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BRIDGE DECK CHLORIDE TESTING PROTOCOLS: Study of US-40 Bridges over the Provo River, Utah

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RESEARCH



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UNIT CONVERSION FACTORS

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in ²	square inches	645.2	square millimeters	mm ²
ft ²	square feet	0.093	square meters	m ²
yd ²	square yard	0.836	square meters	m ²
ac	acres	0.405	hectares	ha
mi ²	square miles	2.59	square kilometers	km ²
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft ³	cubic feet	0.028	cubic meters	m ³
yd ³	cubic yards	0.765	cubic meters	m ³
NOTE: volumes greater than 1000 L shall be shown in m ³				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m ²	cd/m ²
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in ²	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm ²	square millimeters	0.0016	square inches	in ²
m ²	square meters	10.764	square feet	ft ²
m ²	square meters	1.195	square yards	yd ²
ha	hectares	2.47	acres	ac
km ²	square kilometers	0.386	square miles	mi ²
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m ³	cubic meters	35.314	cubic feet	ft ³
m ³	cubic meters	1.307	cubic yards	yd ³
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m ²	candela/m ²	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in ²

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
ppm	parts per million	0.004	pounds per cubic yard	lb / yd ³
mm ² /yr	square millimeters per year	0.00155	square inches per year	in ² /yr

*(assuming concrete unit weight = 145 lb/ft³), applicable in analysis of chloride profiles and fitted models

LIST OF ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
BDI	Bridge Diagnostics, Inc.
CISE	Calibrated Ion-Selective Electrode
ECR	Epoxy-Coated Reinforcement
FHWA	Federal Highway Administration
GPR	Ground-Penetrating Radar
ppm	parts per million
RPLOQ	Request for Pool Letter of Qualifications
SCS	Siva Corrosion Services
UDOT	Utah Department of Transportation
VCS	Vector Corrosion Services

EXECUTIVE SUMMARY

A primary contributor to the degradation of reinforced-concrete bridge decks is chloride-induced corrosion, resulting from application of salts for anti-icing/deicing during the winter months. The Utah Department of Transportation (UDOT) identified the need for a uniform set of protocols to be developed, based on research findings and best practices, for application statewide in the testing and evaluation of chloride concentrations in concrete bridge decks. The purpose of this research is to evaluate different methods of chloride testing, including field sampling and laboratory testing methods, to conduct analyses to compare methods of testing for effectiveness and efficiency, and to recommend protocols to UDOT for future chloride testing in concrete bridge decks.

Research methods included a chloride sampling and testing matrix to be executed by a team of four independent subconsultants. The chloride sampling and testing matrix included comparison and contrast of methods in three categories: concrete sample extraction, sample preparation, and chloride concentration testing. The concrete sample extraction methods included hammer-drill powder sampling and wet concrete core sampling following either uniform 1-inch sample depth increments or a progressive range of ½-inch sample increments that were closely spaced near the surface and spread out with increasing depth. An additional comparison was made between powdered sampling using a constant profile of uniform bit diameter for all depths of samples versus a tapered profile generated by drilling depths in increments of progressively smaller diameter bits. The sample preparation method used was acid-soluble digestion of concrete powder according to similar procedures in either ASTM C1152, *Standard Method for Acid-Soluble Chloride in Mortar and Concrete* or AASHTO T260 *Sampling and Testing for Chloride Ion in Concrete and Concrete Raw Materials*, Procedure A. The chloride concentration testing methods included potentiometric titration and calibrated ion-selective electrode (CISE). Both contrasting methods and replicate samples were allocated among the subconsultants according to the experimental chloride testing matrix to allow statistical comparisons to be made.

Results showed that core sampling and subdivision by cutting and crushing, followed by acid-soluble digestion and potentiometric titration provide the most consistent and reliable determination of chloride concentration profiles. CISE results were highly variable and are not recommended. Recommendations are made regarding location and frequency of sampling as well as selection of sample depths for profiling purposes.

1.0 INTRODUCTION

1.1 Problem Statement

The Utah Department of Transportation (UDOT) has expressed the need to review methods for evaluating bridge decks to classify deck condition and assist in project prioritization and scoping. A primary contributor to reinforced-concrete bridge deck deterioration is chloride-induced corrosion resulting from application of salts for anti-icing/deicing during winter months. UDOT has experienced wide variability amongst consultants in how chloride samples are extracted and tested, and some projects have produced erratic results. A need was expressed for a uniform set of protocols to be developed, based on research findings and best practices, for application statewide in the testing and evaluation of chloride concentrations in concrete bridge decks.

1.2 Objectives

The project a) evaluated state of the practice of chloride testing, including both field sampling and laboratory testing methods, b) conducted research to compare methods of testing for effectiveness and efficiency, and c) recommended protocols for the Department for testing of chloride in concrete bridge decks.

1.3 Scope

Per the approved task proposal, under this task order, WSP and its team were to:

- Review existing bridge documentation
- Perform chloride testing and analysis
- Prepare this UDOT research report

1.4 Outline of Report

Following the Introduction, this report includes:

- Research Methods
- Data Collection
- Data Evaluation and Analysis
- Conclusions
- Recommendations and Implementation

The *research methods* chapter discusses the background of the project and the methodologies used to support the data collection and analysis, including the primary contrasts in sampling and testing methods used to arrive at research findings. The *data collection* chapter explains the specific criteria that were used to sample, the quantity and distribution of samples that were collected for the research, along with how the data were obtained or produced. The chapter on *data evaluation and analysis* includes information on the results of testing and how analysis of the data was performed and the outcomes. Statistical methods and their use are discussed. The *conclusions* chapter includes a summary of the findings and highlights the relevant data that support the conclusions. The chapter on *recommendations and implementation* includes recommendations for draft UDOT protocols to test chloride concentrations in concrete bridge decks. A full special provision is supplied in Appendix A that outlines testing procedures and protocols for chloride testing of bridge decks.

2.0 RESEARCH METHODS

2.1 Overview

The current project was conceived to serve the dual purposes of a) obtaining production data to support a feasibility study for rehabilitation of the twin bridges carrying US-40 over the Provo River and b) producing sufficient data to support comparisons of methods for field sampling and laboratory testing of chloride concentration profiles to inform development of uniform chloride testing protocols.

2.2 Background

Twin bridges (2C 746 eastbound lanes & 4C 746 westbound lanes) carrying US-40 over the Provo River near Heber, UT are each 3-span continuous steel 5-girder superstructures. The structures are 406 and 410 ft long, respectively, with maximum spans of 156 and 158 ft. The girders support cast-in-place reinforced-concrete decks on corrugated metal stay-in-place forms. The subject decks are 42-ft wide curb-to-curb, comprising approximately 17,720 ft² and 17,930 ft², and were built in 1989. They were reported to have previously had polymer overlays, which were removed, and the exposed concrete decks were treated with healer-sealer. Current condition of decks is reported as Fair (2019 inspection reports) and includes significant cracking, spalling and patches, with evidence of additional delaminations developing. A November 2017 sounding survey of both decks was reported in December 2017; the results are summarized in Table 2.1. The structures are typical of highway bridges that have been in service for several decades and whose decks are approaching the need for rehabilitation.

Table 2.1 Deck Damage Survey (UDOT, November 2017)

Bridge	Span	Patches (ft ²)	Delaminations (ft ²)	Average Damage by Area
2C 746 (EBL)	1	530	76	10.3%
	2	1,073	70	
	3	215	19	
4C 746 (WBL)	1	1,297	208	14.0%
	2	1,014	130	
	3	197	54	

2.3 Chloride Testing Methods

The team conducted a literature review of methods that have been developed and deployed in practice for sampling and testing of chloride concentrations in concrete structural elements, especially bridge decks. Internal discussions were also held amongst our assembled team of experts, informal inquiries made of other practitioners within the US highway industry, and review of standard procedures used by other DOTs. The deliberations of the current volunteer AASHTO Bridge Preservation Partnerships National Chloride Testing Working Group, in which several members of our team and UDOT are active, were also considered.

2.3.1 Chloride Diffusion

The most common cause of chloride contamination is the infiltration from sources of deicing salts used for winter maintenance or from brackish, marine or chloride-laden natural waters, such as in coastal zones. For the subject decks, the former is expected to be the case. Chloride ingress from external sources occurs by a number of natural phenomena (absorption, diffusion, etc.), but the overall behavior has been shown empirically to be best represented by diffusion, whereby the driving force for the chloride front to advance is the concentration gradient from the source (at the outer surface) toward the inside (bulk) of the concrete through the pore system of the cement-paste and the paste-to-aggregate particle transition zones. Nature seeks an equilibrium of concentration throughout the medium (e.g. concrete); therefore, chloride moves from high to low concentration. Fick's Second Law of Diffusion represents the incremental change in concentration over each increment of time from a point of higher concentration to an adjacent point of lower concentration. The relationship can be solved to represent diffusion in one dimension, as entering and proceeding normal to the surface of a semi-infinite medium (e.g. into a concrete slab from the top surface). The resulting equation has a form over time that is a curvilinear power function, whereby the concentration is greatest near the source, with a high initial rate of decline and a transition to gradual reduction as depth increases. Figure 2.1 illustrates an example of a Fickian Diffusion Model fitted to field data measurements.

The general form of the model in Equation 1 solution follows the mathematical form:

$$C_{x,t} = C_o \left[1 - \operatorname{erf} \left(\frac{x}{2\sqrt{D_c t}} \right) \right] \quad \text{Equation 1}$$

where:

$C_{x,t}$ = Concentration of species (Cl⁻) at specified depth and time (lb Cl⁻/yd³ concrete)

C_o = Concentration of species (Cl⁻) near surface that drives diffusion (lb Cl⁻/yd³ concrete)

D_c = Coefficient that describes diffusion rate of species through the medium (in²/yr)

x = Depth from the surface (in.)

t = time over which diffusion occurs (yrs)

erf = mathematical Gaussian error function

The effective diffusion coefficient, D_c , is a function of several factors of the concrete including the cement paste constituents (cement + supplementary cementitious materials), the water-cementitious materials ratio (w/cm), and the maturity (age, temperature, moisture, curing regime). D_c will generally decrease rapidly at early ages but rate of change declines asymptotically to approach a stable value, generally after approximately 1 year.

The surface concentration, C_o , depends on the environmental exposure conditions, including the source and frequency of chloride loading, wetting/precipitation cycles and duration of exposure to standing water. For bridge decks that receive deicing applications, the accumulation of chloride in the near-surface region of the concrete (approximately the first ½-inch depth) increases early in the life of the structure dependent upon frequency and severity of winter events and agency deicing/anti-icing practices. Similar to D_c , the C_o value tends to stabilize after a year or so in service, barring any significant change in environmental exposure or winter maintenance practice at the bridge.

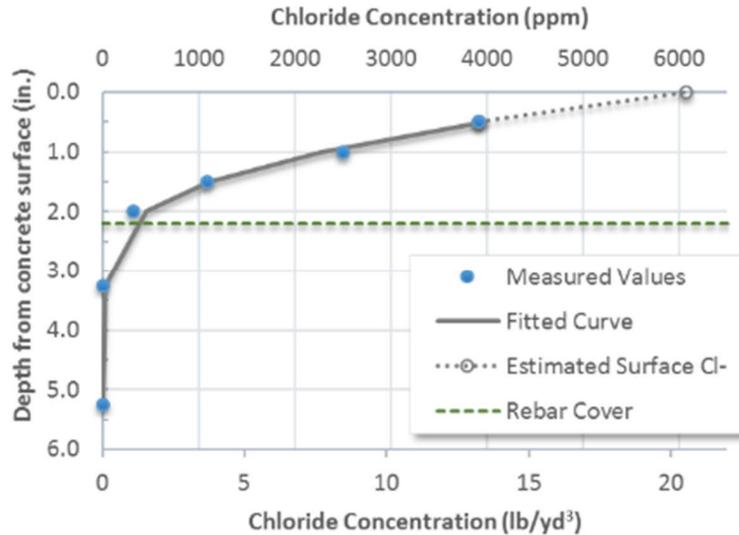


Figure 2.1 Typical Chloride Diffusion Profile

Based on this information, WSP suggested that the most critical information for describing the diffusion of chloride into a deck occurs in the area between the surface and the top-mat of reinforcement. Note also that the concentration of chloride in the top-most ¼ inch of concrete is known to vary widely because the ion transport in this region is dominated by capillary effect and seasonal precipitation can leach some of the chloride back out of the concrete at shallow depths, temporarily reducing the concentration. Subsequent deicing exposures “recharge” this layer and continue to drive diffusion. Though this top layer varies greatly over time, the concentration beneath tends to be stable and more representative of the overall diffusion process. WSP recommended, based on experience of several of our experts, that the increments be kept to ½-inch and that more increments be tested near the surface where concentrations change the most. Nonetheless, it is still important to obtain chloride concentration measurements at depths greater than the outer reinforcement. In fact, it is desirable to obtain at least one reading from each profile at a distance believed to be great enough to not have been affected by chloride diffusion. This measurement would be taken to indicate the background chloride concentration of the concrete, defined as the amount of chloride that was present when the concrete was originally placed, as conveyed by one or more of the basic concrete constituents (aggregate, mix water, cement, or other admixtures). When assessing the rate of chloride diffusion, the background must be removed to determine the appropriate shape of the diffusion

curve, and then added back to determine the expected amount of total chloride present at a given depth at a given time.

2.3.2 Concrete Sampling for Chlorides

The two most common methods of field sampling are hammer-drill powder sampling and coring. Following this is a detailed explanation and illustration of each sample extraction method, including comments with respect to the different options for depth increments.

2.3.2.1 Hammer-drill powder sampling – material is pulverized in-situ and collected in incremental samples in the field. Experts differ on whether it is preferable to drill with constant profile using a single bit diameter or a tapered (or stepped) profile of progressively decreasing bit diameters with successive depth samples (reference section 3.3 for further explanation). Sampling with constant profiles is believed to risk contamination of deeper samples by abrasion of the drill-hole wall at shallower depths by the drill bit during sampling. Sampling with tapered profiles (stepping down bit size in increments with increasing sample depth) is thought to cause inconsistency in concrete paste-to-aggregate volume proportions within the samples, which may bias the results at different depths. The influence of bit diameter is mentioned in Note 14 of ASTM C 1152-04.

Advantages:

- Does not induce run-off of cooling water onto the deck as during coring.
- Samples do not need to be further subdivided or pulverized before preparing for chloride testing (except to ensure the required fineness for acid-digestion).

Disadvantages:

- It is difficult to precisely control the depth increments of the samples.
- Capture of the powder sample in the field is difficult and material may be lost (accounting for wind, having to “spoon” the material into sample containers, etc.).
- There is potential to cross-contaminate samples during extraction.

2.3.2.2 *Core sampling* – a continuous concrete core is extracted in the field using wet coring with a diamond-impregnated steel-core barrel and later subdivided under laboratory conditions. Subdividing may be achieved by dry-cutting and pulverizing disks into powder, or by grinding/milling and capturing powder in a filter.

Advantages:

- The extraction of cores may be accomplished more quickly than powder drilling.
- Core samples may be used for additional tests or evaluation, in addition to chloride testing. These may include photographic documentation, pH/alkalinity testing, petrographic screening for F/T or AAR damage, density, moisture and voids, and air entrainment evaluation.
- Core sample diameter (~2 to 4-inch) is usually much larger than powder drill bit diameter (~0.75 to 1.5-inch), so sample volume is larger, more representative of bulk concrete and less prone to bias from disproportionate sampling of aggregate versus cement paste.
- Depth increments of the chloride profile can be more carefully controlled than powder samples and cross-contamination can be avoided with proper laboratory procedures.
- Intersection of sample with horizontal cracks/delaminations can be easily observed in core or holes.

Disadvantages:

- Additional lab effort is required to further subdivide samples by milling or cutting and pulverizing before preparing for chloride testing.
- Coring apparatus is more difficult to handle than hammer drill and requires a water source for cooling. The cooling water could potentially skew the chloride concentration measurements if core diameter is small.
- Coring may present challenges to avoid reinforcement in densely reinforced-concrete members, depending upon core size.

2.3.3 Sample Preparation

There are two primary methods for preparation of samples for chloride testing by wet chemistry: acid-soluble and water-soluble extraction. Both methods are covered by Procedure A

of AASHTO T260, *Sampling and Testing for Chloride Ion in Concrete and Concrete Raw Materials*; however, related ASTM standards differentiate. ASTM C1152, *Standard Method for Acid-Soluble Chloride in Mortar and Concrete* applies to the acid-soluble, or “total chloride”, extraction method and ASTM C1218, *Standard Method for Water-Soluble Chloride in Mortar and Concrete* applies to the water-soluble extraction method. The acid-soluble extraction method measures the total amount of chloride ions in a concrete sample, including chlorides in the solid phases and the chlorides in pore solution. The water-soluble extraction method measures the amount of chloride ions that can be extracted by leaching a concrete sample in water, which some may refer to as “free chloride”. Experts disagree as to which method is most representative. Supporters of the water-soluble method reason that some chloride is bound in aggregate and potentially in chemical reaction with paste constituents and therefore may not be available to react with reinforcement to cause corrosion, so it is the “free chloride” in solution that is of greatest concern. Those who support use of the acid-soluble method reason that conditions may change within the concrete over time (due to cracking, carbonation or other reactions within the cement paste) that may serve to release bound chloride, thus “total chloride” is more conservative. There is not a precise relationship between water-soluble and acid-soluble results because of the number of factors involved in chloride binding and leaching; however, a “rule-of-thumb” developed from empirical observation is that water-soluble concentrations represent approximately 75% of acid-soluble concentrations for the same concrete. It is important to note that commonly cited “threshold” chloride concentration values (e.g. 0.17 to 1.4% by weight of cement or 1.2 to 2.0 lb/yd³ concrete) were derived from reports by R. Stratfull (1956) and others based on total, or acid-soluble, chloride tests, indicating the concentration at which steel is likely to initiate corrosion. It does not, however, represent the concentration at the time repair or rehabilitation may be required. UDOT’s current criteria of 2.0 and 8.0 lb/yd³ concrete for black steel and ECR, respectively, refer to acid-soluble test results. For this reason, it was recommended that acid-soluble tests be adopted, and that no experimental comparison be undertaken in this study.

2.3.4 Chloride Concentration Testing

As with sample extraction and preparation, there are several methods by which powdered concrete may be tested to determine concentration. AASHTO T260 presents several methods;

Procedure A discusses methods using wet chemistry, which are the most common and well documented, and include potentiometric titration or measurement by the Gran Plot method. AASHTO T260 Procedure B discusses use of an atomic absorption spectrophotometer to determine chloride concentration. Though a valid method, few commercial concrete testing laboratories are equipped to perform Procedure B. ASTM does not publish a standard for determination of chloride in mortar or concrete based on the atomic absorption method. A common and convenient method is the calibrated ion-selective electrode method, which employs acid digestion of concrete powder, as is done with potentiometric titration, but the sample is then measured by immersion of a chloride ion-selective electrode that has been carefully calibrated against a series of standards of known chloride concentration to create a response curve (Weyers 1993, Herald, 1993). The reading can then be taken very quickly by referencing the voltage output of the electrode in solution against the calibration curve. The method is said to give comparable results, but not necessarily as precise as potentiometric titration; for example, the test may be prone to error or loss of calibration if the electrode is not carefully maintained. The calibrated ion-selective electrode (CISE) method does not have an AASHTO or ASTM standard, but commercial test kits are available. For purposes of this study, comparison was made between the two most common methods, potentiometric titration and calibrated electrode (or CISE).

2.3.4.1 Potentiometric titration method – this is the traditional method for chloride determination and is considered the benchmark standard to which other methods are compared.

Advantages:

- The titration method is known to be highly accurate and repeatable, with well-established precision and bias within and between laboratories.
- The chloride values throughout the literature have historically been based on this method.
- Most reputable concrete testing laboratories are equipped to use this method, and significant portions of it are automated, in some cases with the ability to line up series of samples for sequential testing to reduce labor requirements.
- Titration logs can be stored and reviewed if an error is suspected.

Disadvantages:

- Though titrations can be done “by hand”, it is a tedious process, so specialized laboratory equipment is needed to make it most efficient.
- Titrations are more expensive in time and cost to perform than calibrated electrode method.

2.3.4.2 Calibrated Ion-Selective Electrode (CISE) method – this method involves calibration of a chloride ion-selective electrode against a range of standards of known chloride concentration. The resulting calibration curve can be used to input the mV reading from the specifically calibrated electrode and voltmeter combination and output a corresponding chloride concentration.

Advantages:

- The method can be used to very quickly make determinations from multiple samples, as it only takes seconds to make the measurement.
- It can potentially be used in a field environment, provided proper calibration was completed in advance.

Disadvantages:

- The method is prone to greater error (from interpolation or extrapolation) than the potentiometric method.
- Electrodes can stray from “calibration” over time and with changes in environment such as temperature, and so need to be checked frequently.
- Each calibration is unique to the electrode-voltmeter combination and does not convey to other electrodes.
- There is no way to “back-check” the data from a reading to determine if an error occurred.

2.4 Non-Experimental Parameters

In addition to experimental comparison of methods as described above, certain parameters for field testing must be developed that do not lend themselves to experimental comparison or validation within a research program of the current scale; therefore, such parameters were developed through expert elicitation amongst our team, augmented by input

from external practitioners and the literature. Accordingly, the subsequent development of protocols for chloride sampling and testing also addressed:

- a. Locations to test on a bridge deck – Guidance on how to determine appropriate locations to include:
 - Testing within or outside limits of deterioration (i.e., through existing patches or delaminations, near patches, proximity to cracks, etc.)
 - Testing related to bridge features (e.g. within or between wheel-paths, within shoulders, in travel versus passing lanes, influence of drainage paths, etc.)
- b. Frequency of tests - How many tests per deck area, with consideration of age, number and size of spans; minimum number of tests per deck; minimum number of tests per deck condition.
- c. Influence of age and wearing surface/overlay on sampling approach - (e.g. sample overlay with deck, or remove and only sample deck; impacts on depth and increments for profile)
- d. Interpretation of results – though not intended to provide a detailed comparison of analysis and modeling methods, some basic guidance will be provided on interpreting the outputs from the testing and how those data may be evaluated to inform preservation decision-making.

2.5 Testing Plan

A battery of field and laboratory testing was coordinated among WSP’s four subconsultants, which include Bridge Diagnostics, Inc. (BDI), CONCORR, Inc., Siva Corrosion Services (SCS), and Vector Corrosion Services (VCS). Based on preliminary discussions among our team and with UDOT, each firm was asked to suggest their *preferred* sampling and testing methods based on their in-house practices. These were taken into consideration in preparing the proposed experimental scheme. To develop a balanced test program to contrast methods but provide statistical replication for comparisons, each firm was asked to conduct a specific suite of activities, which may match or contrast with their preferred approaches.

The experimental plan compared sample extraction methods. Two teams were asked to conduct powder sampling, one by using constant profiles and the other by using tapered profiles. The other two teams were asked to obtain samples by coring. Though comparison of cutting and pulverizing to milling or grinding as a method of subsampling was originally considered, it was agreed amongst the team's experts that milling or grinding is exceedingly tedious and costly and not appropriate for production-level testing of aged bridge decks; therefore, milling or grinding were not implemented. Laboratories were generally asked to perform concentration tests according to their experience, equipment and typical practice; however, three laboratories were asked to perform tests by both methods, two labs using the same samples for direct comparison of methods, and one lab using separate samples.

Comparative features of the experimental plan also included pairwise sampling by different firms at adjacent locations (within approximately 6 inches), as well as an interlaboratory (round robin) exchange of samples whereby a subset of the powdered samples obtained and tested by one firm were sent to another firm to undergo the same test to compare between-lab variability.

2.6 Summary

The twin bridges (2C 746 EBL & 4C 746 WBL) carrying US-40 over the Provo River were introduced as the subject of evaluation and data collection to support both production assessment for rehabilitation and experimental evaluation to support selection of protocols to guide chloride testing practices statewide. WSP's team of four sub-consultants, BDI, CONCORR, SCS, and VCS, were responsible for sample extraction, preparation and chloride concentration testing methods according to a testing plan to contrast methods for comparison. The condition assessment and rehabilitation recommendations are contained in a separate report to UDOT. This report summarizes the experimental analysis and recommendations for chloride testing protocols.

3.0 DATA COLLECTION

3.1 Overview

Primary data collection for this project entailed obtaining concrete samples from the decks in either solid core or powdered sample form, subdivision of samples into chloride profile increments, sample preparation, and chloride concentration testing. Ancillary data collection included documentation of sample locations, verification sounding around sample locations, non-destructive measurement of top-mat reinforcement locations and clear concrete cover depths, and extraction of concrete cores to determine compressive strength.

3.2 Chloride Profile Increments

The significance of sample depths when generating a chloride profile was discussed in Chapter 2. While UDOT's RPLOQ stipulated that chloride profiles would be established by testing 6 depths of 1-inch increments, for a total depth of 6 inches (ignoring kerf of saw-cut between increments), the WSP team recommended that "progressive" sample depths be considered, wherein ½-inch depth increments would be tested, which would be closely spaced in the region above the top mat and then spread out as depth increased. A final scheme was achieved wherein one testing firm (CONCORR) used the uniform 1-inch depth increments as prescribed and three testing firms (BDI, SCS and VCS) used the progressive ½-inch depth increments for comparison purposes. Specifics will be discussed according to sampling method.

3.3 Sample Extraction

To compare sample extraction methods, the team conducted both powder sample extraction and solid core extraction. For the powder sampling with a hammer drill, a further distinction was use of constant profile versus tapered profile. Figure 3.1 illustrates extraction methods using constant (left) and tapered (right) profiles and Figure 3.2 shows a schematic of the associated profiles. Note that powder samples were collected in a progressive distribution of ½-inch profile increments centered at depths of ½, 1, 1½, 2, 3¼ and 5¼ inches from the deck surface.



Figure 3.1 Powder Concrete Sampling with Constant (left) and Tapered (right) Profiles

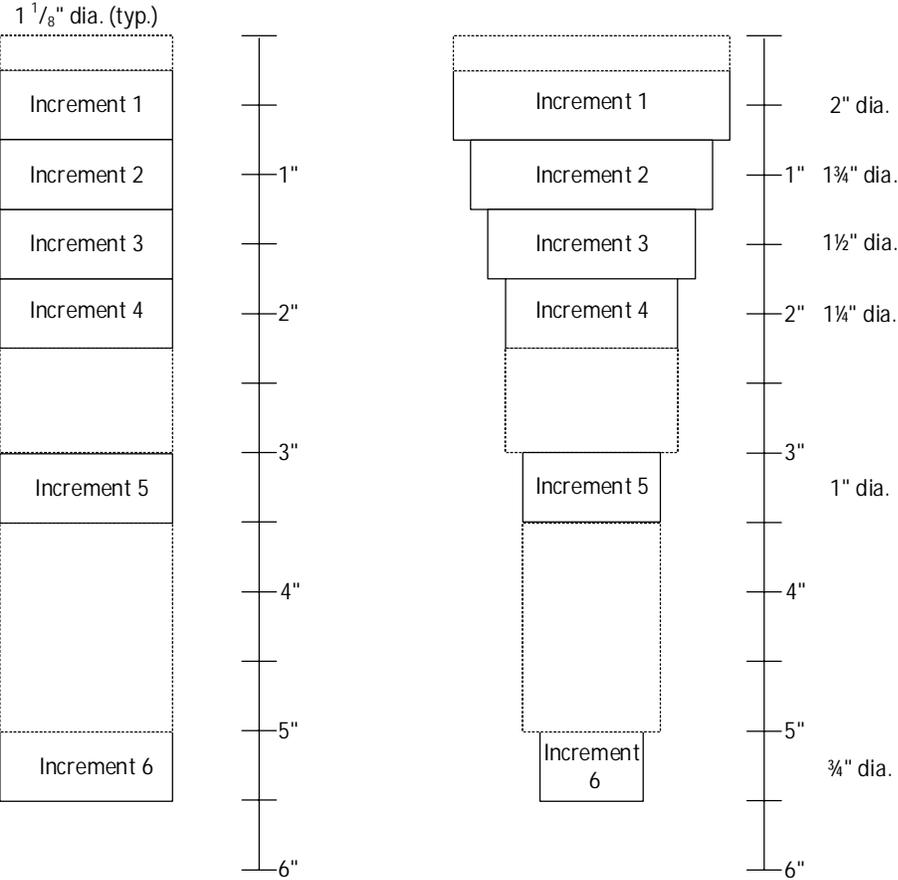


Figure 3.2 Schematics of Constant (left) and Tapered (right) Profiles

The sampling plan also included the core sampling method for comparison. Two of the teams drilled 4-inch nominal diameter concrete cores to a target depth of 6 inches. Figure 3.3

shows the coring operation and core extraction. Figure 3.4 illustrates the nominal size of the core to be extracted, while illustrating the two sets of profile increments, uniform 1-inch increments (left) and progressive ½-inch increments (right), into which the cores were later subdivided in the laboratory. Note that Figure 3.4 shows nominal bar depth for illustration, but cores were specifically located to avoid drilling through reinforcement.



Figure 3.3 Extraction of a 4-inch Concrete Core for Chloride Profiling

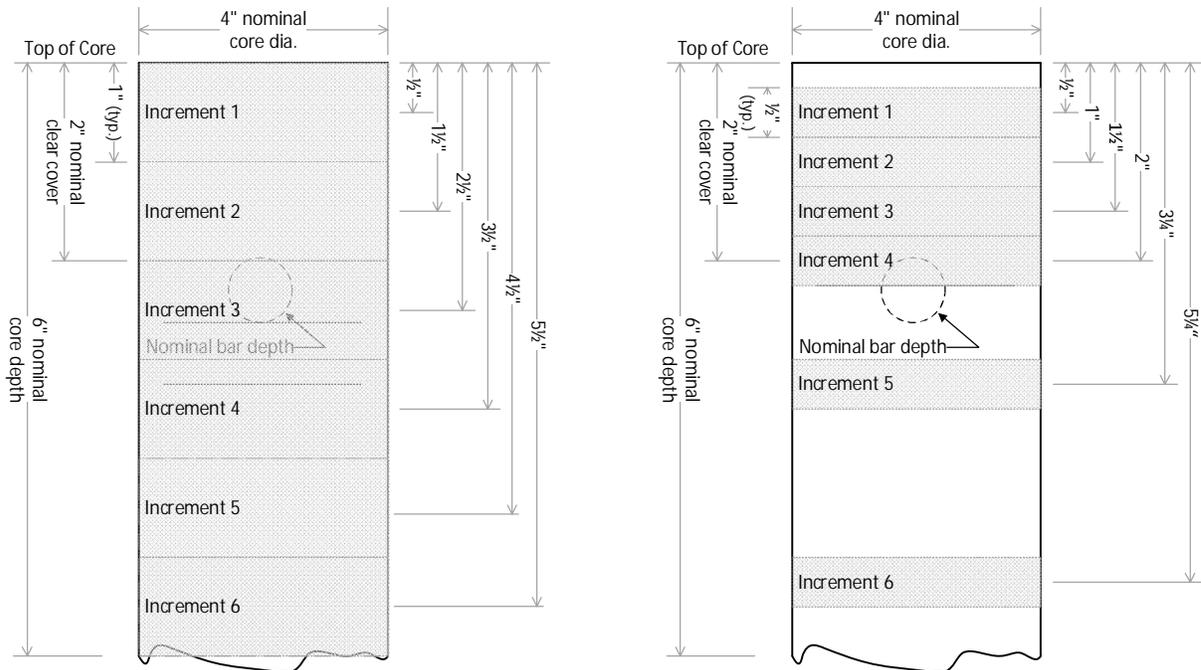


Figure 3.4 Coring Extraction, Uniform (left) and Progressive (right) Depth Increments

3.4 Sample Location and Frequency

To assist in determining sample locations, a composite output of a November 2017 condition survey of the decks was referenced that indicates patches identified visually and delaminations identified by chain drag or hammer sounding. The westbound span has greater concentration of defects than the eastbound span. Interestingly, while the westbound defects are concentrated in the right travel lane and shoulders, as is commonly expected, the damage is greater on the left passing lane on the eastbound span. The cause is not clear but may relate to drainage and/or traffic patterns, since the passing lane and shoulder are on the lower end of the cross-sloped deck of the eastbound lane.

Per the RPLOQ, sample locations were to be taken in travel lanes, typically in wheel paths. WSP recommended that test locations be staggered between travel lanes and shoulders. As is evident from the damage survey, significant chloride ingress can occur in shoulders, depending upon drainage patterns, so these areas were included to ensure representative samples. For the subject bridges, each subconsultant tested 4 sample locations per span, or 24 sample locations total. This was a large number of samples for a routine evaluation of bridges of this size, but a greater number of samples was desired to lend statistical validity to the research. The teams were required to perform sampling from sound, non-patched areas as indicated by the survey and supplemental sounding on site.

Maintenance of traffic was provided for one lane/shoulder combination per bridge per day such that two pairs of teams tested the right lane/shoulder of a bridge, 2C 746 and 4C 746, respectively, on the first day and the alternate pair of teams tested the left lane/shoulder of each bridge on day two. To accommodate peak-hour traffic volumes, the eastbound (downhill) bridge was closed early (Figure 3.5) and westbound (uphill) bridge was closed later, as morning peak traffic tended to be headed west and afternoon peak traffic was headed east. Each subconsultant was assigned a zone (I through IV) for ½ day (see Figure 3.6), and then near mid-day the two teams on a given bridge would exchange zones to complete the work within the lane closure the second ½ day, during which each team would co-locate samples adjacent to those taken by the other team in the morning. Thus, pairwise comparison of profiles from different sampling methods (e.g. powder versus core) was enabled by arranging test locations between pairs of

teams in close proximity (approximately 6 inches). Figure 3.7 shows approximate sampling locations for each consultant on each bridge deck.



Figure 3.5 Morning Lane Closure on Eastbound (2C 746) Bridge

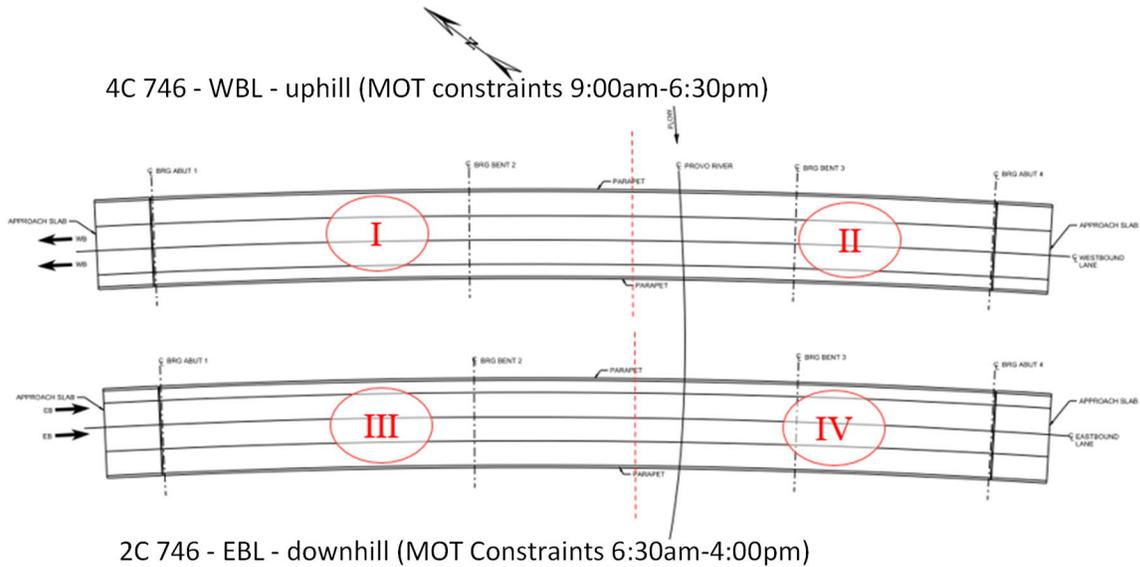


Figure 3.6 Division of Twin Bridges into Zones to Schedule Field Testing

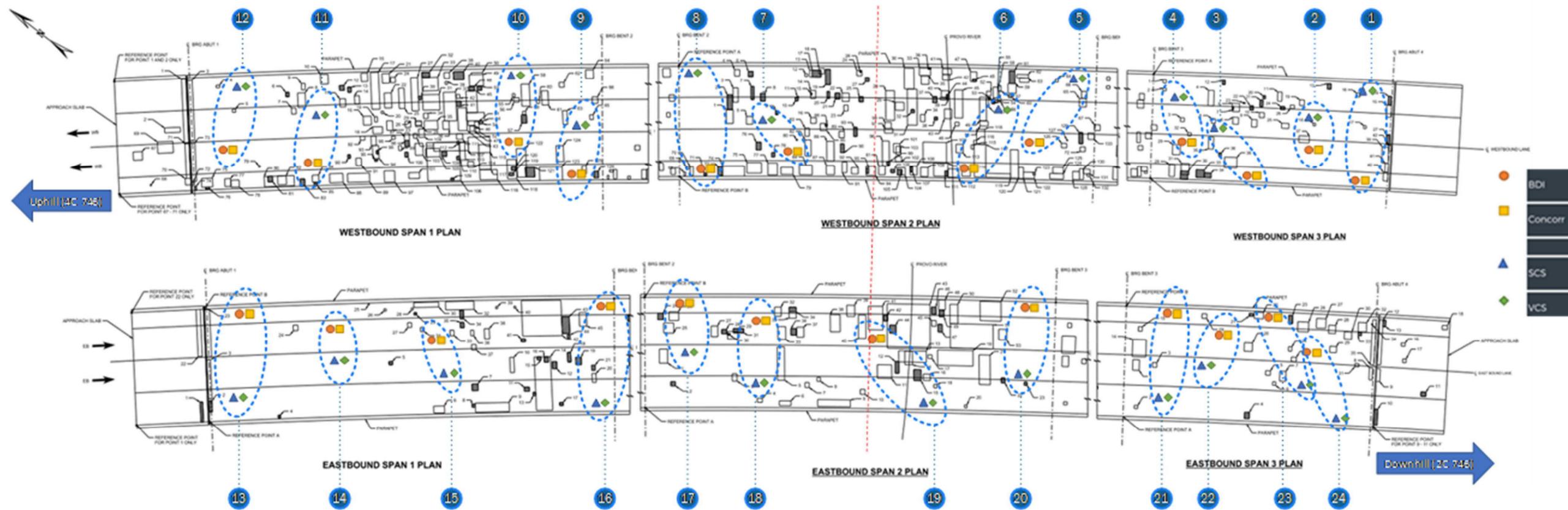


Figure 3.7 Bridge Deck Sampling Locations

3.5 Experimental Matrix

The experimental plan was employed to support comparison of sampling and testing methods. Each team obtained 24 samples for chloride testing and were designated to sample either by hammer-drill powder sampling or by coring. Most teams were assigned both a primary and secondary laboratory test method for their samples to compare titration and calibrated electrode methods. In addition, there was an exchange of samples, comprised of the top 3 depth increments from half the cores taken from each bridge (odd or even numbered) between teams for interlaboratory (round robin) testing. Tables 3.1 and 3.2 show the primary, secondary and interlaboratory testing matrices.

Table 3.1 Primary and Secondary Experimental Test Matrix

Team	Sampling Method	Primary Test Method	Secondary Test Method	Depth Increment
BDI	Powder sample - tapered	Calibrated electrode	Titration (six cores from CONCORR)	Progressive ½-inch
CONCORR	Core sample - pulverize	Titration	Calibrated electrode	Uniform 1-inch
SCS	Core sample - pulverize	Titration	-	Progressive ½-inch
VCS	Powder sample - constant	Titration	Calibrated electrode	Progressive ½-inch

Table 3.2 Interlaboratory Experimental Test Matrix

Team	Sampling Method	Test Method	Depth Increment	Interlaboratory exchange
BDI	Powder sample - tapered	Calibrated electrode	Progressive ½-inch	Odd-numbered cores to CONCORR -> calibrated electrode
CONCORR	Core sample - pulverize	Titration & calibrated electrode	Uniform 1-inch	Even-numbered cores to SCS -> Titration
SCS	Core sample - pulverize	Titration	Progressive ½-inch	Odd-numbered cores to VCS -> Titration
VCS	Powder sample - constant	Titration & calibrated electrode	Progressive ½-inch	Even-numbered cores to BDI -> calibrated electrode

3.6 Supplemental Testing

Detailed sounding survey was not required, but all teams were asked to check locations by hammer sounding prior to sampling. Reinforcement bar locations were marked, and clear cover depths were determined using GPR or pachometer. BDI was also tasked with obtaining cover depth distributions by performing line-scans with ground-coupled GPR along the wheel paths and shoulders. Figure 3.8 shows these activities. Thus, top-mat transverse reinforcement cover depths were measured along the full length of the deck to provide statistical basis for modeling. CONCORR, Inc. was tasked with obtaining four additional concrete cores, two per bridge, located at a mid-span and over a pier to test for compressive strength of the concrete.



Figure 3.8 Sounding of Test Locations (left) and GPR Survey of Cover Depths (right)

3.7 Summary

Data collection was performed according to a matrix of sampling and testing to contrast:

1. powder versus core sample collection,
2. constant versus tapered profiles when powder sampling,

3. uniform versus progressive profile depth increments, and
4. titration versus calibrated ion-selective electrode chloride concentration test methods.

The powder extraction method resulted in powdered material ready for laboratory testing. The core extraction method required subdividing and pulverizing samples at specified progressive or uniform depth increments in the laboratory before testing. Potentiometric titration and calibrated ion-selective electrode (CISE) were both used to test samples that had been prepared according to the acid-soluble method specified in either ASTM C1152 or AASHTO T260, Procedure A. A plan view of the bridge shows the 24 sample locations per team to be tested, for a total of 96 chloride profiles. An experimental matrix outlined the primary and secondary testing methods conducted by each team on its samples, and interlaboratory tests performed on samples from other firms. Supplemental data collection included cover depth distributions at sample location and along GPR line-scans, as well as compressive strength tests of two cores from each bridge.

4.0 DATA EVALUATION

4.1 Overview

WSP's subconsultant teams were grouped into pairs (BDI and CONCORR, SCS and VCS) to enable pairwise comparisons of adjacent samples using contrasting sampling and testing techniques. Upon completion of field sampling, wherein each team extracted 24 samples from the bridge decks as outlined in Figure 3.7, each team was responsible for performing laboratory tests according to the methods outlined in Table 3.1. In addition, there was an exchange of samples between teams for interlaboratory testing as outlined in Table 3.2. Comparisons are made between the results from the teams to highlight similarities and differences related to the different methods of sampling and testing. A summary of the laboratory measurements, chloride profiles and statistical analyses of results from each team or between teams is presented.

4.2 Laboratory Measurements

The results of measurements taken in the laboratory by each team with their respective test methods are presented in the following subsections. The summaries are separated according to bridge and location on the bridge where each sample was taken (e.g. lane or shoulder). Averages for the primary and secondary (where applicable) test methods are provided for individual sampling locations, as well as averages for the entire bridge. Statistical parameters are listed for the interlaboratory exchange of samples and comparison of results between teams.

4.2.1 Chloride Concentration Results from Primary and Secondary Test Methods

As summarized in Table 3.1, each team was prescribed a specific sampling method and one or more testing methods. Teams were paired and assigned sampling locations on either the left or right side of the bridge. The chloride concentration results are organized into separate tables according to:

- Bridge (2C 746 and 4C 746),
- Lane (Left Shoulder, Left Lane, Right Lane, and Right Shoulder)

The results are then tabulated according to the team that performed the testing, the output of their primary and secondary (if applicable) test method, sorted by the nominal depth of the sample in the profile. Table 4.1 through Table 4.4 present the results for Bridge 2C 746, which carries the eastbound lanes, in the order of left shoulder, left lane, right lane and right shoulder.

Table 4.1 Chloride Concentration by Team, Method & Depth (2C 746 EB Left Shoulder)
Eastbound Left Shoulder Chloride Concentrations (ppm)[†]

Testing Team	Test Method (Primary/Secondary)	Sample Depth (in.)	Location						
			13	16	17	20	21	23	Avg.
BDI	CISE	0.5	1,920	1,661	2,194	4,344	3,225	3,694	2,840
	N/A		-	-	-	-	-	-	-
	CISE	1	633	1,342	1,479	3,536	3,444	3,474	2,318
	N/A		-	-	-	-	-	-	-
	CISE	1.5	914	749	2,091	3,282	2,175	2,513	1,954
	N/A		-	-	-	-	-	-	-
	CISE	2	533	1,361	1,361	1,866	2,459	2,028	1,601
	N/A		-	-	-	-	-	-	-
	CISE	3.25	11	310	774	1,215	575	1,215	683
	N/A		-	-	-	-	-	-	-
CISE	5.25	4	4	64	49	15	50	31	
N/A		-	-	-	-	-	-	-	
CONCORR	Titration	0.5	4,079	5,352	5,328	6,482	4,528	5,216	5,164
	CISE		3,073	4,397	4,001	5,702	3,813	4,286	4,212
	Titration	1.5	2,306	3,411	3,701	4,083	4,009	3,371	3,480
	CISE		1,451	2,391	2,784	3,143	3,113	2,433	2,553
	Titration	2.5	932	2,002	2,524	2,452	1,956	3,017	2,147
	CISE		603	1,141	1,727	1,821	1,351	1,912	1,426
	Titration	3.5	231	766	1,671	855	1,192	1,306	1,004
	CISE		108	416	1,141	615	697	741	620
	Titration	4.5	42	225	854	172	323	387	334
	CISE		-2	95	459	80	176	209	169
	Titration	5.5	30	62	282	35	279	105	132
	CISE		-8	0	162	-14	114	24	46

[†] Negative chloride concentrations reported by CISE method result from extrapolation of the fitted voltage-concentration relationship for the calibrated electrode and should be interpreted as zero but are shown as calculated for completeness in reporting.

Table 4.2 Chloride Concentration by Team, Method & Depth (2C 746 EB Left Lane)

Eastbound Left Lane Chloride Concentrations (ppm)[†]

Testing Team	Test Method (Primary/Secondary)	Sample Depth (in.)	Location							
			14	15	18	19	22	24	Avg.	
BDI	CISE	0.5	2,745	2,732	4,499	3,340	3,694	2,037	3,174	
	Titration*		4,310	-	6,340	-	5,210	-	5,287	
	CISE	1	1,047	1,271	4,015	2,853	2,426	2,779	2,399	
	Titration*		3,430	-	4,930	-	3,760	-	4,040	
	CISE	1.5	1,037	1,318	3,142	2,416	1,786	2,841	2,090	
	Titration*		2,770	-	3,670	-	2,860	-	3,100	
	CISE	2	854	850	2,491	1,763	1,615	1,755	1,554	
	Titration*		1,550	-	2,990	-	1,770	-	2,103	
	CISE	3.25	265	145	1,204	1,247	305	638	634	
	Titration*		570	-	1,530	-	550	-	883	
	CISE	5.25	2	1	257	555	12	66	149	
	Titration*		30	-	120	-	20	-	57	
	CONCORR	Titration	0.5	4,794	5,391	5,760	6,679	4,751	6,463	5,640
		CISE		4,032	4,523	4,781	5,981	3,617	4,590	4,587
Titration		1.5	2,592	3,349	3,657	4,938	3,433	4,564	3,756	
CISE			1,779	2,380	3,044	3,859	2,004	2,892	2,660	
Titration		2.5	1,501	1,886	2,339	3,310	1,456	2,719	2,202	
CISE			1,002	1,307	1,773	2,609	803	1,693	1,531	
Titration		3.5	380	887	1,149	2,693	365	1,800	1,212	
CISE			225	554	821	1,813	178	973	760	
Titration		4.5	133	219	284	1,096	94	900	454	
CISE			60	115	154	748	20	466	261	
Titration		5.5	32	45	40	240	35	242	106	
CISE			-2	3	-12	120	-15	85	30	

[†] Negative chloride concentrations reported by CISE method result from extrapolation of the fitted voltage-concentration relationship for the calibrated electrode and should be interpreted as zero but are shown as calculated for completeness in reporting.

* BDI performed titration on matching half of six cores taken by CONCORR

As indicated in the footnote of Table 4.2, a secondary test method was not assigned for samples taken by BDI, but it was decided to subdivide a portion (6) of the core samples taken by CONCORR and forward to BDI to permit direct comparison of results of cores sampled according to uniform versus progressive profile depths. Results are included in these tables and discussed later.

Table 4.3 Chloride Concentration by Team, Method & Depth (2C 746 EB Right Lane)
Eastbound Right Lane Chloride Concentrations (ppm)

Testing Team	Test Method (Primary/Secondary)	Sample Depth (in.)	Location						
			14	15	17	20	22	23	Avg.
SCS	Titration	0.5	5,654	5,274	6,066	5,510	4,977	5,891	5,562
	N/A		-	-	-	-	-	-	-
	Titration	1	4,723	4,431	5,120	5,213	3,487	4,587	4,594
	N/A		-	-	-	-	-	-	-
	Titration	1.5	3,056	3,658	3,599	3,503	3,199	3,441	3,409
	N/A		-	-	-	-	-	-	-
	Titration	2	1,840	2,306	2,744	2,818	1,904	2,410	2,337
	N/A		-	-	-	-	-	-	-
	Titration	3.25	690	938	1,146	864	945	1,042	938
	N/A		-	-	-	-	-	-	-
Titration	5.25	91	204	146	454	193	283	229	
N/A		-	-	-	-	-	-	-	
VCS	Titration	0.5	5,385	5,993	6,872	8,492	5,559	6,866	6,528
	CISE		465	488	539	7,634	741	774	1,773
	Titration	1	5,299	4,829	5,072	6,425	4,323	4,890	5,140
	CISE		461	433	441	3,412	526	617	982
	Titration	1.5	3,425	3,709	3,109	4,753	3,792	1,608	3,399
	CISE		332	346	330	1,865	427	345	607
	Titration	2	2,694	2,319	2,277	2,079	2,749	3,554	2,612
	CISE		322	293	287	945	427	420	449
	Titration	3.25	1,068	946	1,148	1,322	1,612	1,440	1,256
	CISE		147	175	202	581	277	259	273
	Titration	5.25	148	79	229	269	319	206	208
	CISE		56	42	71	172	104	76	87

Table 4.4 Chloride Concentration by Team, Method & Depth (2C 746 EB Right Shoulder)
 Eastbound Right Shoulder Chloride Concentrations (ppm)

Testing Team	Test Method (Primary/Secondary)	Sample Depth (in.)	Location						
			13	16	18	19	21	24	Avg.
SCS	Titration	0.5	4,156	5,462	6,202	4,068	-	3,647	4,707
	N/A		-	-	-	-	-	-	-
	Titration	1	2,699	4,354	5,488	4,441	-	2,204	3,837
	N/A		-	-	-	-	-	-	-
	Titration	1.5	2,121	3,341	4,928	3,038	-	1,973	3,080
	N/A		-	-	-	-	-	-	-
	Titration	2	1,675	2,438	3,357	2,540	-	1,232	2,248
	N/A		-	-	-	-	-	-	-
	Titration	3.25	495	802	1,574	1,270	-	487	926
	N/A		-	-	-	-	-	-	-
	Titration	5.25	99	193	207	218	-	191	182
	N/A		-	-	-	-	-	-	-
VCS	Titration	0.5	3,729	5,947	6,534	5,574	5,407	3,423	5,102
	CISE		505	504	700	782	1,301	442	706
	Titration	1	3,410	4,074	5,081	4,104	5,681	3,348	4,283
	CISE		458	385	623	587	734	499	548
	Titration	1.5	2,277	4,054	2,515	5,351	3,886	2,675	3,460
	CISE		342	490	494	546	559	338	461
	Titration	2	1,446	2,577	2,621	3,938	3,058	2,017	2,610
	CISE		229	381	374	408	480	320	365
	Titration	3.25	397	1,388	1,724	1,808	1,647	996	1,327
	CISE		101	205	257	372	261	189	231
	Titration	5.25	79	128	226	219	201	147	167
	CISE		40	50	101	90	101	59	74

Results for Bridge 4C 746, which carries the westbound lanes, are similarly organized. Table 4.5 through Table 4.8 represent the left shoulder, left lane, right lane and right shoulder, respectively.

Table 4.5 Chloride Concentration by Team, Method & Depth (4C 746 WB Left Shoulder)
Westbound Left Shoulder Chloride Concentrations (ppm)

Testing Team	Testing Method (Primary/Secondary)	Sample Depth (in.)	Sample Location					Avg.
			1	3	6	8	9	
BDI	CISE	0.5	2,054	2,924	7,431	4,496	3,187	4,019
	Titration*		-	6,320	5,620	-	-	5,970
	CISE	1	2,696	3,717	6,606	6,727	3,890	4,727
	Titration*		-	5,390	4,440	-	-	4,915
	CISE	1.5	2,440	1,738	4,516	4,878	3,116	3,337
	Titration*		-	3,720	3,750	-	-	3,735
	CISE	2	1,722	1,463	3,158	2,683	1,566	2,119
	Titration*		-	2,880	3,100	-	-	2,990
	CISE	3.25	328	443	850	1,517	219	671
	Titration*		-	1,520	990	-	-	1,255
	CISE	5.25	8	17	15	394	10	89
	Titration*		-	150	30	-	-	90
CONCORR	Titration	0.5	5,489	5,853	6,306	6,080	4,455	5,637
	CISE		3,967	4,741	4,931	4,868	3,282	4,358
	Titration	1.5	3,580	4,561	4,582	4,135	2,796	3,931
	CISE		2,229	3,282	3,192	3,050	1,687	2,688
	Titration	2.5	2,114	2,553	2,642	1,706	1,427	2,088
	CISE		1,207	1,681	1,803	1,105	781	1,315
	Titration	3.5	881	1,340	1,308	790	292	922
	CISE		429	844	881	456	142	551
	Titration	4.5	219	398	381	277	78	271
	CISE		91	207	200	143	23	133
	Titration	5.5	42	72	100	88	24	65
	CISE		2	10	36	27	-9	13

† Negative chloride concentrations reported by CISE method result from extrapolation of the fitted voltage-concentration relationship for the calibrated electrode and should be interpreted as zero but are shown as calculated for completeness in reporting.

* BDI performed titration on matching half of six cores taken by CONCORR

Table 4.6 Chloride Concentration by Team, Method & Depth (4C 746 WB Left Lane)

Westbound Left Lane Chloride Concentrations (ppm)

Testing Team	Test Method (Primary/Secondary)	Sample Depth (in.)	Location							
			2	4	5	7	10	11	12	Avg.
BDI	CISE	0.5	5,401	7,298	4,051	3,684	2,732	3,489	5,012	4,524
	Titration*		-	-	-	-	-	4,340	-	4,340
	CISE	1	3,305	2,757	3,768	2,364	3,245	2,396	3,943	3,111
	Titration*		-	-	-	-	-	3,560	-	3,560
	CISE	1.5	2,720	1,342	2,473	2,647	2,249	1,080	3,943	2,351
	Titration*		-	-	-	-	-	1,980	-	1,980
	CISE	2	2,757	739	545	2,101	1,361	1,100	2,229	1,547
	Titration*		-	-	-	-	-	930	-	930
	CISE	3.25	1,032	435	82	762	138	27	816	470
	Titration*		-	-	-	-	-	140	-	140
CISE	5.25	13	16	2	12	6	9	12	10	
Titration*		-	-	-	-	-	80	-	80	
CONCORR	Titration	0.5	6,209	6,631	5,731	5,560	6,296	5,434	6,797	6,094
	CISE		5,103	5,240	4,720	4,546	4,910	4,351	5,440	4,902
	Titration	1.5	3,982	3,676	3,919	3,403	3,503	2,107	4,422	3,573
	CISE		2,902	2,575	2,905	2,473	2,339	1,429	3,192	2,545
	Titration	2.5	2,290	2,084	2,169	1,789	1,362	427	2,791	1,845
	CISE		1,491	1,450	1,355	1,303	857	242	1,837	1,219
	Titration	3.5	1,022	1,033	848	713	275	51	1,518	780
	CISE		596	627	468	425	139	13	957	461
	Titration	4.5	275	287	210	205	45	28	457	215
	CISE		134	143	90	99	1	-3	243	101
	Titration	5.5	72	67	73	32	40	29	155	67
	CISE		16	11	9	-2	-12	-5	68	12

† Negative chloride concentrations reported by CISE method result from extrapolation of the fitted voltage-concentration relationship for the calibrated electrode and should be interpreted as zero but are shown as calculated for completeness in reporting.

* BDI performed titration on matching half of six cores taken by CONCORR

Table 4.7 Chloride Concentration by Team, Method & Depth (4C 746 WB Right Lane)
Westbound Right Lane Chloride Concentrations (ppm)

Testing Team	Test Method (Primary/Secondary)	Sample Depth (in.)	Location						
			2	3	6	7	9	11	Avg.
SCS	Titration	0.5	6,924	5,813	6,171	7,043	4,999	6,797	6,291
	N/A		-	-	-	-	-	-	-
	Titration	1	7,003	5,549	4,539	4,853	3,736	3,805	4,914
	N/A		-	-	-	-	-	-	-
	Titration	1.5	4,220	4,141	4,177	3,060	2,807	2,636	3,507
	N/A		-	-	-	-	-	-	-
	Titration	2	2,788	2,793	2,600	2,048	1,820	1,543	2,265
	N/A		-	-	-	-	-	-	-
	Titration	3.25	1,217	954	1,013	451	312	261	701
	N/A		-	-	-	-	-	-	-
	Titration	5.25	143	114	120	125	102	173	130
	N/A		-	-	-	-	-	-	-
VCS	Titration	0.5	6,948	6,601	6,400	7,701	5,599	4,827	6,346
	CISE		4,733	2,336	1,558	1,673	1,959	1,147	2,234
	Titration	1.5	5,531	3,597	5,305	6,567	3,421	4,829	4,875
	CISE		2,819	1,382	1,558	1,403	1,387	1,036	1,598
	Titration	2.5	3,146	3,186	3,234	4,022	2,983	3,523	3,349
	CISE		1,827	1,163	1,051	935	961	900	1,140
	Titration	3.5	2,901	4,108	2,339	2,080	2,228	2,185	2,640
	CISE		1,499	993	958	568	782	547	891
	Titration	4.5	1,553	1,176	423	584	840	506	847
	CISE		611	461	197	247	384	193	349
	Titration	5.5	250	121	110	94	98	82	126
	CISE		172	101	87	77	92	70	100

Table 4.8 Chloride Concentration by Team, Method & Depth (4C 746 WB Right Shoulder)
 Westbound Right Shoulder Chloride Concentrations (ppm)

Testing Team	Testing Method (Primary/Secondary)	Sample Depth (in.)	Sample Location							
			1	4	5	8	10	12	Avg.	
SCS	Titration	0.5	5,171	5,689	5,740	4,187	3,964	4,434	4,864	
	N/A		-	-	-	-	-	-	-	
	Titration	1	3,968	5,005	4,069	4,223	4,242	3,918	4,238	
	N/A		-	-	-	-	-	-	-	
	Titration	1.5	3,098	3,124	2,685	2,647	3,609	2,419	2,930	
	N/A		-	-	-	-	-	-	-	
	Titration	2	2,163	1,710	1,767	1,722	1,449	1,548	1,727	
	N/A		-	-	-	-	-	-	-	
	Titration	3.25	529	380	636	297	242	508	432	
	N/A		-	-	-	-	-	-	-	
	Titration	5.25	213	180	104	119	132	119	145	
	N/A		-	-	-	-	-	-	-	
	VCS	Titration	0.5	6,620	5,111	5,379	5,928	3,696	4,616	5,225
		CISE		5,835	1,850	1,105	3,766	1,074	900	2,422
Titration		1.5	4,206	3,637	4,494	4,298	3,061	3,373	3,845	
CISE			3,070	1,291	919	2,471	784	691	1,538	
Titration		2.5	3,589	2,976	3,299	2,596	2,090	2,474	2,837	
CISE			1,842	878	798	1,311	629	494	992	
Titration		3.5	2,114	2,144	2,561	2,001	1,125	2,072	2,003	
CISE			1,301	676	646	955	379	464	737	
Titration		4.5	620	266	1,071	778	308	655	616	
CISE			427	143	334	434	129	211	280	
Titration		5.5	63	71	101	89	70	71	78	
CISE			117	67	76	110	60	61	82	

4.2.2 Interlaboratory Exchange

To serve as a check on the results of each laboratory on its assigned test methods, the powdered samples for a subset of the profiles were split and forwarded to another team to be tested by the same method. The samples had already been subdivided by the sampling team. Each was then directed to ship the top three profile increments from 12 of 24 (being all odd- or all even-number sample locations) to the other team, for a total of 36 additional concentration tests per team. Results of these interlaboratory tests are organized by sampling and receiving team pairs, separated by bridge, and listed in order of nominal depth for each exchanged sample location. Table 4.9 compares results of BDI specimens also tested by CONCORR using CISE. Similarly, Table 4.10 compares results of VCS samples also tested by BDI, also using CISE.

Table 4.9 Interlaboratory (BDI → CONCORR) Chloride Concentrations by CISE

Eastbound Chloride Concentrations (ppm)											
Testing Team	Test Method	Sample Depth (in.)	Left Lane			Left Shoulder					EB Avg.
			15	19	Avg.	13	17	21	23	Avg.	
BDI	CISE	0.5	2,732	3,340	3,036	1,920	2,194	3,225	3,694	2,758	2,851
		1	1,271	2,853	2,062	633	1,479	3,444	3,474	2,258	2,193
		1.5	1,318	2,416	1,867	914	2,091	2,175	2,513	1,923	1,904
CONCORR	CISE	0.5	4,227	3,667	3,947	2,462	2,407	4,123	4,625	3,404	3,585
		1	2,943	3,664	3,304	1,122	2,033	3,636	3,547	2,585	2,824
		1.5	1,895	2,506	2,200	987	1,552	2,433	2,867	1,960	2,040

Westbound Chloride Concentrations (ppm)											
Testing Team	Test Method	Sample Depth (in.)	Left Lane				Left Shoulder				WB Avg.
			5	7	11	Avg.	1	3	9	Avg.	
BDI	CISE	0.5	4,051	3,684	3,489	3,742	2,054	2,924	3,187	2,722	3,232
		1	3,768	2,364	2,396	2,843	2,696	3,717	3,890	3,434	3,139
		1.5	2,473	2,647	1,080	2,067	2,440	1,738	3,116	2,431	2,249
CONCORR	CISE	0.5	4,888	4,267	3,477	4,211	4,301	4,195	3,438	3,978	4,094
		1	3,809	3,073	2,852	3,245	3,004	3,544	2,652	3,067	3,156
		1.5	2,357	1,978	1,985	2,107	1,785	2,386	2,153	2,108	2,107

Table 4.10 Interlaboratory (VCS → BDI) Chloride Concentrations by CISE

Eastbound Chloride Concentrations (ppm)

Testing Firm	Testing Method	Sample Depth (in.)	Right Lane				Right Shoulder				EB Avg.
			14	20	22	Avg.	16	18	24	Avg.	
VCS	CISE	0.5	465	7,634	741	2,947	504	700	442	549	1,748
		1	461	3,412	526	1,466	385	623	499	502	984
		1.5	332	1,865	427	875	490	494	338	441	658
BDI	CISE	0.5	4,825	6,174	3,241	4,747	4,964	5,510	2,046	4,174	4,460
		1	4,871	4,646	2,838	4,118	3,135	3,700	2,229	3,021	3,570
		1.5	2,643	3,382	2,115	2,713	3,563	2,785	1,525	2,624	2,669

Westbound Chloride Concentrations (ppm)

Testing Firm	Testing Method	Sample Depth (in.)	Right Lane				Right Shoulder				WB Avg.
			2	6	Avg.	4	8	10	12	Avg.	
VCS	CISE	0.5	4,733	1,558	3,146	1,850	3,766	1,074	900	987	2,313
		1.5	2,819	1,558	2,188	1,291	2,471	784	691	738	1,602
		2	1,827	1,051	1,439	878	1,311	629	494	562	1,032
BDI	CISE	0.5	4,088	3,271	3,680	3,241	3,303	1,906	2,473	2,190	3,047
		1.5	4,515	2,976	3,746	2,066	3,366	1,476	2,581	2,028	2,830
		2	1,942	1,336	1,639	1,661	1,262	1,187	1,533	1,360	1,487

Comparison between laboratories based on these CISE data are difficult based solely on individual chloride concentrations, but general trends can be observed wherein CONCORR reported values that were consistently higher than those of BDI, and BDI consistently reported higher values than VCS. Interestingly, BDI and VCS used commercially available field kits for CISE, whereas CONCORR used conventional laboratory equipment, including meter and probe.

Table 4.11 and Table 4.12 show samples tested using potentiometric titration. In the former case, samples by CONCORR were also tested by SCS. In the latter case, samples by SCS were sent to VCS to perform the same tests. In the case of VCS, titrations were not performed in-house, but were outsourced to a testing laboratory operated by Tourney Consulting Group (TCG) based in Kalamazoo, MI. Comparing general trends, SCS values were nearly always lower than companion values reported by CONCORR and by VCS. Thus, some evidence of interlaboratory differences are indicated. Note that SCS performed titration by AASHTO T260,

which uses 3g powdered concrete samples that pass No 50 sieve, whereas CONCORR and VCS followed ASTM C1152, which uses 10g samples and No. 20 sieve. WSP recommends, based upon experience of several of our experts, that these methods be considered comparable.

Table 4.11 Interlaboratory (CONCORR → SCS) Chloride Concentrations by Titration
Eastbound Chloride Concentrations (ppm)

Testing Firm	Test Method	Sample Depth (in.)	Left Lane					Left Shoulder			EB Avg.
			14	18	22	24	Avg.	16	20	Avg.	
CONCORR	Titration	0.5	4,794	5,760	4,751	6,463	5,442	5,352	6,482	5,917	5,600
		1.5	2,592	3,657	3,433	4,564	3,562	3,411	4,083	3,747	3,623
		2	1,501	2,339	1,456	2,719	2,004	2,002	2,452	2,227	2,078
SCS	Titration	0.5	4,130	4,750	4,060	5,170	4,528	4,600	5,680	5,140	4,732
		1.5	1,930	2,680	2,630	3,650	2,723	2,510	2,810	2,660	2,702
		2	1,170	1,860	1,170	2,110	1,578	1,680	1,560	1,620	1,592

Westbound Chloride Concentrations (ppm)

Testing Firm	Test Method	Sample Depth (in.)	Left Lane					Left Shoulder			WB Avg.
			2	4	10	12	Avg.	6	8	Avg.	
CONCORR	Titration	0.5	6,209	6,631	6,296	6,797	6,483	6,306	6,080	6,193	6,387
		1.5	3,982	3,676	3,503	4,422	3,896	4,582	4,135	4,359	4,050
		2	2,290	2,084	1,362	2,791	2,132	2,642	1,706	2,174	2,146
SCS	Titration	0.5	5,410	5,290	4,970	5,590	5,315	5,870	4,990	5,430	5,353
		1.5	3,420	3,440	2,620	3,660	3,285	3,740	3,030	3,385	3,318
		2	2,140	1,680	1,020	2,260	1,775	2,300	1,220	1,760	1,770

Table 4.12 Interlaboratory (SCS → VCS) Chloride Concentrations by Titration

Eastbound Chloride Concentrations (ppm)

Testing Firm	Test Method	Sample Depth (in.)	Right Lane				Right Shoulder				EB Avg.
			15	17	23	Avg.	13	19	21	Avg.	
SCS	Titration	0.5	5,274	6,066	5,891	5,744	4,156	4,068	-	4,112	5,091
		1	4,431	5,120	4,587	4,713	2,699	4,441	-	3,570	4,256
		1.5	3,658	3,599	3,441	3,566	2,121	3,038	-	2,580	3,171
VCS	Titration	0.5	5,690	6,308	5,947	5,982	4,253	4,259	-	4,256	5,291
		1	4,584	5,327	4,815	4,909	2,935	4,500	-	3,718	4,432
		1.5	3,636	3,670	3,313	3,540	2,501	3,166	-	2,834	3,257

Westbound Chloride Concentrations (ppm)

Testing Firm	Test Method	Sample Depth (in.)	Right Lane			Right Shoulder					WB Avg.
			2	6	Avg.	4	8	10	12	Avg.	
SCS	Titration	0.5	6,924	6,171	6,548	5,689	4,187	3,964	4,434	4,569	5,228
		1.5	7,003	4,539	5,771	5,005	4,223	4,242	3,918	4,347	4,822
		2	4,220	4,177	4,199	3,124	2,647	3,609	2,419	2,950	3,366
VCS	Titration	0.5	7,314	6,806	7,060	6,221	5,188	4,353	4,343	5,026	5,704
		1.5	7,407	4,945	6,176	5,201	3,820	3,415	4,016	4,113	4,801
		2	4,599	4,344	4,472	3,271	2,682	2,864	2,503	2,830	3,377

4.3 Analysis of Chloride Profiles and Fitted Models

For each location tested, a profile can be plotted, as shown in Figure 2.1. The model of Fickian diffusion can be fit to determine parameters of surface concentration and effective diffusion coefficient. The sets of profile data generated by each team were fitted to the Fickian model, the surface chloride concentration, C_0 , and effective diffusion coefficient, D_c , were derived, and the goodness of fit was expressed as a regression coefficient, R^2 , from 0 to 1.

4.3.1 Profiles Comparing Primary versus Secondary Test Methods

The first step in analyzing the chloride concentration results from the various teams was to plot chloride concentration profiles as a function of depth. For illustration, the results are provided for each pair of teams by location, where samples were co-located within a few inches proximity, as shown in Figure 4.1. Red marking indicates location of top-mat reinforcement, and sample locations were selected to avoid drilling or coring into reinforcement.



Figure 4.1 Example of Paired Powder and Core Samples Located in Close Proximity

Figure 4.2 through Figure 4.49 provide plots of the chloride concentrations comparing primary and secondary lab-testing methods for each team (as applicable) for each sample location. Individual concentration values, color coded by testing team, are plotted with primary test method as solid marker and secondary method as hollow marker. Fitted curves from the diffusion model are plotted, with the same colors by team, with solid line fitted to primary test data and dashed line fitted to secondary test data. For reference, each plot indicates UDOT's specified nominal 2 lb/yd³ and 8 lb/yd³ corrosion threshold for mild steel and ECR, respectively, as well as the average and 90% confidence interval of cover depths for the subject bridge.

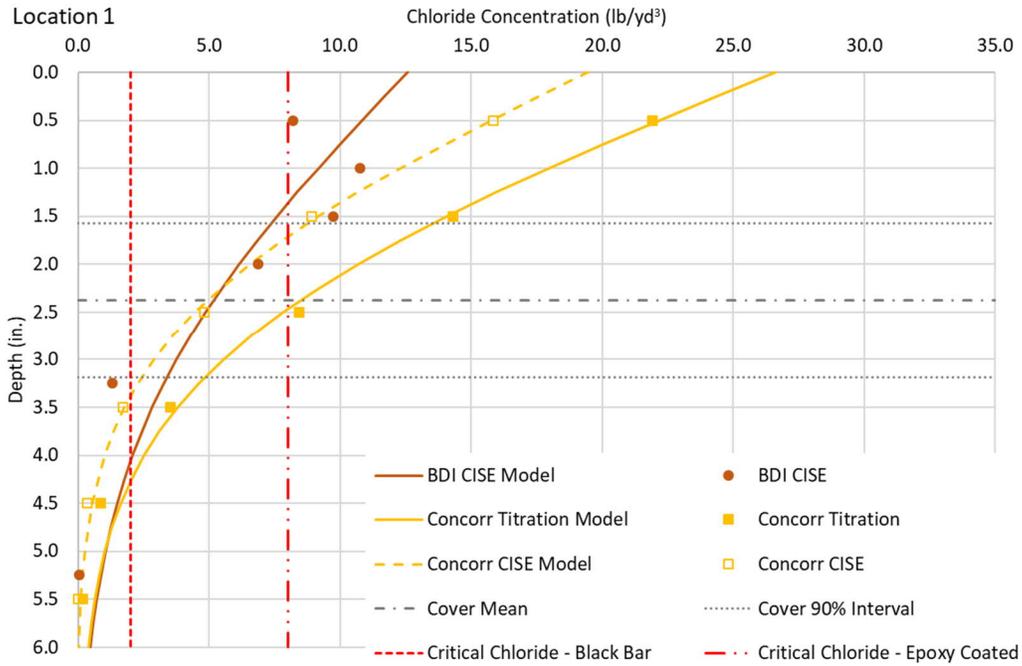


Figure 4.2 Chloride Profiles Models for Location 1 (BDI & CONCORR)

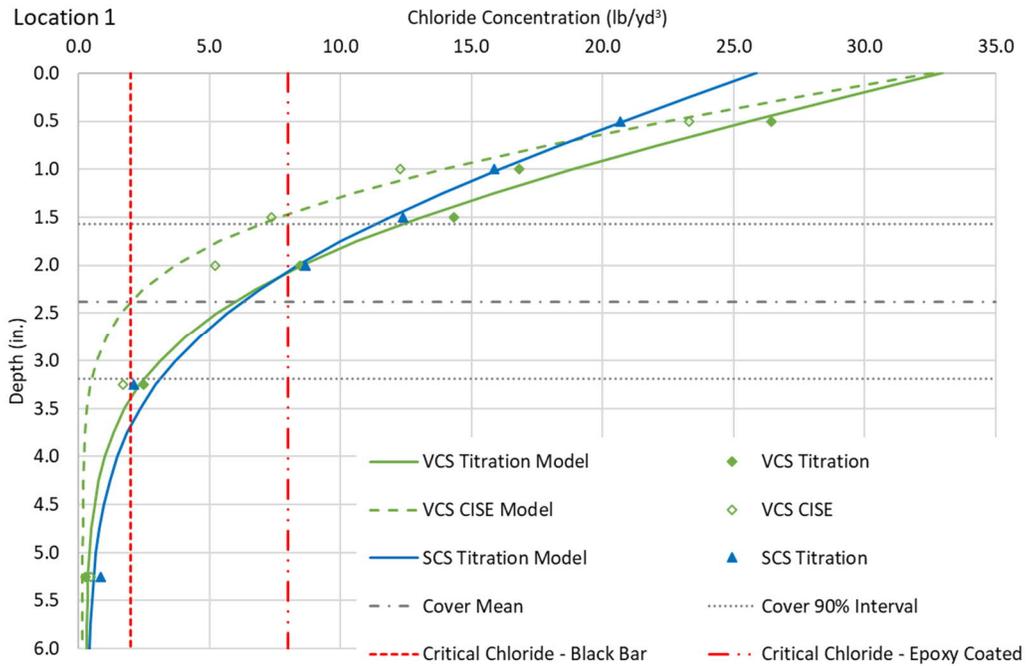


Figure 4.3 Chloride Profiles Models for Location 1 (SCS & VCS)

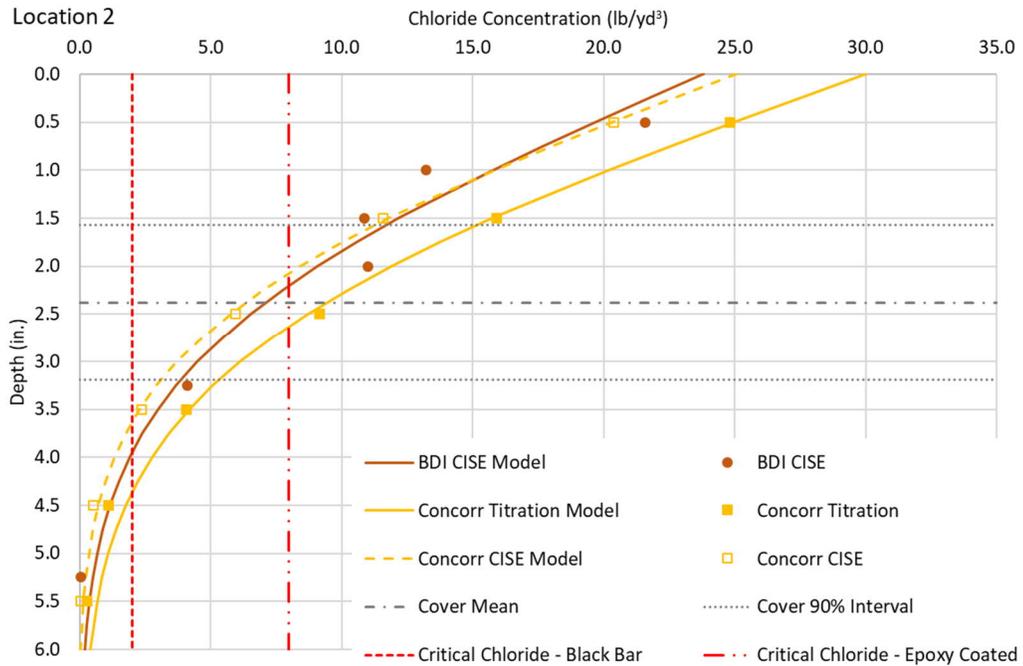


Figure 4.4 Chloride Profiles Models for Location 2 (BDI & CONCORR)

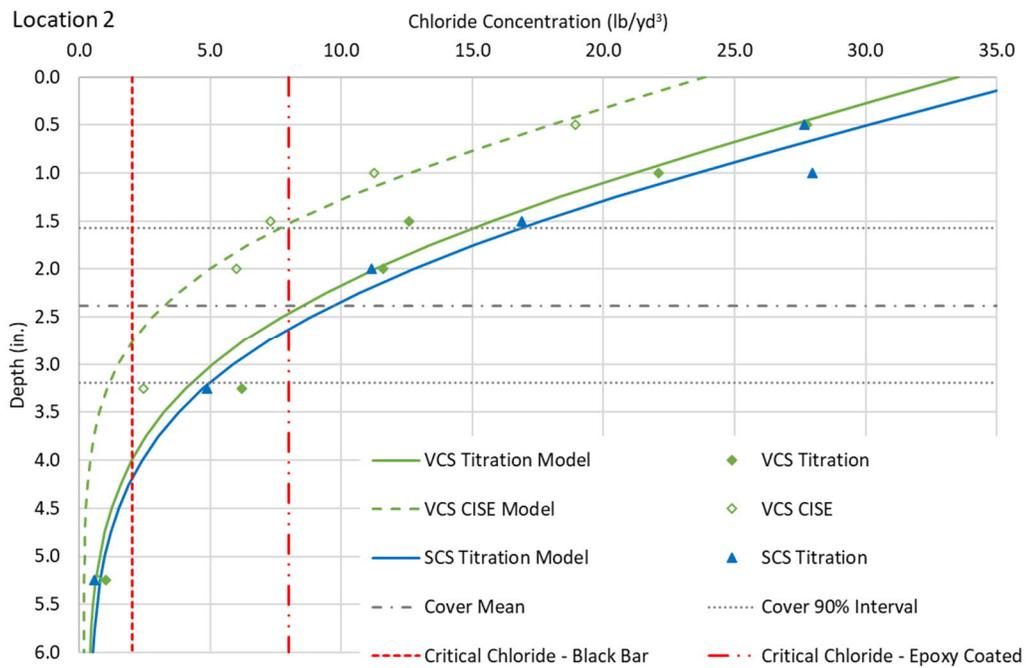


Figure 4.5 Chloride Profiles Models for Location 2 (SCS & VCS)

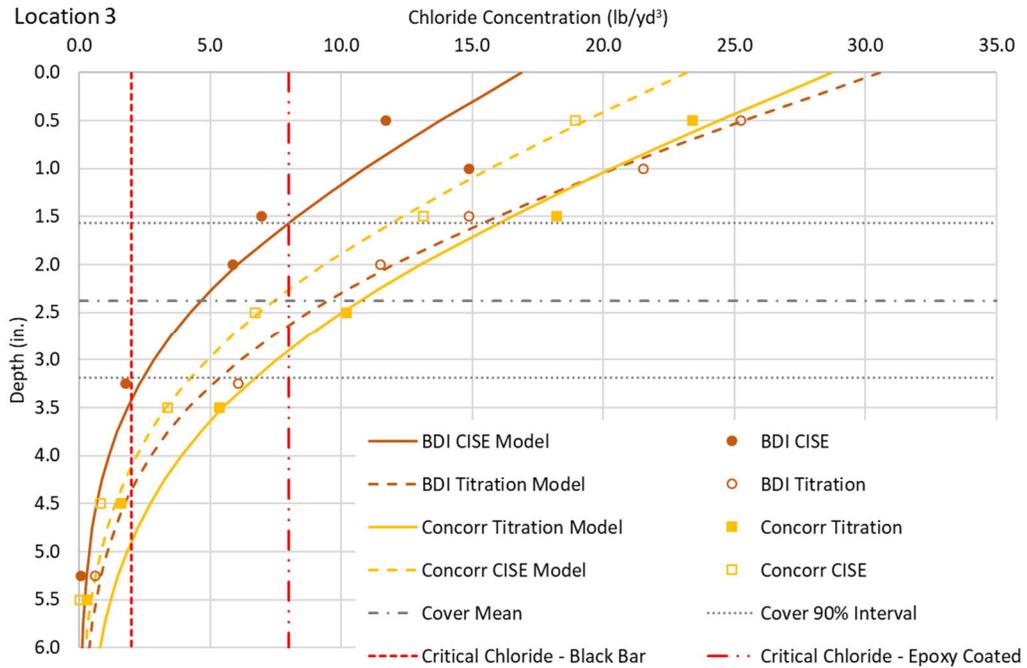


Figure 4.6 Chloride Profiles Models for Location 3 (BDI & CONCORR)

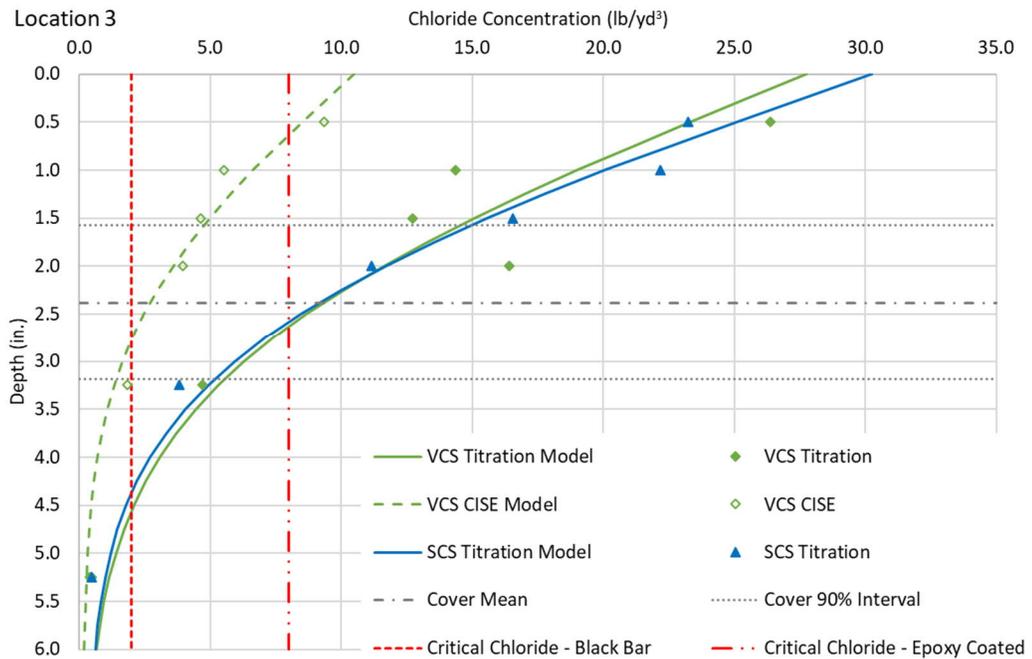


Figure 4.7 Chloride Profiles Models for Location 3 (SCS & VCS)

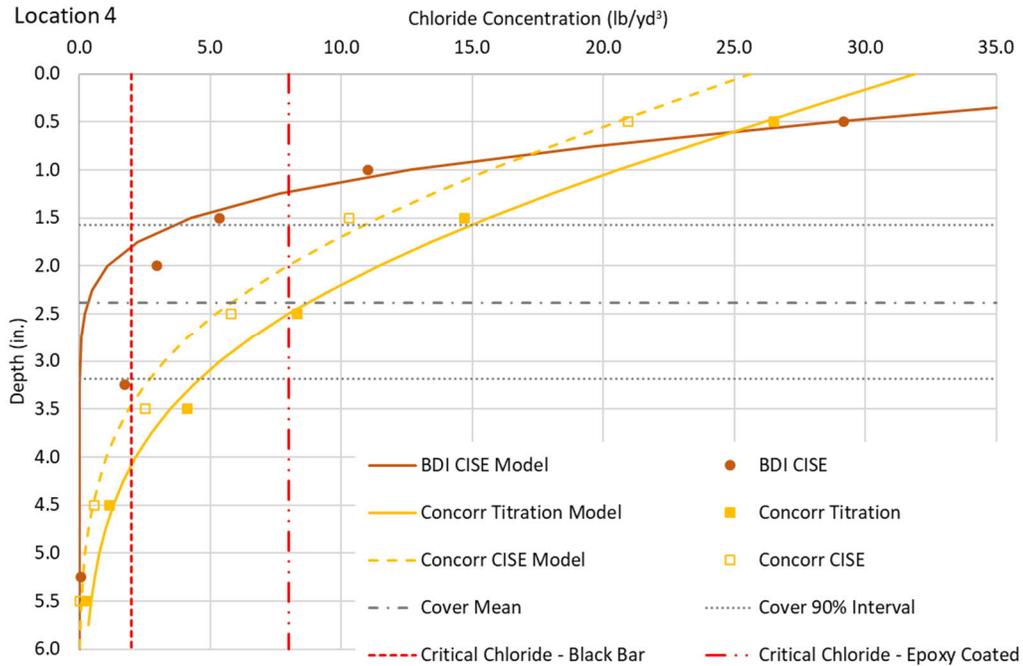


Figure 4.8 Chloride Profiles Models for Location 4 (BDI & CONCORR)

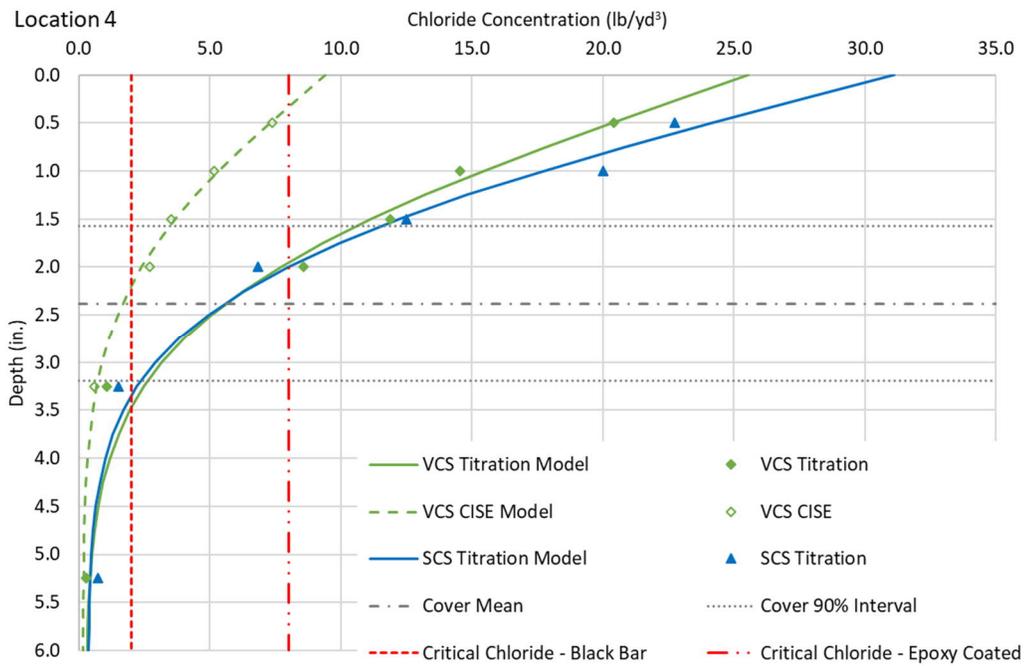


Figure 4.9 Chloride Profiles Models for Location 4 (SCS & VCS)

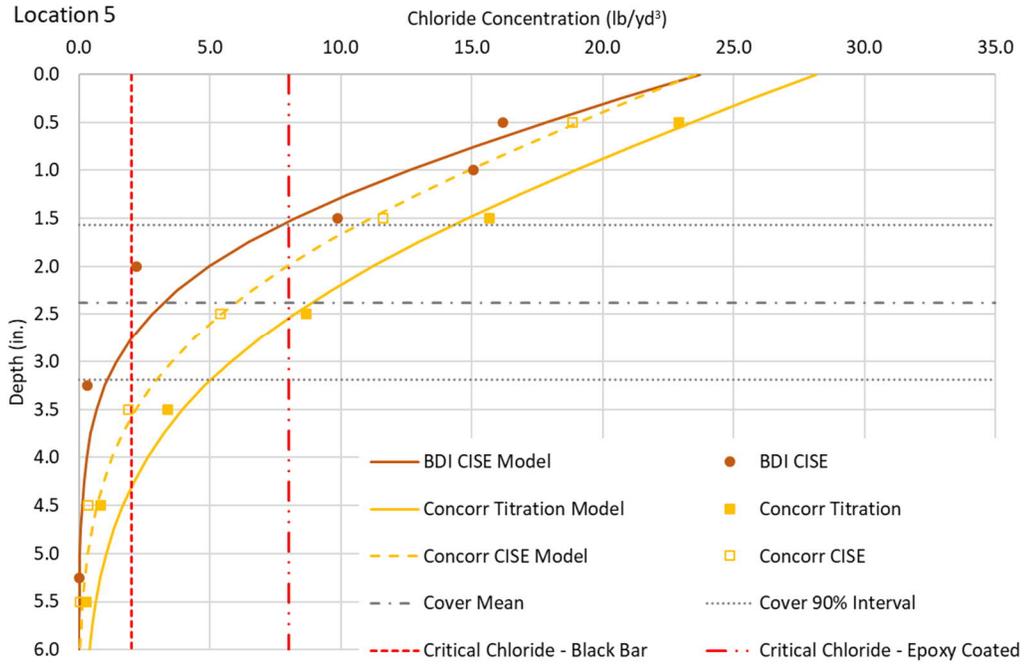


Figure 4.10 Chloride Profiles Models for Location 5 (BDI & CONCORR)

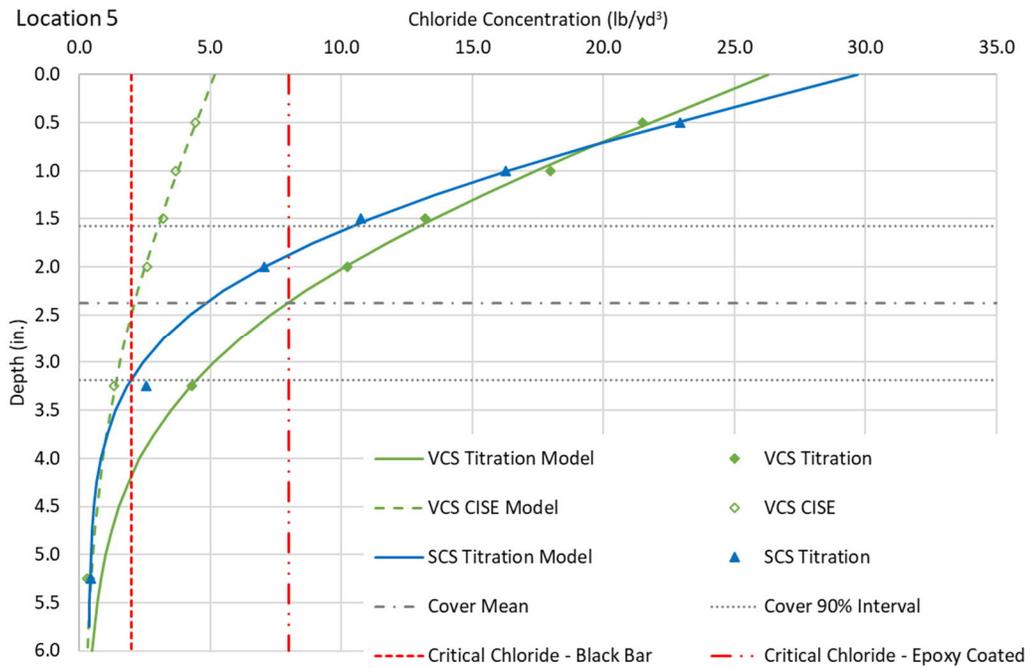


Figure 4.11 Chloride Profiles Models for Location 5 (SCS & VCS)

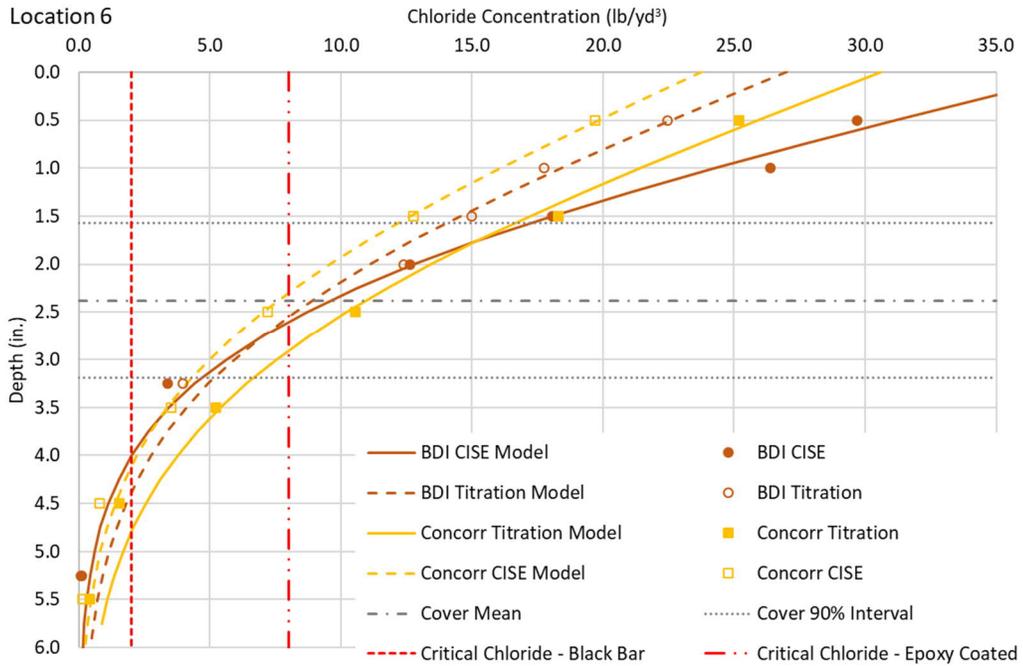


Figure 4.12 Chloride Profiles Models for Location 6 (BDI & CONCORR)

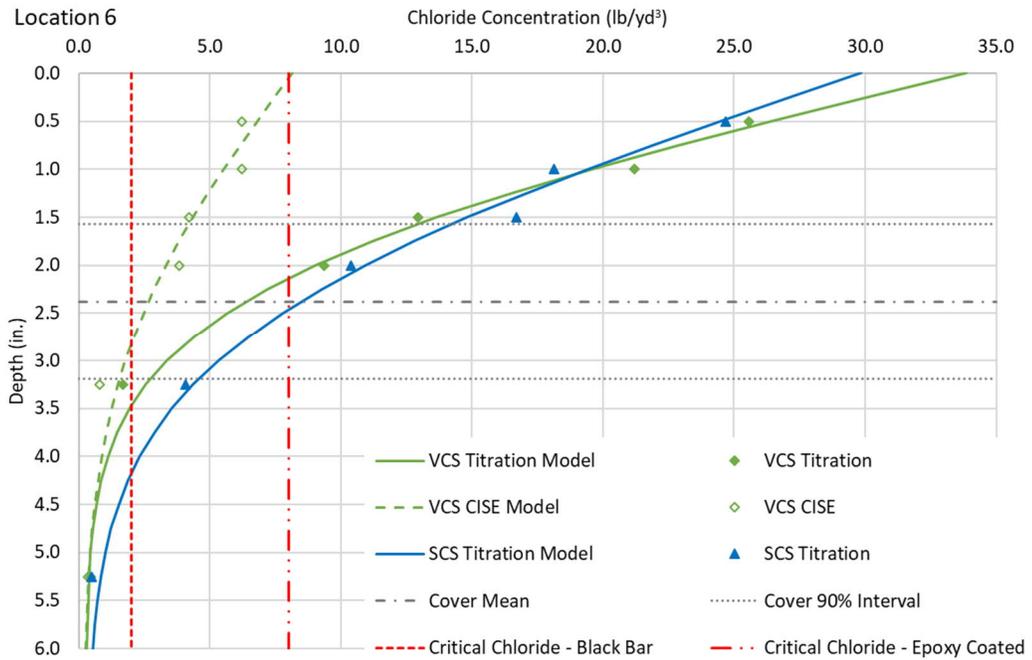


Figure 4.13 Chloride Profiles Models for Location 6 (SCS & VCS)

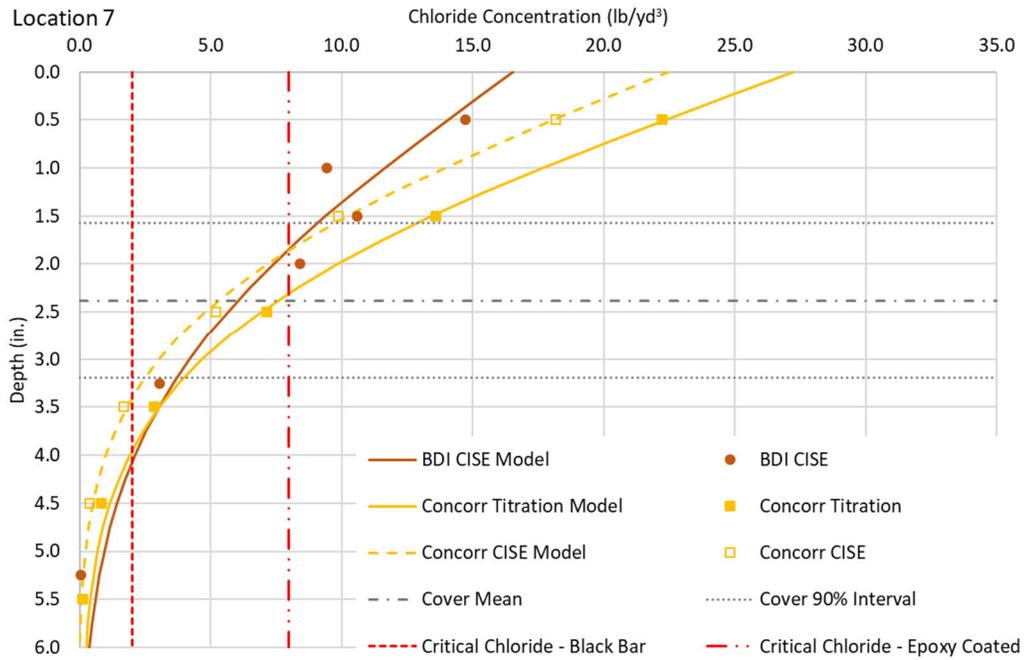


Figure 4.14 Chloride Profiles Models for Location 7 (BDI & CONCORR)

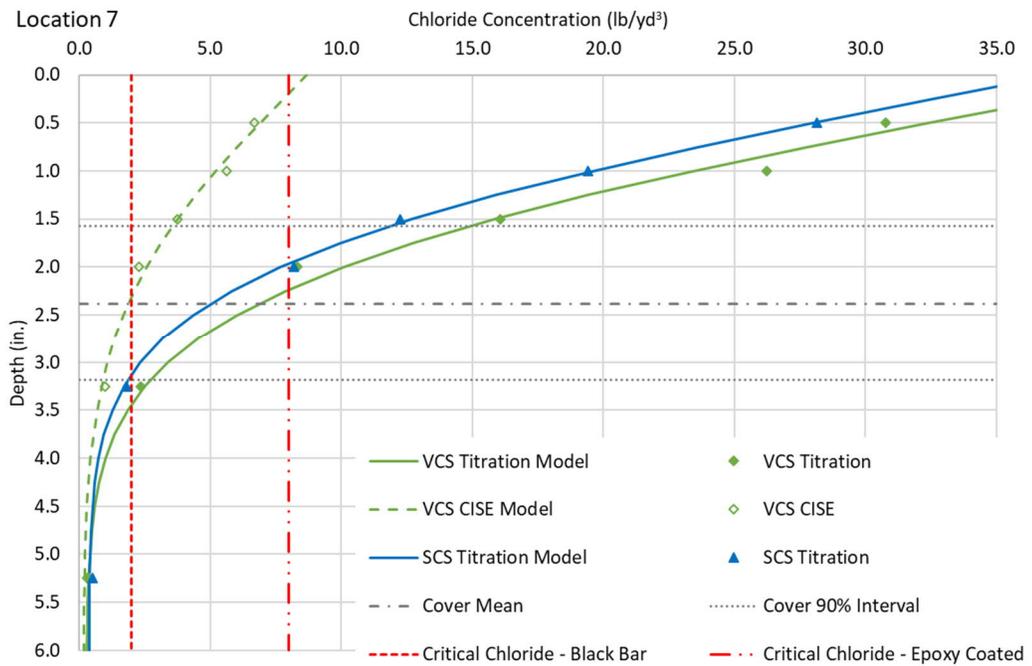


Figure 4.15 Chloride Profiles Models for Location 7 (SCS & VCS)

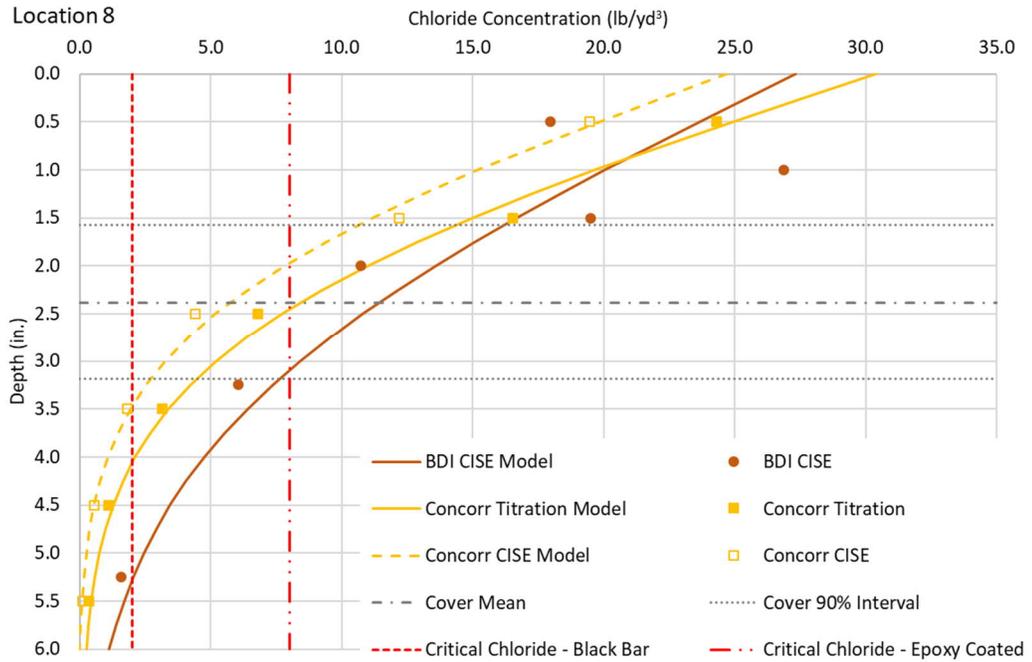


Figure 4.16 Chloride Profiles Models for Location 8 (BDI & CONCORR)

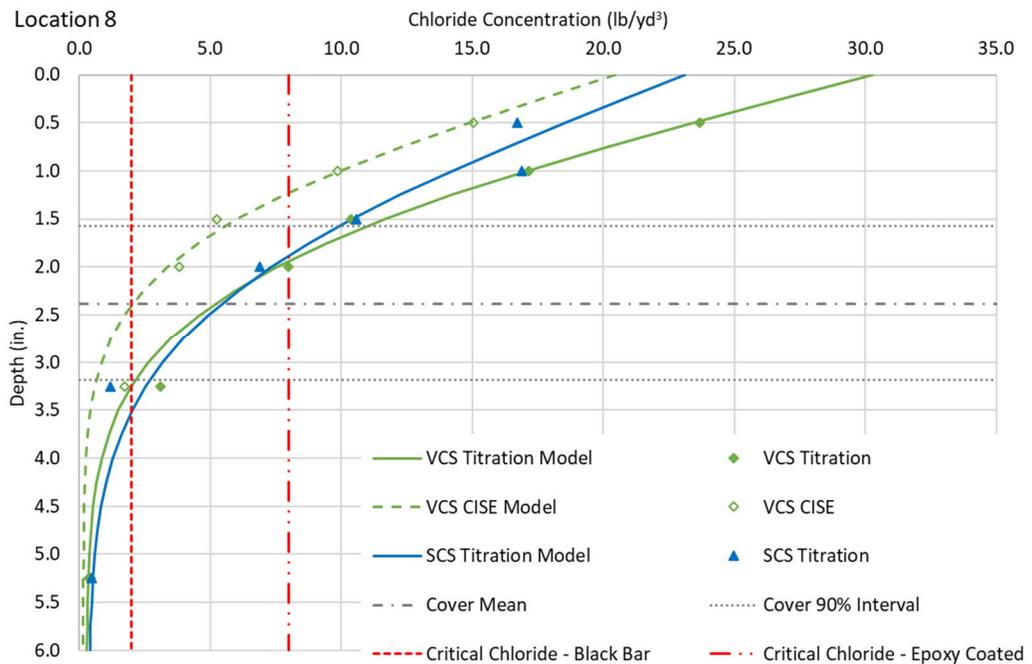


Figure 4.17 Chloride Profiles Models for Location 8 (SCS & VCS)

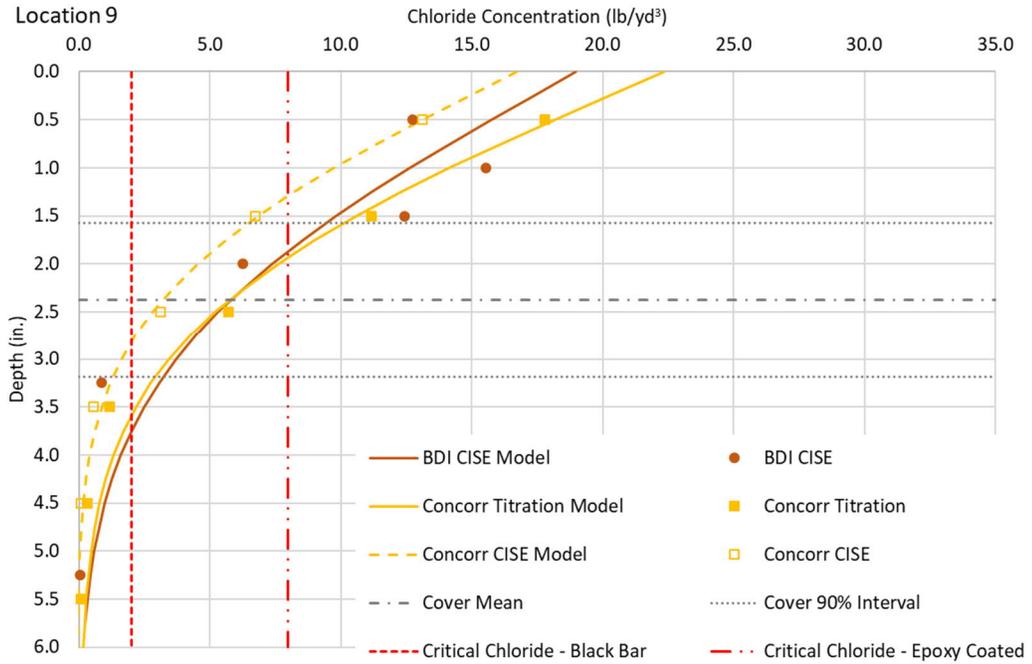


Figure 4.18 Chloride Profiles Models for Location 9 (BDI & CONCORR)

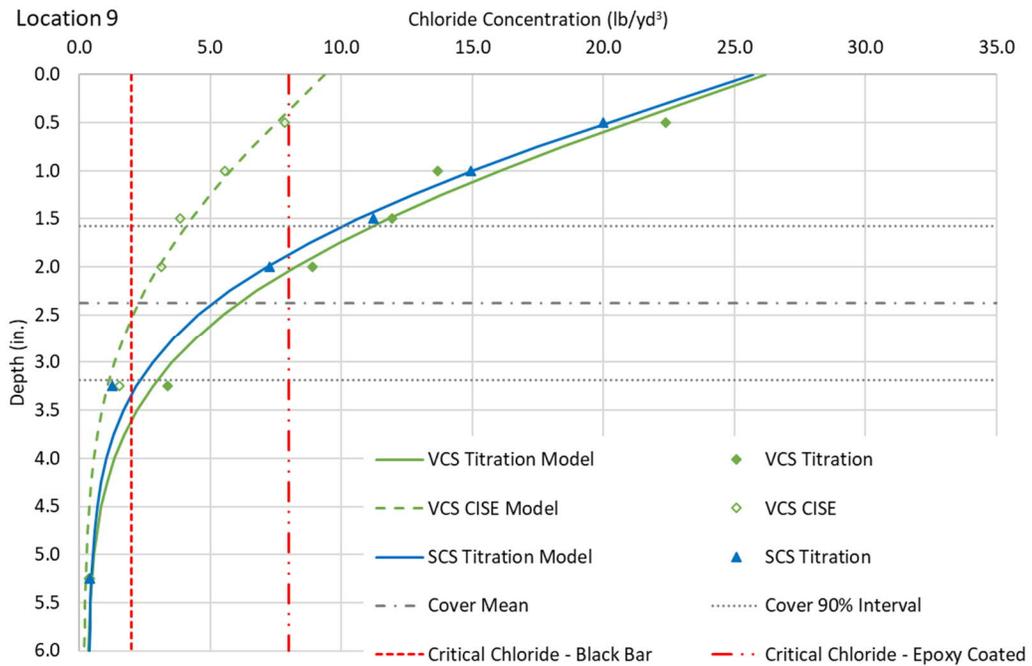


Figure 4.19 Chloride Profiles Models for Location 9 (SCS & VCS)

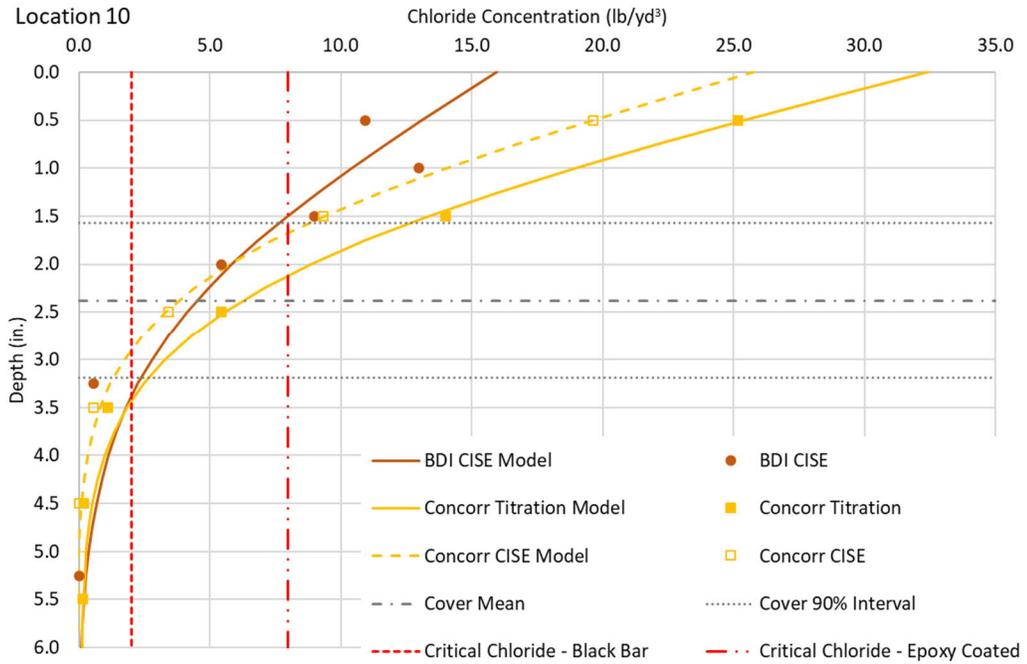


Figure 4.20 Chloride Profiles Models for Location 10 (BDI & CONCORR)

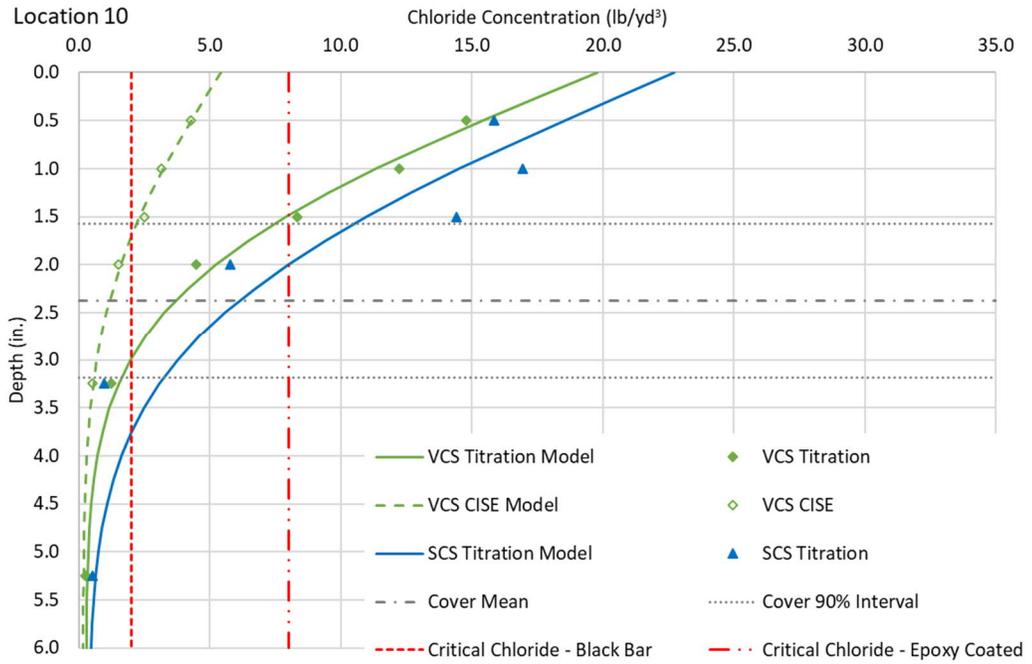


Figure 4.21 Chloride Profiles Models for Location 10 (SCS & VCS)

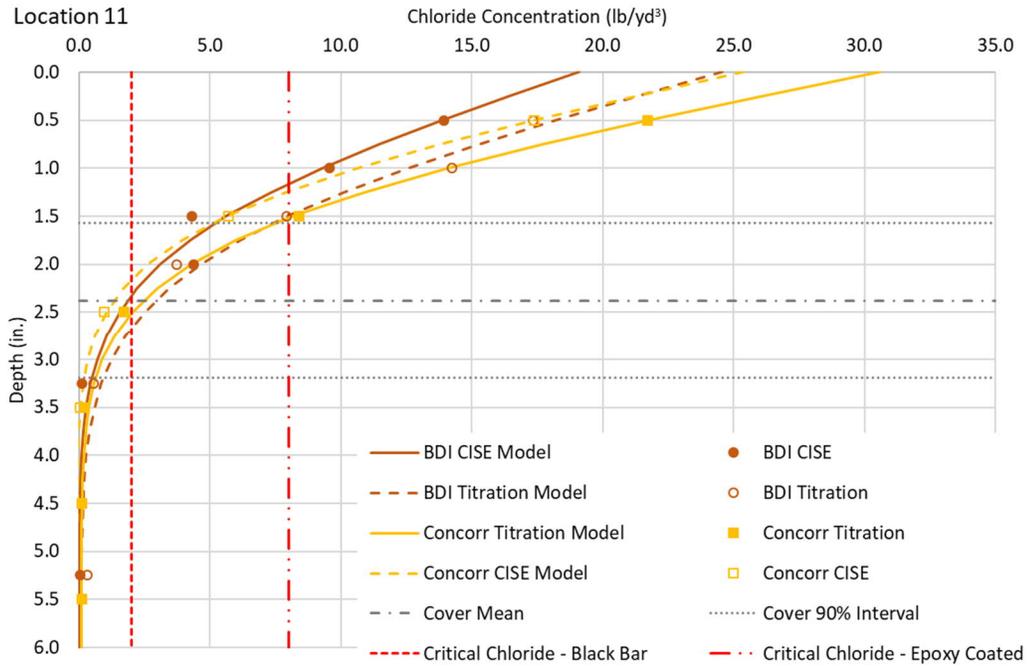


Figure 4.22 Chloride Profiles Models for Location 11 (BDI & CONCORR)

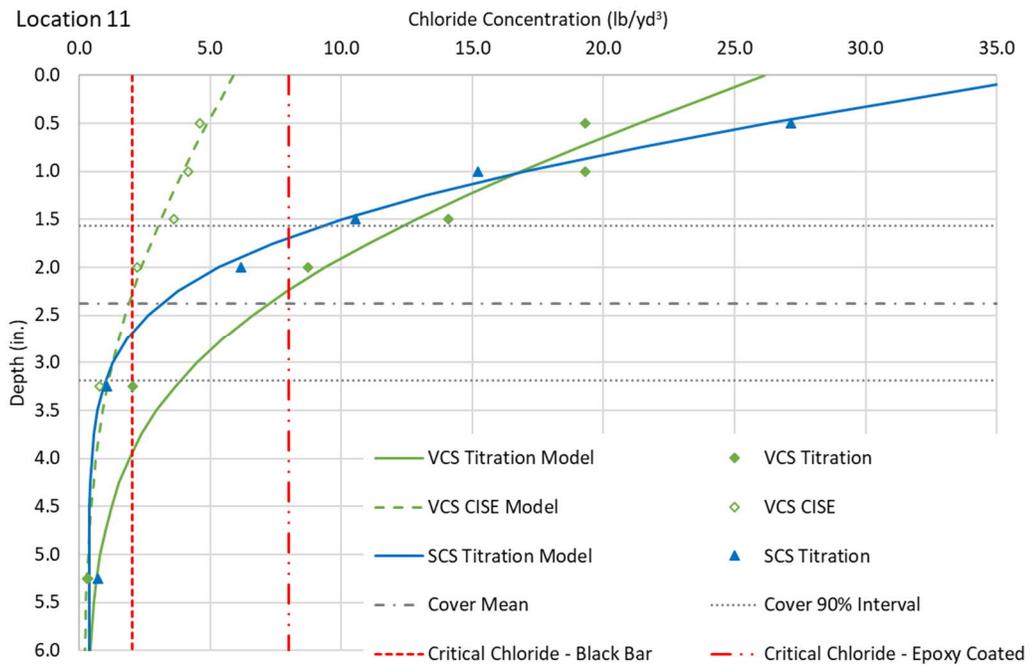


Figure 4.23 Chloride Profiles Models for Location 11 (SCS & VCS)

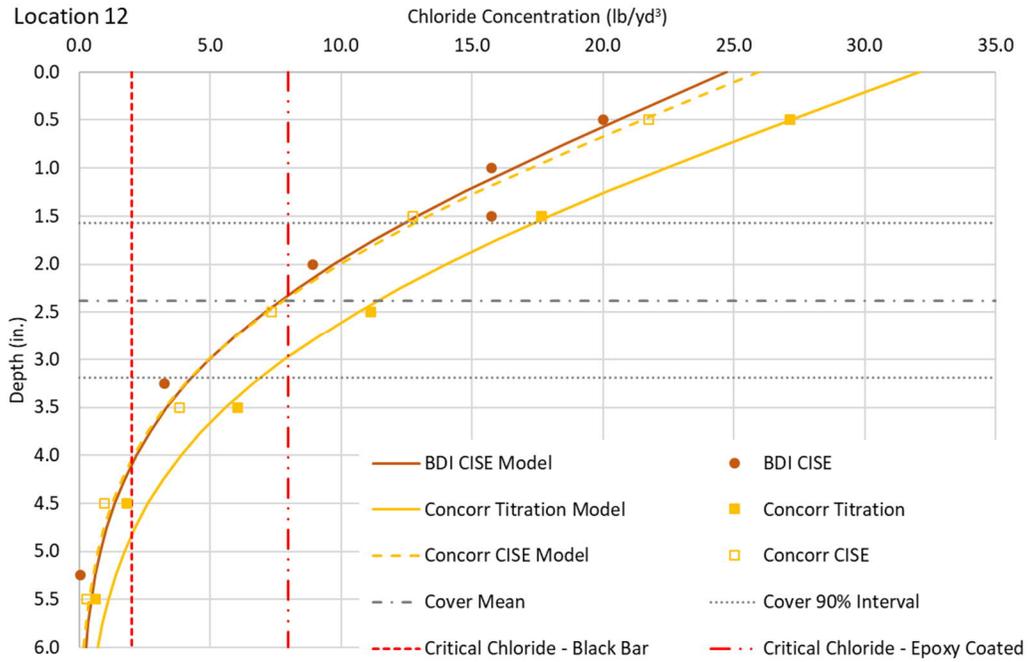


Figure 4.24 Chloride Profiles Models for Location 12 (BDI & CONCORR)

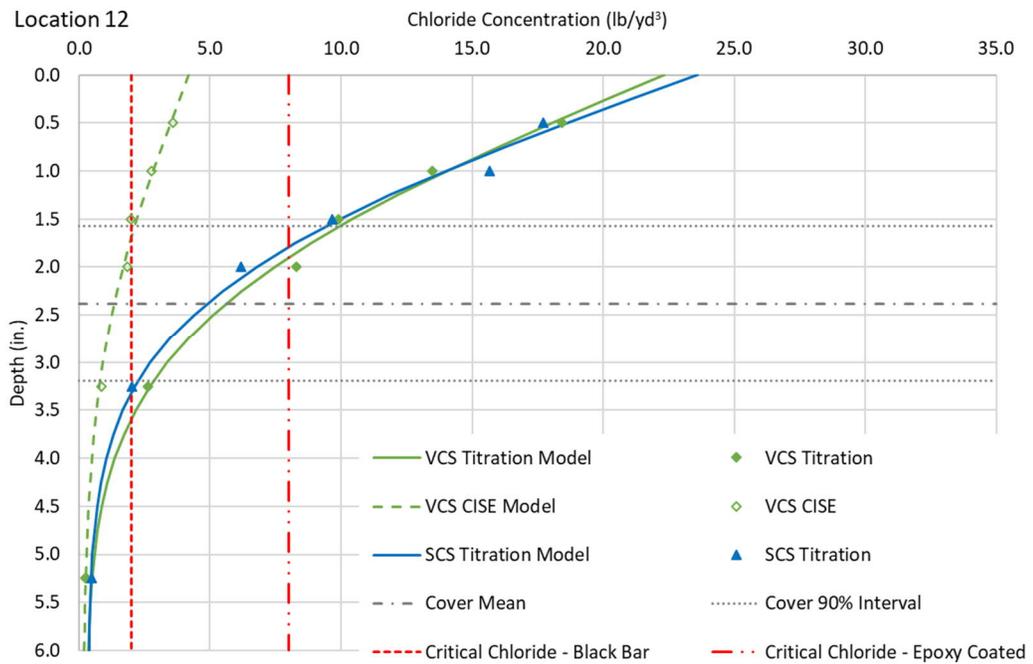


Figure 4.25 Chloride Profiles Models for Location 12 (SCS & VCS)

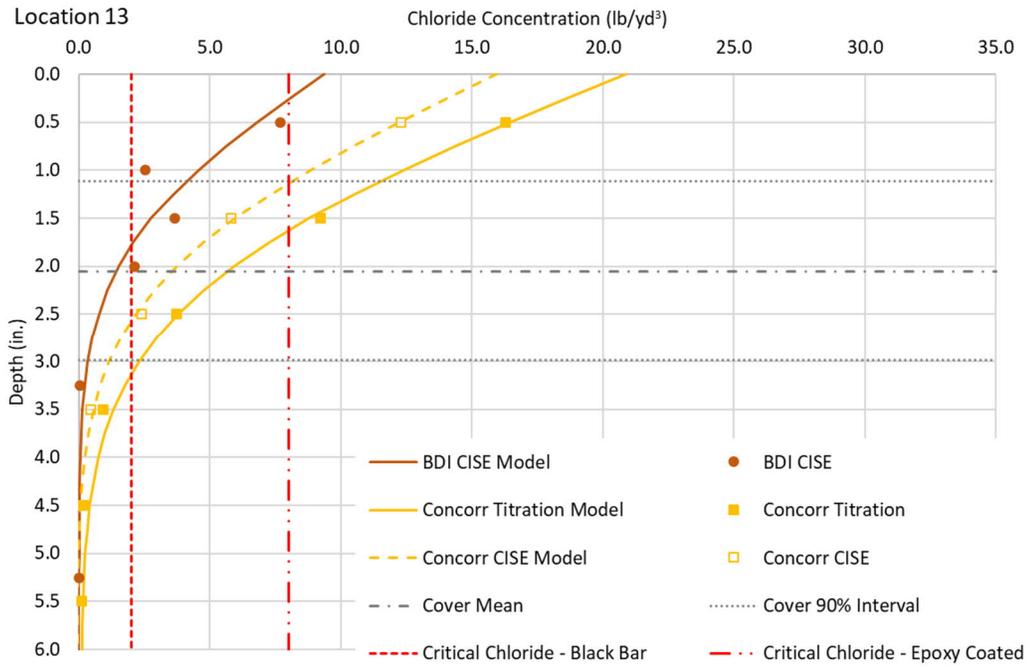


Figure 4.26 Chloride Profiles Models for Location 13 (BDI & CONCORR)

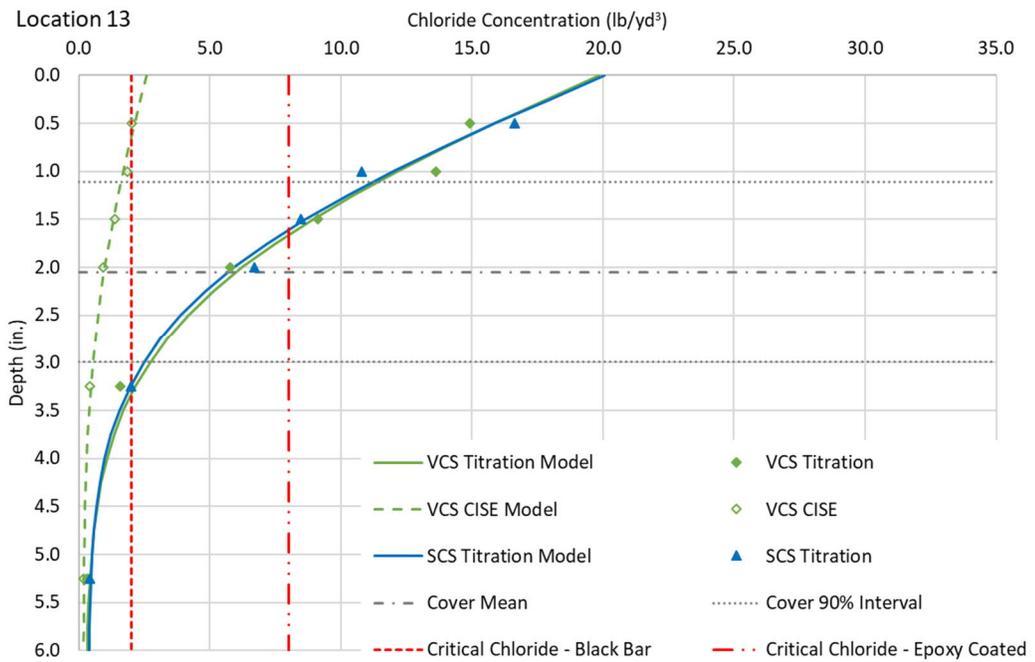


Figure 4.27 Chloride Profiles Models for Location 13 (SCS & VCS)

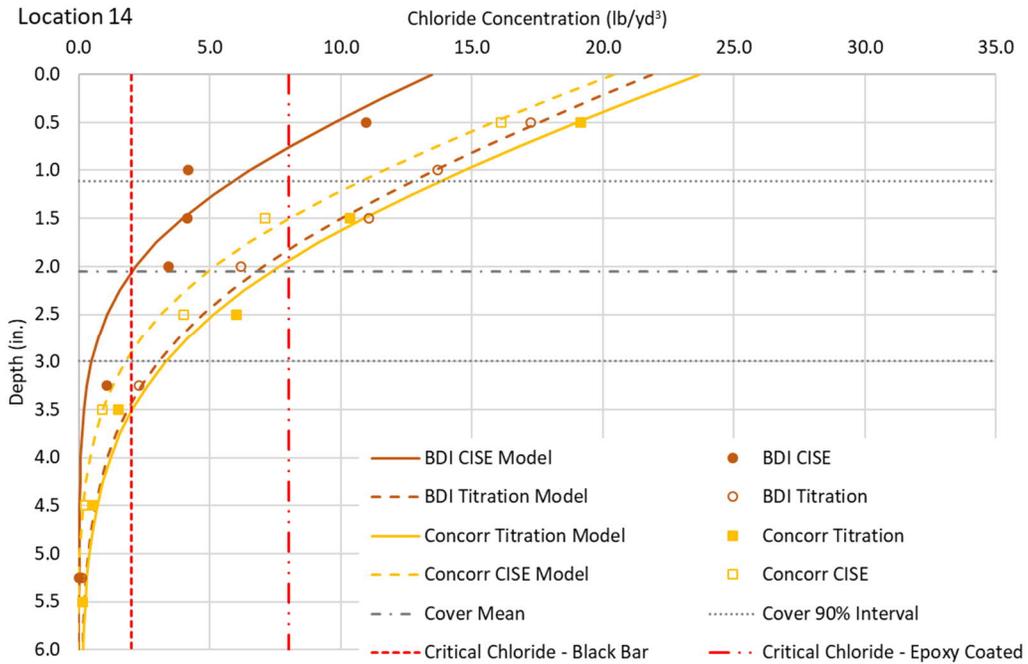


Figure 4.28 Chloride Profiles Models for Location 14 (BDI & CONCORR)

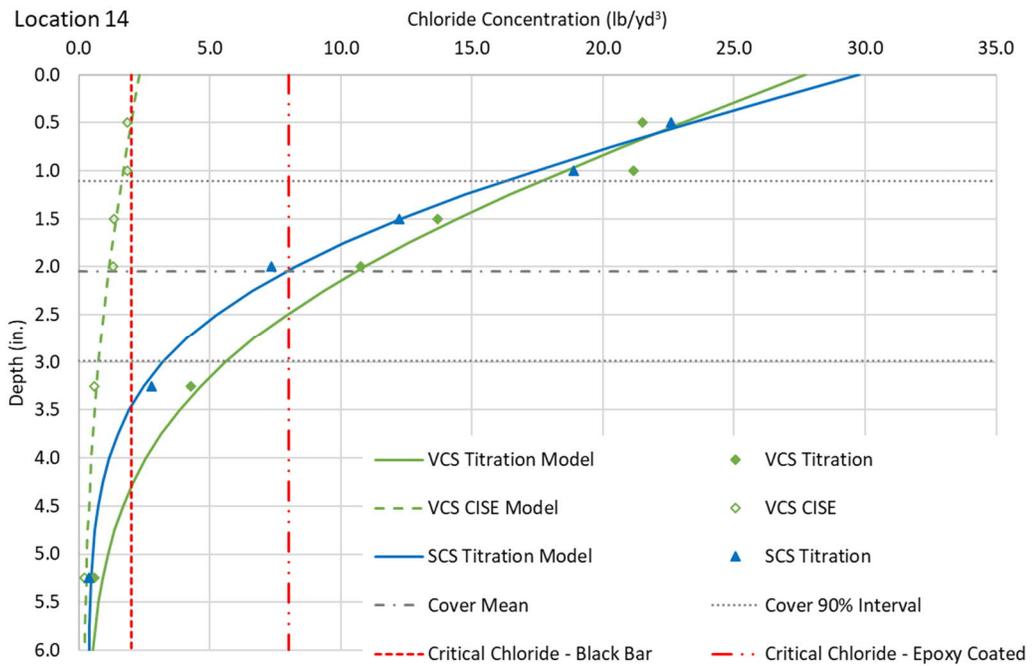


Figure 4.29 Chloride Profiles Models for Location 14 (SCS & VCS)

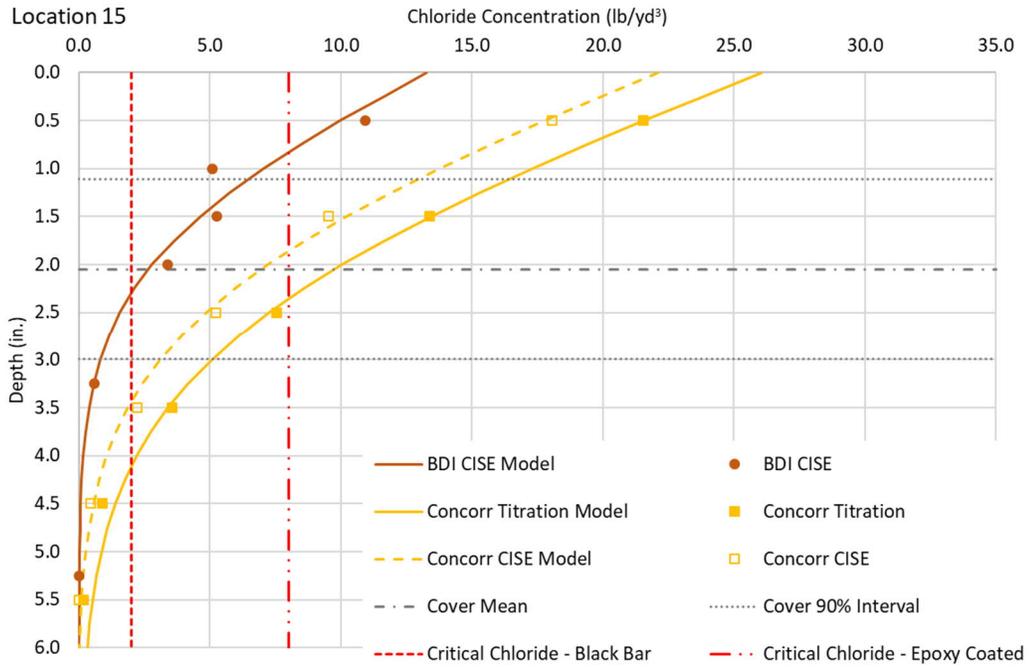


Figure 4.30 Chloride Profiles Models for Location 15 (BDI & CONCORR)

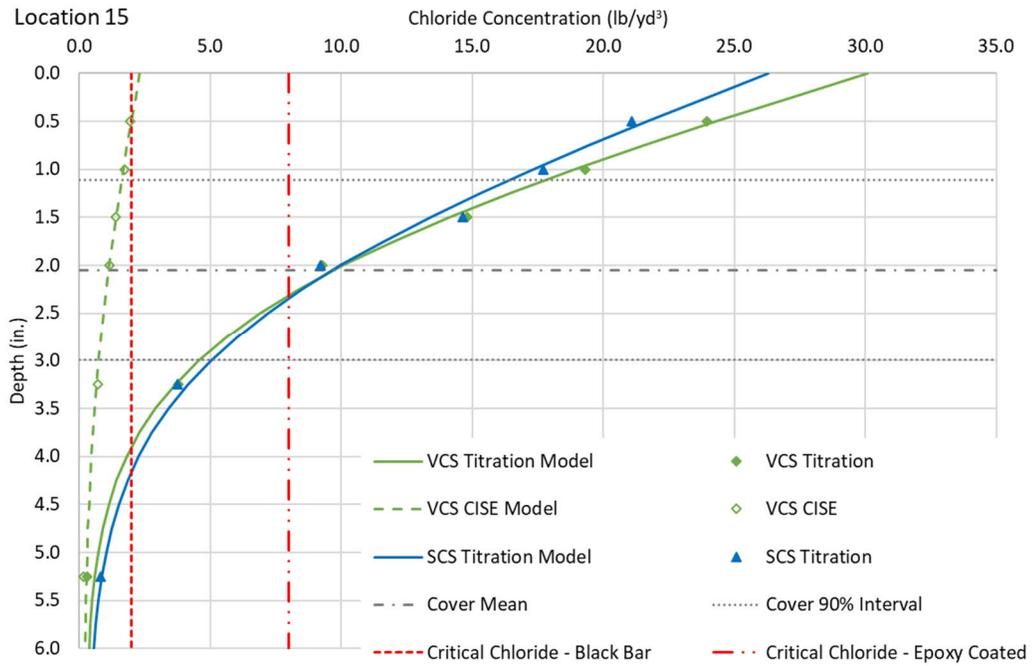


Figure 4.31 Chloride Profiles Models for Location 15 (SCS & VCS)

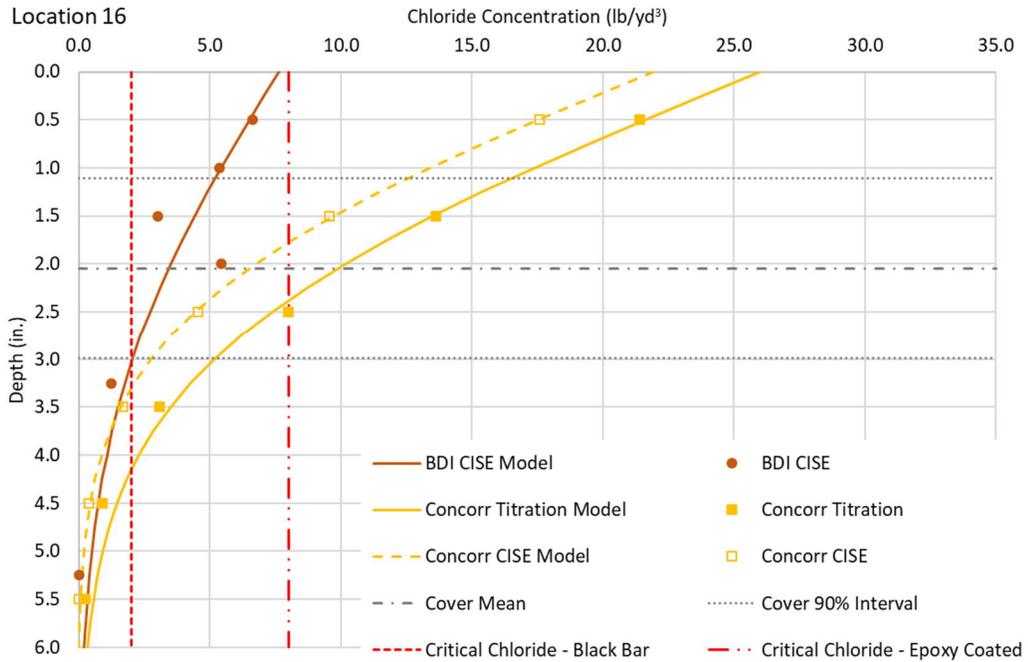


Figure 4.32 Chloride Profiles Models for Location 16 (BDI & CONCORR)

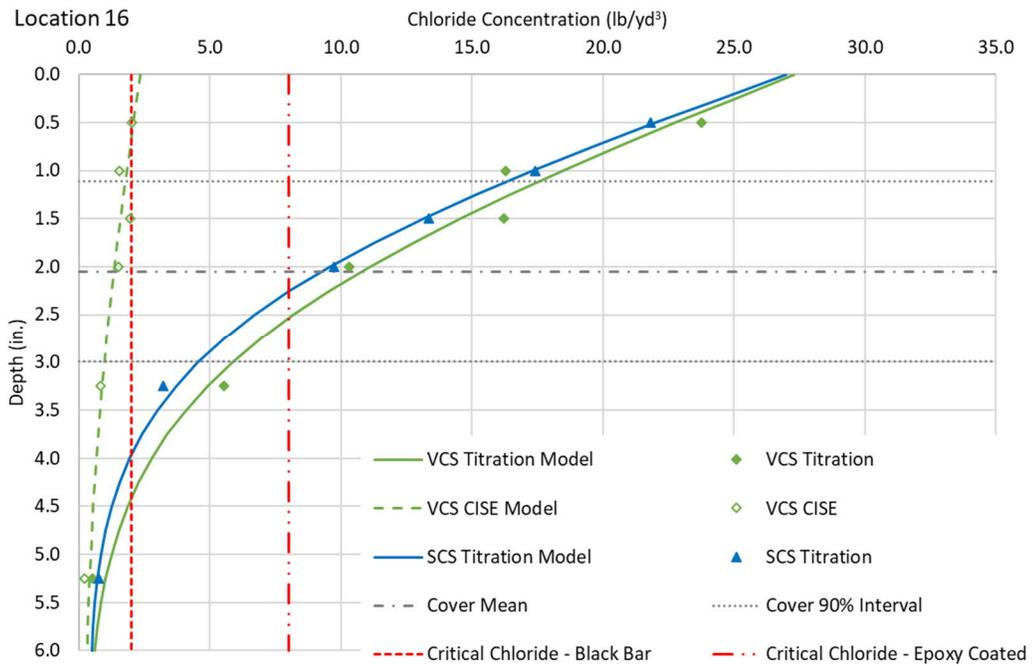


Figure 4.33 Chloride Profiles Models for Location 16 (SCS & VCS)

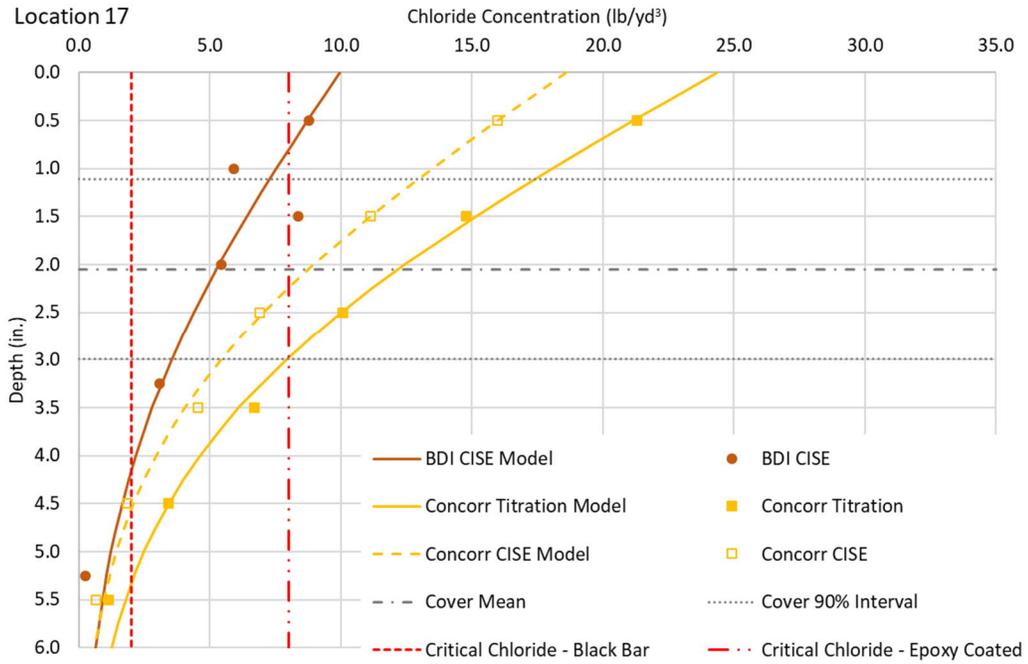


Figure 4.34 Chloride Profiles Models for Location 17 (BDI & CONCORR)

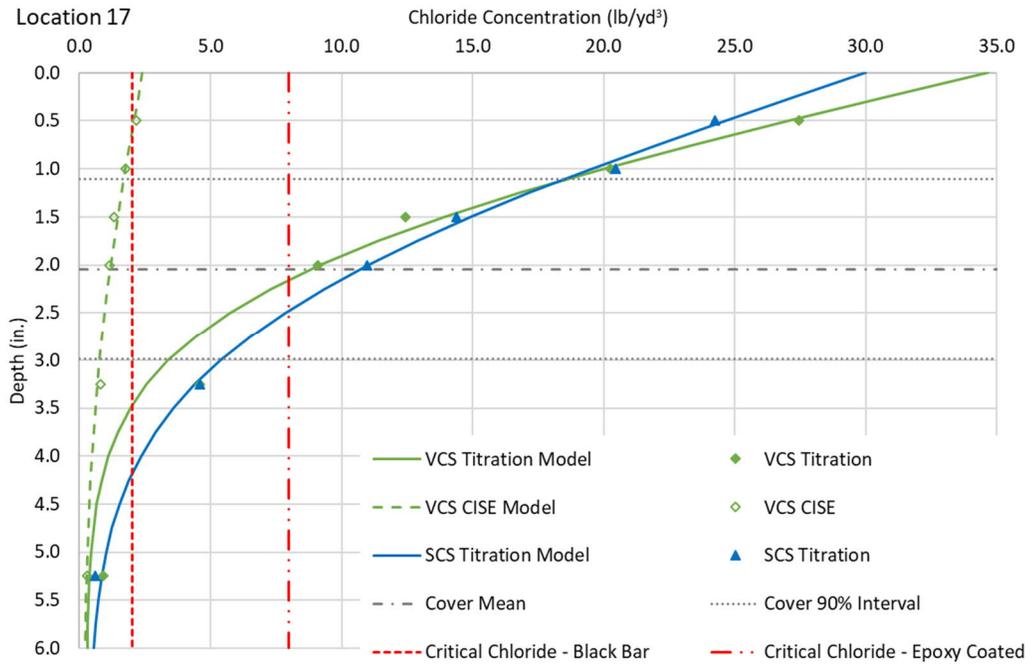


Figure 4.35 Chloride Profiles Models for Location 17 (SCS & VCS)

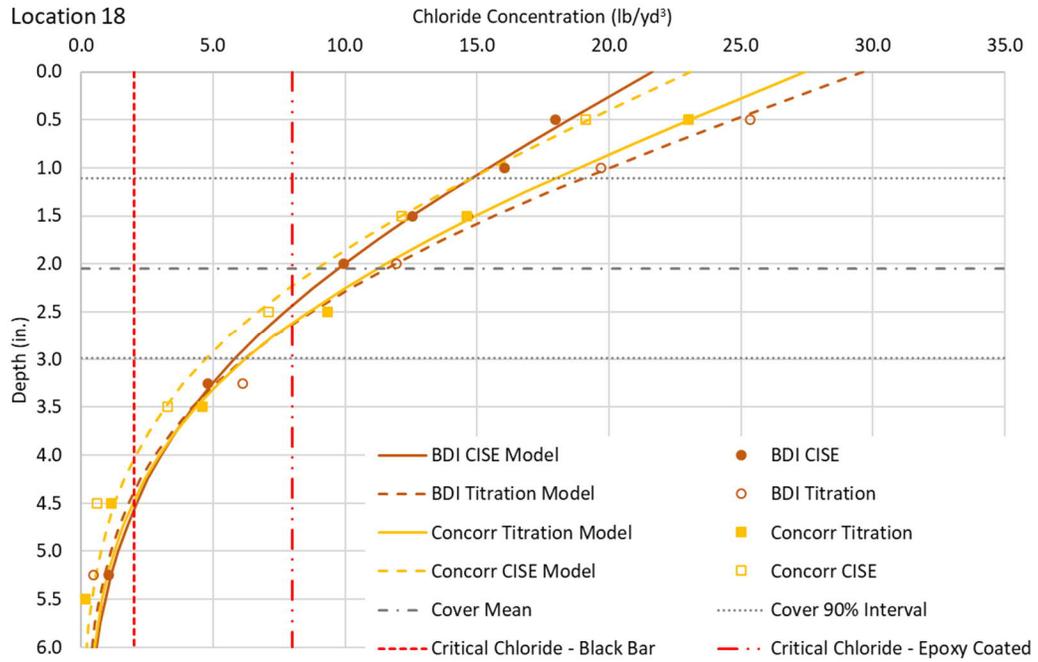


Figure 4.36 Chloride Profiles Models for Location 18 (BDI & CONCORR)

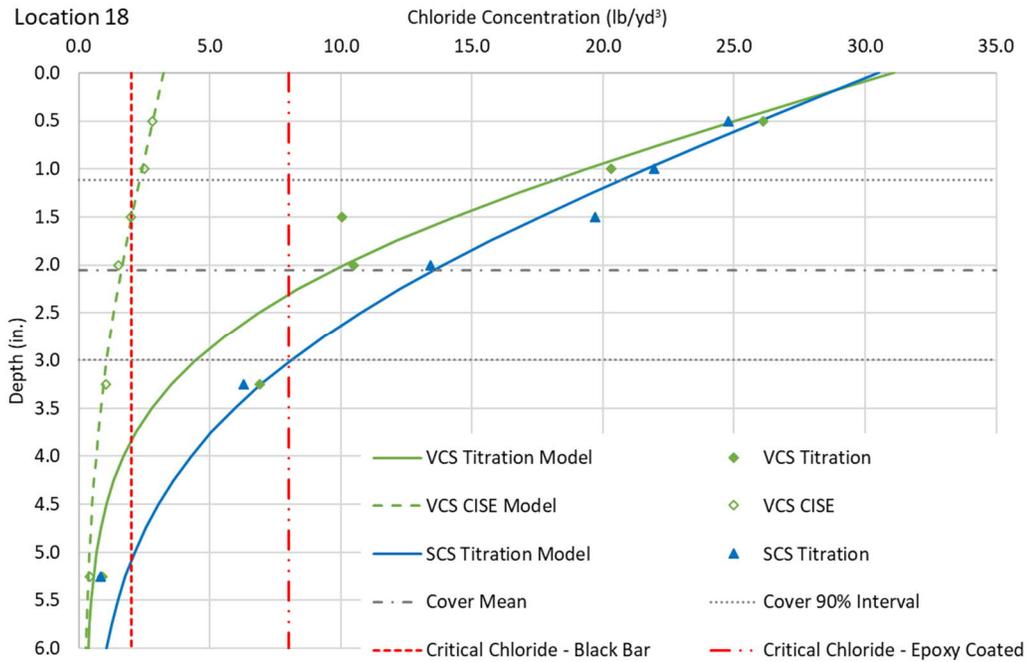


Figure 4.37 Chloride Profiles Models for Location 18 (SCS & VCS)

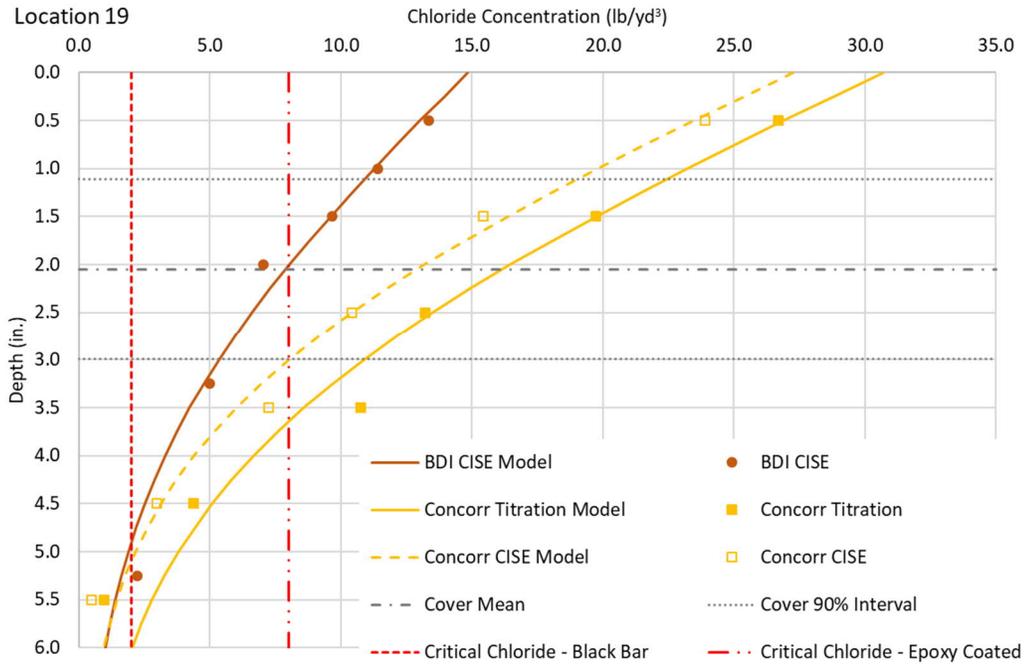


Figure 4.38 Chloride Profiles Models for Location 19 (BDI & CONCORR)

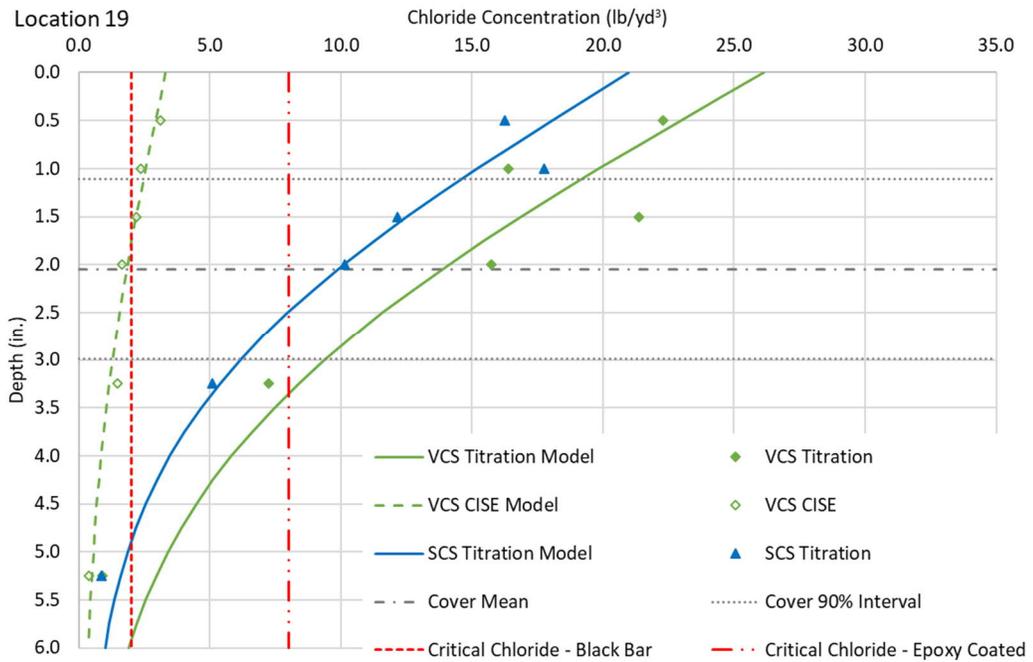


Figure 4.39 Chloride Profiles Models for Location 19 (SCS & VCS)

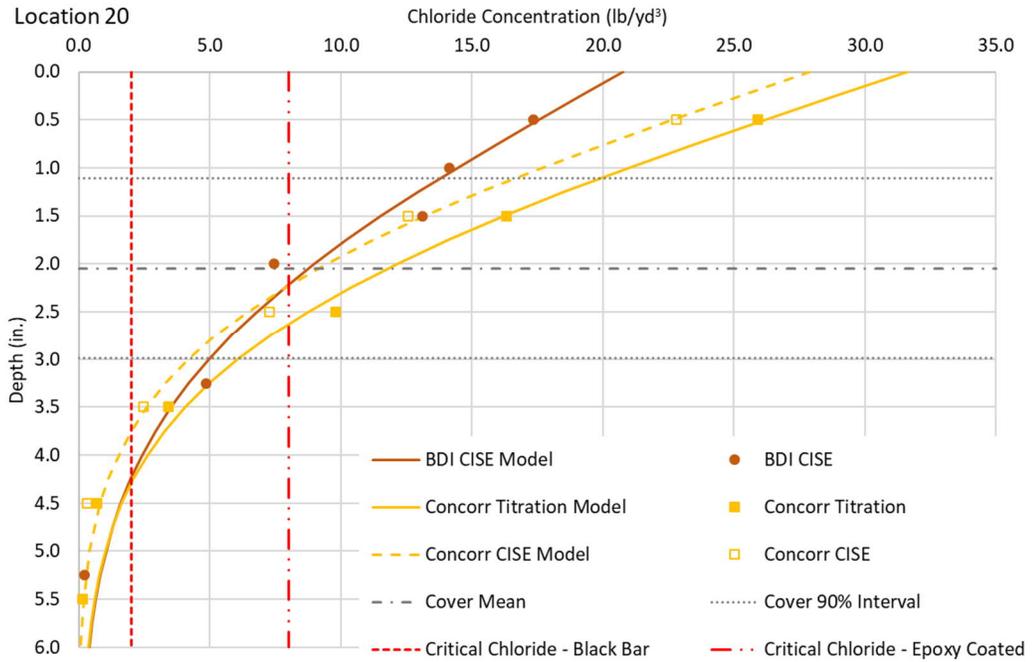


Figure 4.40 Chloride Profiles Models for Location 20 (BDI & CONCORR)

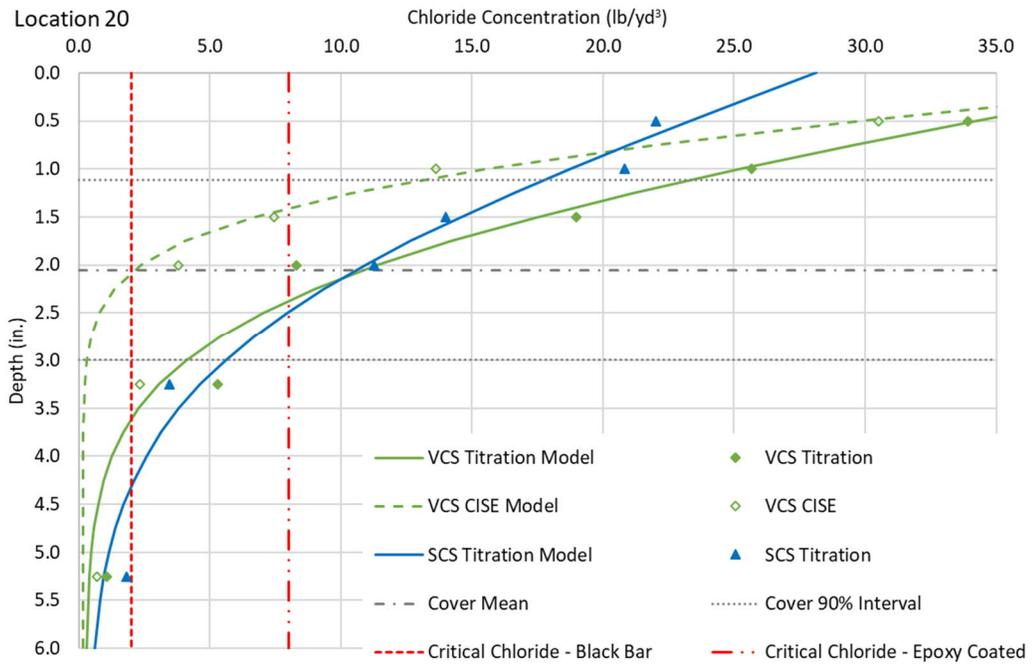


Figure 4.41 Chloride Profiles Models for Location 20 (SCS & VCS)

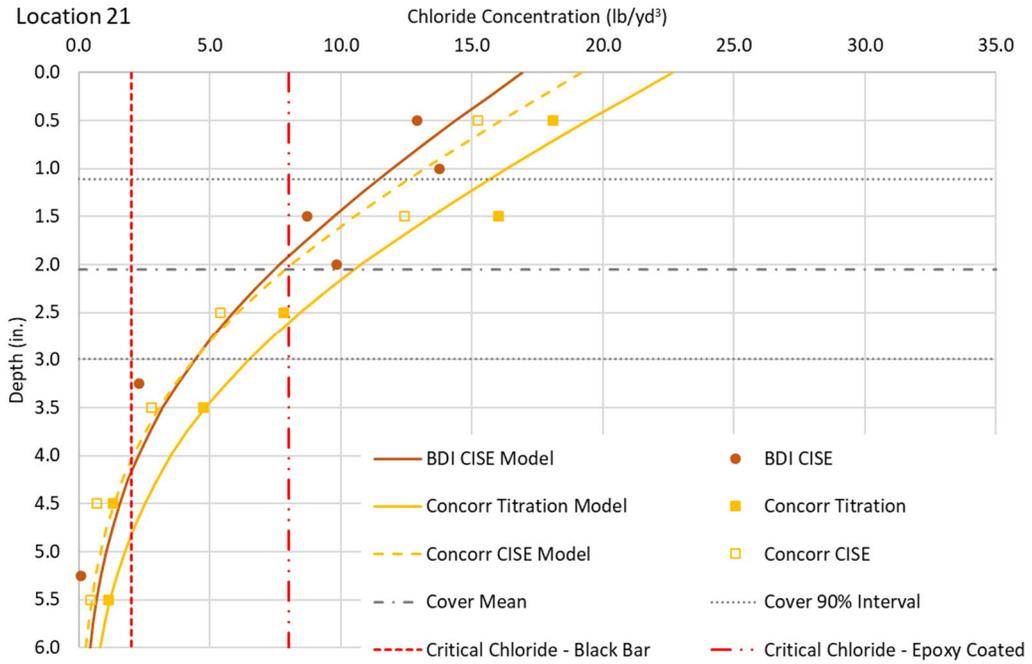


Figure 4.42 Chloride Profiles Models for Location 21 (BDI & CONCORR)

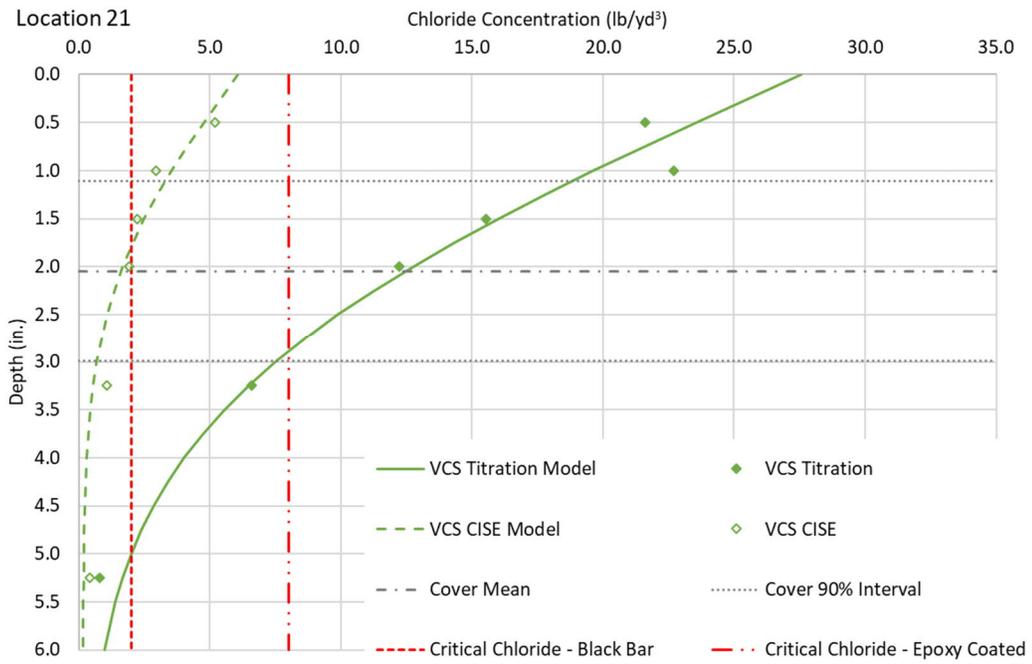


Figure 4.43 Chloride Profiles Models for Location 21 (SCS & VCS)

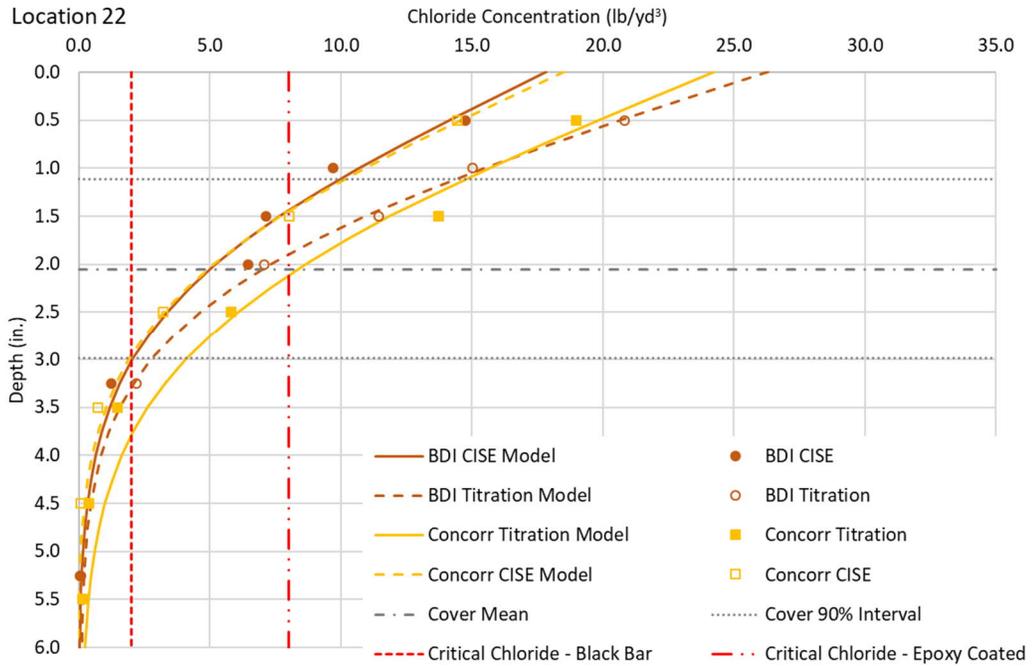


Figure 4.44 Chloride Profiles Models for Location 22 (BDI & CONCORR)

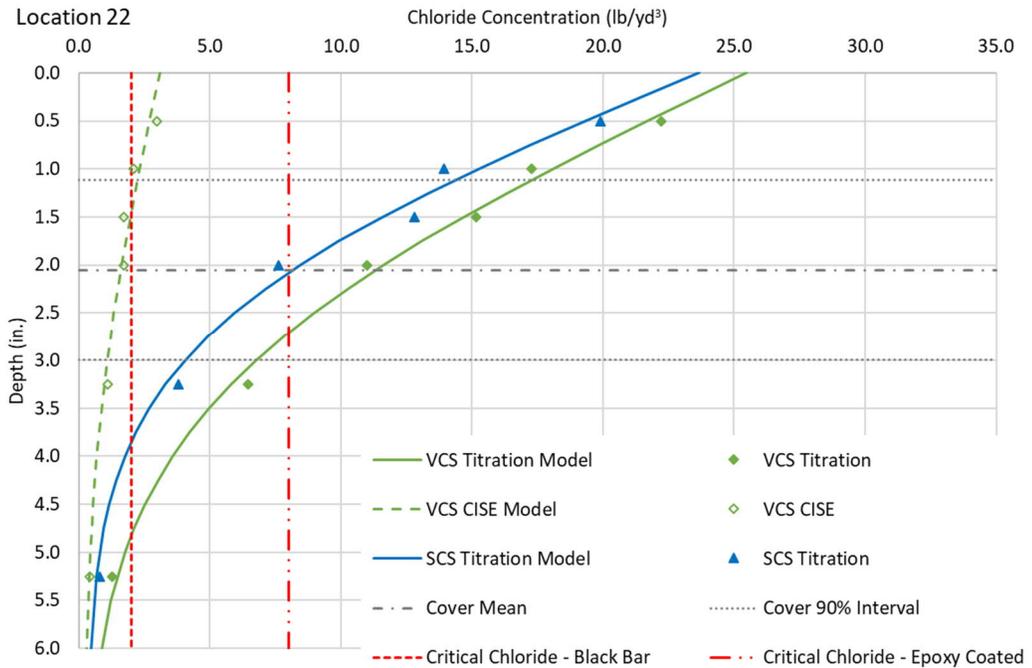


Figure 4.45 Chloride Profiles Models for Location 22 (SCS & VCS)

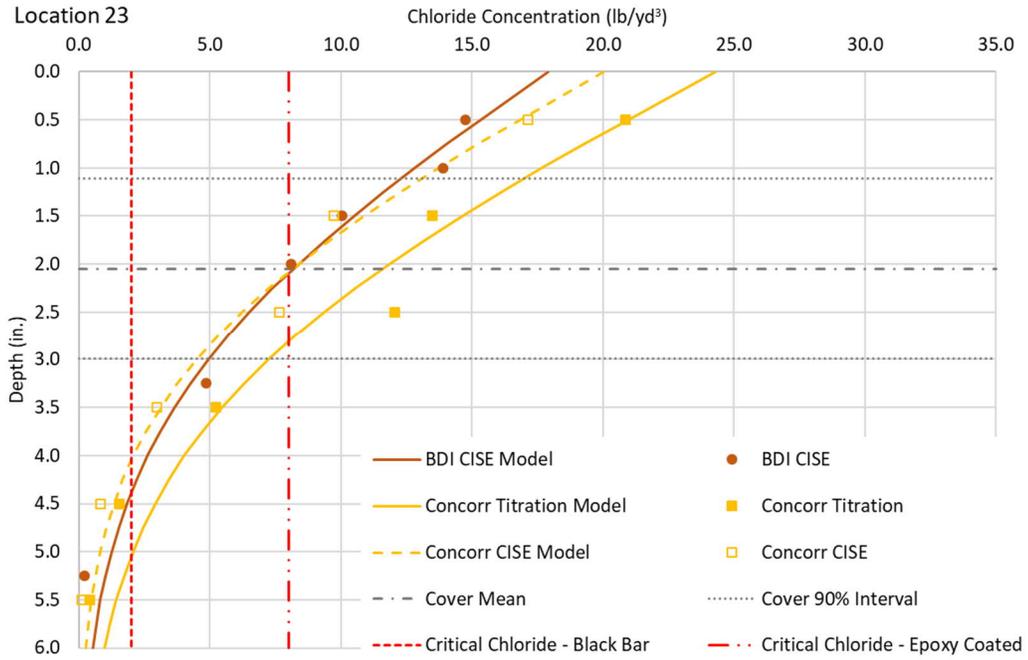


Figure 4.46 Chloride Profiles Models for Location 23 (BDI & CONCORR)

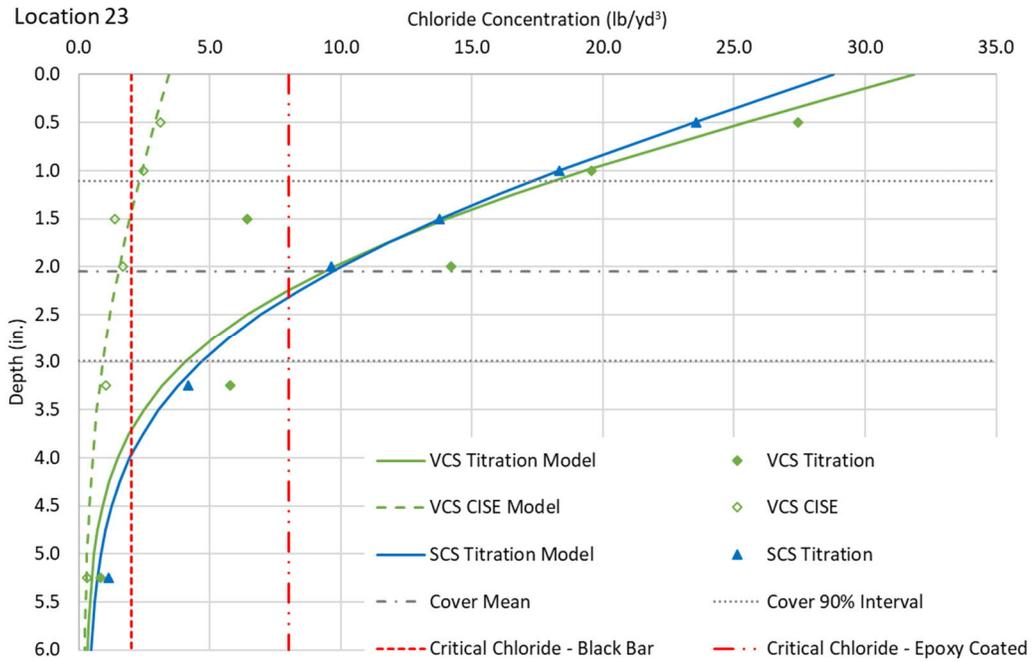


Figure 4.47 Chloride Profiles Models for Location 23 (SCS & VCS)

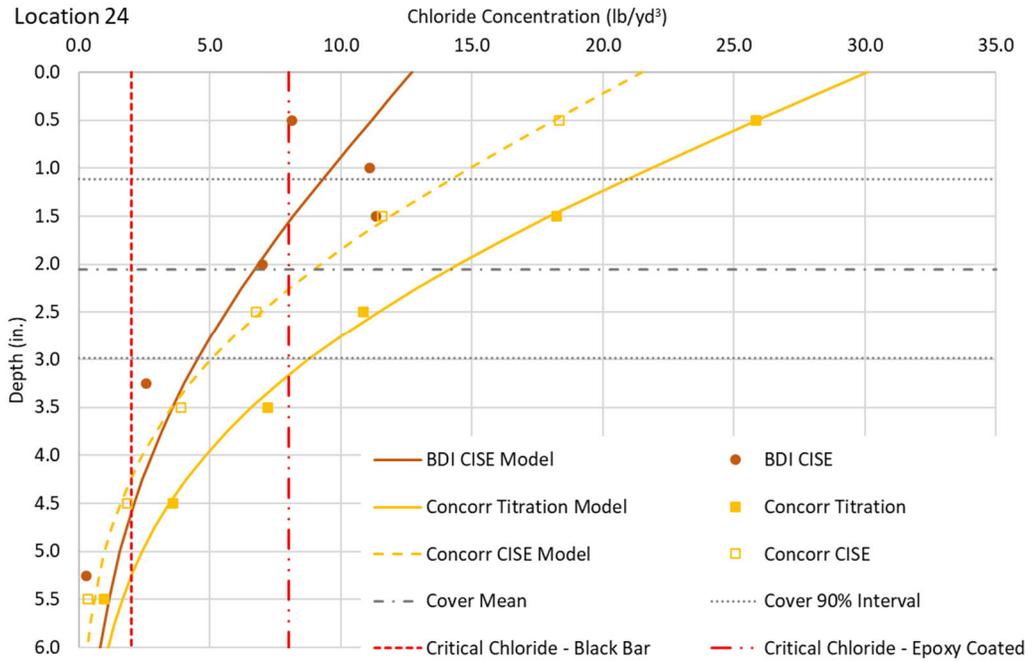


Figure 4.48 Chloride Profiles Models for Location 24 (BDI & CONCORR)

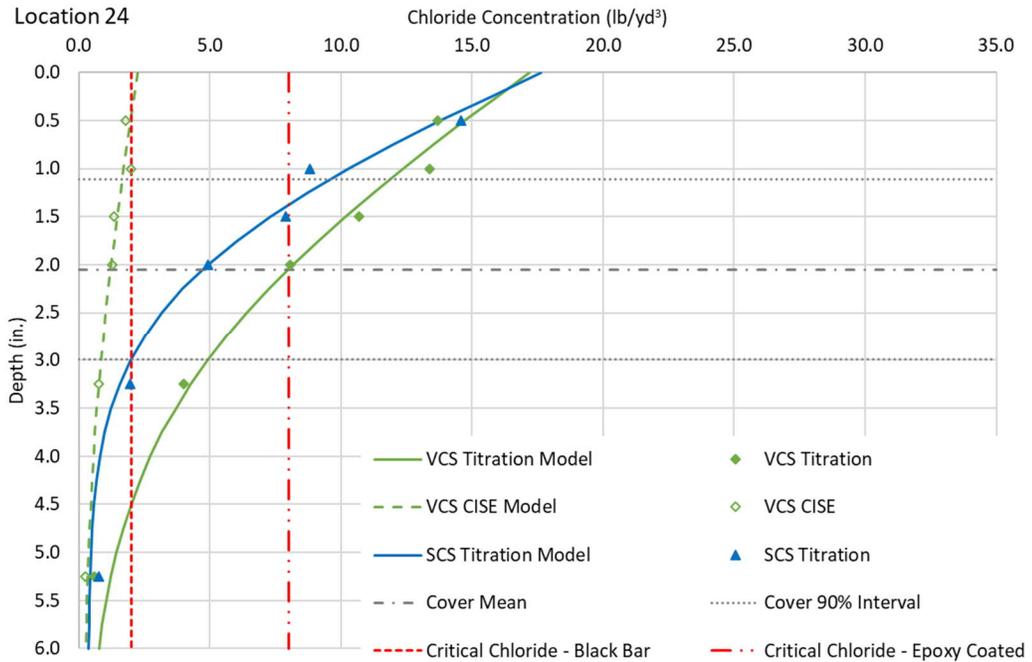


Figure 4.49 Chloride Profiles Models for Location 24 (SCS & VCS)

Note that SCS was not originally assigned a secondary test method; therefore, no secondary results are shown for SCS. Also, one of SCS's cores was lost by the shipping company in transit to the laboratory, so no result is available from SCS for Location 21. Six cores taken by CONCORR were divided and part sent to BDI for titration testing and are included in the plots, but no secondary method was assigned to BDI for cores it extracted in the field.

In the preceding plots, most indicate chloride concentrations exceeding nominal chloride initiation threshold (2.0 lb/yd^3 for the black steel in these decks) down to depths on the order of 3.5 to 4 inches, showing that corrosion of the top-mat reinforcement would be expected in most locations. The current degree of patching and delamination of the deck reported in Table 2.1 is consistent with this finding. A general review indicates that titration results tend to be higher than CISE results for the same cores. This will be explored further through the remainder of the report.

To contrast different test methods on the same samples by the same teams, the output parameters of the fitted model are organized into tables according to bridge and lane, and in each table by team and test method. Surface concentrations, C_o , were converted from parts per million (ppm) to pounds of chloride per cubic yard of concrete (lb/yd^3) assuming a common concrete unit weight of 145 lb/ft^3 , or $3,915 \text{ lb/yd}^3$. Diffusion coefficients, D_c , are expressed in square inches per year (in^2/yr). Table 4.13 through Table 4.16 show model parameters for Bridge 2C 746 and Table 4.17 through Table 4.20 represent Bridge 4C 746.

Trends in the data are easier to characterize in Table 4.13 through Table 4.20. For each bridge and lane, there are generally similar results among values for the same locations tested by titration. There seemed to be greater variability between results from the same locations tested by CISE. Also, there seemed to be significant differences of CISE results from those of titrations. Goodness of fit of the models overall averaged 0.90 or better, except for the CISE tests by BDI on the WB left shoulder (average 0.859). The overall average of model fits was 0.969, with average for titration of 0.980, and average for CISE of 0.956.

Table 4.13 Chloride Profile Model Parameters (2C 746 EB Left Shoulder)

Eastbound Chloride Profile Parameters

Testing Firm	Test Method (Primary/Secondary)	Chloride Profile Parameter	Location						
			13	16	17	20	21	23	Avg.
BDI	CISE	C _o (lb/yd ³)	9.4	7.6	10.0	20.8	16.9	17.9	13.8
		D _c (in ² /yr)	0.034	0.122	0.175	0.108	0.118	0.126	0.114
		R ²	0.851	0.820	0.864	0.973	0.911	0.982	0.900
	Titration	C _o (lb/yd ³)	-	-	-	-	-	-	-
		D _c (in ² /yr)	-	-	-	-	-	-	-
		R ²	-	-	-	-	-	-	-
CONCORR	Titration	C _o (lb/yd ³)	20.9	26.0	24.4	31.6	22.6	24.3	25.0
		D _c (in ² /yr)	0.057	0.089	0.153	0.087	0.130	0.137	0.109
		R ²	0.998	0.997	0.997	0.995	0.961	0.963	0.985
	CISE	C _o (lb/yd ³)	16.0	21.9	18.6	27.9	19.2	20.0	20.6
		D _c (in ² /yr)	0.048	0.065	0.136	0.073	0.105	0.102	0.088
		R ²	0.999	1.000	0.997	0.996	0.972	0.982	0.991

Table 4.14 Chloride Profile Model Parameters (2C 746 EB Left Lane)

Eastbound Chloride Profile Parameters

Testing Firm	Test Method (Primary/Secondary)	Chloride Profile Parameter	Location						Avg.
			14	15	18	19	22	24	
BDI	CISE	C _o (lb/yd ³)	13.5	13.3	21.6	14.8	17.8	12.7	15.6
		D _c (in ² /yr)	0.034	0.043	0.122	0.179	0.060	0.175	0.102
		R ²	0.878	0.930	0.997	0.983	0.978	0.758	0.920
	Titration	C _o (lb/yd ³)	21.9	-	29.6	-	26.3	-	25.9
		D _c (in ² /yr)	0.067	-	0.094	-	0.056	-	0.072
		R ²	0.991	-	0.994	-	0.998	-	0.994
CONCORR	Titration	C _o (lb/yd ³)	23.7	26.1	27.4	30.7	24.3	30.1	27.0
		D _c (in ² /yr)	0.068	0.088	0.101	0.173	0.078	0.133	0.107
		R ²	0.995	0.999	0.995	0.981	0.981	0.997	0.991
	CISE	C _o (lb/yd ³)	20.4	22.1	23.1	27.3	18.5	21.5	22.1
		D _c (in ² /yr)	0.052	0.070	0.094	0.137	0.057	0.107	0.086
		R ²	0.991	0.997	0.997	0.990	0.999	0.998	0.995

Table 4.15 Chloride Profile Model Parameters (2C 746 EB Right Lane)

Eastbound Chloride Profile Parameters

Testing Firm	Test Method (Primary/Secondary)	Chloride Profile Parameter	Location						
			14	15	17	20	22	23	Avg.
SCS	Titration	C _o (lb/yd ³)	29.8	26.3	30.0	28.2	23.7	28.8	27.8
		D _c (in ² /yr)	0.054	0.083	0.079	0.087	0.075	0.073	0.075
		R ²	0.991	0.991	0.997	0.976	0.982	0.999	0.989
	N/A	C _o (lb/yd ³)	-	-	-	-	-	-	-
		D _c (in ² /yr)	-	-	-	-	-	-	-
		R ²	-	-	-	-	-	-	-
VCS	Titration	C _o (lb/yd ³)	27.7	30.1	34.7	44.1	25.5	31.9	32.3
		D _c (in ² /yr)	0.089	0.070	0.052	0.051	0.117	0.062	0.073
		R ²	0.973	0.996	0.986	0.979	0.993	0.819	0.958
	CISE	C _o (lb/yd ³)	2.3	2.3	2.4	48.2	3.1	3.4	10.3
		D _c (in ² /yr)	0.127	0.123	0.122	0.017	0.148	0.104	0.107
		R ²	0.967	0.992	0.979	0.982	0.945	0.911	0.963

Table 4.16 Chloride Profile Model Parameters (2C 746 EB Right Shoulder)

Eastbound Chloride Profile Parameters

Testing Firm	Test Method (Primary/Secondary)	Chloride Profile Parameter	Location						
			13	16	18	19	21	24	Avg.
SCS	Titration	C _o (lb/yd ³)	20.1	27.0	30.5	21.0	-	17.6	23.2
		D _c (in ² /yr)	0.058	0.075	0.116	0.129	-	0.053	0.086
		R ²	0.985	0.999	0.983	0.950	-	0.973	0.978
	N/A	C _o (lb/yd ³)	-	-	-	-	-	-	-
		D _c (in ² /yr)	-	-	-	-	-	-	-
		R ²	-	-	-	-	-	-	-
VCS	Titration	C _o (lb/yd ³)	19.8	27.3	31.1	26.1	27.6	17.2	24.8
		D _c (in ² /yr)	0.063	0.094	0.067	0.173	0.121	0.125	0.107
		R ²	0.980	0.972	0.925	0.883	0.961	0.979	0.950
	CISE	C _o (lb/yd ³)	2.6	2.3	3.2	3.3	6.1	2.2	3.3
		D _c (in ² /yr)	0.073	0.186	0.135	0.176	0.052	0.155	0.129
		R ²	0.985	0.878	0.990	0.941	0.930	0.929	0.942

Table 4.17 Chloride Profile Model Parameters (4C 746 WB Left Shoulder)

Westbound Chloride Profile Parameters

Testing Firm	Testing Method (Primary/Secondary)	Chloride Profile Parameter	Location					Avg.
			1	3	6	8	9	
BDI	CISE	C _o (lb/yd ³)	12.6	16.9	38.6	27.3	19.0	22.9
		D _c (in ² /yr)	0.139	0.079	0.071	0.144	0.090	0.105
		R ²	0.807	0.861	0.989	0.780	0.859	0.859
	Titration	C _o (lb/yd ³)	-	30.6	27.0	-	-	28.8
		D _c (in ² /yr)	-	0.091	0.098	-	-	0.095
		R ²	-	0.991	0.989	-	-	0.990
CONCORR	Titration	C _o (lb/yd ³)	26.6	28.7	30.6	30.4	22.4	27.7
		D _c (in ² /yr)	0.094	0.118	0.110	0.079	0.072	0.095
		R ²	0.996	0.986	0.993	0.992	0.992	0.992
	CISE	C _o (lb/yd ³)	19.5	23.2	23.8	24.7	16.7	21.6
		D _c (in ² /yr)	0.073	0.097	0.096	0.067	0.056	0.078
		R ²	0.999	0.995	0.998	0.994	0.998	0.997

Table 4.18 Chloride Profile Model Parameters (4C 746 WB Left Lane)

Westbound Chloride Profile Parameters

Testing Firm	Test Method (Primary/Secondary)	Chloride Profile Parameter	Location						Avg.	
			2	4	5	7	10	11		12
BDI	CISE	C _o (lb/yd ³)	23.8	50.8	23.7	16.6	16.0	19.1	24.8	25.0
		D _c (in ² /yr)	0.087	0.013	0.042	0.115	0.081	0.034	0.092	0.066
		R ²	0.943	0.982	0.927	0.940	0.893	0.976	0.965	0.947
	Titration	C _o (lb/yd ³)	-	-	-	-	-	24.6	-	24.6
		D _c (in ² /yr)	-	-	-	-	-	0.038	-	0.038
		R ²	-	-	-	-	-	0.982	-	0.982
CONCORR	Titration	C _o (lb/yd ³)	30.0	31.9	28.1	27.3	32.4	30.6	32.1	30.4
		D _c (in ² /yr)	0.092	0.078	0.093	0.079	0.055	0.030	0.109	0.077
		R ²	0.998	0.997	0.994	0.999	0.998	0.999	0.997	0.998
	CISE	C _o (lb/yd ³)	25.1	25.6	23.5	22.5	25.8	25.4	26.0	24.8
		D _c (in ² /yr)	0.073	0.065	0.073	0.068	0.045	0.025	0.088	0.063
		R ²	1.000	0.993	0.998	0.999	1.000	1.000	0.998	0.998

Table 4.19 Chloride Profile Model Parameters (4C 746 WB Right Lane)

Westbound Chloride Profile Parameters

Testing Firm	Test Method (Primary/Secondary)	Chloride Profile Parameter	Location						
			2	3	6	7	9	11	Avg.
SCS	Titration	C _o (lb/yd ³)	37.0	30.3	29.8	37.3	25.7	37.0	32.9
		D _c (in ² /yr)	0.072	0.086	0.079	0.040	0.054	0.030	0.060
		R ²	0.956	0.977	0.987	0.999	0.996	0.990	0.984
	N/A	C _o (lb/yd ³)	-	-	-	-	-	-	-
		D _c (in ² /yr)	-	-	-	-	-	-	-
		R ²	-	-	-	-	-	-	-
VCS	Titration	C _o (lb/yd ³)	33.5	27.7	33.9	42.2	26.2	26.1	31.6
		D _c (in ² /yr)	0.070	0.099	0.053	0.047	0.064	0.077	0.068
		R ²	0.967	0.855	0.991	0.982	0.972	0.957	0.954
	CISE	C _o (lb/yd ³)	23.9	10.5	8.2	8.7	9.3	5.9	11.1
		D _c (in ² /yr)	0.041	0.071	0.092	0.058	0.065	0.089	0.069
		R ²	0.969	0.949	0.951	0.990	0.984	0.970	0.969

Table 4.20 Chloride Profile Model Parameters (4C 746 WB Right Shoulder)

Westbound Chloride Profile Parameters

Testing Firm	Testing Method (Primary/Secondary)	Chloride Profile Parameter	Location						
			1	4	5	8	10	12	Avg.
SCS	Titration	C _o (lb/yd ³)	25.9	31.1	29.7	23.1	22.7	23.6	26.0
		D _c (in ² /yr)	0.066	0.050	0.046	0.064	0.073	0.056	0.059
		R ²	0.996	0.979	0.998	0.953	0.881	0.984	0.965
	N/A	C _o (lb/yd ³)	-	-	-	-	-	-	-
		D _c (in ² /yr)	-	-	-	-	-	-	-
		R ²	-	-	-	-	-	-	-
VCS	Titration	C _o (lb/yd ³)	33.0	25.6	26.3	30.3	19.8	22.3	26.2
		D _c (in ² /yr)	0.051	0.060	0.086	0.049	0.051	0.069	0.061
		R ²	0.954	0.986	0.998	0.991	0.989	0.993	0.985
	CISE	C _o (lb/yd ³)	32.6	9.4	5.2	20.5	5.4	4.2	12.9
		D _c (in ² /yr)	0.026	0.049	0.127	0.033	0.056	0.087	0.063
		R ²	0.980	0.995	0.996	0.985	0.995	0.986	0.990

4.3.2 Profiles Comparing Interlaboratory Exchange Results

For the interlaboratory round robin tests, Table 4.21 and Table 4.22 provide the model output parameters, C_o , D_c , and R^2 of exchanged samples for CISE tests from BDI to CONCORR and VCS to BDI, respectively. For the comparison of CISE tests by BDI and CONCORR on the same powdered samples, there were significant differences. CONCORR reported C_o values higher than those of BDI by an average 16.1 lb/yd³, and the diffusion rates reported by CONCORR were lower by 0.083 in²/yr. The average of correlation coefficients, R^2 , associated with the fit of the diffusion model was better for CONCORR data at 0.989 than for BDI data at 0.908.

Table 4.21 Model Fit of Interlaboratory (BDI → CONCORR) CISE Tests
BDI, CISE Sample Comparison

Core	BDI			CONCORR		
	C_o (lb/yd ³)	D_c (in ² /yr)	R^2	C_o (lb/yd ³)	D_c (in ² /yr)	R^2
C1	12.6	0.139	0.807	31.4	0.019	1.000
C3	16.9	0.079	0.861	32.5	0.016	0.982
C5	23.7	0.042	0.927	34.0	0.020	1.000
C7	16.6	0.115	0.940	33.2	0.012	0.970
C9	19.0	0.090	0.859	36.2	0.009	0.981
C11	19.1	0.034	0.976	32.0	0.021	1.000
C13	9.4	0.034	0.851	31.7	0.007	1.000
C15	13.3	0.043	0.930	29.1	0.013	0.995
C17	10.0	0.175	0.864	28.8	0.015	0.991
C19	14.8	0.179	0.983	39.4	0.010	1.000
C21	16.9	0.118	0.911	26.2	0.012	0.962
C23	17.9	0.126	0.982	29.3	0.022	0.988

Similarly, there were significant differences in results for CISE between VCS and BDI for the same powdered concrete samples. BDI reported surface concentrations on average 20.9 lb/yd³ greater than those of VCS and diffusion rates were 0.079 in²/yr lower. The respective model fit correlation coefficients were 0.964 and 0.989 for VCS and BDI, respectively.

Comparing titration tests on common samples between CONCORR and SCS, as shown in Table 4.23, SCS reported surface concentrations on average 3.85 lb/yd³ lower than CONCORR, and diffusion coefficients averaging 0.042 in²/yr lower. Correlation coefficients were $R^2 = 0.995$ and 0.990 for CONCORR and SCS, respectively.

Table 4.22 Model Fit of Interlaboratory (VCS → BDI) CISE Tests
VCS, CISE Sample Comparison

Core	VCS			BDI		
	C _o (lb/yd ³)	D _c (in ² /yr)	R ²	C _o (lb/yd ³)	D _c (in ² /yr)	R ²
C2	23.9	0.041	0.969	31.4	0.019	1.000
C4	9.4	0.049	0.995	32.5	0.016	0.982
C6	8.2	0.092	0.951	34.0	0.020	1.000
C8	20.5	0.033	0.985	33.2	0.012	0.970
C10	5.4	0.056	0.995	36.2	0.009	0.981
C12	4.2	0.087	0.986	32.0	0.021	1.000
C14	2.3	0.127	0.967	31.7	0.007	1.000
C16	2.3	0.186	0.878	29.1	0.013	0.995
C18	3.2	0.135	0.990	28.8	0.015	0.991
C20	48.2	0.017	0.982	39.4	0.010	1.000
C22	3.1	0.148	0.945	26.2	0.012	0.962
C24	2.2	0.155	0.929	29.3	0.022	0.988

Table 4.23 Model Fit of Interlaboratory (CONCORR → SCS) Titration Tests
CONCORR, Titration Sample Comparison

Core	CONCORR			SCS		
	C _o (lb/yd ³)	D _c (in ² /yr)	R ²	C _o (lb/yd ³)	D _c (in ² /yr)	R ²
C2	30.0	0.092	0.998	26.0	0.063	1.000
C4	31.9	0.078	0.997	26.4	0.052	0.985
C6	30.6	0.110	0.993	28.2	0.066	1.000
C8	30.4	0.079	0.992	25.9	0.038	0.974
C10	32.4	0.055	0.998	26.8	0.028	0.983
C12	32.1	0.109	0.997	26.7	0.069	1.000
C14	23.7	0.068	0.995	22.7	0.022	1.000
C16	26.0	0.089	0.997	23.0	0.041	0.993
C18	27.4	0.101	0.995	23.2	0.048	0.989
C20	31.6	0.087	0.995	29.8	0.033	0.999
C22	24.3	0.078	0.981	20.7	0.039	0.966
C24	30.1	0.133	0.997	24.8	0.074	0.990

In similar comparison of titration of common samples in Table 4.24, VCS showed an average 2.16 lb/yd³ greater surface concentration and 0.048 lower diffusion coefficient than SCS, with correlation coefficients of the model fit at 0.969 for SCS and 0.887 for VCS. Cores C2, C12 and C19 appeared to have significant outlier concentrations in VCS's results.

Table 4.24 Model Fit of Interlaboratory (SCS → VCS) Titration Tests
SCS, Titration Sample Comparison

Core	SCS			VCS		
	C _o (lb/yd ³)	D _c (in ² /yr)	R ²	C _o (lb/yd ³)	D _c (in ² /yr)	R ²
C2	37.0	0.072	0.956	36.8	0.054	0.683
C4	31.1	0.050	0.979	33.2	0.022	0.921
C6	29.8	0.079	0.987	33.3	0.032	0.954
C8	23.1	0.064	0.953	29.7	0.012	0.980
C10	22.7	0.073	0.881	22.3	0.015	1.000
C12	23.6	0.056	0.984	22.7	0.017	0.768
C13	20.1	0.058	0.985	27.3	0.006	0.998
C15	26.3	0.083	0.991	28.2	0.029	0.999
C17	30.0	0.079	0.997	32.3	0.029	0.948
C19	21.0	0.129	0.950	20.2	0.051	0.542
C23	28.8	0.073	0.999	31.3	0.022	0.965

General observations from these round robin results are that some variability can be expected between laboratories, but the degree of variability associated with CISE appears to be very high in comparison to titration testing.

This observation should be considered in light of the fact that with any test there are different sources of variability. In addition to the inherent variability in actual chloride concentration between samples (or subsamples) caused by true variations in material properties being measured (such as chloride concentration within a heterogenous concrete material), there are sources of error that may be introduced by aspects of the test method itself, such as the degree of purity of reactants, the condition and calibration of test equipment, the degree to which personnel precisely replicate procedures, and others, which may result in variation of results from one test to the next within a single laboratory. Further, there is variability that may be introduced if the same material is tested by multiple laboratories, which may be further influenced by differences in reactants, equipment, calibration, and procedures. Multi-laboratory variability is generally greater than single laboratory variability since there is no commonality of specific test reactants, apparatus, or operators.

Standard test methods, such as is the case with ASTM C 1152, include statements regarding precision and bias, which reflect the expected single-laboratory and multi-laboratory standard deviations derived from prior research, as well as the bias of measurements by the test

method relative to the true condition, if such can be reliably established. Similar variability occurs with all tests; however, for CISE, where a standard does not exist, the single and multi-laboratory variability is not documented. This highlights the importance of industry standards to ensure uniformity of test methods and accreditation programs to ensure laboratories are appropriately equipped and closely follow such standards.

4.3.3 Profiles Comparing Progressive versus Uniform Sample Depth Increments

As noted previously, one of the experimental variables considered was the influence of sample depth increments, wherein cores at uniform 1-inch increments through 6 depths were compared to core sampling at ½-inch increments over a progressive spacing of 6 depths, as was illustrated in Figure 3.4. To achieve this comparison, six cores taken by CONCORR were cut longitudinally and ½ of each core was shipped to BDI. CONCORR divided its half of each core into even 1-inch profile increments and tested according to prescribed methods (titration and CISE). BDI divided its half of each core into the progressive ½-inch increments and tested by titration. Since depth increments differed, direct comparison of individual chloride concentrations was not practical. However, plots of chloride concentration profiles using both sets of data permit pairwise comparison (Figure 4.50 through Figure 4.55). Fitting the Fickian diffusion model to profiles allowed comparison of surface concentration and effective diffusion coefficients taken from both sets of tests of the same cores.

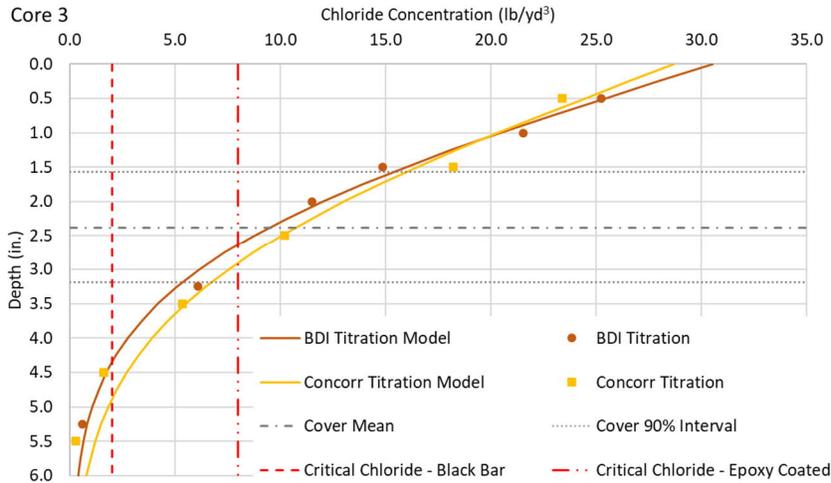


Figure 4.50 Comparative Titration Profiles Between Labs for CONCORR Core 3

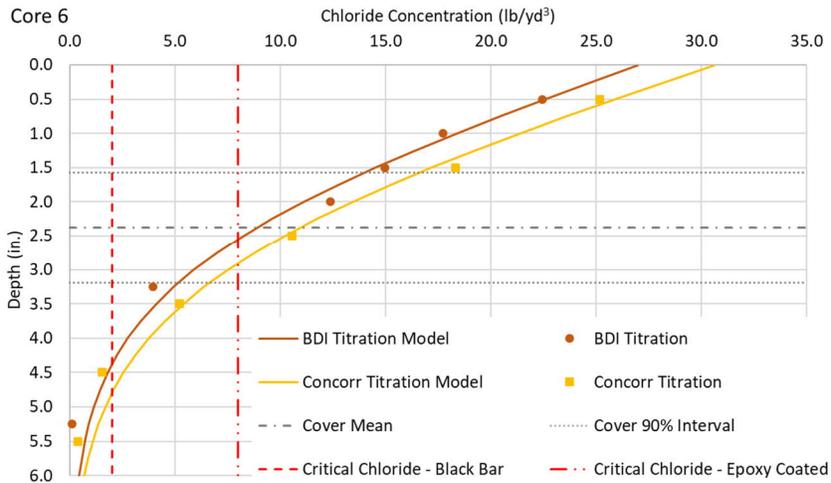


Figure 4.51 Comparative Titration Profiles Between Labs for CONCORR Core 6

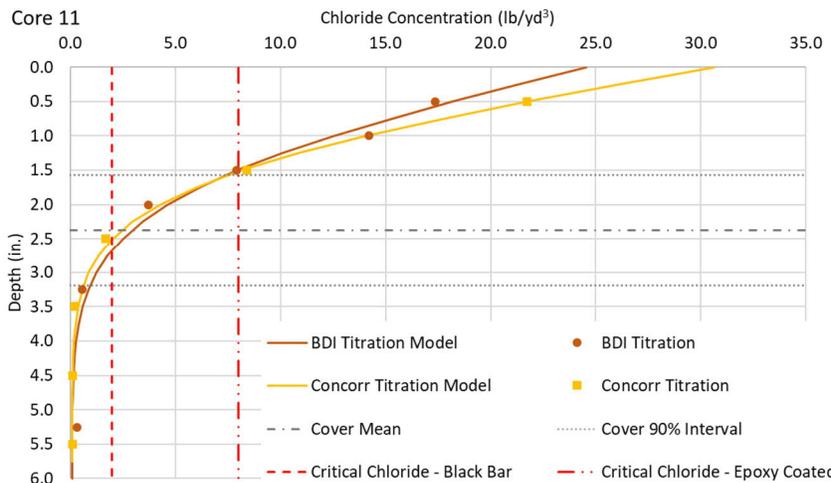


Figure 4.52 Comparative Titration Profiles Between Labs for CONCORR Core 11

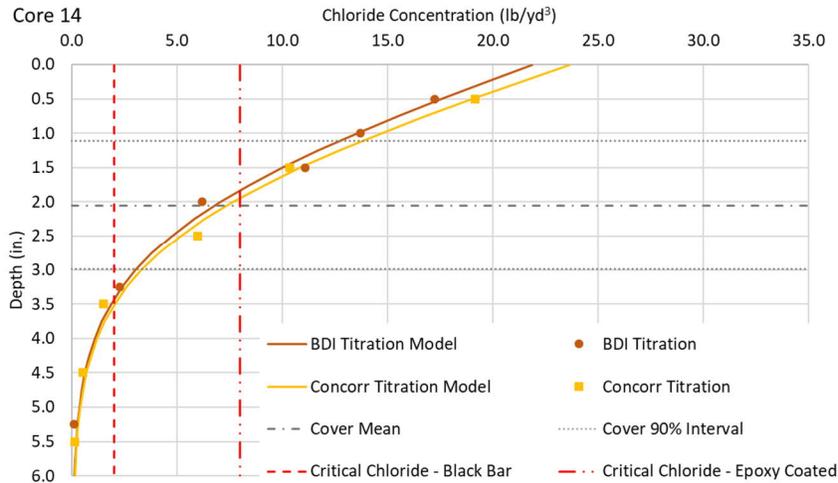


Figure 4.53 Comparative Titration Profiles Between Labs for CONCORR Core 14

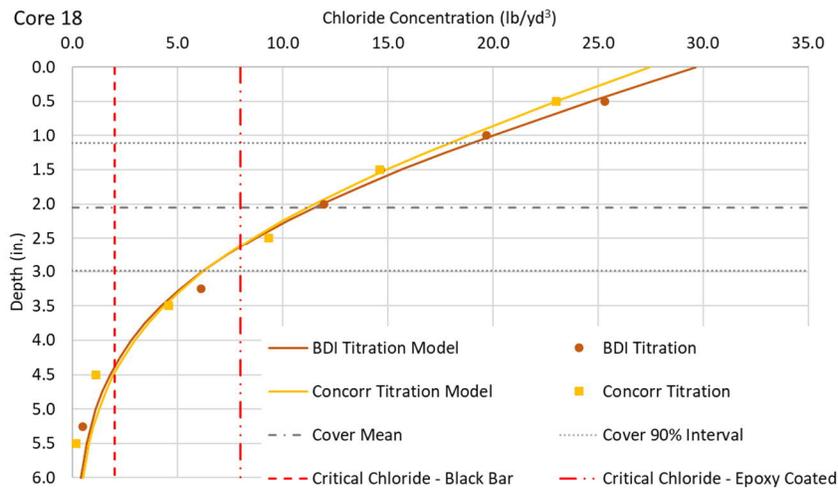


Figure 4.54 Comparative Titration Profiles Between Labs for CONCORR Core 18

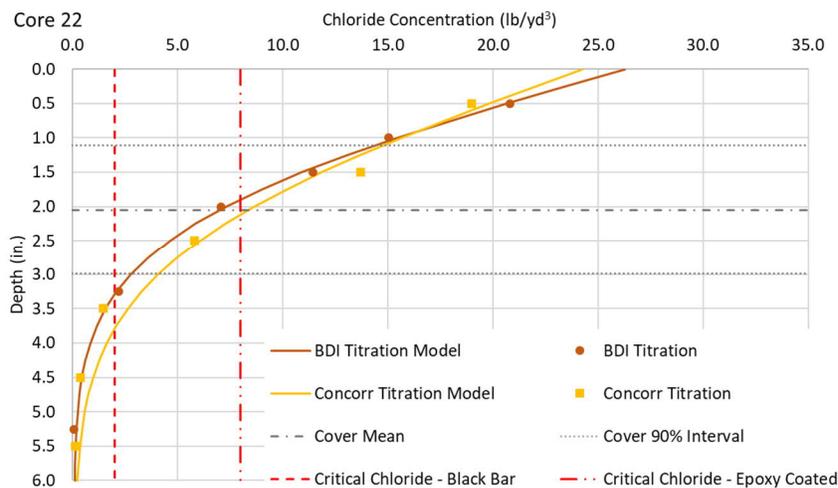


Figure 4.55 Comparative Titration Profiles Between Labs for CONCORR Core 22

A review of Figure 4.50 through Figure 4.55 demonstrates that the overall profiles were very similar. In a few cases, the 1-inch increments resulted in concentrations at individual depths that were higher than for the ½-inch increments, but this was not a consistent trend. In most cases, the extrapolated surface concentrations obtained from the 1-inch uniform profiles were slightly higher than those for the ½-inch progressive profiles. This may be due to high near-surface concentrations that were captured with full 1-inch increments starting at the surface, whereas the top sample of the ½-inch progressive increments started at a depth of ¼ inch.

4.4 Statistical Analysis of Experimental Factors

In addition to comparison of model parameters, various comparisons of the results were made to contrast the sampling and testing variables. These methods employed a mix of statistical plots and tests, including bivariate plots, Student t-Tests, and multi-variate regressions.

4.4.1 Primary versus Secondary Laboratory Test Methods by Team

One of the most direct comparisons that could be made among the study variables is that of the contrasting test methods conducted on the same samples by the same team. In the following bivariate plots, for each given sample the chloride concentrations from a primary test method is plotted against the y-axis, and concentration from a secondary test method is plotted against the x-axis. The result is a scatter plot that expresses the relationship between the two tests for the same sample and shows the trend among all such pairs of tests. If the results, as might be expected, were to be identical between the two tests, then all data points on the bivariate plot would overlay the 45° line, referred to as the “Line of Equivalence.” An ideal correlation would have a linear fit (indicated in plots by blue dashed line) with a slope of 1.0 and an intercept of 0. Points above and left of the line indicate that the primary method reports a higher concentration than the secondary method (slope of linear fit >1), and those below and to the right of the line indicate the secondary method gives higher concentrations than the primary (slope of linear fit <1), which we will refer to as bias. The tight grouping of results along a line indicate strong correlation between the results, even if the values do not match, such that the result of one method may be reasonably predicted from the result of the other through development of a

regression equation. However, if the plot demonstrates significant scatter, then one or both methods has introduced significant variability in the results and strong correlation may not exist.

Figure 4.56 depicts the comparison of titration tests versus CISE tests of powdered concrete samples obtained with hammer drill using tapered profiles in progressively spaced ½-inch increments. The plot shows the comparative results at each of 6 sample depths from six cores. The linear fit has a slope of 1.05 and intercept of 528 ppm. While the plot shows a fair amount of scatter, a correlation coefficient of 0.846 is reported.

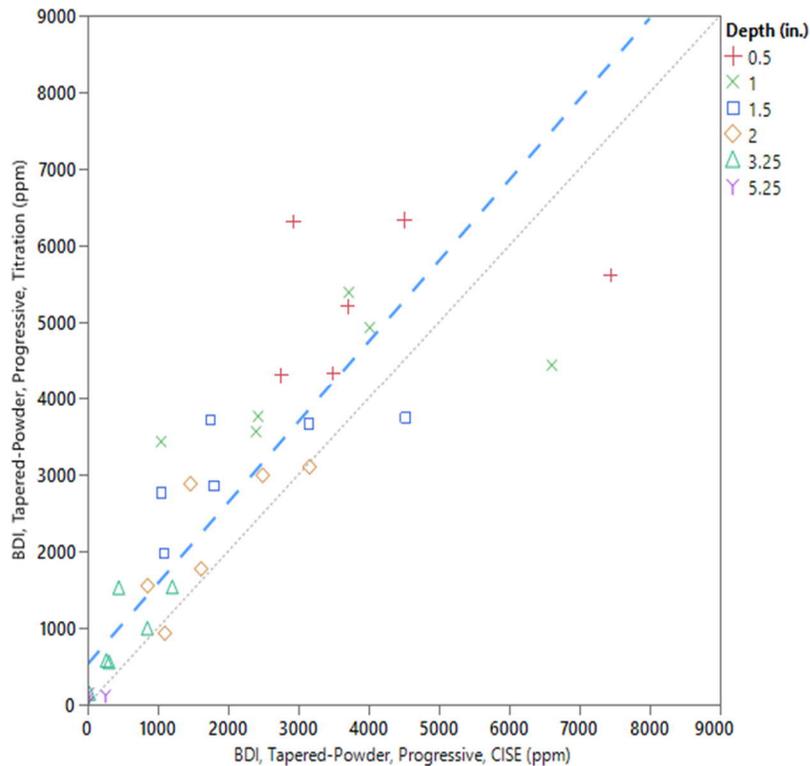


Figure 4.56 Titration vs CISE (ppm) of Tapered Profile Powder Samples by BDI

Figure 4.57 depicts the comparison of titration tests versus CISE tests of cored concrete samples at uniformly spaced 1-inch increments. The plot shows the comparative results at each of 6 sample depths from 24 cores. The linear fit has a slope of 1.24 and intercept of 204 ppm, indicating that titration consistently gives higher concentration values. The plot shows little scatter, and the relationship is predictable, with a very strong correlation coefficient of 0.993.

In Figure 4.58, titration tests versus CISE tests are compared of powdered samples taken by hammer drill with constant profile at progressively spaced ½-inch increments. The plot shows the comparative results at each of 6 sample depths from 24 cores. The linear fit has a

slope of 2.03 and intercept of 1273 ppm, indicating that titration consistently gives much higher concentration values than CISE. The plot shows significant scatter, and the relationship is not very predictable, with a poor correlation coefficient of 0.627. The scatter of CISE values, especially at high concentrations, calls into question the reliability of this method. Indeed, the VCS team experienced significant difficulties with the CISE probe calibration, which will be discussed further.

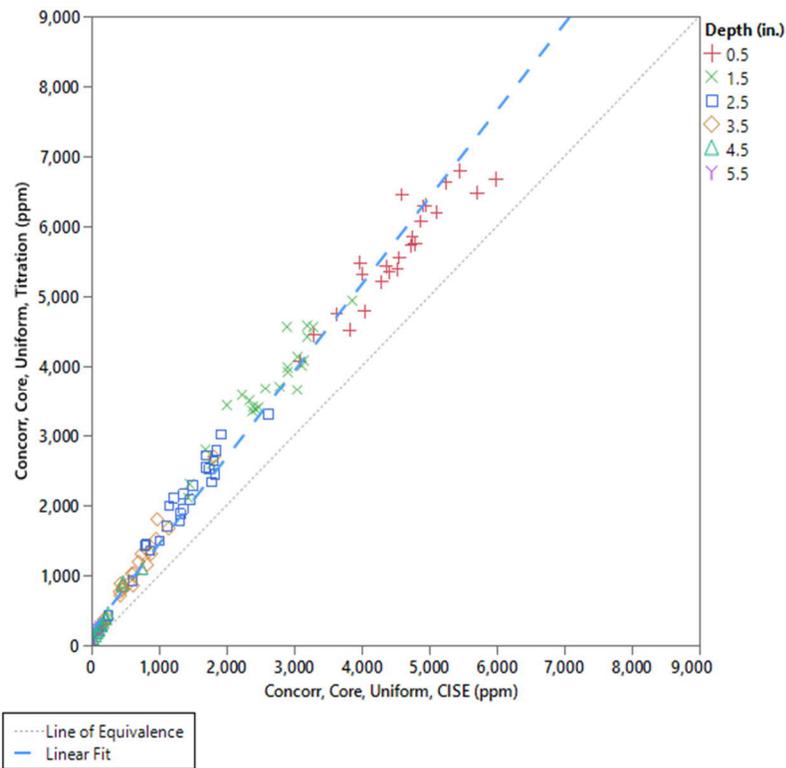


Figure 4.57 Titration vs CISE for Uniform Profile Core Samples by CONCORR

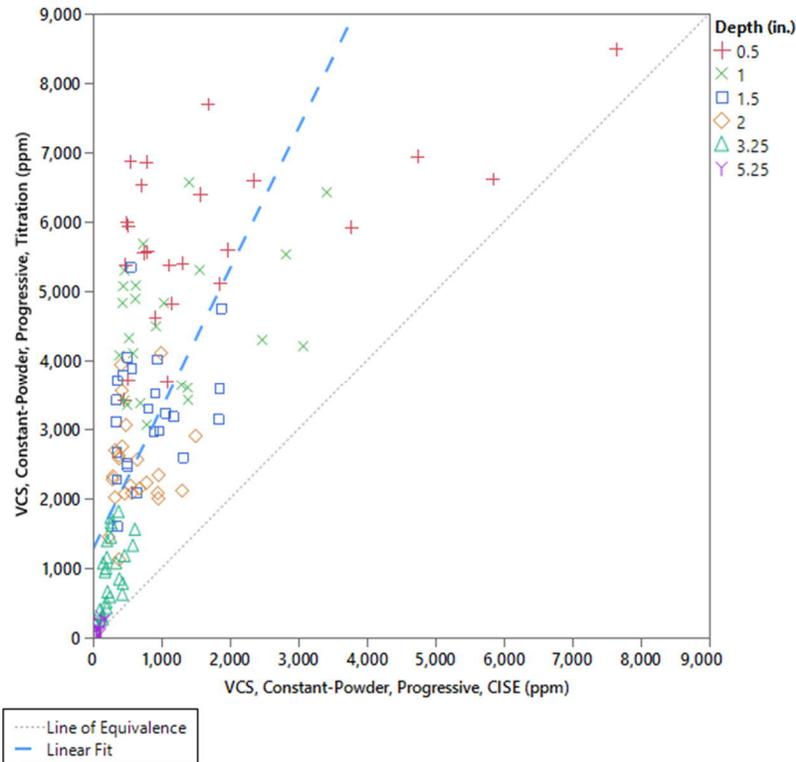


Figure 4.58 Titration vs CISE for Progressive Constant Profile Powder Samples by VCS

Comparison of the primary and secondary test methods on the same cores should ideally result in the same chloride concentrations at each respective depth of a core. The results of such pairs can be evaluated by subtracting the value of one test result from that of the other test of the same sample. If the difference is not zero, then there is bias between the tests. A statistical test, the Student t-test, is used to compare the paired values for the sets of cores from each team.

Figure 4.59 presents the results of titration and CISE methods from 36 powder samples from 6 cores as conducted by BDI. The figure shows parallel dot plots with mean and 90% confidence intervals for each method. The confidence intervals overlap significantly. A t-test evaluates the differences between methods ($\text{CISE} - \text{titration} = \Delta$); a plot shows the range of Δ values and the reported mean of Δ is -638 ppm, indicated by the red line in the distribution plot. The p-value for a two-tailed test is 0.1632 ($p > 0.05$) and the t Ratio is -1.41 with 69 degrees of freedom, DF ($|t \text{ Ratio}| < 2.00$), which indicate that the populations of chloride results from the two methods are not statistically different at a 0.05 confidence level. However, higher average concentrations are reported by the titration tests (2,649 ppm) than the CISE tests (2,010 ppm).

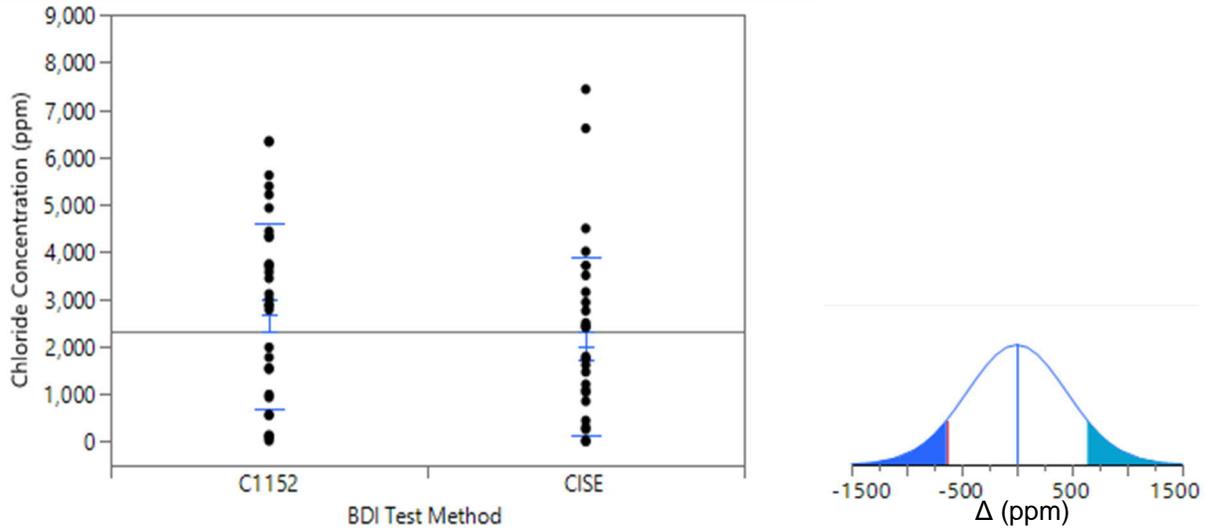


Figure 4.59 Statistical t-test Comparing BDI Titration to CISE

A similar comparison is made in Figure 4.60 of 144 samples from 24 cores tested by CONCORR. Again, there is some overlap of confidence intervals in the dot plots; however, the t-test of differences between tests ($\text{CISE} - \text{titration} = \Delta$) shows mean value of $\Delta = -578$ ppm. A plot of the t-test shows that the mean difference in values is significantly far from zero, as indicated by the red bar near the tail of the distribution. The p-value for the two-tailed test is 0.0094 ($p \ll 0.05$) and the t Ratio is -2.61 with 273 DF ($|t \text{ Ratio}| > 1.96$), both of which indicate that the results from the two methods are statistically different. As before, higher average concentration values are reported by titration (2,128 ppm) than by CISE (1,549 ppm).

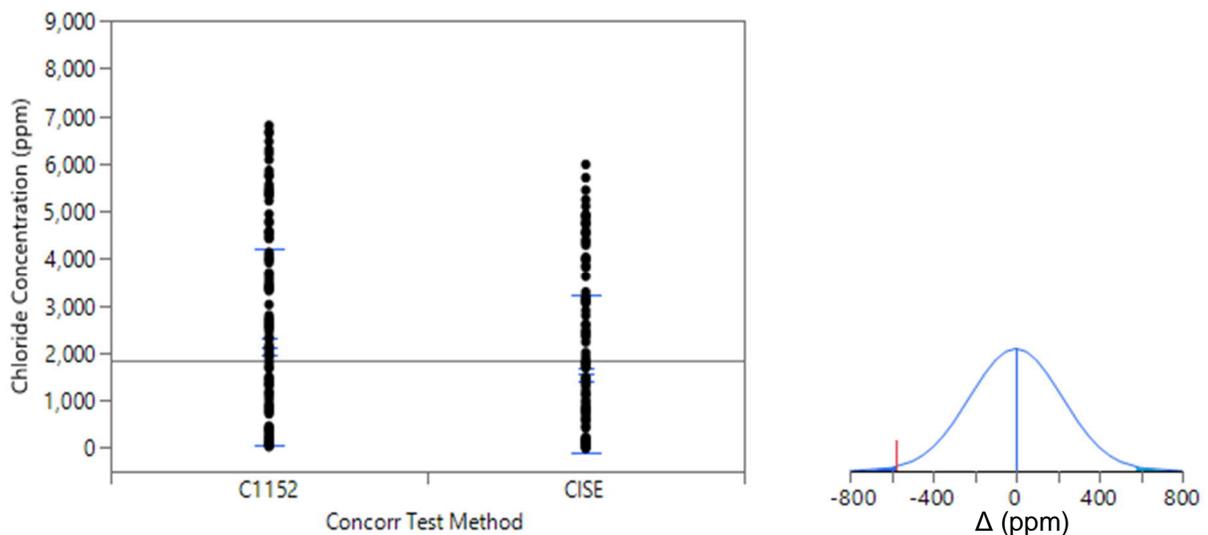


Figure 4.60 Statistical t-test Comparing CONCORR Titration to CISE

Figure 4.61 compares 144 samples from 24 cores tested by VCS. Confidence intervals in the dot plots overlap relatively little. The t-test of differences between tests ($\text{CISE} - \text{titration} = \Delta$) shows mean value of $\Delta = -2,082$ ppm, which is a large discrepancy, as indicated by the red bar beyond the tail of the distribution. The p-value for the two-tailed test is 0.0001 ($p \ll 0.05$) and the t Ratio is -10.67 with 208 DF ($|t \text{ Ratio}| \gg 1.96$), both of which indicate that the results from the two methods are statistically different by a large degree. Much higher average concentration values are reported by titration (2,870 ppm) than by CISE (788 ppm).

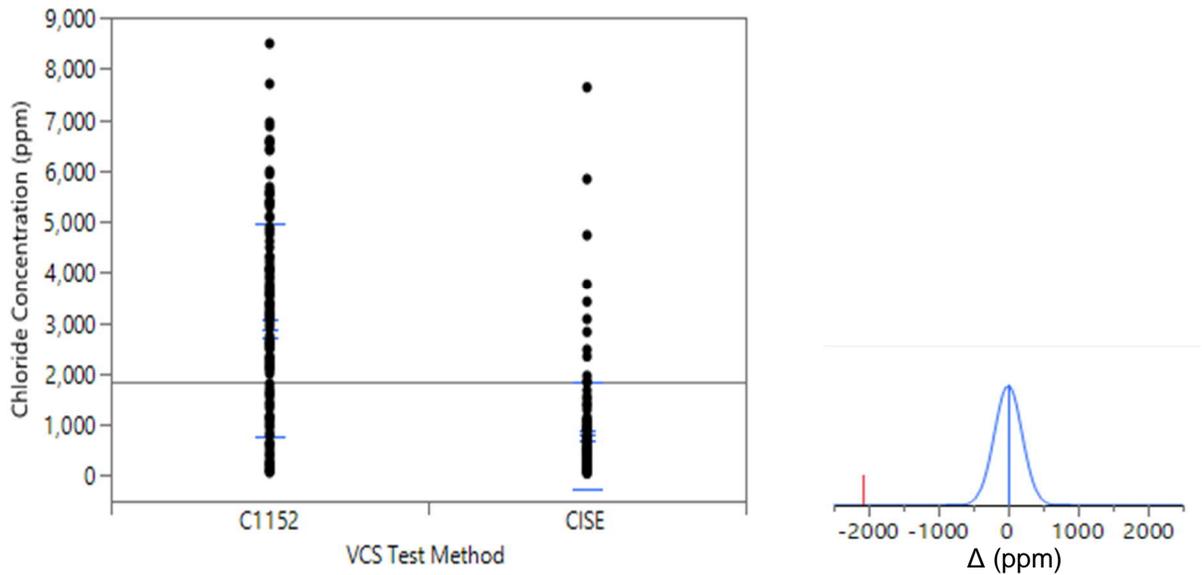


Figure 4.61 Statistical t-test Comparing VCS Titration to CISE

4.4.2 Interlaboratory Tests of Same Samples Using Same Test Method

Each team received 36 powdered samples (3 depths \times 12 cores) from another team for comparative testing using the same method. As with primary and secondary test methods, a bivariate plot is used to compare the pairwise results between labs. Results from the originating team are plotted against the y-axis, and results from the receiving team are plotted against the x-axis. If both labs return matching concentrations for a sample, the resulting point will lie on the line of equivalence (with slope = 1). Values appear closer to the axis reporting higher concentration for a given specimen. A linear fit of the data reflects bias.

Samples originated by VCS were subject to interlaboratory tests by BDI. The samples were obtained by hammer drilling using a constant profile and sampling at progressive 1/2-inch depth ranges. Both laboratories performed the CISE method. For the 36 samples, VCS reported

concentrations with average of 1,389 ppm and standard deviation of 1,502 ppm. BDI reported concentrations averaging 3,010 ppm with a standard deviation of 1,290 ppm. The values reported by VCS were significantly lower overall, but with much higher variability. In Figure 4.62, the linear fit indicated a slope of 1.16 and y-intercept of -2,114 ppm; the correlation coefficient of 0.48 indicates very poor correlation between the two sets of tests. The slope was greatly influenced by a few very high concentrations reported for 0.5-inch depth by VCS.

Samples originated by BDI were subject to interlaboratory tests by CONCORR. These samples were obtained by hammer drilling using tapered profiles and sampling at progressive ½-inch depth ranges. Both laboratories performed CISE method to determine chloride concentrations. For the 36 subject samples, BDI reported concentrations averaging 2,595 ppm with a standard deviation of 906 ppm. CONCORR reported concentrations with average of 2,968 ppm and standard deviation of 998 ppm. Thus, the values reported by BDI were somewhat lower overall, but with slightly lower or similar variability, both having coefficients of variation near 34%. This is reflected in Figure 4.63. A linear fit indicated a slope of 0.91 and y-intercept of -99 ppm; the correlation coefficient of 0.73 indicates that there is fair correlation between the two sets of tests, with the slope of the line influenced by several high concentrations reported for 0.5-inch depth by CONCORR. Variability between the two sets of tests did appear to increase as chloride concentration increased; this appears to be common for CISE measurements.

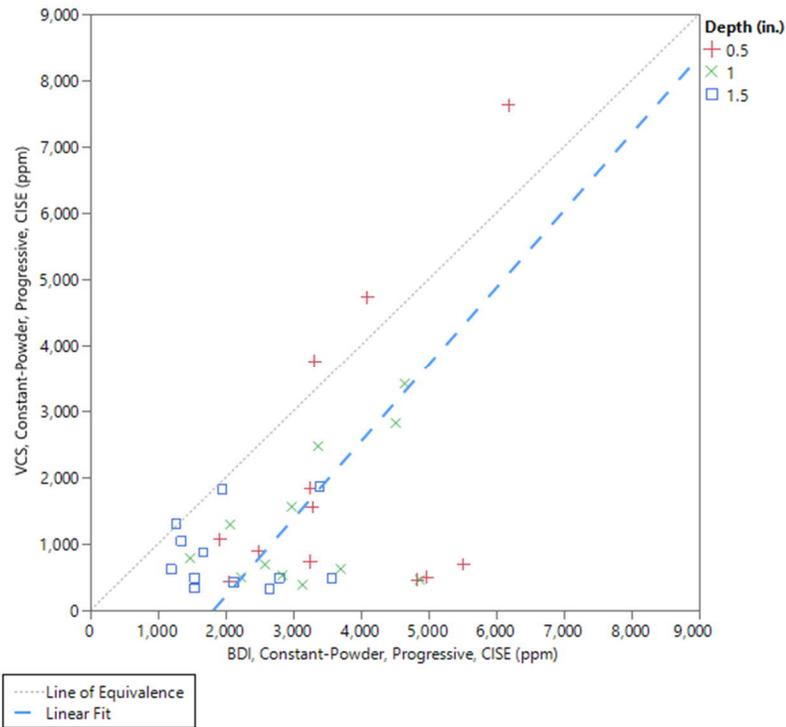


Figure 4.62 Interlaboratory (VCS→BDI) CISE Tests, Progressive Constant Profile Powder Samples

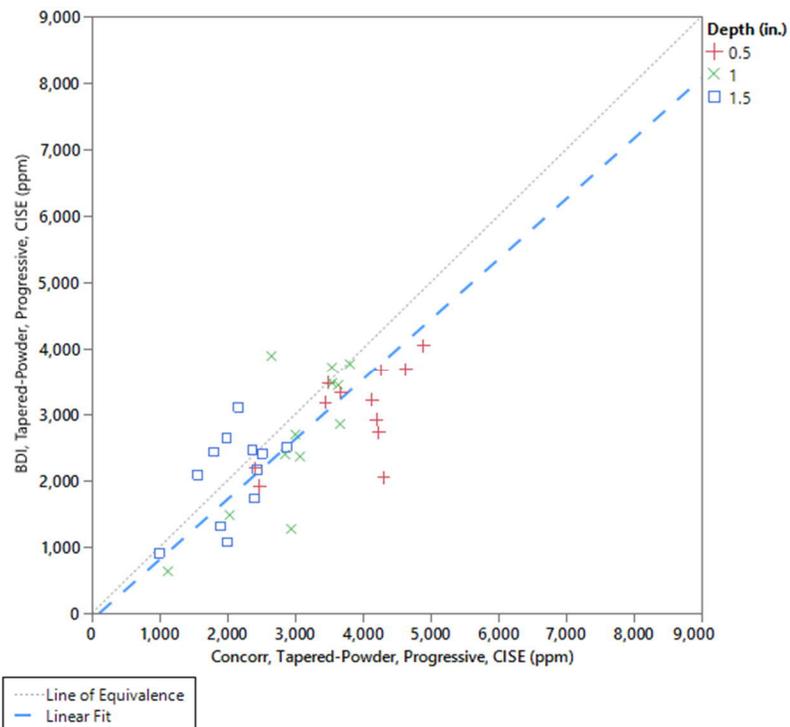


Figure 4.63 Interlaboratory (BDI→CONCORR) CISE Tests, Progressive Tapered Profile Powder Samples

Samples originated by CONCORR were subject to interlaboratory tests by SCS. The samples were obtained by coring and were subdivided into uniform 1-inch depth ranges in the laboratory by dry-cutting and pulverizing. Both laboratories performed the titration method, CONCORR according to ASTM C1152 and SCS according to AASHTO T260. For the 36 samples, CONCORR reported concentrations with average of 3,945 ppm and standard deviation of 1,660 ppm. SCS reported concentrations averaging 3,244 ppm with a standard deviation of 1,497 ppm. The values reported by SCS were lower overall, with lower variability with coefficient of variation of 42% versus 46% for CONCORR. The linear fit in Figure 4.64 indicated a slope of 1.11 and y-intercept of 347 ppm; the correlation coefficient of 0.95 indicates very strong correlation between the two sets of tests.

Samples originated by SCS were subject to interlaboratory tests by VCS. The samples were obtained by coring and were subdivided into progressive ½-inch depth ranges in the laboratory by dry-cutting and pulverizing. Both laboratories performed the titration method, SCS according to AASHTO T260 and VCS according to ASTM C1152. For the 33 samples, SCS reported concentrations with average of 4,336 ppm and standard deviation of 1,207 ppm. SCS reported concentrations averaging 4,491 ppm with a standard deviation of 1,346 ppm. The values reported by SCS were lower overall, with lower variability, though both had relatively low coefficients of variation of 28% for SCS versus 30% for VCS. The linear fit in Figure 4.65 indicated a slope of 0.90 and y-intercept of 311 ppm; the correlation coefficient of 0.97 indicates very strong correlation between the two sets of tests.

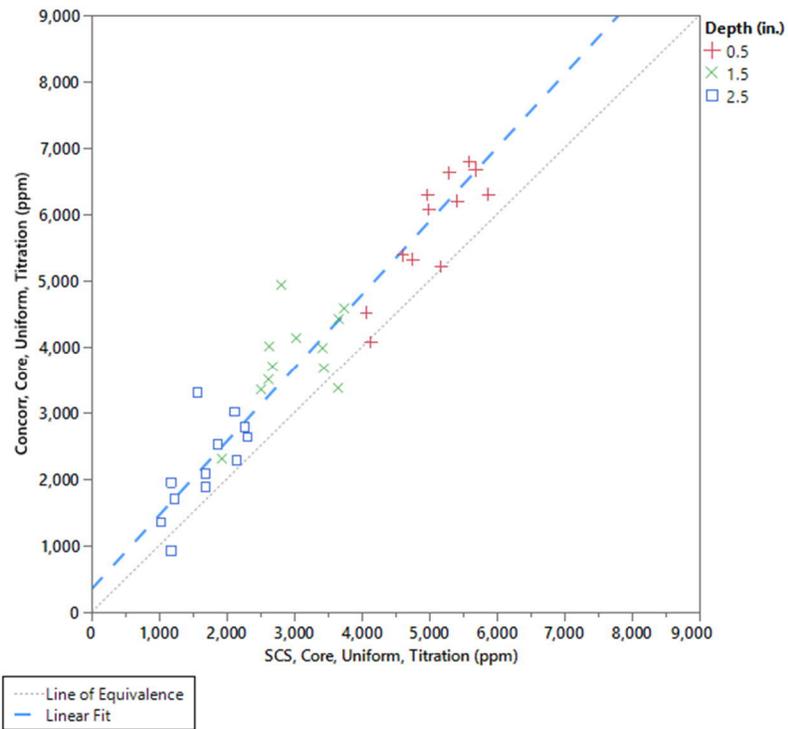


Figure 4.64 Interlaboratory (CONCORR→SCS) Titration Tests, Uniform Core Samples

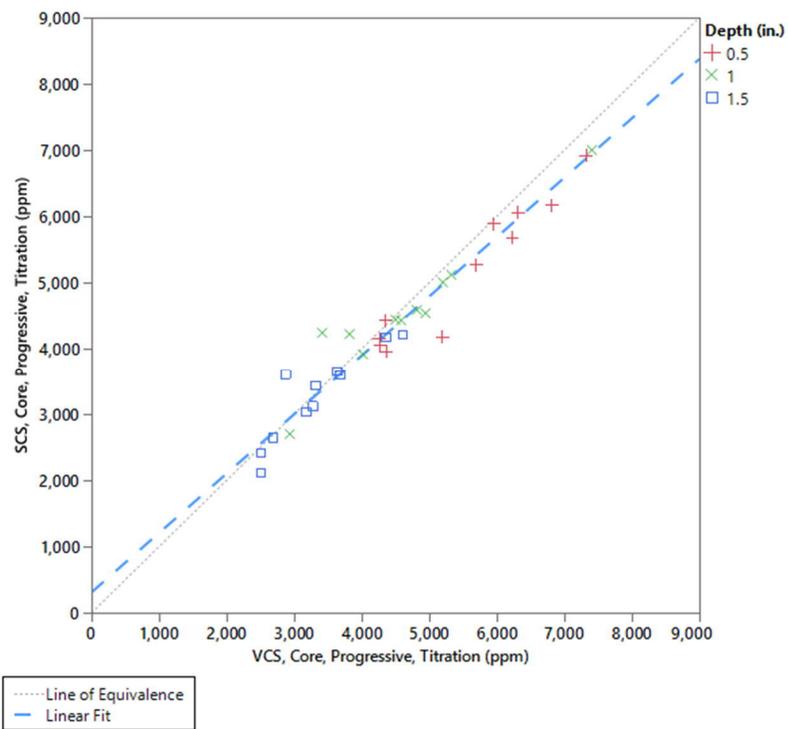


Figure 4.65 Interlaboratory (SCS→VCS) Titration Tests, Progressive Core Samples

To further compare the interlaboratory exchange results, t-tests were conducted to compare the paired test results from two teams of the same samples. Figure 4.66 compares dot plots for CISE measurements of powdered samples taken by VCS and tested by BDI and shows poor overlap of confidence intervals. The average of differences ($VCS - BDI = \Delta$) is -1,621 ppm, where VCS results are lower, as shown by the red line outside the tail of the distribution. Two-tail p-value of 0.0001 ($\ll 0.05$) and t Ratio of -4.91 with 68 DF (> 2.00) indicate that results of the two methods are statistically different.

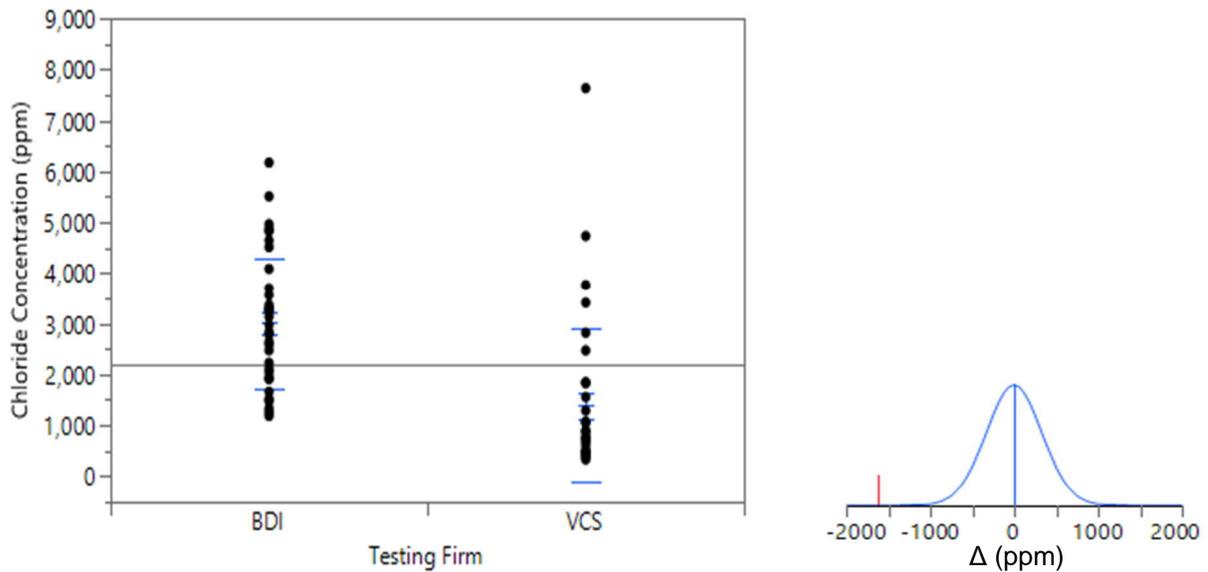


Figure 4.66 Statistical t-test Comparing Interlaboratory (VCS→BDI) CISE Tests

Figure 4.67 compares dot plots for CISE measurements of powdered samples taken by BDI and tested by CONCORR which shows moderate overlap of confidence intervals. The average of differences ($CONCORR - BDI = \Delta$) is 373 ppm, where CONCORR results are higher, as shown by the red line inside the upper tail of the distribution. Two-tail p-value of 0.10 (> 0.05) and t Ratio of 1.66 with 69 DF (< 2.00) indicate that results of the two methods are not statistically different.

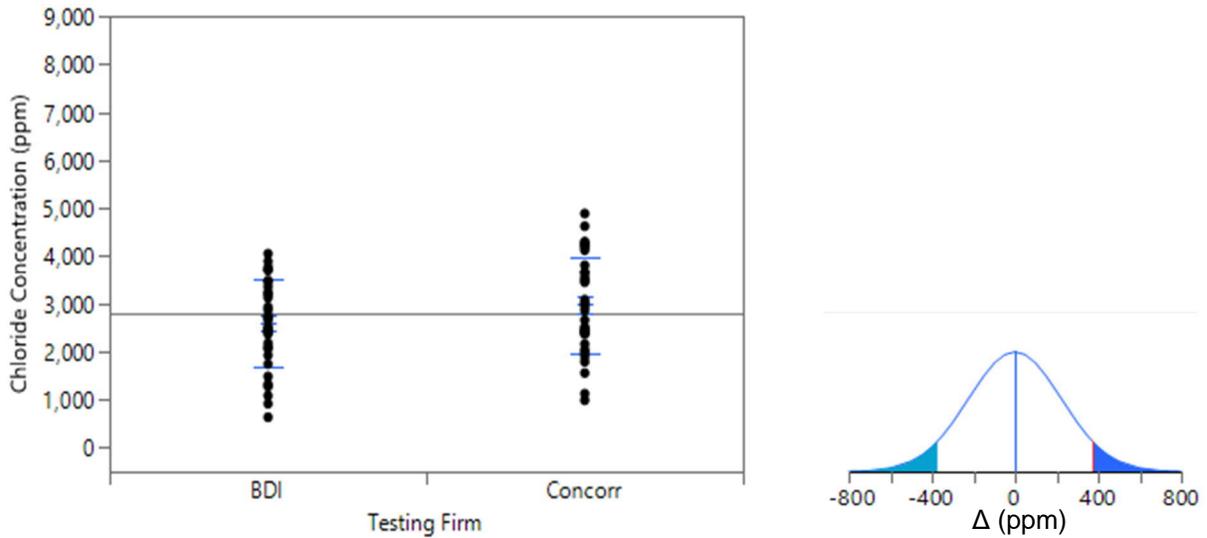


Figure 4.67 Statistical t-test Comparing Interlaboratory (BDI→CONCORR) CISE Tests

Figure 4.68 which compares dot plots for titration measurements of core samples taken by CONCORR and tested by SCS, shows moderate overlap of confidence intervals. The average of differences ($SCS - CONCORR = \Delta$) is -700 ppm, where CONCORR results are higher, as shown by the red line inside the lower tail of the distribution. Two-tail p-value of 0.064 (>0.05) and t Ratio of -1.88 with 69 DF ($|t \text{ Ratio}| < 2.00$) indicate that results of the two methods are not statistically different.

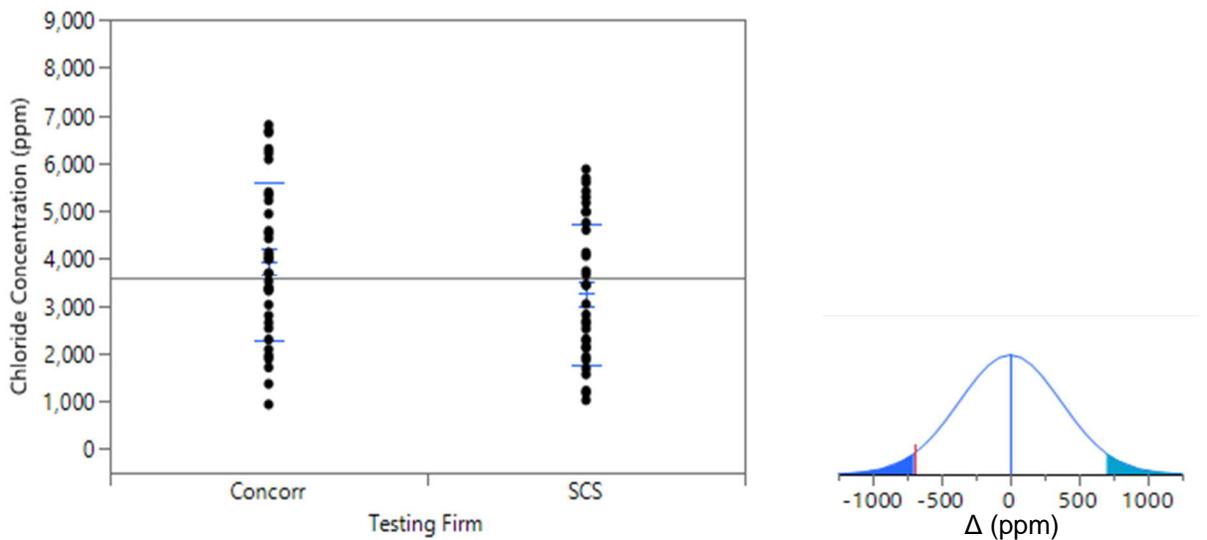


Figure 4.68 Statistical t-test Comparing Interlaboratory (CONCORR→SCS) Titration Tests

Figure 4.69 compares dot plots for titration measurements of core samples taken by SCS and tested by VCS. The figure shows strong overlap of confidence intervals. The average of differences ($VCS - SCS = \Delta$) is 155 ppm, where VCS results are slightly higher, as shown by the red line inside the upper tail of the distribution. Two-tail p-value of 0.624 (>0.05) and t Ratio of 0.49 with 63 DF ($|t \text{ Ratio}| < 2.00$) indicate that results of the two methods are not statistically different. Indeed, the distributions are very similar based on these results.

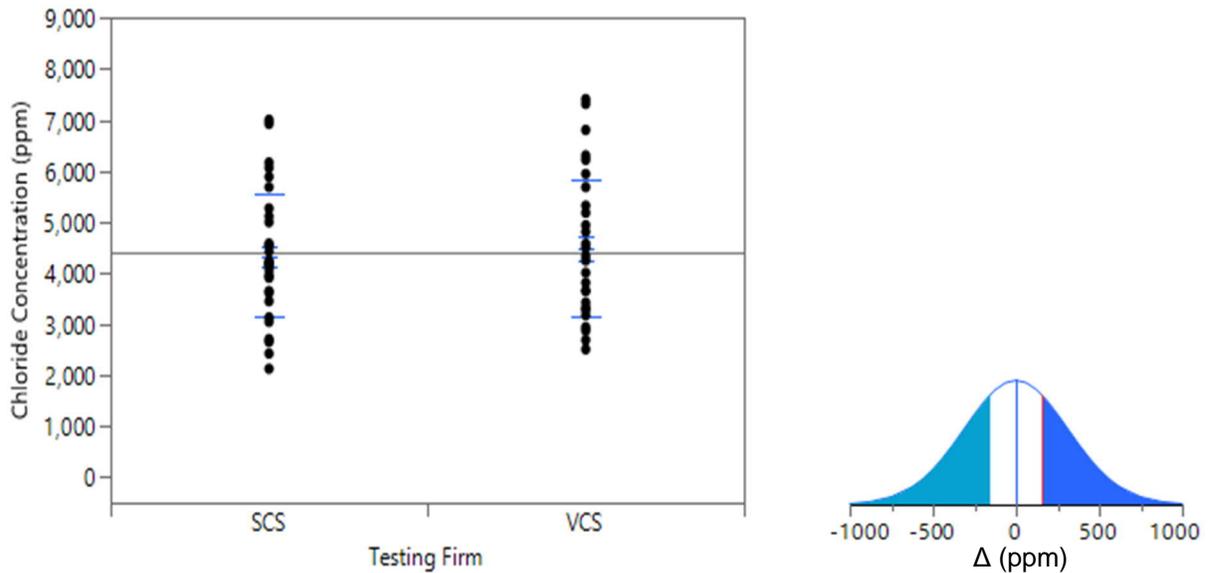


Figure 4.69 Statistical t-test Comparing Interlaboratory (SCS→VCS) Titration Tests

4.4.3 Progressive versus Uniform Sample Depth Increments

One of the experimental factors to be tested was the influence of sample depth increment (uniform versus progressive). Figure 4.70 compares dot plots for titration measurements of six core samples taken by CONCORR and subdivided and tested by both BDI and CONCORR, the former in progressive 1/2-inch increments and the latter in uniform 1-inch increments. The figure shows strong overlap of confidence intervals. The average of differences ($CONCORR - BDI = \Delta$) is 126 ppm, where CONCORR results are slightly higher, as shown by the red line well inside the upper tail of the distribution. Two-tail p-value of 0.784 ($>>0.05$) and t Ratio of 0.28 with 8 DF ($|t \text{ Ratio}| \ll 2.00$) indicate that results of the two methods are not statistically different. Indeed, the distributions are extremely similar based on these results.

Another comparison can be made among samples from CONCORR and SCS wherein each team obtained cores throughout the two bridges; CONCORR used uniform 1-inch sample depths and SCS used progressive ½-inch sample depths. Figure 4.71 compares dot plots for titration measurements of 24 core samples taken by CONCORR and 23 cores taken by SCS. The figure shows strong overlap of confidence intervals. The average of differences (SCS – CONCORR = Δ) is -286 ppm, where SCS results are slightly lower than those of CONCORR, as shown by the red line inside the lower tail of the distribution. Two-tail p-value of 0.298 (>0.05) and t Ratio of -1.05 with 41 DF ($|t \text{ Ratio}| < 1.98$) indicate that results of the two methods are not statistically different. Given that these samples were not taken in a pairwise fashion (within about 6 inches proximity), but instead were always in the opposite lane/shoulder, the similarity in results is positive. The two sets of results show that there is not a significant influence of progressive versus uniform test increments and either could be used so long as the resulting profile is deep enough to adequately capture the range of chloride concentrations in the concrete.

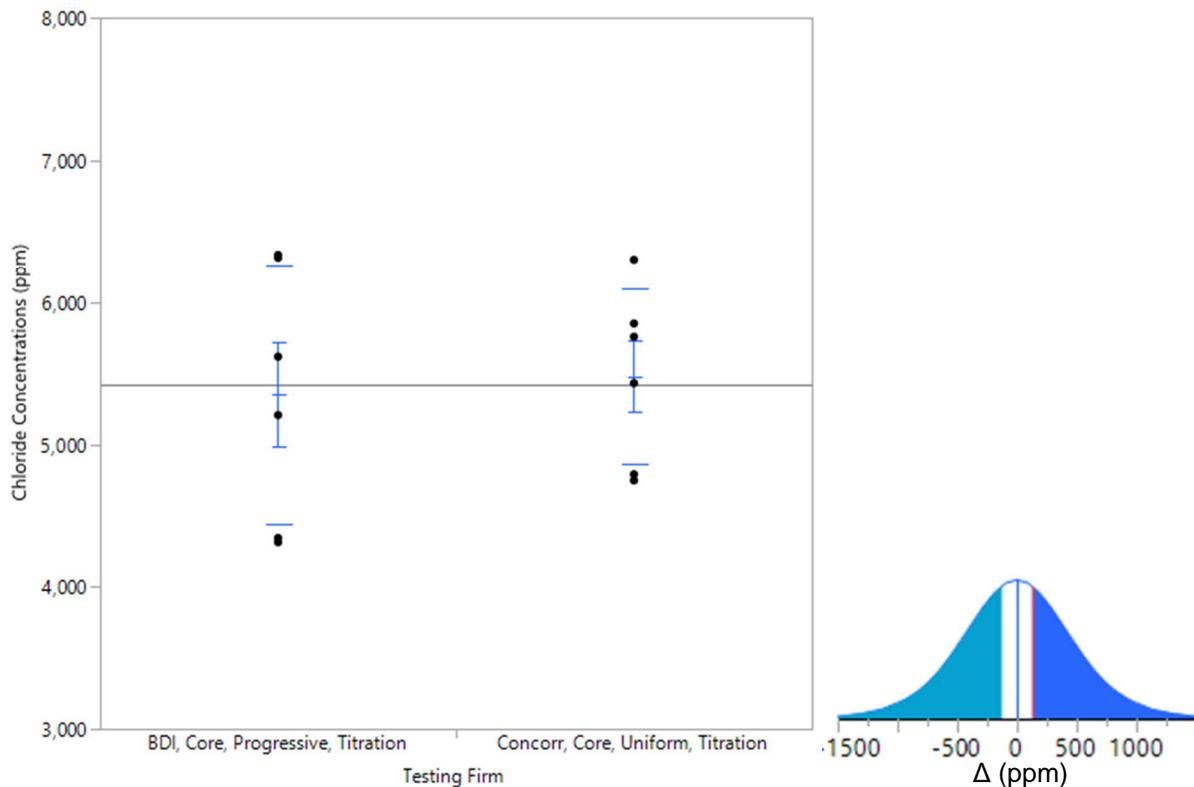


Figure 4.70 Statistical t-test Comparing Different Sample Depth Increments in Same Cores

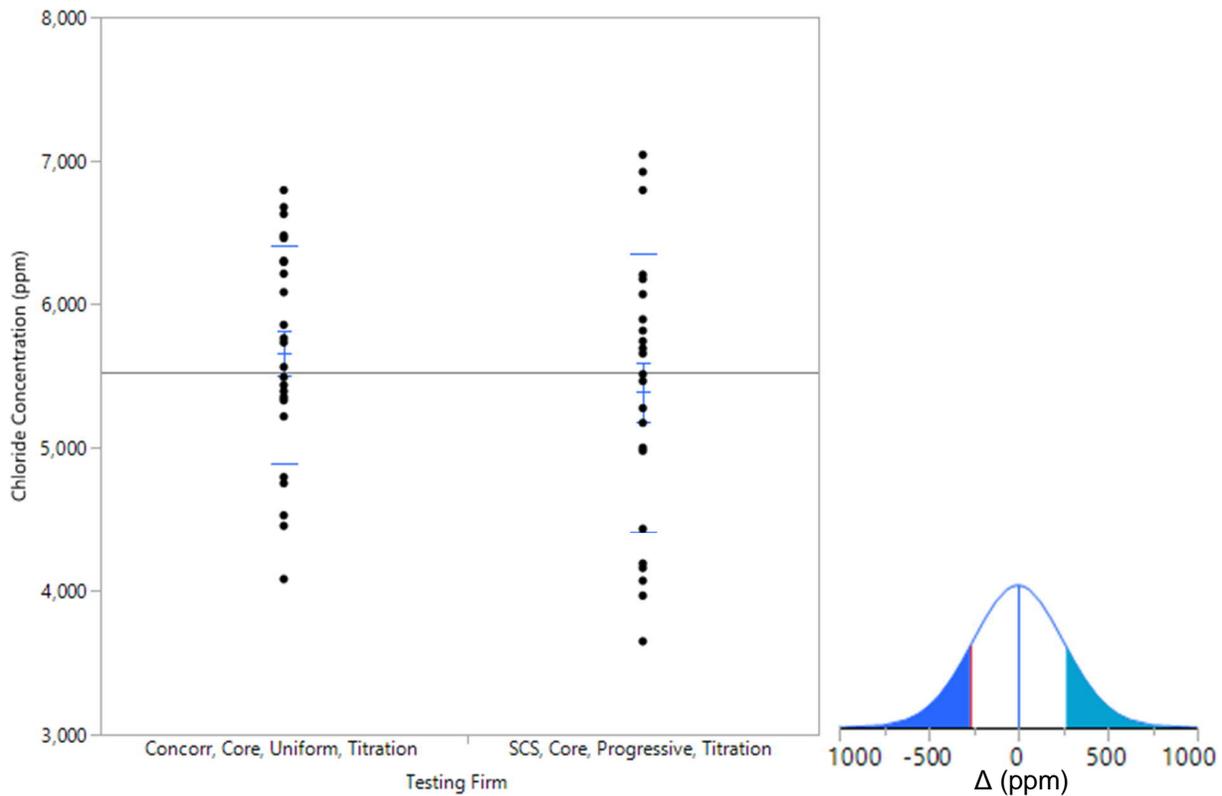


Figure 4.71 Statistical t-test of Different Depth Increments in Cores Across Both Bridges

4.4.4 Coring versus Powder Sampling

Another experimental factor was comparison of sampling procedures by coring and pulverizing versus powder sampling in the field with a hammer drill. Figure 4.72 presents a bivariate fit presenting a pointwise matching of collocated core samples by SCS and constant profile powder samples by VCS. Both sets were tested by titration. VCS samples had a mean concentration of 2,850 ppm and SCS sample mean was 2,680 ppm. The slope of the fitted line is 0.95 and the intercept is -22 ppm, which are sufficiently close to unity and zero, respectively, to indicate good predictability and correlation between the two sampling methods. The goodness of fit ($R^2 = 0.93$) indicates that differences between pairwise results were not widely variable, though, as might be expected, greater variability is associated with concentrations obtained nearer the deck surface.

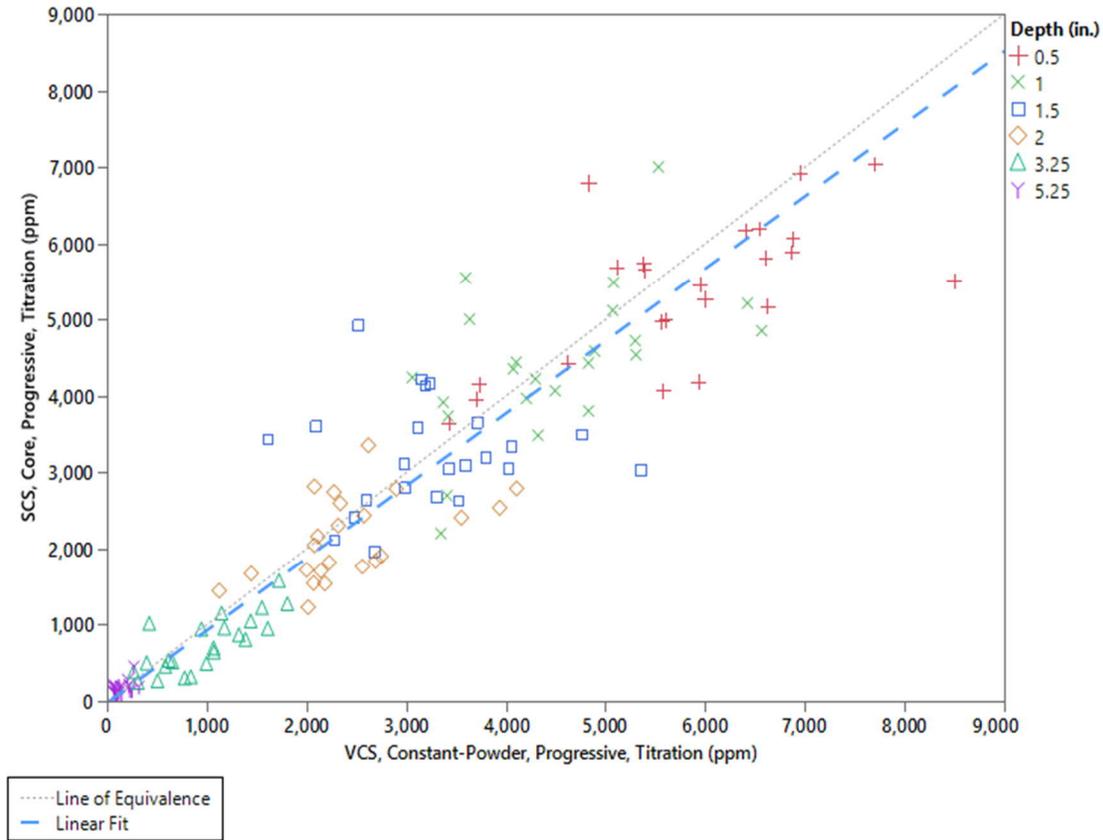


Figure 4.72 Pointwise Comparison of Core versus Powder Sampling Methods

To further investigate the relationship between the two methods for the collocated cores, Figure 4.73 presents box-and-whisker plots that represent the distribution of chloride concentrations of 23 cores by SCS and 24 powder samples by VCS separated by bridge and grouped as a function of depth. In each case, the box represents the 25% through 75% quartiles and the line in between is the mean. External whiskers represent the range (maximum and minimum) and the first line inside the whisker is the upper and lower decile (10th and 90th percentile).

The means and middle quartiles at each depth are comparable, though a few depth ranges show evidence of outliers. In general, the powder sampling (VCS) appears to exhibit slightly higher variance and incidence of outliers. Powder samples in some cases show higher concentration outliers, which suggests but does not prove that some cross-contamination with layers above could have occurred.

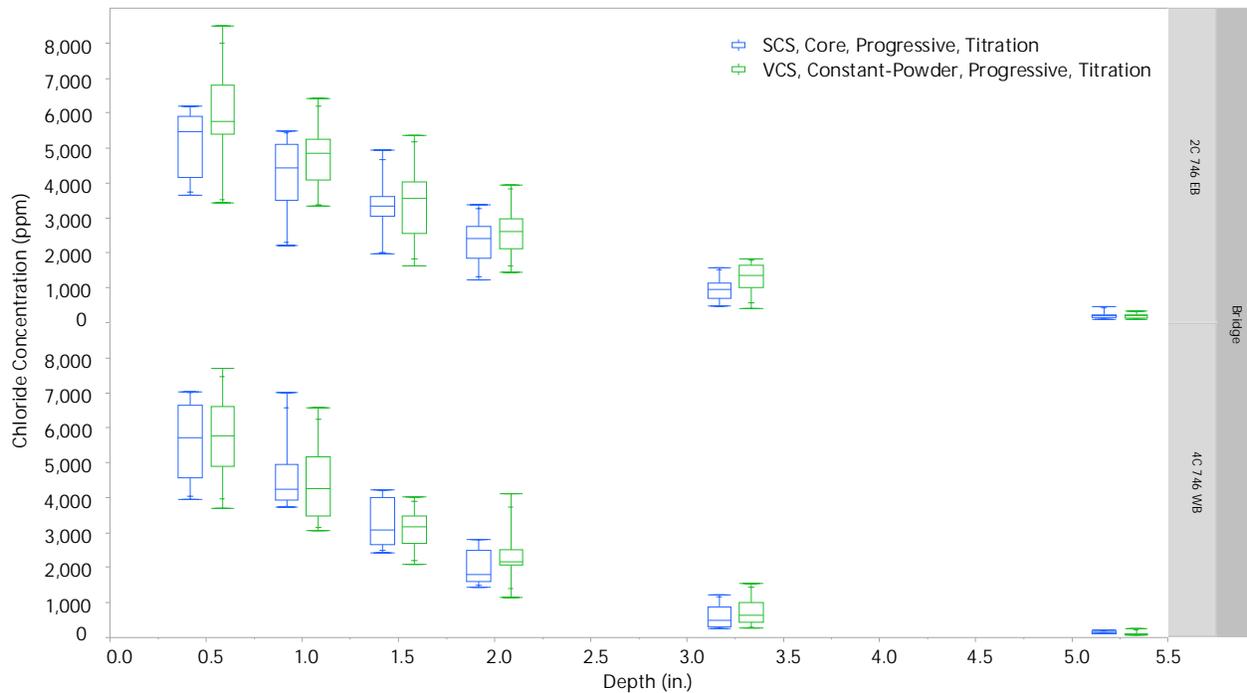


Figure 4.73 Box-and-Whisker Plots of Core (SCS) and Powder (VCS) Titration Samples

Figure 4.74 provides similar comparison of cores taken by CONCORR to tapered profile powder samples taken by BDI, all tested by CISE. Since CONCORR used uniform depth increments, not all groupings match by depth, so general trends can only be observed for measurements with matching depths. Match of means and middle quartiles is not as good as with the previous comparison, especially at the ½-inch depth. Core (CONCORR) values tended to be higher but less variable than those from powder samples (BDI). There is significant variability in both data sets, but more outliers are apparent in the powder sampling, particularly toward the high end on the westbound bridge. Based on previous observations, this effect is believed to be partially attributable to the variability of the CISE testing method and does not solely reflect differences in the core versus powder sampling methods.

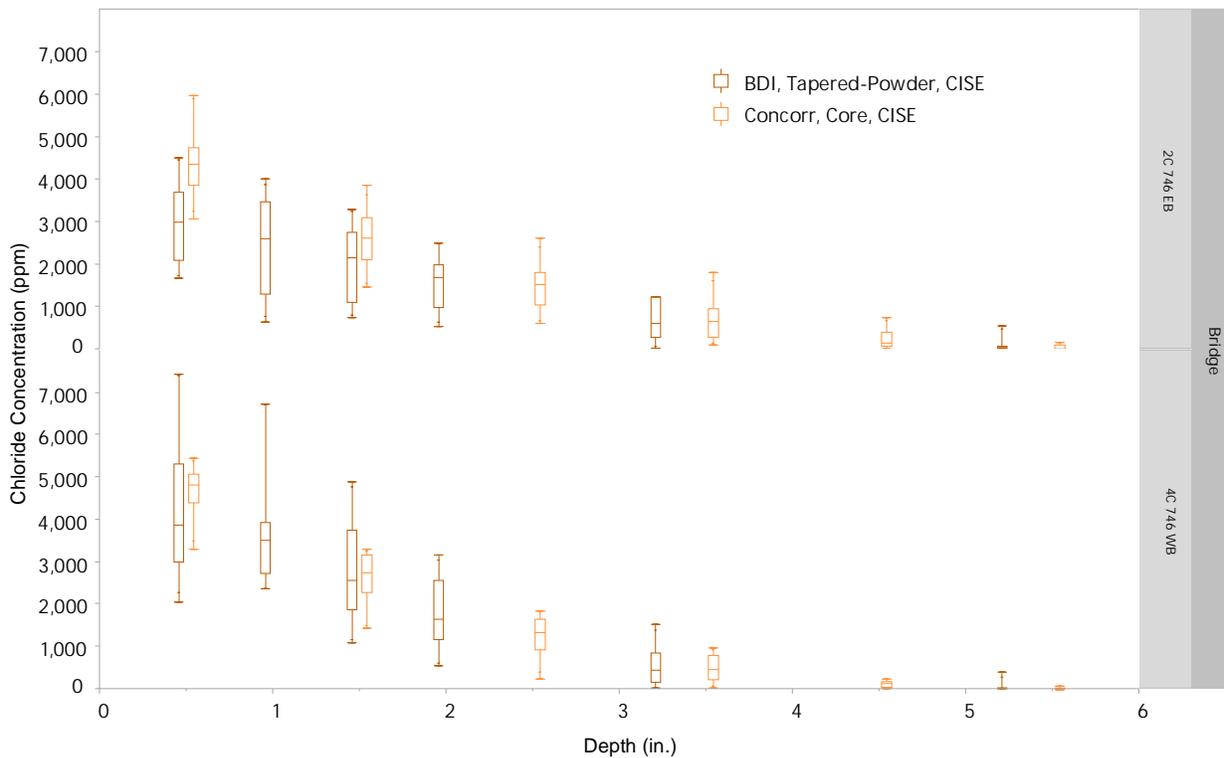


Figure 4.74 Box-and-Whisker Plots of Core (CONCORR) and Powder (BDI) CISE Samples

4.4.5 Tapered versus Constant Profiles for Powder Sampling

The experimental matrix also was intended to address the question of tapered profiles versus constant profiles when performing powder sampling with a hammer drill. Figure 4.75 shows box-and-whisker plots of 24 locations each tested by VCS and BDI. Results of both titration and CISE tests are presented and grouped according to bridge and as a function of depth. From titration tests, the constant profile results were often higher than those taken with tapered profiles. Again, a few of the distributions are skewed with outliers appearing at the high end, especially for the constant profiles, which may suggest a few cases of cross-contamination of deeper layers from above. On the other hand, lower average chloride concentrations from deeper samples could indicate a bias in the tapered profiles as the sample volume relative to aggregate size decreases. The trend is not definitive from these plots. Again, CISE results are significantly lower than titration values and more variable, which is believed to be a result of the test method, not the sampling method.

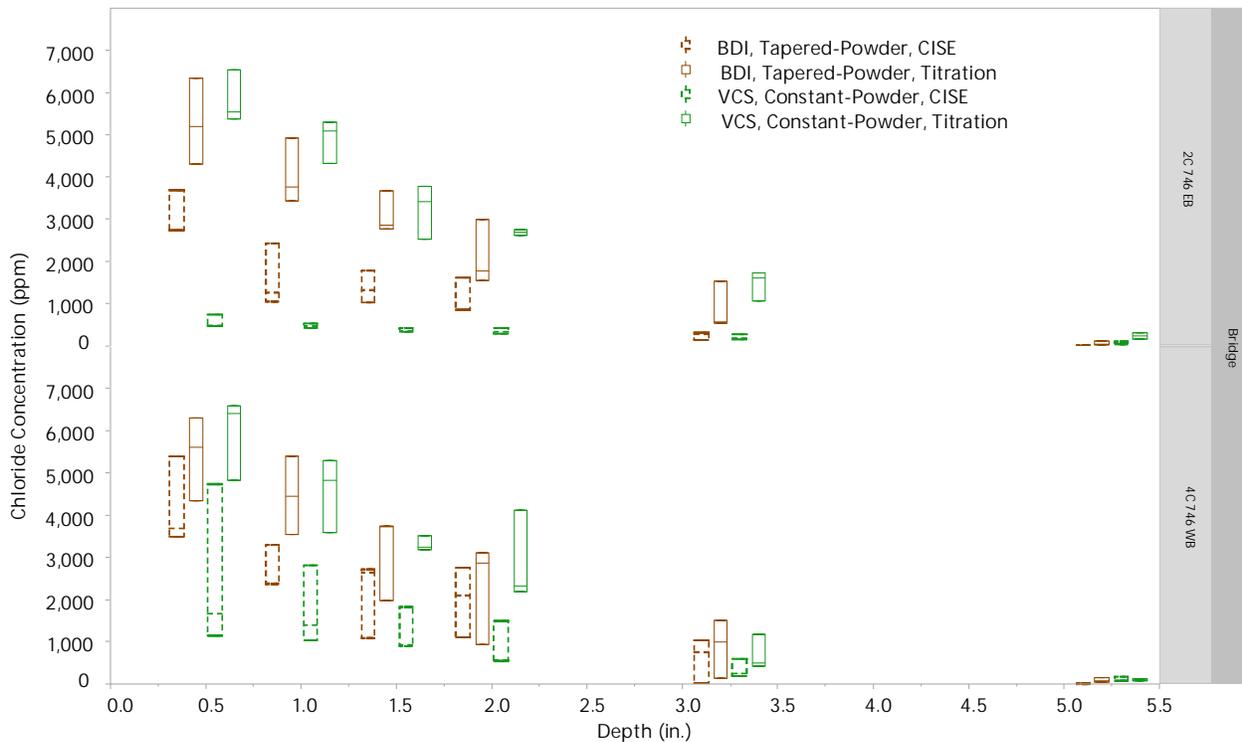


Figure 4.75 Comparing Tapered Profiles (BDI) and Constant Profiles (VCS) for Powder Samples

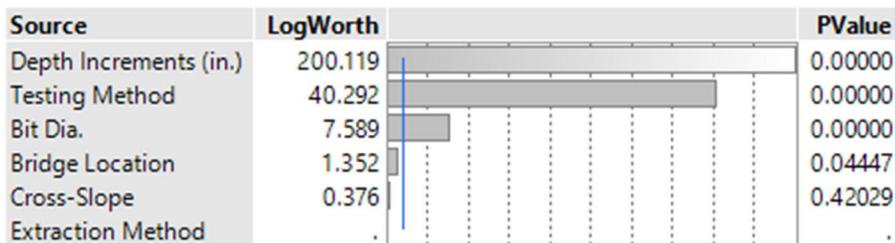
4.4.6 Evaluation of Factors by Multivariate Analysis

In an effort to further deconvolute the interactive effects of the various experimental factors on the reported chloride concentrations, the researchers undertook a multivariate linear regression analysis using both continuous and categorical variables, wherein all the reported chloride concentrations were considered. For the first regression, the dependent (output) variable was chloride concentration (ppm). Potential factors considered in the regression included:

- location on deck (travel lane vs shoulder)
- cross-slope (uphill or downhill side)
- depth (chloride concentration changes with the depth of the sample taken),
- extraction method (core vs powder)
- powder sampling profile (tapered vs constant)
- laboratory test method (titration vs CISE)

Results of the analysis, presented in Figure 4.76, show that depth (as expected) has the greatest influence, followed by test method, bit diameter, and lane location, all of which were

significant contributors (at the 0.05 level). Surprisingly, cross-slope and extraction method did not have a statistically strong influence on the results. Cumulatively, the regression had a correlation coefficient of 0.68. The parameter estimates in Figure 4.76 can be interpreted as to the nature of the effects. Intercept represents the cumulative “error” of effects that cannot be explained by the other variables, demonstrating that the regression model is not a perfect predictor of outcome. However, looking in order at the relative influence of the factors considered, extraction method indicates cores had higher concentrations than powder samples, but the effect was not strong. The negative factor for depth indicates that the chloride concentration decreases with increasing depth. The negative factor for test method shows that CISE resulted in lower concentrations than titration. Samples inside a travel lane were indicated to have higher concentrations than those in shoulders. Counterintuitively, downslope measurements were lower than upslope measurements, but the effect was so small that this is not considered a valid predictor in the regression. Finally, constant profiles were found to be associated with lower concentrations than tapered profiles overall. Bit diameter was not applicable to cores.



Parameter Estimates					
Term		Estimate	Std Error	t Ratio	Prob> t
Intercept	Biased	4232.105	66.27068	63.86	<.0001*
Extraction Method[Core]	Biased	88.148931	42.15224	2.09	0.0368*
Depth Increments (in.)		-881.0025	22.0194	-40.01	<.0001*
Testing Method[CISE]		-587.4636	41.58551	-14.13	<.0001*
Bridge Location[Lane]		73.295453	36.42092	2.01	0.0445*
Cross-Slope[Downslope]		-29.28798	36.32453	-0.81	0.4203
Bit Dia.[Constant]	Biased	-332.6344	59.20336	-5.62	<.0001*
Bit Dia.[Core]	Zeroed	0	0	.	.

Figure 4.76 Multivariate Linear Regression Analysis of Chloride Concentration (ppm)

A similar regression was performed looking at surface concentration (C_o , in lb/yd^3) as the dependent variable and considering appropriate factors. In this case, the continuous variable of depth was excluded, but the categorical variable of depth increment (uniform or progressive) in sampling was considered. In this case, test method, bit diameter, and lane location were significant predictors. Depth profile increment was marginally influential, and cross-slope and extraction method did not significantly serve to predict C_o . Again, sampling within the travel lane tended to increase chloride results, whereas tests by CISE and sampling by constant profiles were associated with lower concentration values. Interestingly, sampling with the progressive depth increments was associated with slightly lower chloride concentrations, but this factor barely misses the 0.05 threshold of statistical significance. Cross-slope and extraction method do not appear to have a statistically significant influence. The strength of regression fit was only 0.43.

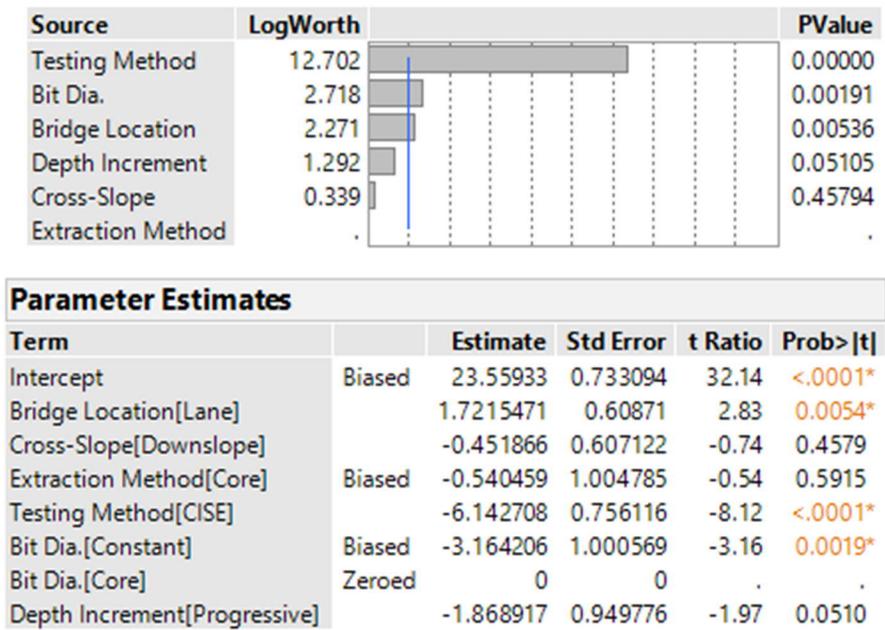


Figure 4.77 Multivariate Linear Regression Analysis of Surface Concentration, C_o (lb/yd^3)

Finally, multivariate linear regression was applied with diffusion coefficient (D_c , in in^2/yr) as the dependent variable. In this case the only statistically significant predictors were lane location and extraction method, where cores had a negative effect on diffusion coefficient. The strength of regression fit was very poor at 0.08, so this portion of the analysis is not considered to be very descriptive of the relationships.

Source	LogWorth	PValue
Bridge Location	1.532	0.02941
Depth Increment	1.189	0.06468
Bit Dia.	0.634	0.23215
Cross-Slope	0.417	0.38250
Testing Method	0.085	0.82292
Extraction Method	.	.

Parameter Estimates					
Term		Estimate	Std Error	t Ratio	Prob> t
Intercept	Biased	0.0890912	0.003559	25.04	<.0001*
Bridge Location[Lane]		-0.006501	0.002955	-2.20	0.0294*
Cross-Slope[Downslope]		-0.002582	0.002947	-0.88	0.3825
Extraction Method[Core]	Biased	-0.010155	0.004877	-2.08	0.0391*
Testing Method[CISE]		-0.000823	0.00367	-0.22	0.8229
Bit Dia.[Constant]	Biased	-0.005828	0.004857	-1.20	0.2322
Bit Dia.[Core]	Zeroed	0	0	.	.
Depth Increment[Progressive]		-0.008584	0.00461	-1.86	0.0647

Figure 4.78 Multivariate Linear Regression Analysis of Diffusion Coefficient, D_c (in^2/yr)

To round out the discussion of multivariate analysis on chloride profile parameters, C_o and D_c , shows mean values associated with categorical factors in the experimental matrix. This table confirms the higher values of C_o are associated with travel lanes, upslope locations, cores, tapered profile sampling, uniform depth increments, and titration lab testing versus their categorical alternatives. For D_c , higher values are associated with shoulder, upslope, powder sampling, tapered profiles, uniform depth increments and CISE testing, though many of these differences are very slight. Variations in C_o are of greater concern in this comparison.

Table 4.25 Mean Diffusion Model Parameters from Multivariate Analysis

Multivariate Mean Chloride Profile Parameter Comparison

Independent Variables	C_o (lb/ft ³)	D_c (in ² /yr)
Bridge Location		
Lane	24.4	0.078
Shoulder	20.7	0.091
Cross-Slope		
Upslope	23.1	0.087
Downslope	22.2	0.082
Extraction Method		
Core	25.9	0.081
Powder	19.2	0.088
Profile (Bit Diameters)		
Tapered	19.4	0.095
Constant	19.1	0.085
Depth Increment		
Uniform	25.0	0.087
Progressive	21.6	0.083
Testing Method		
Titration	27.9	0.081
CISE	17.1	0.088

4.5 Summary

The chloride concentration data were tabulated according to bridge, lane, sampling and testing method. Chloride profiles as a function of depth were presented along with fits of the Fickian diffusion model and compared to one another. Output parameters, C_o , D_c , and the correlation coefficients, R^2 , were summarized. The data and output parameters were then subject to a number of statistical tests and analyses to test the relationships of chloride test results to experimental factors relating to sampling methods and testing methods. Finally, a multivariate analysis was performed to test the strength of each factor in influencing the resulting chloride concentration and diffusion parameter results.

5.0 CONCLUSIONS

5.1 Summary

A comprehensive field study to obtain chloride concentrations from two heavily contaminated reinforced-concrete bridge decks was used to evaluate sampling and testing alternatives, with the goal of defining the best procedures to be used for statewide deck chloride sampling protocols. Parameters of interest included:

- coring versus powder sampling of concrete in the field
- if powder sampling is performed, are constant or tapered profiles preferable
- uniform versus progressive sample depths to create profiles
- potentiometric titration versus calibrated electrode methods for chloride tests

Additional information was sought from the data regarding location of sampling, comparing travel lanes to shoulders and evaluating the influence of cross-slope.

5.2 Findings

The following section provides primary findings of the study and a short discussion of each.

5.2.1 CISE Chloride Tests Provide Highly Variable Results

Complications with calibrated ion-selective electrode testing to determine chloride concentrations were apparent with the initial test results. Early calculations by VCS showed excessive variability and values that were unrealistically high. Efforts to extend the calibration curve to avoid extrapolation of results outside the calibration range did improve the response, but high variability in the output persists. CONCORR also ran a version of the CISE test, though they used laboratory equipment already in hand rather than one of the commercially available kits. CONCORR was able to provide a more reliable calibration and measurements, but it did require extending the range of calibration solutions to much higher concentration to encapsulate the range of chloride concentrations encountered in this study. It should be noted that under most

production circumstances, comparative titration data may not be available to check the calibration and identify suitable range for the CISE method.

Subsequent analysis shows that CISE results were highly variable and considerably different in many cases from the companion titration results. Since potentiometric titration has long stood in practice as the definitive standard, and there are indeed longstanding published standards (ASTM 1152 and AASHTO T260) for this method, the practical question was not whether CISE provides more accurate results than titration, but rather whether CISE could be used as a more cost-effective alternative to titration, as the latter involves significant equipment and is time-consuming when conducted for large numbers of tests.

The findings of this study are that CISE is highly variable and gives values that are typically lower than titration. There appears to be great difficulty in establishing correlation curves that provide consistent accuracy and results are especially erratic at very high chloride concentrations. Two of the three laboratories in the study performed CISE using a commercially available kit that is marketed for rapid field testing. As shown in section 4.4.1, particularly Figure 4.57, the third laboratory (CONCORR) following the same general method, but using laboratory grade meters and probes typically used for titration testing, was able to provide results with much lower variability and values much closer to, and linearly aligned with, companion titration tests, but the reported values would still underpredict chloride contamination and corrosion potential.

5.2.2 Titration Method Provides the Most Reproducible Results

From the results for interlaboratory titration tests in section 4.4.2, the titration method gives more consistent results, even between laboratories, as reflected by the high correlation coefficients and comparatively low variability between CONCORR and SCS. Also, the use of ASTM C1152 versus AASHTO T260, Procedure A did not seem to negatively affect the consistency of results. By contrast, the CISE results show significantly lower correlation and higher variability both within and between laboratories under many of the analyses conducted.

5.2.3 Uniform and Progressive Depth Increments Produce Similar Profiles

As shown by the statistical analysis of the chloride results of same cores tested by CONCORR and BDI, and statistical comparison of respective cores between CONCORR and SCS, as well as the profiles shown in section 4.3.3, very little distinction could be made between profiles taken with uniform versus progressive sample depths. Though C_o values from uniform sampling averaged slightly higher, the multivariate analysis did not find the categorical differentiation of uniform versus progressive increments for profiles to be statistically relevant.

5.2.4 Coring and Powder Sampling Provide Comparable Results

Comparisons of cored samples versus powdered samples showed that both give similar results, as discussed in section 4.4.4, though the variability of core sample results is lower than that of powder samples.

5.2.5 Constant Profiles Result in Slightly Higher Chloride Than Tapered Profiles

The cause and the significance is not clear from the analysis presented in 4.4.5, but it did appear that when associated with titration tests, the use of a constant profile in conducting chloride profiles resulted in slightly higher chloride concentrations as compared to the tapered profile. Interestingly, the multivariate analysis predicted that constant profile samples would be slightly lower, rather than higher, but this seems to be heavily influenced by CISE test values, the accuracy of which comes into question from the discussion above. Whether the differences between constant and tapered profiles result from occasional cross-contamination or inconsistent sample sizes is not apparent. However, the constant profile results compared very favorably with results from cores and seemed to have lower variability than tapered profile values.

5.2.6 Lane Location Matters but Cross-Slope Does Not

These phenomena may be unique to the test bridges in question, but it appears that test locations within travel lanes (especially wheel paths) exhibit greater chloride concentrations than those in shoulders. Discussion in section 4.4.6 indicates the impact of the rather significant cross-slope of the two bridges was surprisingly negligible, as locations along the downslope

shoulder (where snow and ice would be expected to accumulate during winter maintenance and drainage would carry salt-laden run-off) did not have greater chloride concentrations than the upslope shoulder. One hypothesis would be that the tracking of salt and the pumping action of pneumatic tires in the wheel paths serves to concentrate salt in the concrete in lane locations.

5.3 Limitations and Challenges

The subject study focused on testing of twin highway bridges that are approximately 30 years of age and representative of a moderately aggressive service environment. The number of samples obtained during the study far exceed that which would be expected in a routine evaluation but were necessary to provide statistical representation to support the comparison of multiple overlapping variables. Though considered reasonably representative of common conditions on Utah highways, not all possible scenarios could be considered.

6.0 RECOMMENDATIONS AND IMPLEMENTATION

6.1 Recommendations

Based on the findings of this study, the WSP team recommends that UDOT develop protocols for chloride testing of bridge decks based on the following criteria:

Chloride testing by potentiometric titration should be considered the preferred method and benchmark standard. Based on these results, testing in accordance with either AASHTO T 260, Procedure A or ASTM C 1152 should be considered equally acceptable, according to UDOT preference. In all such cases, sample preparation by the acid-soluble (total chloride) method is recommended. If any other mode of chloride determination is to be considered, it should be validated against that standard. Therefore, if a more expedient method, such as CISE, is to be considered, subject to UDOT approval, it should be incumbent on the testing firm to perform companion validation testing of a representative sample ($\geq 10\%$) by titration as above.

Chloride sampling may be effectively accomplished by coring or hammer-drill powder sampling. Where accuracy is considered especially critical, coring should be considered the preferred and benchmark method, as core sampling permits careful subsampling in a controlled laboratory environment and provides larger sample volumes to permit replicate testing. Cores also have the added benefit of permitting other observations and tests, such as carbonation and density, on portions of the same sample. Powder sampling by hammer drill is an acceptable alternative. Based on results, there is not great distinction between constant and tapered profiles, though constant profiles give higher (more conservative) values, have slightly lower variability, and require less effort in the field because the technician does not need to repeatedly change bits. Powder sampling can be challenging under windy or wet conditions but may be easier to perform than wet coring on vertical and overhead surfaces (e.g. substructures). Precautions against cross-contamination should be taken using any of these methods.

The use of uniform 1-inch or progressive ½-inch depth increments resulted in comparable chloride profiles in the current study. However, the subject decks were contaminated, such that concentrations in excess of 2 lb/yd³ (mild steel) and concentrations approaching 8 lb/yd³ (ECR) were measured at depths of 4 inches or more and near the reinforcement level, respectively. In

the case of younger bridge decks, or those in less aggressive deicing climates, the use of 1-inch increments runs the risk of discovering measurable chloride at only the shallowest depths, and not obtaining enough data points as a function of depth to produce an accurate chloride profile. In such cases, it is recommended that progressive ½-inch increments be used at shallow depth to ensure that chloride that is expected to be highest nearest the surface is accurately reflected. For older decks that are expected to have high levels of chloride contamination, uniform 1-inch increments can provide reliable results.

Further guidance to be provided includes the location of testing to support feasibility studies for rehabilitation. From this study, it is important to adequately sample from wheel paths in the travel lanes. Sampling from sound areas away from cracks is advised to represent the bulk diffusion of concrete, though in cases of extensive cracking, some proportion of cracks may be targeted.

Further guidance on minimum number of samples per bridge and representative samples per unit area will be presented as rules of thumb for the protocols. It is also recommended that data be reported, not only as individual concentrations per depth, but also plotted as profiles versus cover depth distributions and nominal chloride thresholds, as shown herein, to better visualize the degree and rate of chloride contamination to support decision-making.

6.2 Implementation Plan

The subject study culminates in a set of draft protocols for bridge deck chloride sampling and testing that will be considered for statewide implementation (Appendix A). Implementation will require cooperation of the central bridge and materials divisions to standardize and communicate to regional office personnel.

REFERENCES

- AASHTO, “Standard Method of Test for Sampling and Testing for Chloride Ion in Concrete and Concrete Raw Materials”, Test Method T260-97, American Society of State Highway and Transportation Officials, Washington, DC, (2016).
- ASTM, “Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete”, C1152–04, ASTM International, West Conshohocken, PA, (Reapproved 2012).
- ASTM, “Standard Method for Water-Soluble Chloride in Mortar and Concrete”, C1218, ASTM International, West Conshohocken, PA, (Reapproved 2012).
- Herald, S.E., Henry, M., Al-Qadi, I.L., Weyers, R.E., Feeney, M.A., Howlum, S.F., and Cady, P.D., “Condition Evaluation of Concrete Bridges Relative to Reinforcement Corrosion– Volume 6: Method for Field Determination of total Chloride Content”, SHRP-S-328, Strategic Highway Research Program, National Academy of Sciences, Washington, DC, 1993, 158pp.
- R. F. Stratfull, “The corrosion of steel in a reinforced concrete bridge”, *Corrosion* 13 (3) (1956) 173–178.
- Utah Department of Transportation (Structures Division), “Statewide Bridge Inspections 2017-2021 – U.S. 40 over Provo River”, Project F-ST99(396), PIN 14666, 7 pp. December 2017.
- Weyers, R. E., Brown, M., Al-Qadi, I. L., and Henry, M., “A Rapid Method for Measuring the Acid-Soluble Chloride Content of Powdered Concrete Samples,” *Cement, Concrete, and Aggregates*, CCAAGDP, Vol. 15, No. 1, Summer 1993, pp. 3–13

APPENDIX A: Special Provision of Deck Chloride Testing

SPECIAL PROVISION

**PROJECT #
PIN #**

SECTION 02758S

BRIDGE DECK CHLORIDE CONCENTRATION TESTING

Add Section 02758.

PART 1 GENERAL

1.1 SECTION INCLUDES

- A. Chloride concentration testing of bridge decks, including decks with cementitious overlays, asphalt overlays, thin bonded polymer overlays, and polyester concrete overlays
- B. Compressive strength testing of bridge decks

1.2 RELATED SECTIONS

- A. Section 02741: Hot Mix Asphalt (HMA)
- B. Section 02744: Stone Matrix Asphalt (SMA)

1.3 REFERENCES

- A. AASHTO T 22: Compressive Strength of Cylindrical Concrete Specimens
- B. AASHTO T 24: Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
- C. AASHTO T 260: Sampling and Testing for Chloride Ion in Concrete and Concrete Raw Materials
- D. ASTM C 114: Chemical Analysis of Hydraulic Cement
- E. ASTM C 805: Rebound Number of Hardened Concrete
- F. ASTM C 928: Packaged, Dry, Rapid-Hardening Cementitious Materials for Concrete Repairs

- G. ASTM C 1152: Acid-Soluble Chloride in Mortar and Concrete
- H. ASTM D 6432: Standard Guide for Using the Surface Ground Penetrating Radar (GPR) Method for Subsurface Investigation

1.4 DEFINITIONS

- A. Testing Company – The party responsible for the planning, coring, testing and reporting

1.5 SUBMITTALS

- A. Testing Company qualifications for review. Include at least the following:
 - 1. Company name
 - 2. Name, phone number, and documented experience of the Testing Company's Field Testing Manager
 - a. List at least three projects where the Field Testing Manager was responsible for guiding and assisting coring and testing operations.
 - 3. List of at least five projects of similar size, scope, and climatic conditions completed in the last three years. List the following for each project:
 - a. Project name, bridge locations (state, routes, and bridge identifiers), owner, scope of work, and approximate date of the project.
 - b. Number of test locations, testing methods, and equipment used.
 - c. One owner/agent reference and contact information (phone and email).
 - 1) Satisfactory references are those responsible for oversight or inspection of the project.
 - 4. Laboratory accreditations.
- B. Chloride Concentration and Compressive Strength Testing Plan for review. Include at least the following.
 - 1. Plan showing core locations
 - 2. Method to remove the overlay at core locations, as applicable
 - 3. Method to determine the top mat of reinforcing steel's location and cover depth, including the number and distribution of cover readings
 - 4. Method to determine the thickness of the deck
 - 5. Core length (L) and core diameter (D)
 - 6. Coring equipment and procedures for coring
 - 7. Plan to identify and avoid damaging prestressing steel, if present
 - 8. Sample depths of the chloride concentration testing cores

9. Procedure for extracting powdered concrete samples (subsampling of the core)
 10. Procedure for repairing damage caused by coring operations
 11. Procedure for identifying, storing, and shipping concrete cores
 12. Procedure for testing the powdered concrete samples
 13. Schedule, including site operations dates, submittal dates, and completion dates
- C. Chloride Concentration and Compressive Strength Testing Report for review. Include at least the following:
1. Narratives
 - a. Title sheet
 - b. Table of contents
 - c. Executive summary
 - d. Description of work performed including all requirements of the testing plan
 - e. Test methodology
 - f. Results
 2. Graphics
 - a. Plan showing core locations and reference names on an 11x17 sheet
 - 1) Draw in CAD software at a reasonable scale for legibility.
 - 2) Overlay and label locations of cores on a plan view of the bridge deck produced to scale.
 - b. Photographic documentation of all extracted cores
 - c. Charts showing individual chloride concentrations on the x-axis (pounds chloride per cubic yard of concrete) versus depth (inch) in reverse order on the y-axis (with 0 inch depth at top and x-axis labels at top of chart)
 - 1) State the unit weight of concrete used, and whether measured or assumed, to convert to pounds chloride per cubic yard of concrete.
 - d. Figure showing the average and the 90 percent confidence interval of reinforcing steel cover depth distributions to the top mat of reinforcing steel (transverse or longitudinal, whichever is nearest the surface)
 - e. Figure showing measured chloride concentration and thresholds of 2 lb/yd³ for unprotected reinforcing steel and 8 lb/yd³ for epoxy coated reinforcing steel
 3. Tables
 - a. Chloride concentration for each test sample number shown in Table 1
 - 1) Include a reference to each core location.
 - 2) List chloride concentration results in pounds per cubic yard (lb/yd³).

- b. Maximum, minimum, average, and standard deviation of the chloride concentrations of each test sample number shown in Table 1, as applicable
 - c. Compressive strengths of concrete cores, as applicable
 - 1) Include a reference to each core location.
 - 2) Include core storage temperature and humidity before testing.
 - 3) List concrete compressive strength results in pounds-force per square inch (psi).
 - e. Maximum, minimum, average, and standard deviation of the cover depth distributions to the top mat of reinforcing steel (transverse or longitudinal, whichever is nearest the surface)
 - f. Length of cores before and after capping, as applicable
 - g. Date of core extraction and date the core is placed in a sealed plastic bag
 - h. Date of trimming and date of testing
 - i. Core density, based on gross dimensions of the prepared core specimen and weight of specimen in air, before capping, as applicable
- D. Manufacturer's product data sheets and installation instructions for proposed repair materials for information.

1.6 LABORATORY ACCREDITATIONS

- A. Laboratories performing the chloride concentration and concrete compressive strength testing must have a program that is either one of the following:
- 1. Accredited by the AASHTO Accreditation Program for Cementitious Material – Chemical Tests and Concrete testing for the tests being performed
 - 2. Inspected by the ASTM Cement and Concrete Reference Laboratory (CCRL) with a status of Satisfactory for Cement with a specific inspection of ASTM C 1152, including qualification of methods for chemical testing derived from ASTM C 114.
- B. Laboratories must remain AASHTO accredited, or maintain CCRL inspection status, for the duration of the project.
- 1. Do not perform work if accreditation or inspection status has expired.
- C. Notify the Department of any change in accreditation status.

1.7 TESTING COMPANY'S FIELD TESTING MANAGER REQUIREMENTS

- A. Testing Company's Field Testing Manager must:

1. Have at least five years of experience with the proposed testing procedures and with guiding and assisting coring and testing operations
2. Provide technical support and training to field personnel and the Department during coring and testing operations
3. Attend the preconstruction conference
 - a. Instruct field personnel and the Engineer of anything that could adversely affect coring and testing operations.
4. Be on site during coring and testing operations
5. Be available for consultation throughout the duration of the project

PART 2 PRODUCTS

2.1 REPAIR MATERIAL

- A. Rapid Setting Repair Mortar – Refer to ASTM C 928.
 1. Provide Type R3
 2. Provide patch materials free of magnesium phosphate
- B. Asphalt patching material
 1. Use patch material compatible with the existing asphalt overlay
 2. Refer to Section 02741 and Section 02744

2.2 EQUIPMENT

- A. Coring device
 1. Use either a vehicle-mounted coring device or a device temporarily anchored into the bridge deck.
 - a. Do not use a handheld coring device.
- B. Reinforcing steel locating
 1. GPR with appropriate ground-coupled antenna with frequency between 1.5 and 3.0 GHz according to ASTM D 6432
 2. Pachometer (also known as covermeter)

2.3 WATER

- A. Use potable water free from harmful salts, reactive chemicals, and any other contaminants.

PART 3 EXECUTION

3.1 GENERAL

- A. Follow the authorized Chloride Concentration and Compressive Strength Testing Plan.
- B. Prevent material and debris from falling into streams, pedestrian areas, traffic areas, or railroad tracks.

3.2 PREPARATION

- A. Use GPR or pachometer to locate reinforcing steel at each core location.
 - 1. Mark reinforcing steel locations clearly on the concrete surface to avoid reinforcing steel during coring procedures.
 - 2. Record location and reinforcing steel cover depth.
- B. Measure and record reinforcing steel cover depth randomly across the deck at a rate of 10 locations per 1000 sq ft and at least 30 locations.
 - 1. A series of GPR line-scans transverse to the top layer of reinforcing steel, at approximately 5 ft intervals distributed uniformly across the deck, may be substituted for the collection at random locations.
- C. Use either hammer sounding or chain dragging to identify whether delaminations are present.

3.3 CORING AND TESTING

- A. Core concrete by wet coring for both concrete chloride concentration and compressive strength testing.
 - 1. Powdered concrete sampling is not permitted
 - 2. Stop drilling if reinforcing steel is encountered
 - a. Extract and dispose of the core of the drilled portion and take a replacement core.
- B. Core frequency
 - 1. Provide $0.075 \times \sqrt{\text{deck area}}$ cores for chloride concentration testing
 - 2. Provide $0.050 \times \sqrt{\text{deck area}}$ cores for compressive strength testing
 - 3. Use existing plans or field measurements to calculate the deck area in square feet. Use the length from backwall of abutment to backwall of abutment and the width from face of parapet to face of parapet.
 - 4. Round the number of testing cores determined from the equation up to the nearest whole number
 - 5. Provide three cores if the calculated number is less than three
- C. Core locations
 - 1. Stagger the core locations between travel lanes and shoulders
 - 2. Locate the cores in wheel paths in the travel lanes

3. Locate the cores in sound areas free of delaminations, cracks, or spalls
 4. Locate cores at least 2 ft away from delaminations, cracks, spalls, deck drains, joints, or girder top flanges
 5. Do not take cores from approach slabs
- D. Core length
1. Cast-in-place decks (full depth)
 - a. Slab depth minus 1 inch
 2. Decks constructed with partial-depth precast concrete deck panels
 - a. Cast-in-place portion minus 1 inch
 - b. Do not penetrate partial-depth precast panels while coring
- E. Core diameter
1. Chloride concentration testing
 - a. Minimum nominal diameter: the larger of 2½ inch or two times the nominal maximum aggregate size
 2. Compressive strength testing
 - a. Minimum nominal diameter: the larger of 3.7 inch or two times the nominal maximum aggregate size
 - 1) Propose an alternate diameter if an L/D ratio of at least 1.0 is not achievable with the proposed length of core.
- F. Coring
1. Do not core over live traffic
 2. Do not core the full depth of the deck
 3. Do not drop the core below the deck
 4. Do not core during rain, when road surface moisture is present, or during adverse weather conditions
- G. Determine the concrete compressive strength based on AASHTO T 22 or AASHTO T 24
1. Refer to ASTM C 805 if rebound testing is used to supplement core testing.
- H. Subsamples of the chloride concentration testing cores
1. Divide cores into samples and test the ½ inch centered on the depth shown in Table 1.
 - a. For example, for test sample number 2 shown in Table 1 for a bridge deck greater than 10 years in age, test concrete from 1¼ inch to 1¾ inch.
 2. Refer to Table 1 for the test sample depths for chloride concentration testing.

- a. Measure the age from date of original deck construction or cementitious overlay placement, if present, to the date of core extraction.
- b. Measure the depth from top of deck to center of test sample number.
- c. Modify test sample depths if the bridge deck cast-in-place concrete thickness is less than the depth required to follow Table 1.

Table 1

Test Sample Depths		
Test Sample Number	Bridge deck less than or equal to 10 years in age	Bridge deck greater than 10 years in age
	Depth (inch)	Depth (inch)
1	½	½
2	1	1½
3	1½	2½
4	2½	3½
5	3½	4½

3. Refer to AASHTO T 260.
 - a. Prepare powder samples by the acid-soluble (total chloride) method under Procedure A.
 - 1) Prevent cross-contamination of samples.
- I. Remnants of cores and samples
 1. Store the remnants of chloride concentration cores (intact concrete and powder) in an air-dry condition until the Chloride Concentration and Compressive Strength Testing Report is authorized.
 2. Store untested compressive strength specimens in a sealed plastic bag or nonabsorbent container to prevent moisture loss until the Chloride Concentration and Compressive Strength Testing Report is authorized.

3.4 REPAIR CORE HOLES

- A. Remove loose materials by compressed air with at least 90 psi pressure.
 1. Keep the core hole clean until repair material has been placed.
- B. Follow manufacturer's product data sheets and installation instructions for placing, finishing and curing repair material.
- C. Patch core holes in the concrete deck with rapid setting repair mortar and strike off level with deck surface.

1. Strike the rapid setting repair mortar off level with the overlay surface if the deck has an existing cementitious overlay, thin bonded polymer overlay, or polyester concrete overlay.
 2. Strike the rapid setting repair mortar off level with the existing concrete if the deck has an asphalt wearing surface.
 - a) Use asphalt patching material above the rapid setting repair mortar to restore a flush surface with the adjacent asphalt.
- D. Patch failure – Remove the patch completely and repair the core hole again if the patch fails to bond to the existing concrete.

3.5 LIMITATION

- A. Do not open to traffic until rapid setting repair mortar has achieved a compressive strength of approximately 3500 psi as measured by a rebound hammer.

END OF SECTION