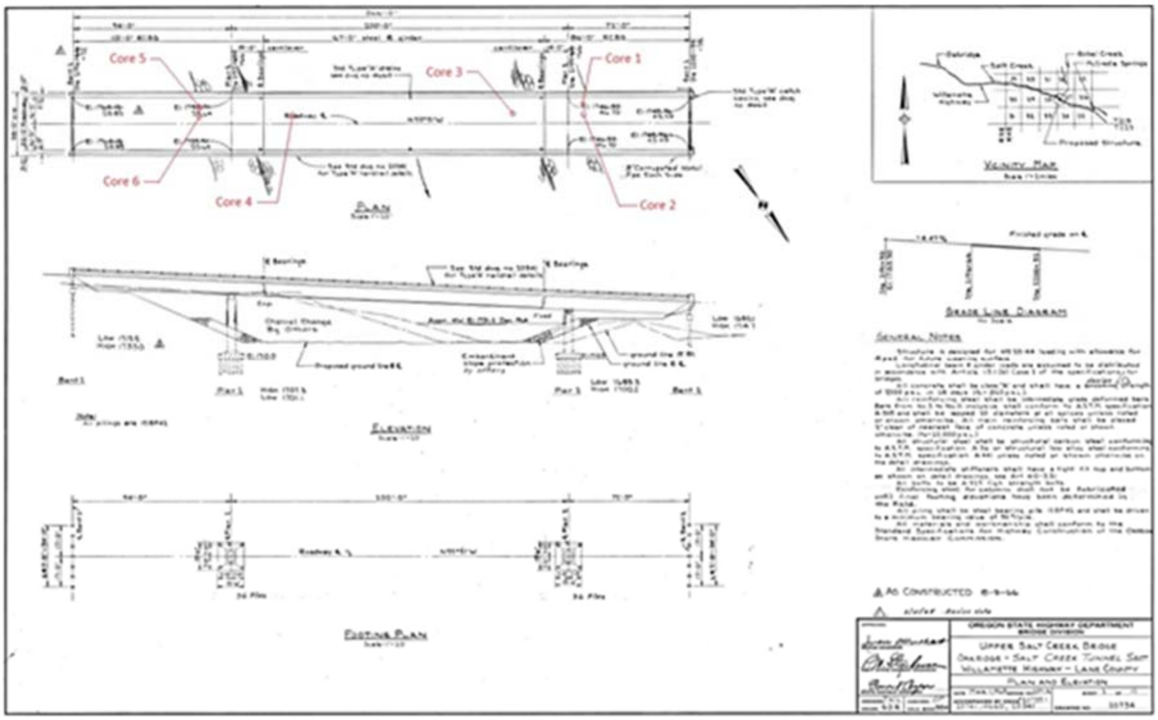
BR2071A: Damage on Deck of Span 1

Sampling and Testing:

A more comprehensive set of sampling and testing was performed in March of 2016 which consisted of 6 cores taken from the deck.

All 6 of the cores were taken from the eastbound lane due to ease of lane closures. This was deemed acceptable as the visible defects on the surface were spaced fairly evenly throughout the width of the deck.

Cores were tested for chlorides according to ASTM C1152/C1152M at ½" depth increments starting at the deck surface after removal of the epoxy wearing surface.



Salt Creek BR02071A Core Locations

Results:

Sample #	Cf, %								Cmax, %	Dc, in^2/yr
	0-0.5"	0.5"-1"	1"-1.5"	1.5"-2"	2"-2.5"	2.5"-3"	3"-3.5"	3.5"-4"		
1	0.192	0.108	0.063	0.029	0.011	n/a	n/a	n/a	0.229	0.0123
2	0.187	0.134	0.066	0.043	0.023	n/a	n/a	n/a	0.232	0.0172
3	0.184	0.143	0.102	0.047	0.020	n/a	n/a	n/a	0.243	0.0211
4	0.243	0.113	0.042	0.028	0.010	n/a	n/a	n/a	0.248	0.0101
5	0.220	0.187	0.088	0.052	0.014	n/a	n/a	n/a	0.276	0.219
6	0.103	0.086	0.056	0.041	0.021	n/a	n/a	n/a	0.145	0.0225

Average	Cmax, %	Dc, in^2/yr
Average	0.229	0.0175

Cf = chloride concentration by weight of sample
Cmax = chloride surface concentration
Dc = diffusion coefficient

Note: At time of analysis ODOT was ignoring the 0-0.5” value when calculating surface concentrations and diffusion coefficients.

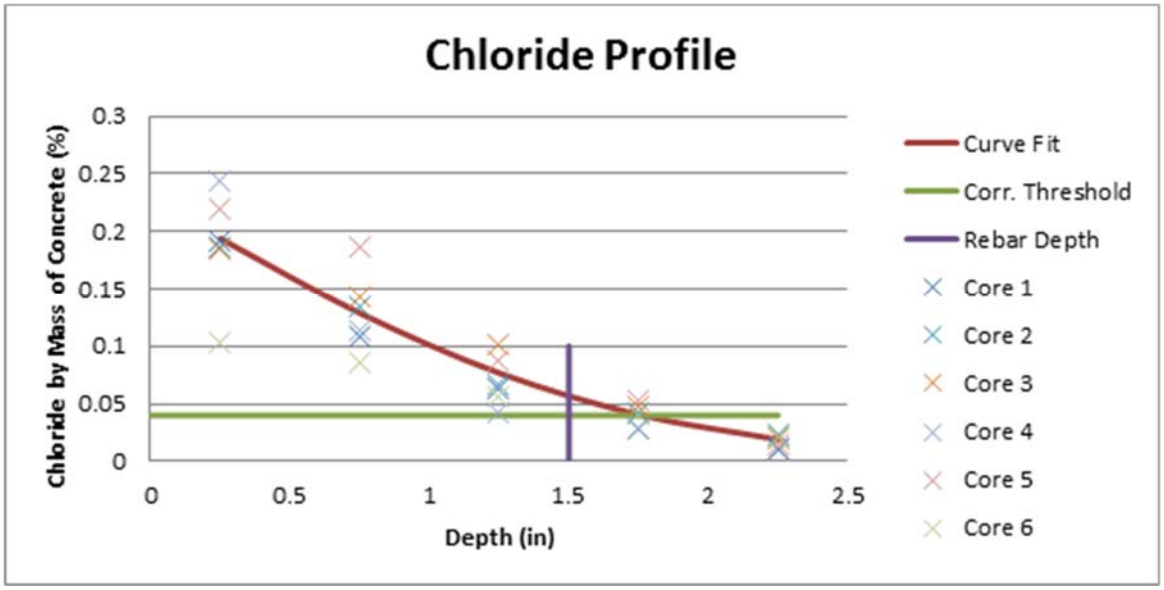


Figure 21: BR02071A Chloride Concentrations (Curve Fit, 6 Deck Cores)

Recommendations:

The deck shows chloride contamination throughout. Even though most of the distress is shown in span 1, there are corrosion induced cracks showing through the rest of the deck and it is a matter of time before the entire deck is in the same condition as span 1.

Contaminated concrete should be removed and replaced with new material from the entire deck to a depth of 2” to ensure that existing chlorides below removal depth don’t exceed the chloride threshold at the reinforcement level as they diffuse back into new material.

Methods of removal and placement of repair material would have to be carefully considered given the cantilevered spans. Further analysis should be performed on whether rehabilitation of the deck is preferable to replacement of the bridge.

It is advised to add an additional 1” of cover above existing grade creating a total of 2.5” clearance from reinforcement matching current design standards to ensure the overlay meets an assumed minimum service life of 30 years.

Oregon DOT Hwy 1 over Hwy 273
BR09259 & BR09259A

Background:

BR09259 and BR09259A at M.P. 5.32 on Hwy 1 (Route IS5) are pre-stressed concrete girder design constructed in 1965. An overlay was placed on the decks sometime between 1976 and 1978 using the “Iowa method” which utilized a very dry and dense concrete mix to help protect against chloride ingress. The decks have spalls and cracks throughout with a large concentration of spalls at the joints with the approach panels due to corrosion of shear dowels in combination with traffic impact of the headers.

BR09259 (Southbound)

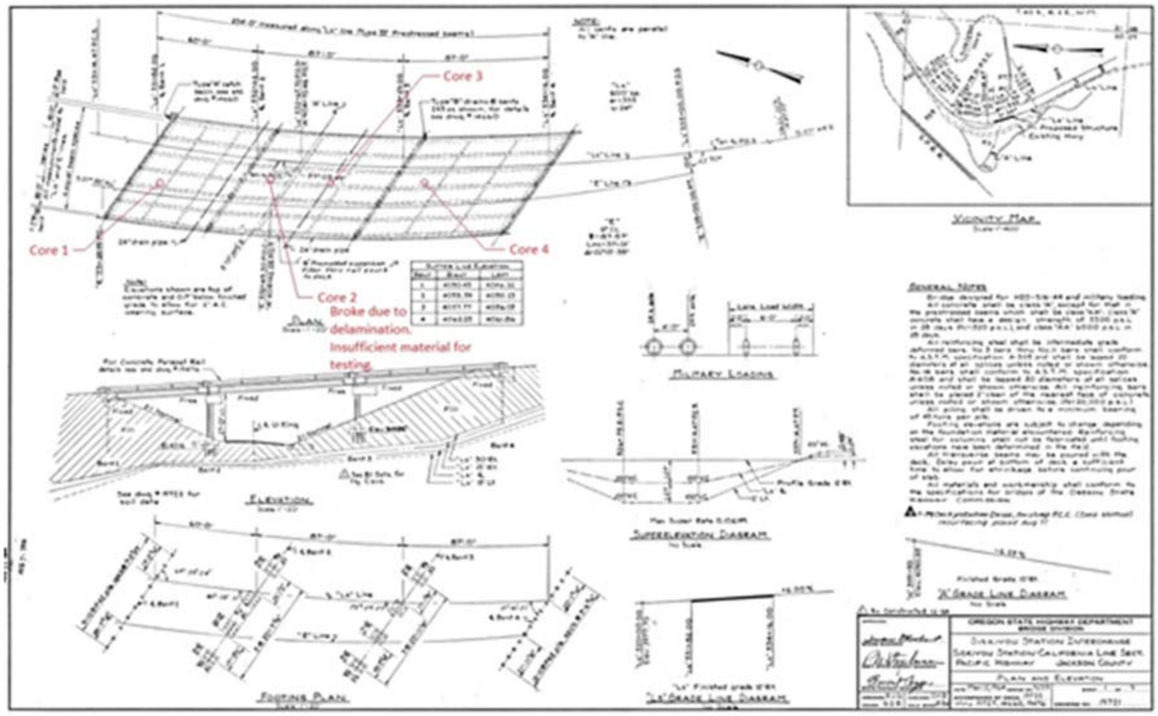
BR09259A (Northbound)

Sampling and Testing:

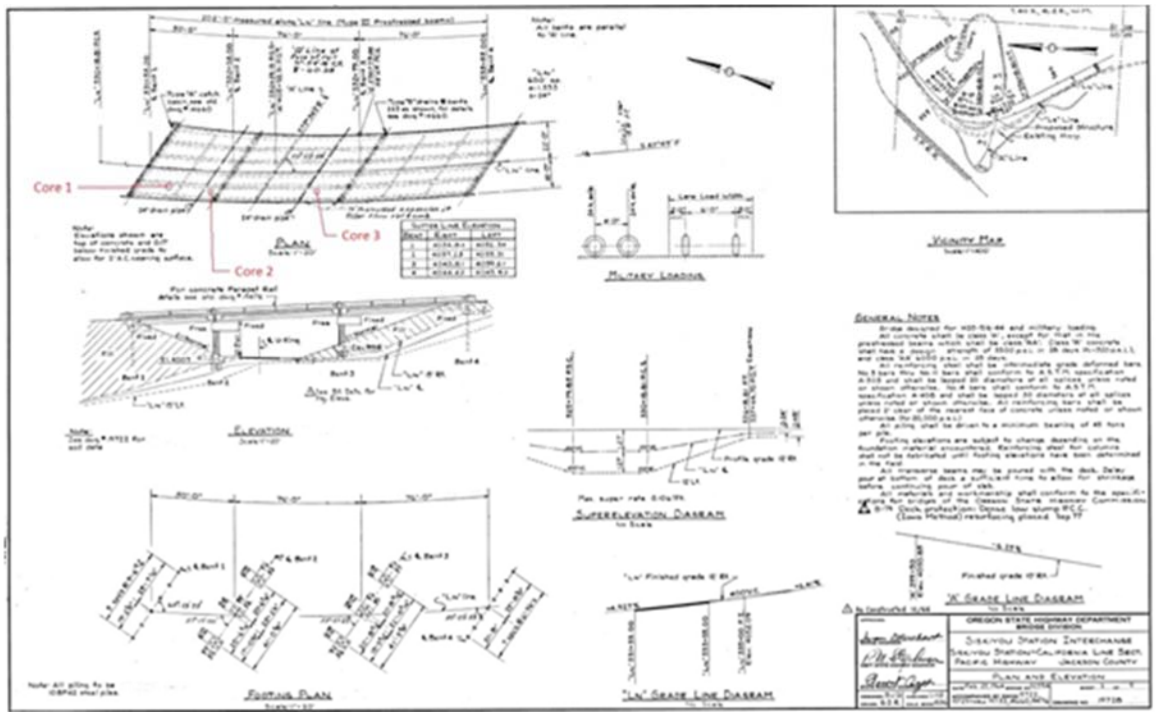
Sampling and testing was performed in April of 2016 which consisted of 4x4” cores taken from the decks.

All 7 of the deck cores were taken from the right travel lane due to ease of traffic control. One core from 09259 broke shallow due to a delamination and was not sent in for testing. 3 Cores were obtained from 09259A due to time constraints. The overlay portion from core 1 from 09259A was destroyed on extraction and not tested. Core 3 from 09259A broke shallow and did not yield any parent material to test.

The 6 deck cores were tested for chlorides according to ASTM C1152/C1152M at ½" depth increments starting at the deck surface.



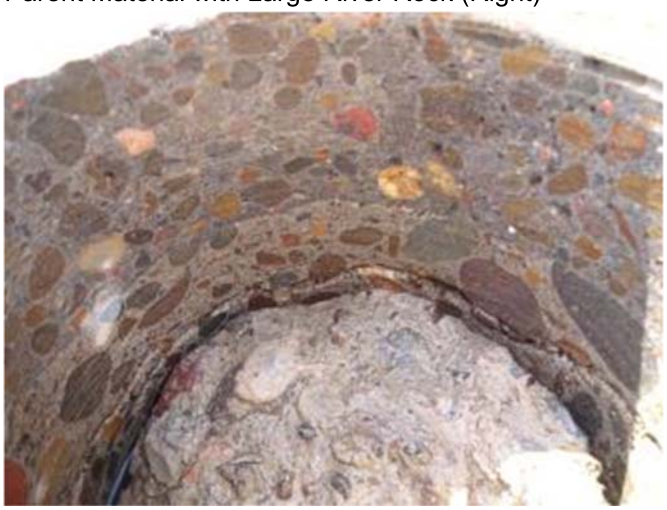
Hwy 1 over Hwy 273 SB BR09259 Core Locations



Hwy 1 over Hwy 273 NB BR09259A Core Locations

BR09259 Repair Area at Deck-Impact Panel Joint

BR09259: Core Showing Overlay (left),
Parent Material with Large River Rock (Right)



BR09259A: Core Hole Showing Relatively Shallow Portion of Overlay
With Corrosion Induced Fracture at Top Mat Plane

Results:

Hwy 1 Over Hwy 273 SB BR09259

Sample #	Cf, %								Cmax, %	Dc, in^2/yr
	0-0.5"	0.5"-1"	1"-1.5"	1.5"-2"	2"-2.5"	2.5"-3"	3"-3.5"	3.5"-4"		
1 Overlay	0.416	0.200	0.122	0.088*	n/a	n/a	n/a	n/a	0.475	0.0129
1 Parent	n/a	n/a	n/a	n/a	0.088	0.076	0.048	0.033	0.533	0.0362
3 Overlay	0.858	0.368	0.129	0.104*	n/a	n/a	n/a	n/a	0.798	0.0114
3 Parent	n/a	n/a	n/a	n/a	0.085	0.077	0.049	0.047	0.528	0.0325
4 Overlay	0.767	0.704	0.211	0.090*	n/a	n/a	n/a	n/a	1.250	0.0143
4 Parent	n/a	n/a	n/a	n/a	0.086	0.056	n/a	n/a	0.378	0.0352

Average, Overlay	0.841	0.0129
Average, Parent Material	0.478	0.0346

*Sample contains both overlay and parent material, not used in numerical analysis

Hwy 1 Over Hwy 273 NB BR09259A

Sample #	Cf, %								Cmax, %	Dc, in^2/yr
	0-0.5"	0.5"-1"	1"-1.5"	1.5"-2"	2"-2.5"	2.5"-3"	3"-3.5"	3.5"-4"		
1 Parent	n/a	n/a	n/a	0.320	0.157	0.105	0.066	0.058	1.030	0.0276
2 Overlay	0.793	0.168	0.073	n/a	n/a	n/a	n/a	n/a	0.364	0.0124
2 Parent	n/a	n/a	n/a	0.101	0.050	0.059	n/a	n/a	0.368	0.0262
3 Overlay	0.767	0.109	0.109	0.046	n/a	n/a	n/a	n/a	0.256	0.0198

Average, Overlay	0.310	0.0161
Average, Parent Material	0.699	0.0269

Cf = chloride concentration by weight of sample
Cmax = chloride surface concentration
Dc = diffusion coefficient
Note: At time of analysis ODOT was ignoring the 0-0.5” value when calculating surface concentrations and diffusion coefficients.

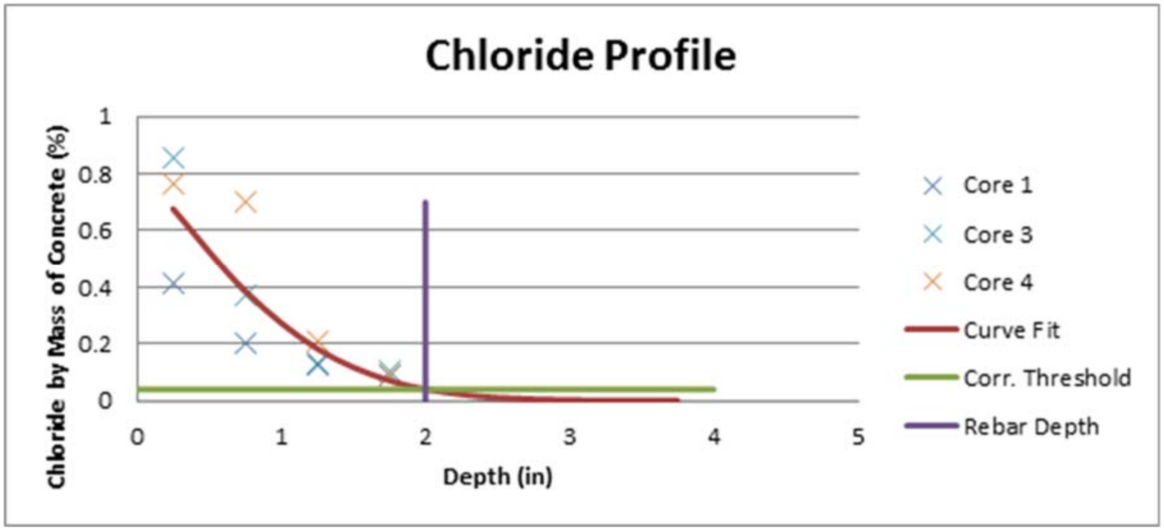


Figure 22: BR09259 Chloride Concentrations of Rigid Overlay (Curve Fit, 3 Samples)

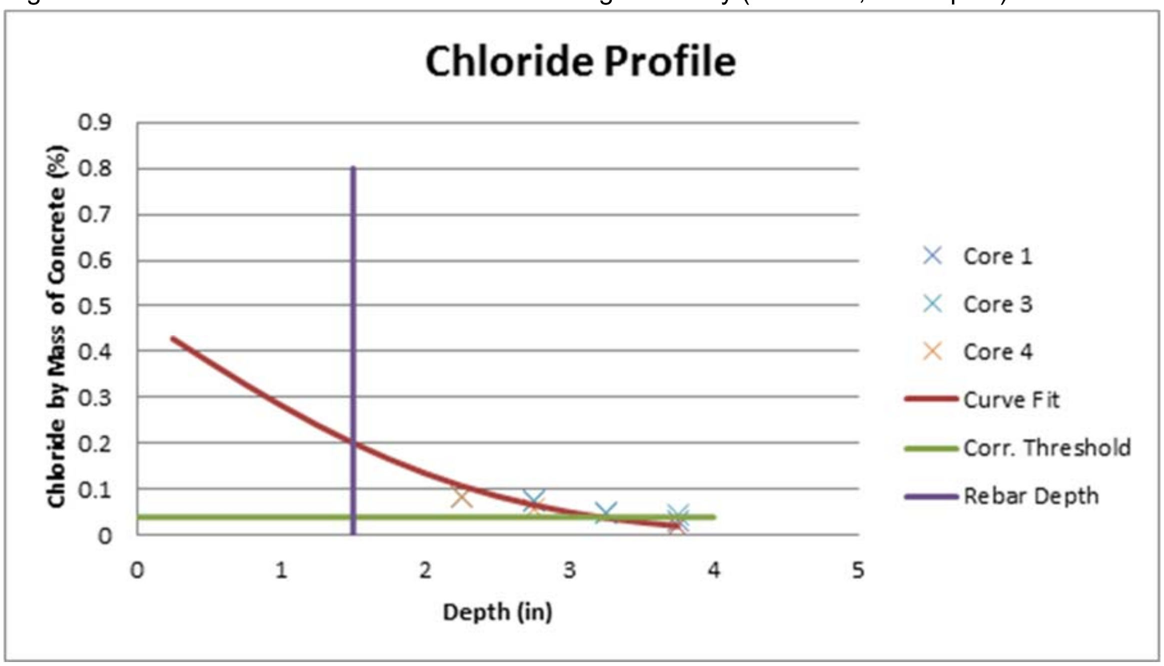


Figure 23: BR09259 Chloride Concentrations of Parent Material (Curve Fit, 3 Cores)

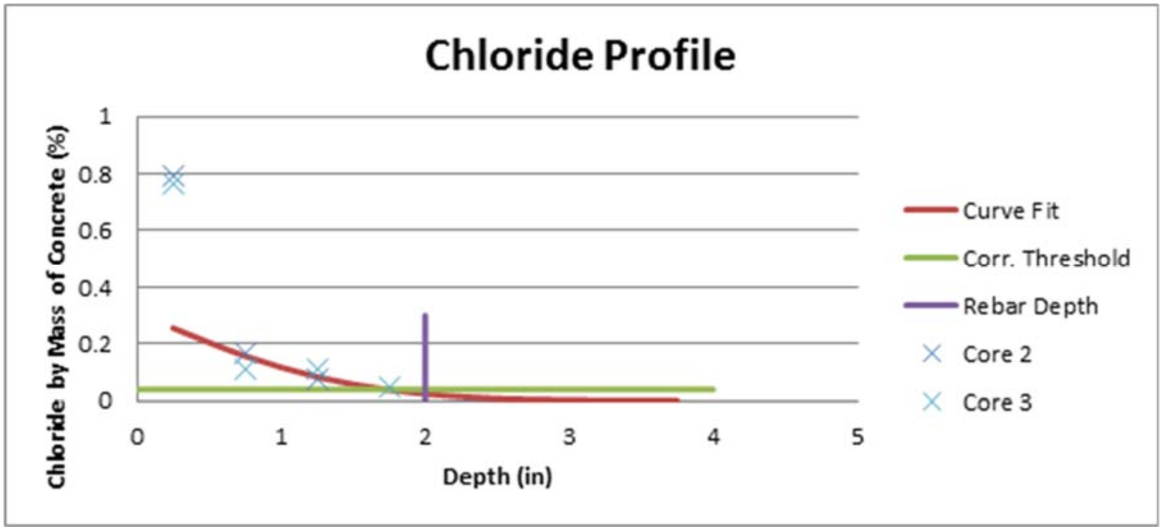


Figure 24: BR09259A Chloride Concentrations of Rigid Overlay (Curve Fit, 2 Cores)

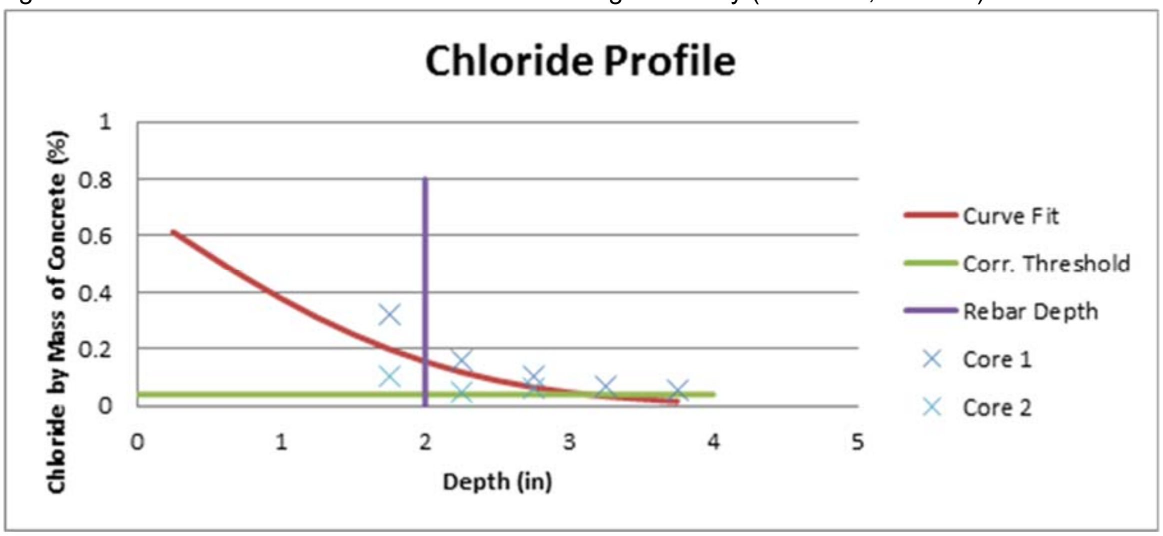


Figure 25: BR09259A Chloride Concentrations of Parent Material (Curve Fit, 2 Cores)

Analysis:

It should be noted that data points nearest the surface were not used for curve fitting in this analysis as these data points often do not agree with an ideal model. ODOT now considers the data set both with and without these data points before determining a course of action.

These decks show chloride contamination above the corrosion threshold at or approaching the level of reinforcement in the overlays. The parent concrete has contaminated concrete down to about 3”-4” below the surface of the concrete. All of this contaminated material would need to be removed in order to ensure delamination does not continue and chloride does not migrate toward the bottom mat. To remove this much material, it is assumed that hydro-demolition would be the least damaging to reinforcement and the most cost effective method of removal.

The impact panels also require extensive repair and detailing modifications to avoid spalling of dowels in the future.

Assuming the original construction plans were followed and the “Iowa Method” overlay was constructed with 2” cover over the rebar, the current deck thicknesses are 7.5”. This method of construction means there is a variable thickness in the overlay as spalls were repaired. This was observed in the core samples.

The density of the overlay material would require relatively high pressure hydro-demolition that would likely punch through the additional 3.5” of parent material due to a combination of being older (harder, brittle), less dense, and having large smooth aggregate.

Given this combination of corrosion and constructability issues, replacement of the decks and impact panels on BR09259 and BR09259A is recommended.

Given the history of this area, alternate construction materials or practices which elevate corrosion resistance or eliminate/minimize chloride intrusion should be explored when replacing these decks. (ODOT has decided to place a polyester polymer wearing surface on the new decks after initial curing has completed).

Appendix B – Boilerplate Statement of Work

(This document is provided as a general outline for specifying concrete sample collection and subsequent chloride concentration testing. It is up to the specifying Agency to determine desired outcomes and tailor language to fit its needs. This document does not provide terms and condition language as this language varies by Agency. Boilerplate instructional language appears in orange italics.)

(The Contract may include as attachments, in a format according to your Agency's standards, a map showing structure locations, traffic control plans, and as-built plans showing plan & elevation views as well as reinforcement details for the elements being tested. If any special access or environmental controls are required, right of way maps, right of entry documents, access management or erosion control plans may also be included.)

TASKS, DELIVERABLES and SCHEDULE

1. Submittals

1.1 Document Review, Project Coordination, Core Location Selection

Consultant shall review Agency provided, bridge plans and deck conditions to determine appropriate core locations to take core samples that will evaluate extent of salt exposure. Consultant shall take into account reinforcement details and deck thickness to minimize damage to the structure.

Locations and samples are to:

1. Be representative of salt exposure. *(Add more specific language if desired. i.e. half of samples within a wheel path and half outside of a wheel path. This may be supplemented by an appendix if drawn plans are desired.)*
2. Consider drainage and take samples in locations that represent both the most extreme and the least extreme deicer exposure. *(Add more specific language if desired. i.e. all samples between fog lines or a certain number of samples taken from the shoulder. This may be supplemented by an appendix if drawn plans are desired.)*
3. Consider reinforcement details and avoid taking samples in areas that have small spacing such as areas with additional negative moment or railing reinforcement.
4. Consider traffic control and impact to the public. It is appropriate to sacrifice some of the drainage considerations to minimize impact to the travelling public and hazards introduced when changing traffic control. It is typically appropriate to take all samples

from a single lane of a 4 lane structure unless there is reason to believe other lanes may have a different exposure. *(Delete or add more specific as site conditions dictate)*

Provide a patching material according to: *(Insert name of qualified products list and a web link or a list of Agency approved patching materials as applicable)*

Deliverables:
Consultant shall submit the selected core locations on bridge plans for Agency approval *(Insert desired review time. 30 days is typically reasonable.)* calendar days prior to collection of core samples.

Consultant shall submit procedures for completing all field collection work and all equipment and materials necessary to complete the work as specified. *(Insert appropriate document format if not indicated elsewhere in Contract boilerplate language)*

2. Collection of Core Samples

2.1 Core Removal Field Work

Consultant shall take the required number of (4) inch core samples (nominal bit O.D.), *(Review as-built details for constructability. The core diameter should ideally be 2 times the maximum aggregate size if possible.)* capture slurry and dispose of off-site according the *(Insert applicable Agency Specifications for Construction covering waste management)* from the locations specified in Appendix 1 below.

Consultant shall locate reinforcement by an industry approved method and ensure Consultant shall not cut steel reinforcement. Consultant shall submit cut sheets of all reinforcement locating equipment and only take cores from sound concrete. Consultant shall use a chain drag or sound concrete with a 16 oz. hammer to determine if the location is sound and suitable for sampling and shift core locations as necessary. If a removed core is found to be fractured, another sound core shall be obtained from a similar location on the structure.

Consultant shall record as-built core locations.

Consultant shall ensure that removed Cores are at least 2” longer than the bottom of the deepest chloride test for processing. Consultant shall cut cores 3” deeper than the bottom of the deepest chloride test to be performed, except when deck thickness or bottom mat reinforcement details do not permit, due to uneven fractures when breaking the core out. Consultant shall leave at least 1” between the core cutting depth and the deck soffit.

Consultant shall break cores with a wedge or masonry chisel and a hammer taking care not to damage the sample. Carefully remove the core without damaging. Consultant shall place each core in its own sealed bag with appropriate labels. Typically, this can be accomplished by using two standard screwdrivers as chopsticks or a piece of tie wire as a lasso.

Consultant shall ensure the following process is followed:

1. Remove water from the core hole,
2. Take a picture of the overall location of the core, a close-up of the core, and a close-up of the core hole at the largest angle possible to capture the condition of the hole's wall,
3. Take additional photos of noteworthy features such as fractures, spalls, and overlay conditions. *(*Take a photo with a tape measure indicating overlay thickness.*) (If applicable)*
4. Provide pictures with the chloride content report or data analysis.
5. Patch core holes according to the patch material manufacturer's recommendations.
6. Do not allow traffic to drive over the core locations until the patch material has set.
   A. Using hot water in the concrete mix can greatly reduce set times, but also reduces workable times. Indirect heat from a weed burner or a work truck exhaust can also reduce set times

*(*Deliverables: Consultant shall ensure field samples *(*are delivered to*) (*collected by*) (Insert laboratory name)* for testing by *(Insert date)*.*) (Use this deliverable if an Agency run or 3rd party lab is to be utilized. If an intermediate date is needed to avoid conflict with other work being performed on a structure, indicate date in this deliverable.)*

2.2 Traffic Control

Consultant shall provide traffic control according to *(Insert name of Agency traffic control handbook or reference traffic control plans by appendix. Insert web link if applicable.)*

*(*Consultant shall contact *(Insert name of appropriate trucking mobility entity)* with a highway restriction notice for scheduling of lane closures *(Insert requisite notice period)* days prior to scheduled work. The notice can be found at: *(Insert link)) (If applicable)*

Consultant shall contact applicable Agency parties for each work site *(Insert desired review time. 30 days is typically reasonable.)* calendar days prior to scheduled work as specified in Appendix 1 below. Consultant shall adjust their work schedule as necessary to avoid conflict with other work being performed on the *(*highway*)(*roadway*)*:

Consultant shall have at least one copy of the approved site specific traffic control plan on hand during sample collection.

(Deliverables:
Consultant shall provide the traffic control plans for each work site in the appropriate submittal and provide traffic control according to *(Insert Agency traffic control handbook name)*.

Note: Copied pages from the *(Insert Agency traffic control handbook name)* with all appropriate equipment and spacing highlighted is appropriate. If multiple work sites utilize the same traffic control plan, only one copy is necessary in the submittal.) *(For use with an Agency traffic control handbook.)*

3. Testing and Data Analysis

3.1 Core Processing and Testing

Mark the ¼" closest to the top surface of the core (not including any thin bonded epoxy wearing surface), cut and discard. Mark (½") *(Adjust if desired)* increments from the new top surface generated by the ¼" cut.

Carefully keeping a consistent naming convention throughout processing, cut (5) *(Adjust if desired)* slices on center of the (½") *(Adjust if desired)* markings, then crush and pulverize each sample slice to pass through a 850-μm (No. 20) sieve. (If a Portland cement or latex overlay is present note which slices contain overlay, substrate, or both materials. Cut, crush, and pulverize all overlay depths and 5 depths into the substrate material if core length allows.) *(If applicable adjust number of slices or indicate all overlay depths and 5 slices into substrate. It is important to note that structural overlay as-built depths often vary from what is listed on plans even if stamped "as-constructed")*

Test each sample according to ASTM-C1152/1152M or AASHTO-T260 and record results. *(Substitute listed test methods with ASTM C1218 if water soluble chloride testing is desired)*

3.2 Analysis and Reporting

Consultant shall graphically plot resulting chloride test data using the midpoint depths of the core slices from 3.1. Use resulting test data to calculate and graphically plot on the same figure the effective chloride surface concentration and diffusion coefficient using the midpoint depths of the core slices from 3.1, consistent with chapter 4 of the TSP2 Bridge Deck Chloride Testing Report: *(Provide a current web link to the NBPP: Bridge Deck Chloride Testing Report or insert appropriate excerpts for calculations.)*

For bridges with overlays perform separate curve fits for the overlay material and original construction material. Consultant is not to use samples containing both materials in calculations. Consultant shall adjust the depths to match the overlay interface if necessary.

Note: If not apparent on the bridge plans, the Agency will assist in determining an appropriate age of the overlay.

For the analysis, Consultant should assume:

- Constant chloride loading over the exposure period of the material.
- (• Chloride penetration into the original construction material after an overlay had been placed is negligible. Adjust exposure "age" of the base material to the year the overlay was placed.) *(If applicable)*

Consultant shall coordinate with Agency if data prove these assumptions invalid for a set of samples, by discussing other avenues of analysis before proceeding.

Consultant shall provide calculations and a graphical representation of the collected data and curve fit that shows the depth of the (shallowest reinforcement) *(If possible, a field survey of in place cover showing average depth +/- a standard deviation best describes risk of corrosion damage. This can be accomplished by GPR or cover meters and ground truthing. Take into account traffic control impacts, costs, and sampling rates when specifying.)* as called-out on the plans and the corrosion threshold as *(Insert appropriate chloride threshold for your geographic region. 0.04% by weight of concrete or 1.5 lbs/cu. yd. may be considered for mix designs not considered "high performance" [SCM modified] if no other threshold is indicated)*.

Deliverables:
Consultant shall provide a written report with as-built drawings, all photographs with a core log detailing relevant field data from Task 2.1, calculations, and graphical representations as specified by *(Insert completion date. Insert appropriate document format if not indicated elsewhere in Contract boilerplate language)*.

Appendix 1

Bridge Locations and Agency Contacts

Core Locations – Take *(Insert number of samples. If multiple numbers exist add a column to the following table)* cores from each the following structures:

Highway	Route	Structure #	Milepost	Year Built	Deck Notes

Contacts:

(Provide a list of Agency contacts for coordination)

Appendix C – QUANTIFYING BRIDGE DECK CORROSION RISK

BRIDGE DECK CORROSION RISK LEVEL NUMBER IDENTIFICATION =

$$\begin{aligned}
&\left[\left(\text{LEVEL 1 Protection (Wearing Surface)}\right)\right] * \left[(\text{Passive or Active Deck Corrosion Protection System})\right.\\
&\quad \left. * (\text{Level 3 Protection (Type of Rebar)})\right]\\
&\quad * \left[(\text{Environment(Cl ion Exposure)})\right] * \{\textstyle\sum[(\text{A1}) * (\text{Deck Cracking Percentage}) + (\text{A2})\\
&\quad * (\text{Deck Cracking Size}) + (\text{A3}) * (\text{Bridge Importance \&AADT \& AADTT}) + (\text{A4})\\
&\quad * (\text{LEVEL 2 Protection (Concrete Matrix \& Concrete Cover}) + (\text{A5})\\
&\quad * (\text{Level 3 Protection (Coating of Rebar)} \ + (\text{A6}) * (\text{ Structure Age \& Chloride Exposure})\\
&\quad + \ (\text{A7}) * (\text{Deck Repair History}) \ + \ \ (\text{A8}) * (\text{Deck Replacement Difficulty \& Detour})\\
&\quad + \ (\text{A9}) * (\text{Daily Vehicle Operating Cost}) \ + \ (\text{A10})\\
&\quad * (\text{Miscellaneous (Poor Draingage \& Scaling)})\big)]\}
\end{aligned}$$

BRIDGE DECK CORROSION RISK LEVEL NUMBER IDENTIFICATION = Quantifiable number to identify deck corrosion susceptibility and thus the need for deck chloride sampling.

<u>Variables:</u>

LEVEL 1 Protection (Wearing Surface) = Highest Significant Factor in determining deck corrosion susceptibility. (If a waterproofing protection system is applied and is in good shape a factor of say 0.01 would apply.)

Passive or Active Deck Corrosion Protection system = Highest Significant Factor in determining deck corrosion susceptibility. (Likewise, if the corrosion protection system is working and is in good shape a factor of say 0.01 would apply.)

LEVEL 3 Protection (Type of Rebar) = Highest Significant Factor in determining deck corrosion susceptibility. (Likewise, if stainless steel or galvanized rebar is used and is in good shape a factor of say 0.01 would apply.)

Environment (Cl ion Exposure) = Highest Significant Factor in determining deck corrosion susceptibility. (If the bridge location is in an area that receives snow and ice, then this variable could be 70-40 or a high number based exposure to Chloride Ion exposure.)

Deck Cracking Percentage = Significant Factor in determining deck corrosion susceptibility. (If the bridge deck has significant percentage of deck cracking, then this number represent the quantity identified via element level data.)

Deck Cracking Size = Significant Factor in determining deck corrosion susceptibility. (If the bridge deck has significant percentage of deck cracking sizes, then this number represent the size of the crack via element level data.)

Bridge Importance & AADT & AADTT = Significant Factor in determining deck corrosion impact. (If the bridge is significant and has a high AADT, then this number represent a high number to illustrate the importance and AADT & AADTT.)

LEVEL 2 Protection (Concrete Matrix & Concrete Cover) = Significant Factor in determining deck corrosion susceptibility. (if the bridge deck concrete matrix has low permeability/cracking, fibrous additives to prevent cracking, or admixtures to prevent corrosion, or "larger than typical" concrete cover, then this number represent a low number to illustrate the importance of this variable is reducing corrosion susceptibility.)

LEVEL 3 Protection (Coating of Rebar) = Significant Factor in determining deck corrosion susceptibility. (If epoxy coated rebar is used and is in good shape, then this number represent a low number to illustrate the importance of this variable is reducing corrosion susceptibility.) This assumes the owner has seen good performance of epoxy reinforced rebar in reducing deck corrosion.

Structure Age & Chloride Exposure = Significant Factor in determining deck corrosion susceptibility. (If the bridge is older and has had multiple years of chloride exposure, then this number represent a high number to illustrate the higher potential for chloride penetration into the concrete matrix and a higher potential for corrosion.)

Deck Repair History = Significant Factor in determining deck corrosion susceptibility. (If the bridge has had a history of spalls and repairs, then this number represent a high number to illustrate the higher potential for chloride penetration to the rebar level and a higher potential for corrosion.)

Deck Replacement Difficulty & Detour = Significant Factor in determining deck corrosion impact. (If the bridge deck is difficult to replace (Box girders) or the detour for replacement is long, then this number represent a high number to illustrate the importance of Deck Replacement Difficulty & Detour.)

Daily Vehicle Operating Cost = Significant Factor in determining deck corrosion impact. (If the daily vehicle operating cost over the bridge is high, then this number represent a high number to illustrate the importance of Daily Vehicle Operating Cost.)

Miscellaneous (Poor Drainage & Scaling) = Significant Factor in determining deck corrosion susceptibility. (If the deck drainage is poor or the deck is scaling, then this number represent a high number to illustrate the importance of Daily Vehicle Operating Cost.)

Factors:

A1 to A10 = Represents Weighting Factors that attempt to place importance on the variables above. The in determining deck corrosion susceptibility. (A3 lowest number (say 0.01), A2 low number (say 0.1).

Context:

The above equation attempts to develop a qualitative approach to determining if the bridge deck is a good candidate for chloride sampling. The goal was to try to separate the population of bridge deck (Network level) into High, Medium, and Low Risk for deck corrosion. Thus, the higher the RISK LEVEL NUMBER IDENTIFICATION number the bridge deck has a higher risk for corrosion. Thus, the bridge should have a more rigorous and systematic approach to performing deck chloride sampling. Conversely, the lower the RISK LEVEL NUMBER IDENTIFICATION number the bridge deck has a lower risk for corrosion. Thus, the bridge may not have minimal or no approach to performing deck chloride sampling. The medium RISK LEVEL NUMBER IDENTIFICATION number the bridge deck has means it is subject to a medium risk for corrosion. Thus, the bridge should have a less rigorous and less frequent approach to performing deck chloride sampling. Ideally RISK LEVEL NUMBER IDENTIFICATION between 100-60 would be high risk, 60-30 would be medium risk, and 30-0 would be low risk. Please note the equation is theoretical and has not been confirmed in practice. Ultimately, trial and error and experience will tailor the equation to meet the needs of the owner.