2014-03-18

Development of a Chloride Concentration Sampling Protocol for Concrete Bridge Decks

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A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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March 2014

ABSTRACT

Development of a Chloride Concentration Sampling Protocol for Concrete Bridge Decks

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As the primary cause of concrete bridge deck deterioration in the United States is corrosion of the steel reinforcement as a result of the application of chloride-based deicing salts, chloride concentration testing is among the most common techniques for evaluating the condition of a concrete bridge deck. The objectives of this research were to 1) compare concrete drilling and powder collection techniques to develop a sampling protocol for accurately measuring chloride concentrations and 2) determine the number of chloride concentration test locations necessary for adequately characterizing the chloride concentration of a given bridge deck.

Laboratory experiments on concrete drilling and powder collection were conducted to compare current concrete powder sampling techniques, including constant and stepwise drilling methods and spoon and vacuum powder collection methods. In addition, three charts were prepared to determine the number of chloride concentration test locations necessary for adequately characterizing the chloride concentration of a given bridge deck. The number of samples is dependent on reliability, spatial variability in chloride concentration, and an allowable difference between sample and population means.

For the experiment on drilling, this research shows that the practice of decreasing the size of the drill bit in a stepwise fashion with increasing sampling depth reduces the possibility of abrading concrete from the sides of the hole above the sampling depth, where the chloride concentrations are higher, during drilling of lower lifts. For the experiment on powder collection, this research demonstrates that representative samples of concrete powder can be collected with either a spoon or a vacuum. Based on the results of this research, the stepwise drilling method and either the spoon or vacuum powder collection method are recommended for application. In addition, the charts developed in this research are recommended for estimating the number of chloride concentration test locations necessary for adequately characterizing the chloride concentration of a given bridge deck. This research will be helpful in effectively assessing the condition of concrete bridge decks with respect to chloride-induced corrosion of the reinforcing steel and prioritizing bridge maintenance and rehabilitation projects.

Key words: chloride concentration, concrete bridge deck, corrosion, drilling method, powder collection method, reliability, sampling.

ACKNOWLEDGEMENTS

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1   INTRODUCTION

1.1   Problem Statement

According to the 2013 Report Card for America's Infrastructure, 24.9 percent of the nation's approximately 607,000 bridges are defined as structurally deficient or functionally obsolete. Additionally, comparing the average bridge age of 43 years to a typical design life of 50 years clearly indicates that many of the nation's bridges are nearing the end of their service life (ASCE 2013). Therefore, because a large percentage of America's bridges will require rehabilitation and/or reconstruction in the near future, implementation of effective bridge management practices is increasingly important.

While reinforced concrete bridges can become structurally deficient or functionally obsolete through several mechanisms, corrosion of the steel reinforcement as a result of the application of chloride-based deicing salts is the primary cause of bridge deck deterioration in the United States (ASTM 1978, Enright 2000, Guthrie and Linford 2006, Melhem and Chang 2003, Mindess et al. 2003). Corrosion causes the reinforcing bars to rust and expand, which in turn causes the surrounding concrete to crack, spall, and delaminate (Stewart and Val 2003). This damage decreases the structural capacity of bridge decks and leads to premature bridge failure (Guthrie and Linford 2006, Stewart and Val 2003).

When evaluating the condition of a concrete bridge deck with respect to corrosion, determining the chloride concentration profile is important (ASTM 1978, Herald et. al. 1992).

Chloride concentration testing is typically performed at multiple depths through the top of a bridge deck to obtain chloride concentration profiles. Previous researchers have used chloride concentration testing to investigate the influence of chloride concentrations on initial surface treatment timing (Birdsall et al. 2007, Guthrie et al. 2011); high-performance concrete in highway structures (Goodspeed et al. 2003); maintenance, rehabilitation, and replacement timing (Guthrie and Linford 2006); and durability of full-span prestressed concrete form panels (Peterman et al. 1999); as well as other aspects. While chloride concentration testing is a common element of research activities related to corrosion of concrete bridge decks, the literature lacks research on the effect of different sampling methods on chloride concentrations in concrete bridge decks and the development of a protocol for accurate and efficient chloride concentration testing.

Two American Society for Testing and Materials (ASTM) standards relate to chloride concentration testing of concrete, including ASTM C1152-04 (Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete) and ASTM C1218-99 (Standard Test Method for Water-Soluble Chloride in Mortar and Concrete). In addition, the American Association of State Highway and Transportation Officials (AASHTO) has published AASHTO T 260-97 (Sampling and Testing for Chloride Ion in Concrete and Concrete Raw Materials) on this topic. These standards outline, in detail, specific procedures for analyzing concrete powder samples for chloride content, and much research has been devoted to improving both the water- and acid-soluble techniques (Carmen 2002, Climent 1999, Herald et al 1992); however, these standards lack specific protocols for the concrete sampling process, including procedures for concrete drilling and powder collection and determination of how many test locations should be sampled for adequately characterizing the chloride concentration of a bridge deck of interest.

1.2   Research Objectives and Scope

The objectives of this research were therefore to 1) compare concrete drilling and powder collection techniques to develop a sampling protocol for accurately measuring chloride concentrations and 2) determine the number of chloride concentration test locations necessary for adequately characterizing the chloride concentration of a given bridge deck. The results of this research are expected to be helpful in effectively assessing the condition of concrete bridge decks with respect to chloride-induced corrosion of the reinforcing steel and prioritizing bridge maintenance and rehabilitation projects.

This research involved evaluation of both laboratory and field data. The laboratory data were collected through two experiments that compared concrete powder sampling techniques performed on six concrete slabs that were prepared and tested at the Brigham Young University (BYU) Highway Materials Laboratory. The field data were collected from 17 concrete bridge decks located in California, Minnesota, Utah, and Virginia; these data were used to determine the number of chloride concentration test locations required for adequately characterizing the chloride concentration a given bridge deck depending on the chloride concentration and a specified level of reliability.

1.3   Outline of Report

This report contains five chapters. Chapter 1 presents the problem statement, objectives, and scope of this research. Chapter 2 gives background information on corrosion of reinforcing steel in concrete bridge decks and current chloride concentration testing practices. Chapters 3 and 4 explain the procedures and results, respectively, associated with the laboratory and field

data analyses performed in this research. Finally, Chapter 5 provides conclusions and

recommends a protocol for chloride concentration testing based on the research findings.

2   BACKGROUND

2.1   Overview

Bridge deck deterioration and condition assessment are important topics relevant to this research. Specifically, the following sections present the results of a literature review on corrosion of reinforcing steel in concrete and on current chloride concentration testing methods.

2.2   Corrosion of Reinforcing Steel in Concrete

Bridge deck deterioration is a gradual process influenced by many factors, such as traffic loading, current deck condition, environmental effects, bridge design, and material properties (Guthrie and Linford 2006). These factors can influence the severity of various deck deterioration mechanisms, including freeze-thaw cycles, sulfate attack, alkali-silica reaction, and both carbonation- and chloride-induced corrosion. In particular, the corrosion of steel reinforcement as a result of the application of chloride-based deicing salts is a primary cause of bridge deck deterioration in the United States (ASTM 1978, Enright 2000, Guthrie and Linford 2006, Melhem and Chang 2003, Mindess et al. 2003).

The results of a questionnaire survey evaluating deck maintenance practices among 28 state departments of transportation (DOTs) in the United States indicate that the most commonly used deicer is sodium chloride, as shown in Figure 2-1 (Hema et al. 2004), although magnesium chloride and calcium chloride are also widely used. These deicers are ionic salts that dissolve upon contact with water and lower the freezing temperature of the resulting solution
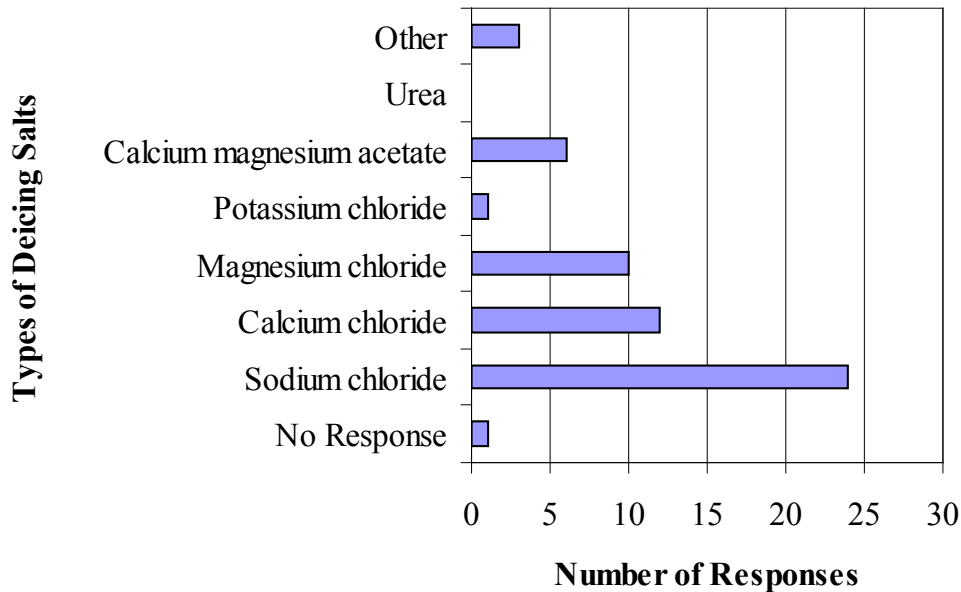
Figure 2-1: Types of deicing salts used on bridge decks.

(Thomas 2013). While sodium chloride has been observed to effectively remove snow and ice from roadways at temperatures as low as 15°F, calcium and magnesium chlorides can be effective at temperatures approaching -5°F (Thomas 2013). Although actual deicing salt application rates vary greatly with storm magnitude and climate, general application rates of solid salts range from 100 to 300 pounds per lane mile (Peters Chemical Company 2006, Thomas 2013), while applicate rates for brines range from 30 to 40 gallons per lane mile (Thomas 2013). Figure 2-2 shows a typical deicing salt application (Cederberg Inc. 2013).

As soon as deicing salts come in contact with water on the surface of a bridge deck, dissolution begins, and the ions begin to penetrate the concrete by traveling through the pore water in a process called diffusion (Arora et al. 1997). Diffusion is characterized by the movement of ions from areas of high concentration to areas of low concentration (Birdsall et al. 2007). Additional deicing salt applications over time and continued downward chloride ion

Figure 2-2: Typical deicing salt application.

diffusion cause chloride concentrations to be highest at the deck surface and decrease with increasing concrete depth. Chloride concentrations greater than the threshold of 2 lb Cl^-/yd^3 of concrete can initiate corrosion of uncoated reinforcing steel within the concrete (Mindess et al. 2003). Because the concrete cover thickness over the top mat of reinforcing steel on a bridge deck is typically just 2.0 to 3.0 in., the top mat is generally exposed to critical chloride concentrations before the bottom mat.

Under normal conditions, steel reinforcement does not corrode; the naturally high pH of the pore water in concrete promotes the formation of a passive oxide film on the surface of the steel that prevents corrosion (Arora et al. 1997, Cady and Weyers 1984, Mindess et al. 2003). However, when chloride ions penetrate the concrete, they break down the natural passive oxide film on the surface of the reinforcing steel and lower the pH of the pore water through a series of chemical reactions (Arora et al.1997, Guthrie et al. 2001, Mindess et al. 2003, Sumsion and

7

Guthrie 2013). The instability of the oxide layer resulting from these effects causes the reinforcing steel to become susceptible to corrosion (Guthrie et al. 2001, Mindess et al. 2003).

Because corrosion products are two to six times greater in volume than the parent steel (Callahan 1970, McCarthy et. al. 2004, Suda et. al. 1993, Young et. al.1998), the corrosion process generates tensile stresses within the concrete and eventually causes cracking, spalling, delamination, and potholes on bridge decks (Hema et al. 2004, Stewart and Val 2003). These concrete failure mechanisms can cause serious structural damage that leads to premature failure of the bridge deck (Guthrie and Linford 2006, Stewart and Val 2003).

Several design and construction measures are available for mitigating corrosion of reinforcing steel in concrete bridge decks. Such procedures include specification of epoxy-coated rebar, low-permeability concrete, corrosion-inhibiting concrete admixtures, greater concrete cover thickness, application of deck surface treatments, restriction of stay-in-place-metal-forms, use of cathodic protection, and good construction practices, including proper consolidation, good curing, and careful handling of epoxy-coated rebar if specified (Birdsall et al. 2007, Guthrie et al. 2006, Guthrie et al. 2011, Hema et al. 2004). Evaluating the efficiency of any of these mitigation techniques with respect to minimizing chloride ingress necessitates a concrete sampling protocol for accurately measuring chloride concentrations and determining the number of locations necessary for adequately characterizing the chloride concentration of a given bridge deck.

2.3   Chloride Concentration Testing Methods

As illustrated in Figure 2-3, which shows data from the same questionnaire survey previously mentioned (Hema et al. 2004), chloride concentration testing is among the most

8
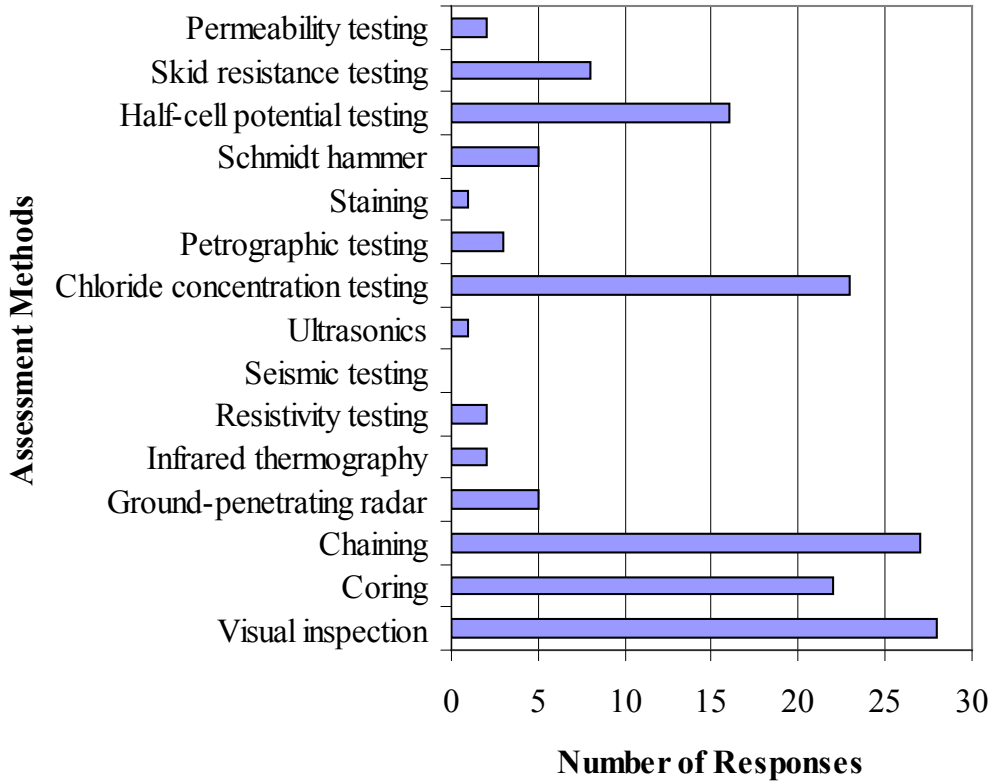
Figure 2-3: Common condition assessment methods for concrete bridge decks.

common techniques for evaluating the condition of a concrete bridge deck (ASTM 1978). This test is typically performed on pulverized concrete samples removed from multiple depths through the top of a bridge deck at multiple locations to obtain chloride concentration profiles and evaluate the bridge deck with respect to corrosion. The following sections discuss concrete powder sampling techniques and the determination of the number of test locations.

2.3.1   Sampling of Concrete Powder

When the concrete samples are pulverized in the field, the sampling process generally involves concrete drilling, concrete powder collection, and cleaning of the drilling and powder collection equipment. This process is repeated at each test location on the bridge deck, and the

pulverized samples are then subjected to chemical titration in the laboratory to determine chloride content.

Selected aspects of this process are governed by established standards for chloride concentration testing. In particular, two ASTM standards and one AASHTO standard related to chloride concentration testing have been published, including ASTM C1152-04 (Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete), ASTM C1218-99 (Standard Test Method for Water-Soluble Chloride in Mortar and Concrete), and AASHTO T 260-97 (Sampling and Testing for Chloride Ion in Concrete and Concrete Raw Materials). These standards specifically explain the chloride titration process but lack detail about the sampling process, including how many test locations are necessary for adequately characterizing the chloride concentration of the bridge deck of interest.

Regarding the sampling process, sections 6.1.3.1 and 6.1.3.2 of ASTM C1152-04 (6.1.2.1 and 6.1.2.2 of ASTM C1218-99) provide the following general instructions:

6.1.3.1 (6.1.2.1) Using the rotary impact drill, drill perpendicular to the concrete surface…to a specified depth or a depth sufficient to obtain a representative sample of the concrete mixture of at least 20 g of powdered material. To prevent contamination, avoid contact of sample with hands and other sources of perspiration. Clean all sampling tools prior to each sampling operation.

6.1.3.2 (6.1.2.2) Transfer powdered sample into the sample container using a spoon or other suitable means.

Similarly, sections 4.1.3.2 to 4.1.3.5 of AASHTO T 260-97 give the following instructions:

4.1.3.2 Using a drill or pulverizing bit, drill until the depth indicator seats itself on the concrete surface.

10

4.1.3.3 Thoroughly clean the drilled hole and surrounding area utilizing the "blow out" bulb or other suitable means.

4.1.3.4 Reset the depth indicator to permit 0.5 in. additional drilling.

4.1.3.5 Pulverize the concrete until the depth indicator again seats itself on the concrete. Note: Care must be exercised during this pulverizing operation to prevent the drill bit from abrading concrete from the sides of the hole above the sampling depth. To insure against this, some users utilize a 0.25-in. smaller diameter bit in this step than that used in Section 4.1.3.2.

4.1.3.6 Collect at least 10 g of the material remaining in the hole using a spoon and place in the sample container.

As evidenced by the fact that various drilling and powder collection techniques have been implemented in practice, these limited instructions are open to interpretation. The following sections discuss commonly used drilling and powder collection techniques.

2.3.1.1 Drilling Techniques

There are two drilling methods commonly used in chloride concentration testing. The first involves use of a single drill bit size for all depths sampled; this technique is referred to as the "constant" method in this report. In contrast, the second method, which is referred to as the "stepwise" method in this report, involves use of multiple drill bits with decreasing bit diameters for deeper sample depths, consistent with AASHTO T 260-97. Decreasing the size of the drill bit in a stepwise fashion with increasing sampling depth reduces the possibility of abrading concrete from the sides of the hole above the sampling depth, where the chloride concentrations are higher, during the drilling of lower lifts. The objective of this method is to prevent contamination between lifts and thereby reduce the likelihood of obtaining inaccurate chloride

11

concentrations. With respect to drilling, this research focused on comparing the chloride concentrations obtained using the constant and stepwise drilling methods.

2.3.1.2 Powder Removal Techniques

Both ASTM C1152-04 and ASTM C1218-99 state that the pulverized concrete powder should be removed "using a spoon or other suitable means." Some researchers employ a vacuum system as a "suitable" method for removing concrete powder (Kirkpatrick et. al. 2002). However, there is speculation as to whether the concrete powder collected on the filter paper in a vacuum system is adequately representative of the total powder sample. With respect to powder removal, this research focused on comparing the chloride concentrations resulting from traditional spoon collection with those resulting from vacuum collection.

2.3.2   Determination of Number of Test Locations

Chloride concentration data will be most meaningful when sufficient testing has been conducted to properly characterize a bridge deck of interest. Chloride concentration samples are taken with the goal of learning about the state of an entire bridge deck while sampling at only a few locations.

In one research study (Sumsion 2013), researchers performed chloride concentration testing at 1-ft intervals on 5-ft by 9-ft samples removed from four decommissioned bridge decks in Utah, for a total of 40 test locations per deck sample. Figure 2-4 illustrates the spatial variability associated with chloride concentration testing on one bridge deck sample at a depth of 2.0 to 2.5 in., which was the depth of the top mat of reinforcing steel. For this deck sample, chloride concentrations ranged from 2.8 to 6.6 lb Cl^-/yd^3 of concrete, depending on the location. Because such variation between samples within a given bridge deck is inevitable, multiple
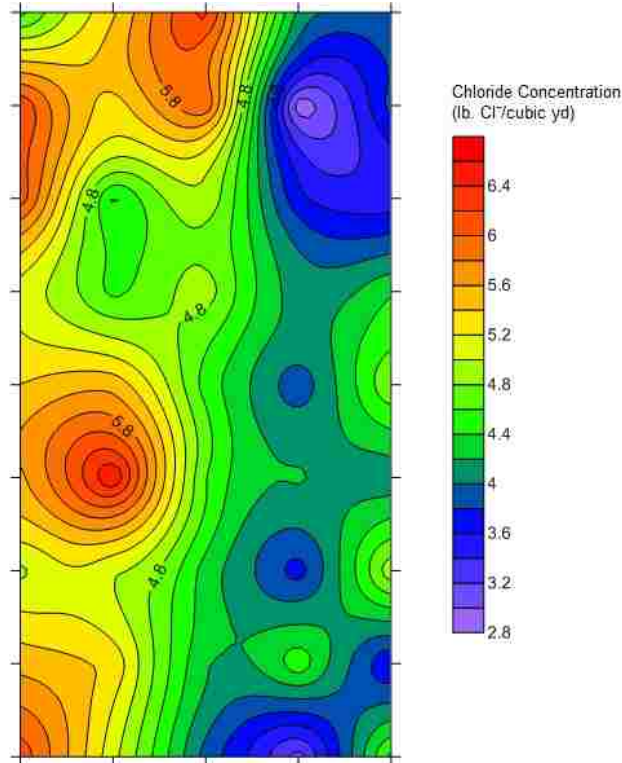
Figure 2-4: Example of chloride concentration variability.

samples are necessary to reduce the variation of the average sample measurement from the "true" value, or population mean. While a larger sample size can give an operator greater confidence that the measured sample average is more representative of the population mean, obtaining large quantities of samples for chloride concentration testing is expensive and time-consuming, and excessive testing could actually compromise the structural integrity of a deck. However, a smaller sample size may not be sufficiently representative of the population mean and may therefore lead to inaccurate inferences about the actual condition of the bridge deck. Therefore, optimizing the number of test locations required for adequately characterizing the chloride concentration of a given bridge deck is important.

In addition, the test locations on a deck should be randomly selected to ensure that the collected data are representative of the deck; where possible, each point on the deck should be

given an equal chance at being selected. Determining the number of chloride concentration test locations required for adequately characterizing the chloride concentration of a given bridge deck was an objective of this research.

2.4   Summary

Bridge deck deterioration is a gradual process influenced by many factors. In particular, the corrosion of steel reinforcement as a result of the application of chloride-based deicing salts is a primary cause of bridge deck deterioration in the United States. Deicing salts penetrate the concrete by traveling through the pore water, and chloride concentrations greater than the threshold of 2 lb Cl^-/yd^3 of concrete can initiate corrosion of the reinforcing steel within the concrete. The corrosion process generates tensile stresses within the concrete and eventually causes serious structural damage that can lead to premature failure of the bridge deck.

Chloride concentration testing is among the most common techniques for evaluating the condition of a concrete bridge deck. This test is typically performed on pulverized concrete samples removed from multiple depths through the top of a bridge deck at multiple locations to obtain chloride concentration profiles and evaluate the bridge deck with respect to corrosion. Selected aspects of this process are governed by established standards for chloride concentration testing. In particular, two ASTM standards and one AASHTO standard related to chloride concentration testing have been published. However, as evidenced by the fact that various drilling and powder collection techniques have been implemented in practice, these limited instructions are open to interpretation.

With respect to drilling, this research focused on comparing the chloride concentrations obtained using the constant and stepwise drilling methods. With respect to powder removal, this research focused on comparing the chloride concentrations resulting from traditional spoon

14

collection with those resulting from vacuum collection. Additionally, determining the number of

chloride concentration test locations required for adequately characterizing the chloride

concentration of a given bridge deck was an objective of this research.

3 PROCEDURES

3.1 Overview

In this research, laboratory experiments on concrete drilling and powder collection were conducted to compare current concrete powder sampling techniques. In addition, statistical analyses were performed on field data collected from concrete bridge decks throughout the United States to determine the number of chloride concentration test locations necessary for adequately characterizing the chloride concentration of a given bridge deck. The procedures are described in the following sections.

3.2 Sampling of Concrete Powder

Two experiments were designed and performed to compare two concrete drilling methods and two powder collection methods. The experiment on drilling was designed to compare the constant and stepwise drilling methods and involved preparation and testing of one large slab, comprising five separate layers designed to achieve a chloride concentration gradient typical of concrete bridge decks in Utah. The experiment on powder collection was designed to compare the spoon and vacuum powder collection methods and involved preparation and testing of five small slabs each corresponding to one layer in the large slab. The experiments were coordinated so that the test slabs could be prepared from the same concrete batches for convenience. The following sections discuss the design, mixing, and casting of several concrete

slabs; the sampling process for both the experiment on drilling and the experiment on powder collection; chemical analysis of the concrete samples to determine chloride concentration; and statistical tests used to evaluate the data.

3.2.1   Design, Mixing, and Casting of Concrete Slabs

The basic concrete mixture design used for this research was developed in previous work at Brigham Young University (Guthrie and Pinkerton 2007). The mixture design, provided in Table 3-1, was characterized by a water-to-cementitious materials ratio of 0.44, a slump of 4.0 ± 1.0 in., and an entrained air content of 6.0 ± 1.0 percent. In the table, the saturated-surface-dry (SSD) weights of the coarse and fine aggregates are given.

For the experiment on drilling, a 33-in. by 54-in. concrete slab was cast in five, 1-in. layers. To facilitate casting in layers, horizontal lines were drawn on the inside faces of the frame in 1.0-in. intervals as shown in Figure 3-1. Each layer had an increasing amount of sodium chloride to simulate a typical chloride concentration profile, shown in Table 3-2, for Utah bridge decks (Guthrie et al. 2006). Each concrete layer was mixed in separate batches and cast sequentially. The measured weigh-outs for each batch are provided in Table 3-3.

Table 3-1: Concrete Mixture Design

Ingredient	Weight Per Cubic Yard (lb)	Specific Gravity	Volume Per Cubic Yard (yd^3)
Coarse Aggregate (SSD)	1714.0	2.62	0.388
Fine Aggregate (SSD)	1071.0	2.59	0.245
Cement	519.0	3.15	0.098
Fly Ash	115.0	2.30	0.030
Free Water	280.0	1.00	0.166
Air	-	-	0.073
Total	3699.5	-	1.000

Figure 3-1: Frame prepared for drilling experiment.

Table 3-2: Typical Chloride Concentration Profile for Concrete Bridge Decks in Utah

Depth (in.)	Chloride Concentration (lb Cl^-/yd^3 Concrete)
1	21.9
2	12.8
3	6.9
4	3.0

Table 3-3: Measured-Out Weights Per Batch

Ingredient	Measured-Out Weight (lb)				
	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5
Coarse Aggregate (Dry)	129.5	129.5	129.5	129.5	129.5
Fine Aggregate (Dry)	80.0	80.0	80.0	80.0	80.0
Cement	39.8	39.8	39.8	39.8	39.8
Fly Ash	8.8	8.8	8.8	8.8	8.8
Water	25.5	25.5	25.5	25.5	27.5
Air	0.038	0.038	0.038	0.038	0.038
Sodium Chloride	2.3	1.15	0.57	0.29	0.00
Total	285.9	284.8	284.2	283.9	285.6

The required concentration of sodium chloride mixed into each batch was calculated according to Equation 3.1:

$$NaCl = C\left(1 + \frac{22.988}{34.453}\right)$$ (3.1)

where $NaCl$ = concentration of sodium chloride added to a concrete mixture design to obtain the design chloride concentration, lb $NaCl^-$/yd^3 of concrete

C = design chloride concentration, lb Cl^-/yd^3 of concrete

In Equation 3.1, 22.988 and 35.453 are the molecular weights in g/mol of sodium and chloride, respectively. The computed concentration of sodium chloride necessary to achieve the design chloride concentration was multiplied by the volume of each concrete batch to obtain the measured-out weight of salt.

Each batch was manually prepared in a drum mixer according to a mixing procedure developed in previous research at Brigham Young University (Guthrie and Pinkerton 2007). The following 10 steps outline the mixing procedure:

Step 1.   The inside walls of the mixer were moistened before each batch was mixed to prevent the mixer from absorbing a portion of the free water in the concrete mixture. This was done by spraying the inside surface of the mixer with water and pouring the excess water out of the mixer.

Step 2.   Once the walls of the concrete mixer were sufficiently moistened, 75 percent of the total water for the mixture was placed in the mixer. The sodium chloride was also added to the mixture with the water during this step if chlorides were specified for the given batch.

20

Step 3.   Once the initial allotment of water was added, all of the aggregates for the mixture were added in an oven-dry state. The mixer was allowed to rotate while the aggregates were added, as shown in Figure 3-2.

Step 4.   After all of the aggregates were added, the aggregates and water were mixed together for 1 minute.

Step 5.   The mixer was then stopped, and the mixture of aggregates and water was allowed to sit for 15 minutes while the aggregates absorbed water. To prevent any loss of water through evaporation, the mixer opening was covered with a sheet of plastic during this period, as shown in Figure 3-3.

Step 6.   After the mixture of water and aggregates equilibrated for 15 minutes, the air entrainer was diluted in 2 lb of water, which was then added to the

Figure 3-2: Aggregates and water in concrete mixer.

Figure 3-3: Concrete mixer opening covered with plastic sheeting.

mixer. The mixer was allowed to rotate while the solution of air entrainer and water was added.

Step 7. The mixer was allowed to rotate for 1 additional minute after the solution of air entrainer and water was added.

Step 8. The cement, fly ash, and remaining water were then added to the mixer. To facilitate adequate mixing of the cement and fly ash with the aggregate, the mixer was allowed to rotate while the cement, fly ash, and water were added.

Step 9. After all the materials for the mixture were added, final mixing was performed. The mixer was rotated for 3 minutes, stopped and covered with plastic for 3 minutes, and then rotated for 1 additional minute. The waiting period was provided to allow further moistening of the cement and fly ash.

Step 10.   Finally, after mixing was complete, tests were performed to determine the

slump and percent air entrainment. Slump was tested in accordance with

ASTM C143-05 (Standard Test Method of Slump for Hydraulic Cement

Concrete), and the air content was calculated in accordance with ASTM

C138-05 (Unit Weight, Yield, and Air Content (Gravimetric) of Concrete)

by comparing the actual unit weight with the theoretical unit weight.

The concrete was then placed and smoothed using magnesium trowels and screeded following the lines marked on the inside of the frame to ensure a uniform thickness of 1.0 in., as shown in Figure 3-4. As soon as the concrete had reached initial set, the subsequent layer was mixed and cast on top of the previous layer following the same procedure. After 24 hours, the concrete was covered with wet burlap to minimize moisture loss during curing.

Figure 3-4: Screeding a lift.

For the experiment on powder collection, five small slabs were also cast in conjunction with each layer of the large slab. The concrete was mixed and cured following the procedure previously described for the experiment on drilling. All six slabs, for both experiments, are shown in Figure 3-5. The slabs were cured for 28 days before testing proceeded.

Figure 3-5: Experimental slabs after casting.

3.2.2 Experiment on Drilling

For the large slab, six locations for both the constant drilling method and the stepwise drilling method were selected for testing. The test locations are shown in Figure 3-6 and were distributed so that both drilling methods would be equally affected by any spatial variability in chloride concentration across the slab. A minimum distance of 3 in. between the edge of a hole and the edge of a slab was ensured to minimize the influence of possible boundary effects in the testing.
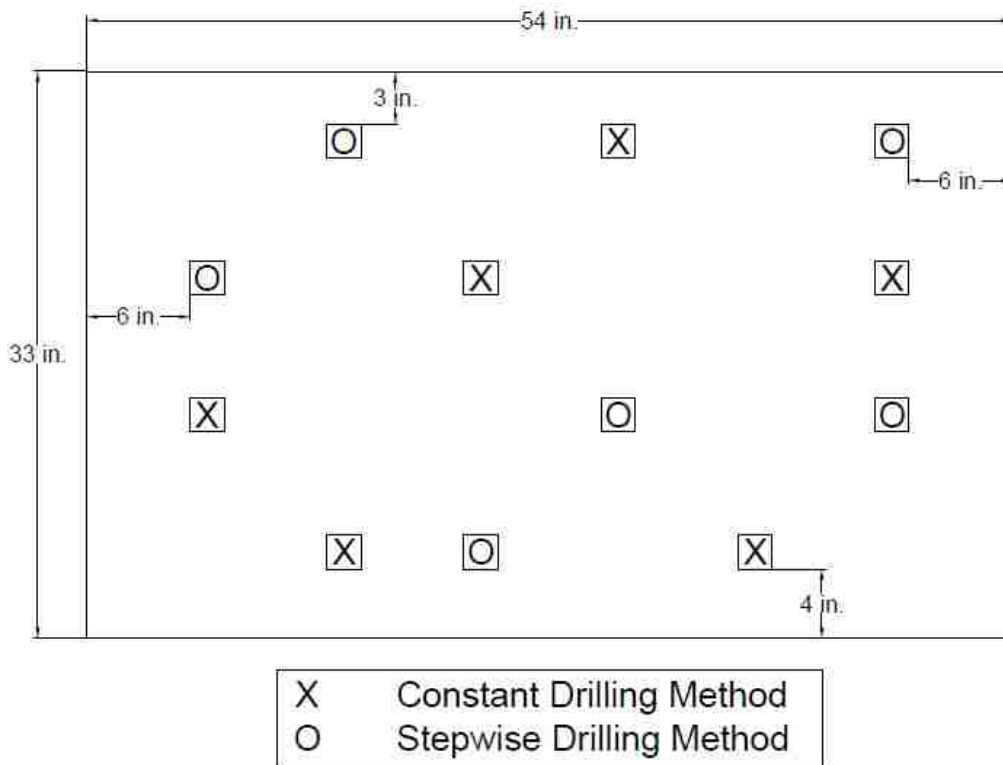
Figure 3-6: Sampling locations for experiment on drilling.

For this research, a drill bit diameter of 1.125 in. was specified for the constant drilling

method, while a series of eight bit diameters was specified for the stepwise method. These bits

ranged in diameter from 1.75 in. to 0.75 in., with each successive bit diameter being smaller than

the previous one. Figures 3-7 and 3-8 illustrate the drilling profiles for the constant drilling

method and the stepwise drilling method, respectively. For each method, eight 0.5-in. depth

intervals were sampled for a total profile depth of 4.0 in.

For the stepwise method, a length of colored duct tape was wrapped around each drill bit,

as shown in Figure 3-9, so that the lower edge of the tape corresponded to the appropriate

drilling depth to facilitate easy depth control. After each lift was drilled, the hole was measured

to ensure that the correct sampling depth was achieved. Figure 3-10 shows the drilling portion of
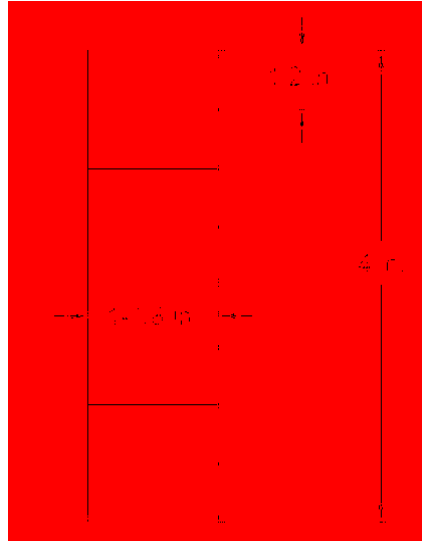
Figure 3-7: Profile for constant drilling method.
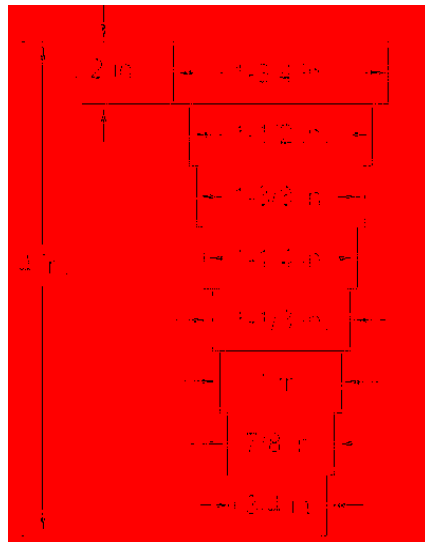
Figure 3-8: Profile for stepwise drilling method.

the sampling process. For this experiment, the spoon method of powder collection was used to

collect the concrete powder regardless of which drilling technique was used. After the

appropriate depth was achieved, the concrete powder was collected with a spoon, the test area

was vacuumed, and the sampling tools were cleaned with compressed air to remove residual

Figure 3-9: Drill bits for stepwise drilling method.

Figure 3-10: Drilling a slab.

powder and prevent contamination between samples. Subsequent lifts were drilled and sampled following the same procedure.

3.2.3 Experiment on Powder Collection

For each of the five small slabs, three test locations for both the spoon collection method and the vacuum collection method were selected for testing. The sampling layout is shown in Figure 3-11. For both powder collection methods, the concrete was drilled in two 1.0-in. depth intervals with a 1.25-in. drill bit. The concrete powder was then collected using either the spoon or vacuum collection method. The concrete powder collected from the second 1.0-in. interval was used for this research.

For the spoon collection method, after the first lift was drilled, the concrete powder was collected in a plastic bag using a small brush and spoon as depicted in Figure 3-12. The sample area was then vacuumed to remove residual powder, the sampling tools were cleaned with
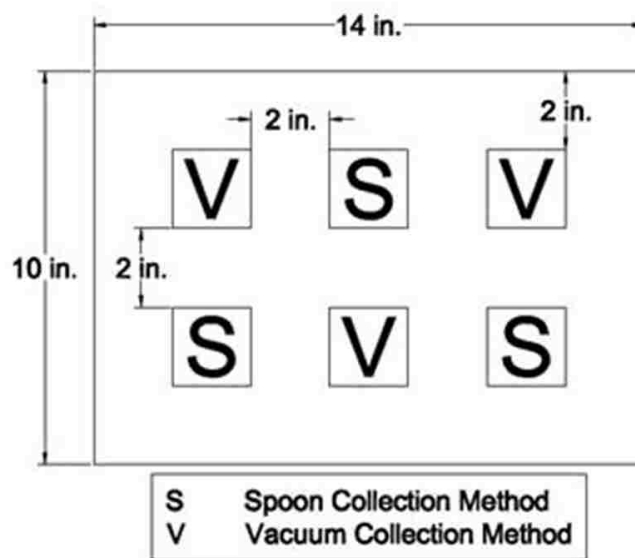
Figure 3-11: Sampling locations for experiment on powder collection.

Figure 3-12: Spoon collection method.

compressed air, the next 1.0-in. lift was drilled, and the concrete powder was collected. This procedure was followed for subsequent sample locations.

For the vacuum collection method, a vacuum attachment and filter paper assembly were fabricated for use with a large wet/dry vacuum. As shown in Figure 3-13, the attachment was created using a series of flexible plastic tubes, with a paper filter placed between the two smallest tubes to form a pocket in which to collect the concrete powder. The filter paper was deliberately placed near the collection point to reduce the length of tube through which the powder would travel and therefore minimize the number of attachment pieces that would need to be cleaned between samples as required to minimize potential contamination.

After the first lift was drilled, the concrete powder was collected in the filter paper using the vacuum as shown in Figure 3-14. The filter paper and the collected concrete powder were then removed from the nozzle and placed in a plastic bag, and the two smallest attachment tubes

were cleaned with compressed air. This procedure was followed for subsequent sample

locations.

Figure 3-133: Vacuum attachment with paper filter.

Figure 3-14: Vacuum collection method.

3.2.4 Chloride Analysis

After all the samples for both the experiment on drilling and the experiment on powder collection were obtained, each concrete powder sample was analyzed using laboratory titration in general accordance with AASHTO T 260-97 (Sampling and Testing for Chloride Ion in Concrete and Concrete Raw Materials). Samples having a target weight of 0.1 oz were oven-dried for 24 hours and then digested using nitric acid and hydrogen peroxide to release the acid-soluble chlorides. Figure 3-15 shows the digestion portion of the procedure. The solution was then filtered, and the filtrate was titrated with silver nitrate as shown in Figure 3-16. The measured chloride percentage was then multiplied by a concrete density of 150 pcf, which is a common value for concrete (Hurd 2002), and converted to units of lb Cl^-/yd^3 of concrete.
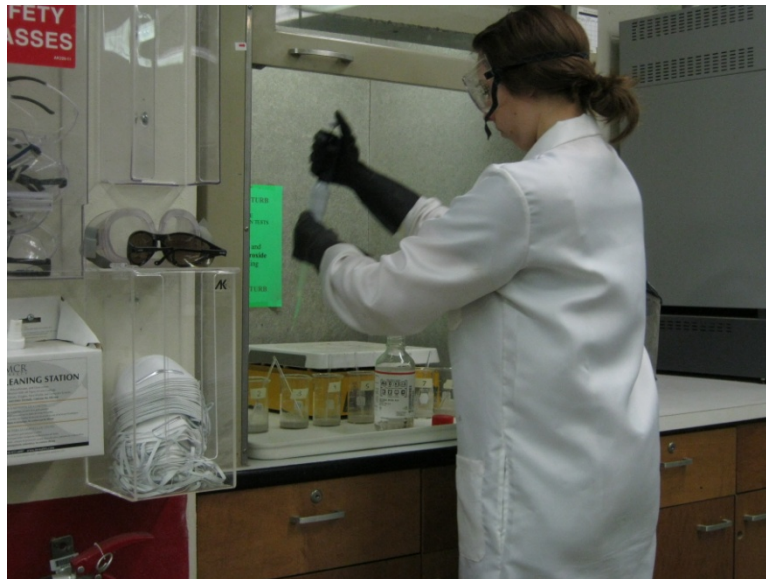
Figure 3-15: Chemical digestion of concrete powder samples.
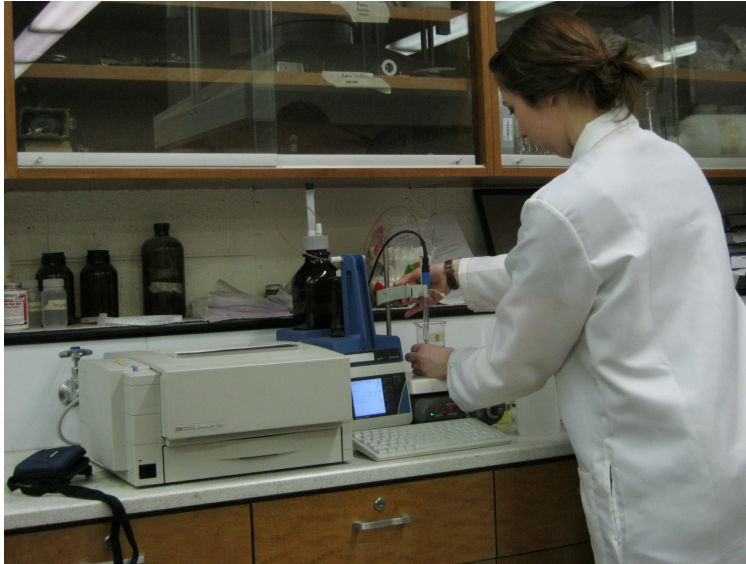
Figure 3-16: Titration of concrete powder samples.

3.2.5 Statistical Analyses

Statistical analyses were performed on the data collected in both the experiment on drilling and the experiment on powder collection. For the experiment on drilling, *t*-tests were performed to determine if the differences in chloride concentrations obtained by the constant drilling method and the stepwise drilling method were statistically significant. In the analysis of each depth interval, the null hypothesis was that the chloride concentrations associated with the constant method were less than or equal to the chloride concentrations associated with the stepwise method. The alternative hypothesis was that the chloride concentrations associated with the constant method were greater than the chloride concentrations associated with the stepwise method. Because this was a limited data set in an exploratory study, a *p*-value of 0.15 was specified as a threshold for distinguishing between chloride concentrations associated with the two drilling methods. For interpretation of the *t*-test results, a chloride concentration difference of 1 lb Cl^-/yd^3 of concrete between the average chloride concentrations for the two drilling methods was considered to be practically important. This difference of 1 lb Cl^-/yd^3 of

concrete was selected because it is a reasonably small unit of measurement for chloride concentrations, and concentrations of this magnitude are harmless with respect to corrosion; as explained previously, chloride concentrations less than 2 lb Cl$^-$/yd^3 of concrete are not expected to initiate corrosion of the reinforcing steel within the concrete.

For the experiment on powder collection, t-tests were performed to determine if the differences in chloride concentrations obtained by the vacuum collection method and the spoon collection method were statistically significant. In the analysis of each slab, the null hypothesis was that the chloride concentrations associated with the vacuum collection method were equal to the chloride concentrations associated with the spoon collection method. The alternative hypothesis was that the chloride concentrations associated with the vacuum collection method were not equal to the chloride concentrations associated with the spoon collection method. A p-value of 0.15 and a difference of 1 lb Cl$^-$/yd^3 of concrete were again used in the analysis and interpretation of the test results.

3.3   Determination of Number of Test Locations

Statistical analyses were performed on field data collected from concrete bridge decks throughout the United States to determine the number of chloride concentration test locations necessary for adequately characterizing the chloride concentration of a given bridge deck. The data compilation and statistical procedures are discussed in the following sections.

3.3.1   Data Compilation

Chloride concentration data collected from 17 bridge decks in previous research at BYU (Brigham Young University 2010, Guthrie and Linford 2006) were used to determine the number of chloride concentration test locations necessary for adequately characterizing the chloride

concentration of a given bridge deck depending on the chloride concentration and a specified

level of reliability. Fourteen of the bridge decks were located in Utah, while the remaining three

decks were located in California, Minnesota, and Virginia. These bridge decks represent a wide

variety of deicing salt exposure and therefore exhibit a wide range in chloride concentrations at

the depth of the rebar. For each bridge deck included in this analysis, the deck ID and the

average and standard deviation associated with chloride concentration at the depth of the rebar

are provided in Table 3-4. The concrete samples were collected using stepwise drilling and

spoon collection. Chloride concentrations for each test location at the depth of the rebar are

provided in Appendix B.

Table 3-4: Average Chloride Concentrations at Depth of Rebar

Deck ID	Chloride Concentration (lb CI$^-$/yd^3 Concrete)	
	Average	Std. Dev.
C-919	0.1	0.1
24 0287L	0.2	0.1
F-205	0.3	0.2
F-500	0.4	0.4
C-752	0.6	0.3
C-438	0.8	0.4
F-506	2.3	1.4
1074	4.2	2.4
F-504	6.0	2.3
C-759	6.0	1.4
C-688	6.3	4.1
5718	6.3	4.7
C-460	11.8	4.8
C-699	13.0	8.1
C-726	13.7	4.5
C-698	15.8	6.6
C-760	17.3	5.4

3.3.2   Statistical Analyses

Statistical analyses of the compiled data were performed to determine the number of chloride concentration test locations necessary for adequately characterizing the chloride concentration of a given bridge deck according to Equation 3.2 (Ott and Longnecker 2001):

$$n = \left(\frac{t_{\alpha/2} \cdot s}{\Delta x} \right)^2$$

(3.2)

where n = number of required test locations

$t_{\alpha/2}$ = two-tailed probability statistic

s = standard deviation in chloride concentration, lb Cl⁻/yd³ of concrete

Δx = specified tolerance in chloride concentration, lb Cl⁻/yd³ of concrete

The required number of samples computed using Equation 3.2 is dependent on reliability, which is incorporated in the two-tailed probability statistic as shown in Table B-1 in Appendix B; spatial variability in chloride concentration, which is represented by standard deviation; and an allowable difference between sample and population means, which is the specified tolerance. If the spatial variability in chloride concentration is known or can be assumed, Equation 3.2 allows the user to specify a tolerance and reliability and then compute the number of samples necessary for adequately characterizing the chloride concentration of a bridge deck with respect to chloride concentration. Once the data are collected, the user can enter the actual standard deviation into Equation 3.2 to compute the actual tolerance for a selected level of reliability, for example.

In this research, Equation 3.2 was used to create three separate charts for each of three reliability levels, including 95, 85, and 75 percent. The α values corresponding to these reliability levels were used to compute values for $t_{\alpha/2}$ for use in the equation. For each level of

reliability, five tolerance values of 1.0, 1.5, 2.0, 2.5, and 3.0 lb Cl$^-$/yd^3 of concrete were evaluated. Estimates of standard deviation as a function of chloride concentration were obtained using regression analysis of the compiled data shown in Table 3-4. In the analysis, in which each bridge constituted a single observation point, the mathematical equation $y = ax^b$, where a and b are coefficients, was determined to be the best model, as it produced the highest coefficient of determination, or R^2 value (Ott and Longnecker 2001). As Equation 3.2 is based on the assumption that measurements come from normally distributed populations, an Anderson-Darling test for normality was performed on the data set for each bridge; in this test, p-values greater than 0.05 indicate that the given data set is normally distributed.

3.4   Summary

In this research, laboratory experiments on concrete drilling and powder collection methods were conducted to compare current concrete powder sampling techniques. The experiment on drilling involved preparation and testing of one large slab, comprising five separate layers designed to achieve a chloride concentration gradient typical of concrete bridge decks in Utah. The experiment on powder collection involved preparation and testing of five small slabs each corresponding to one layer in the large slab. For the large slab, six locations for both the constant drilling method and the stepwise drilling method were selected for testing. For each of the five small slabs, three test locations for both the spoon collection method and the vacuum collection method were selected. After all the samples for both the experiment on drilling and the experiment on powder collection were obtained, each concrete powder sample was analyzed using laboratory titration. Statistical analyses were performed on the data collected in both the experiment on drilling and the experiment on powder collection.

In addition, statistical analyses were performed on field data collected from concrete bridge decks throughout the United States to determine the number of chloride concentration test locations necessary for adequately characterizing the chloride concentration of a given bridge deck. The number of samples is dependent on reliability, spatial variability in chloride concentration, and an allowable difference between sample and population means. In this research, three separate charts for each of three reliability levels, including 95, 85, and 75 percent, were created, and five tolerance values of 1.0, 1.5, 2.0, 2.5, and 3.0 lb Cl^-/yd^3 of concrete were evaluated.

4   RESULTS

4.1   Overview

The results of the laboratory experiments on concrete drilling and powder collection, as well as the statistical analyses performed on field data to determine the number of chloride concentration test locations necessary for adequately characterizing the chloride concentration of a given bridge deck, are described in the following sections.

4.2   Sampling of Concrete Powder

The properties of each concrete mixture prepared for the laboratory experiments, as well as the results of both experiments on concrete drilling and powder collection, are presented in the following sections. Raw data for both experiments are presented in Appendix A.

4.2.1   Concrete Properties

The slump, air content, and water-to-cementitious materials ratios for each concrete batch prepared for this research are presented in Table 4-1. All of the properties for each batch were within typical ranges for concrete bridge deck construction (Hema et al. 2004).

Table 4-1: Concrete Properties

Batch	Slump (in.)	Air Content (%)	Water-to-Cementitious Materials Ratio
1	6.50	5.58	0.44
2	5.75	3.94	0.44
3	5.00	5.08	0.44
4	6.50	5.78	0.44
5	4.00	3.95	0.48
Average	5.55	4.87	0.45

4.2.2 Experiment on Drilling

The average chloride concentrations obtained from the constant and stepwise drilling methods with respect to depth are shown in Figure 4-1. The apparent discontinuity in the chloride concentration profile at a depth interval of 1.0 to 1.5 in., where the chloride
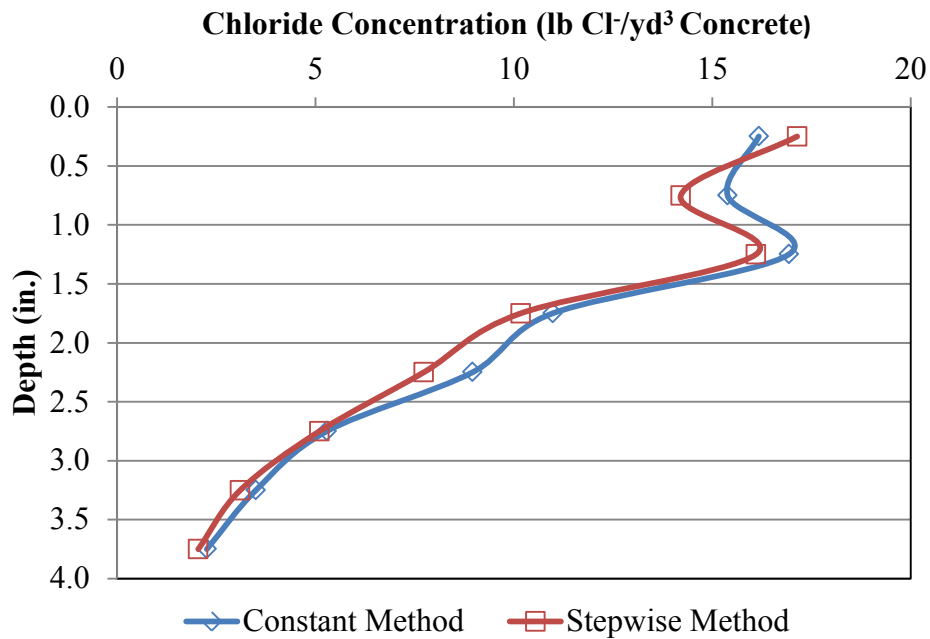
Figure 4-1: Average chloride concentrations for experiment on drilling.

concentration is higher, is attributable to downward diffusion of chloride ions from the top

surface of the slab; as the slab surface dried during the several weeks between curing and testing,

the decreased amount of pore water concentrated the chlorides at the surface, which in turn

caused accelerated downward chloride diffusion. The same trend can be observed in chloride

concentration profiles published in other research (Sumsion 2013).

Table 4-2 lists the results of the t-tests performed on the collected data. Three of the

eight lifts had p-values below 0.15, which was the threshold specified for distinguishing between

chloride concentrations associated with the two drilling methods compared in this exploratory

study, while five of the lifts had p-values greater than 0.15. The t-test performed on the first lift

produced a p-value of 0.927, indicating that the null hypothesis could not be rejected, or the

alternative hypothesis could not be accepted. In this case, insufficient evidence exists to indicate

that the chloride concentration associated with the constant drilling method was greater than the

chloride concentration associated with the stepwise drilling method. Also, the difference

between the chloride concentrations did not exceed the specified practical difference of 1

Table 4-2: Results for Experiment on Drilling

Lift	Depth Interval (in.)	Chloride Concentration (lb Cl^-/yd^3 Concrete)				Difference	p-value
		Constant Method		Stepwise Method			
		Average	St. Dev.	Average	St. Dev.		
1	0.0 - 0.5	16.17	0.96	17.14	1.14	-0.97	0.927
2	0.5 - 1.0	15.38	1.14	14.21	1.87	1.18	0.112
3	1.0 - 1.5	16.93	2.35	16.10	1.94	0.83	0.261
4	1.5 - 2.0	10.98	1.26	10.17	1.46	0.81	0.166
5	2.0 - 2.5	8.96	1.08	7.73	1.67	1.23	0.085
6	2.5 - 3.0	5.28	0.56	5.10	0.67	0.18	0.310
7	3.0 - 3.5	3.50	0.88	3.11	0.88	0.39	0.288
8	3.5 - 4.0	2.26	0.18	2.05	0.23	0.21	0.051

lb Cl⁻/yd³ of concrete. These results were expected since contamination of the first lift by abrading concrete from the sides of the hole above the sampling depth was not possible.

The *t*-tests performed on the second and fifth lifts indicated that the differences in chloride concentrations at these lifts were statistically significant. The *p*-values for the second and fifth lifts were 0.112 and 0.085, respectively, which means that the null hypothesis could be rejected and the alternative hypothesis could be accepted. In this case, sufficient evidence exists to indicate that the chloride concentration associated with the constant drilling method was greater than the chloride concentration associated with the stepwise drilling method. The differences were also of practical importance, being greater than 1 lb Cl⁻/yd³ of concrete. In a typical bridge deck, the steel reinforcement is commonly placed at the depth associated with the fifth lift, between 2.0 and 2.5 in. (Mindess et al. 2003, Russell 2004); therefore, the constant drilling method produced artificially high chloride concentrations at the typical depth of reinforcement. As previously explained, during drilling of lower lifts in the constant drilling method, the drill bit can abrade concrete from the sides of the hole above the sampling depth, where the chloride concentrations are higher, thus producing artificially high chloride concentrations in the lower lifts as demonstrated in this research.

In contrast, the *t*-tests performed on the third, fourth, sixth, and seventh lifts indicated that the differences in chloride concentrations were neither statistically significant nor practically important. Finally, the *t*-test performed on the eighth lift indicated that the difference in chloride concentration was statistically significant, with a *p*-value of 0.051, but not practically important, with a difference of 0.21 lb Cl⁻/yd³. This result is attributable to the comparatively low standard deviations associated with the chloride concentrations measured at the eighth lift.

4.2.3 Experiment on Powder Collection

The average chloride concentrations obtained from both the spoon and vacuum powder collection methods for each of the five smaller slabs are shown in Figure 4-2. Although the concrete used to cast slab 5 was not batched with sodium chloride, the non-zero chloride concentrations for that slab probably resulted from trace amounts of chlorides occurring naturally in the aggregates.

Table 4-3 lists the results of the *t*-tests performed on the collected data. Only the *p*-value associated with slab 3 was less than 0.15, which was the threshold specified for distinguishing between chloride concentrations associated with the two powder collection methods compared in this exploratory study. This result indicates that the null hypothesis could be rejected and the
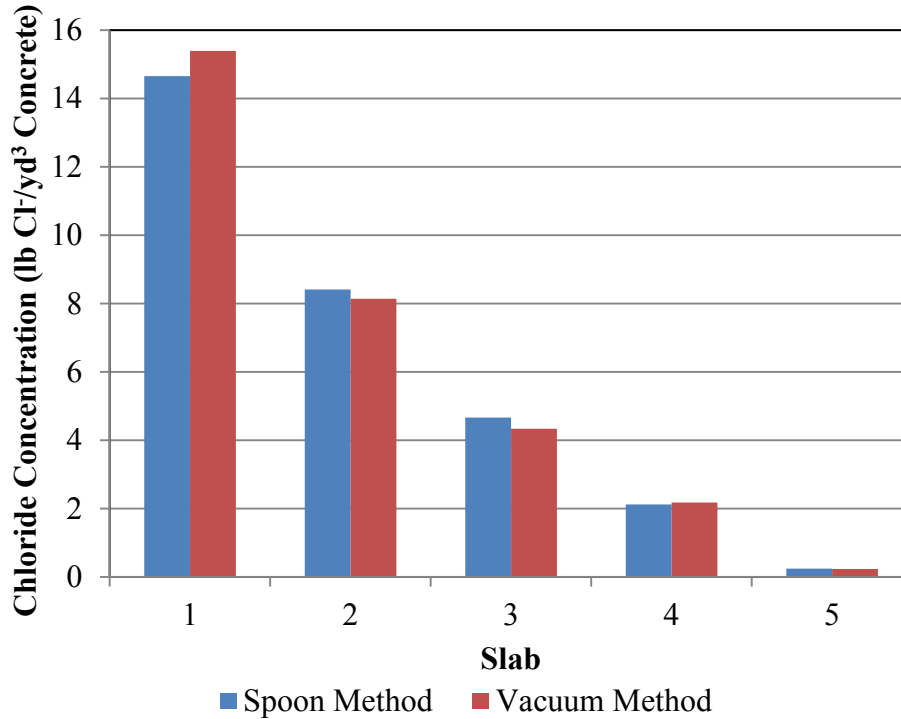
Figure 4-2: Average chloride concentrations for experiment on powder collection.

Table 4-3: Results for Experiment on Powder Collection

Slab	Chloride Concentration (lb Cl⁻/yd³ Concrete)				Difference	p-value
	Spoon Method		Vacuum Method			
	Average	St. Dev.	Average	St. Dev.		
1	14.65	1.12	15.39	0.954	0.74	0.446
2	8.41	0.98	8.14	0.86	-0.27	0.745
3	4.66	0.15	4.34	0.03	-0.33	0.065
4	2.12	0.17	2.18	0.11	0.06	0.673
5	0.24	0.01	0.24	0.03	0.00	0.843

alternative hypothesis could be accepted. In this case, sufficient evidence exists to indicate that the chloride concentrations associated with the spoon collection method were not equal to the chloride concentrations associated with the vacuum collection method. This result is attributable to the comparatively low standard deviations associated with the chloride concentrations measured on slab 3.

However, for all the other cases, the p-values were greater than 0.15, indicating that the null hypothesis could not be rejected and the alternative hypothesis could not be accepted. In these cases, insufficient evidence exists to indicate that the chloride concentrations associated with the spoon and vacuum collection methods were different.

4.3   Determination of Number of Test Locations

In the process of determining the number of chloride concentration test locations necessary for adequately characterizing the chloride concentration of a given bridge deck, the spatial variability in chloride concentration must be considered in advance. For this purpose, estimates of standard deviation as a function of chloride concentration were obtained using regression analysis of data collected from 17 bridge decks in previous research at BYU (Brigham

Young University 2010, Guthrie and Linford 2006). The data are plotted in Figure 4-3, and the model for the computed regression line is given in Equation 4.1, which has a very high R^2 value of 0.9471:

$$s = 0.5678c^{0.8815} \tag{4.1}$$

where s = standard deviation for chloride concentration, lb Cl⁻/yd^3

   c = chloride concentration, lb Cl⁻/yd^3 of concrete

The results of the Anderson-Darling test performed to evaluate the assumption of normality for each of the data sets are listed in Table 4-4. Having p-values greater than 0.05, 12 of the 17 bridge decks were shown to exhibit normally distributed chloride concentrations. The other five bridge decks had p-values less than the threshold p-value of 0.05, four of which have
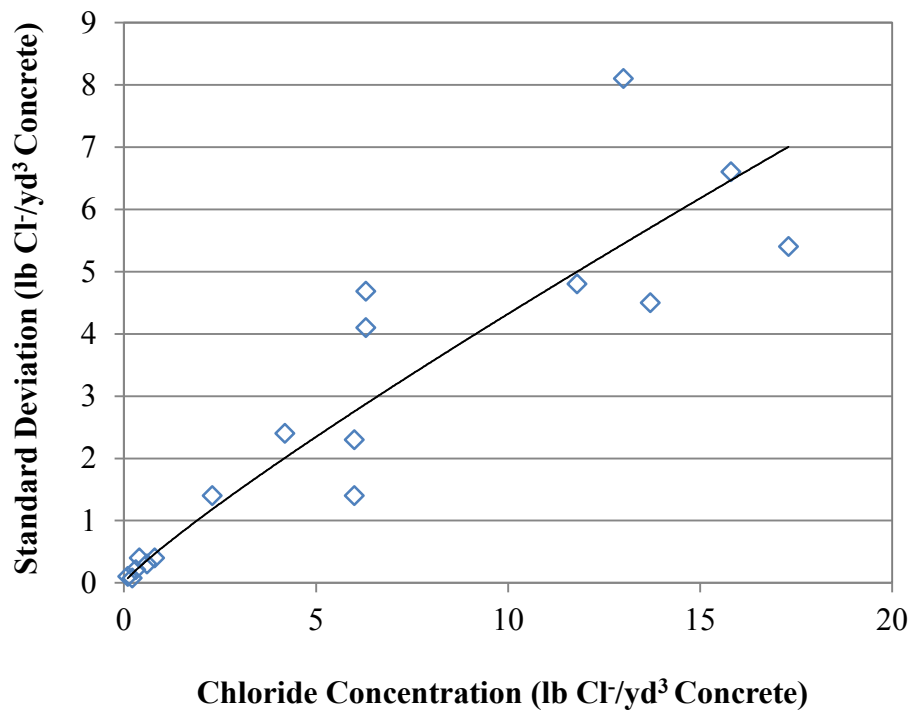
Figure 4-3: Average chloride concentration and standard deviation data for bridge decks.

45

Table 4-4: Results of Anderson-Darling Test

Deck ID	p-value
24 0287L	0.018
1074	0.524
5718	0.007
F-205	0.010
F-506	0.503
C-460	0.331
C-688	0.149
C-698	0.629
C-699	0.608
C-726	0.424
C-752	0.573
C-759	0.905
C-760	0.639
F-500	0.015
F-504	0.516
C-438	0.356
C-919	0.007

very low average chloride concentrations (less than 0.5 lb Cl⁻/yd³ of concrete) that cause

positively skewed distributions. Consequently, the recommendations developed in this research

for the number of test locations necessary for adequately characterizing the chloride

concentration of a given bridge deck may not be applicable to bridge decks with very low

chloride concentrations at the depth of the rebar.

Substituting Equation 4.1 for standard deviation in Equation 3.2 yields Equation 4.2 for

estimating the number of test locations required for chloride concentration testing:

$$n = \left(\frac{t_{\alpha/2}\left(0.5678c^{0.8815}\right)}{\Delta x} \right)^2 \qquad\qquad (4.2)$$

where n = number of required test locations

$t_{\alpha/2}$ = two-tailed probability statistic

$\Delta x =$ specified tolerance in chloride concentration, lb Cl⁻/yd³ of concrete

$c =$ chloride concentration, lb Cl⁻/yd³ of concrete

Based on Equation 4.2, the charts shown in Figures 4-4 to 4-6 were prepared for estimating the number of chloride concentration test locations necessary for adequately characterizing the chloride concentration of a given bridge deck depending on specified levels of reliability, tolerance, and chloride concentration. Specifically, reliability levels of 95, 85, and 75 percent were considered with tolerance levels of 1.0, 1.5, 2.0, 2.5, and 3.0 lb Cl⁻/yd³ of concrete and chloride concentrations up to 20 lb Cl⁻/yd³ of concrete. Tables containing data used in the creation of Figures 4-4 to 4-6 are presented in Appendix B. The levels of reliability and tolerance should be selected by the user to ensure appropriate confidence in the results, and the
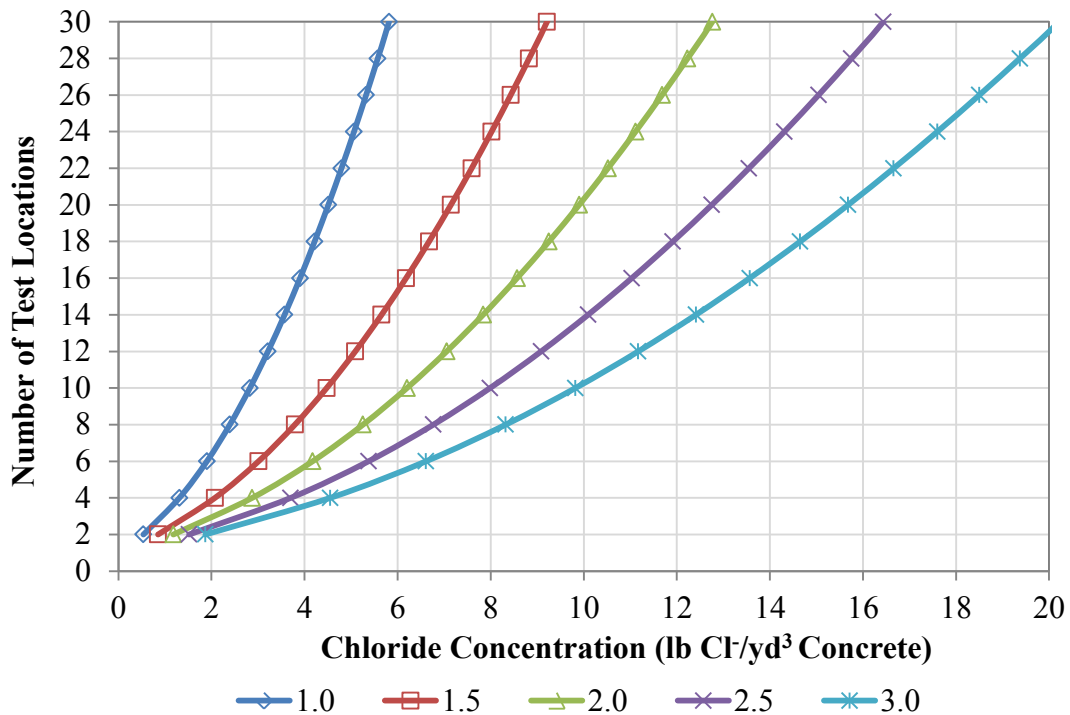
Figure 4-4: Number of chloride concentration test locations for 95% reliability.
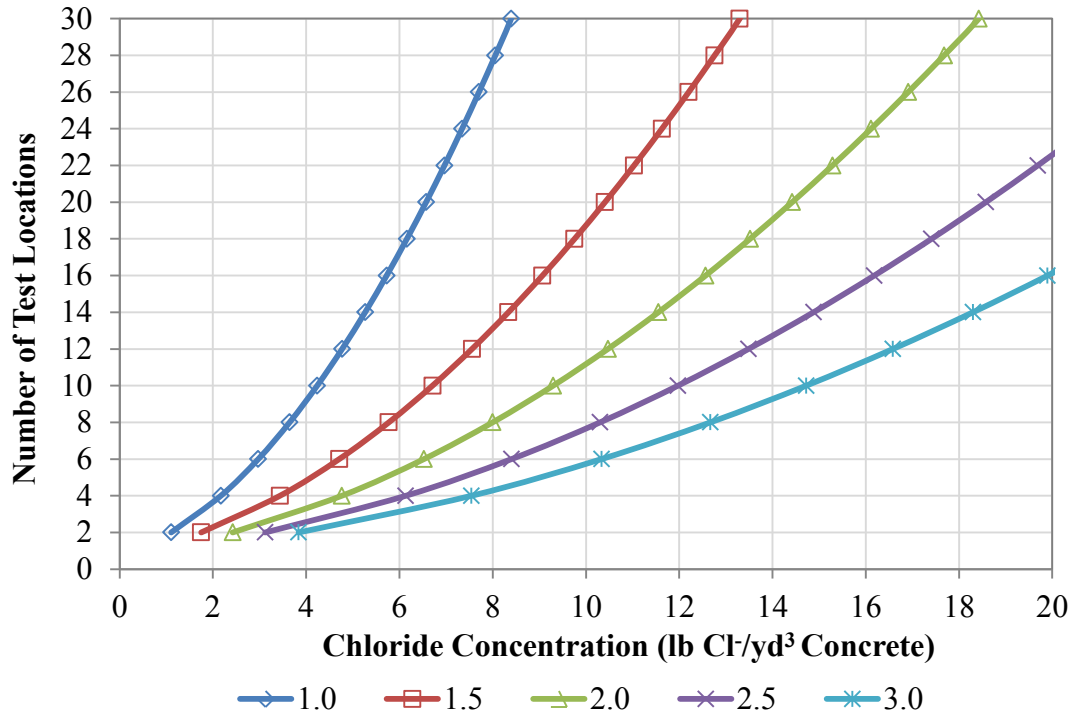
Figure 4-5: Number of chloride concentration test locations for 85% reliability.
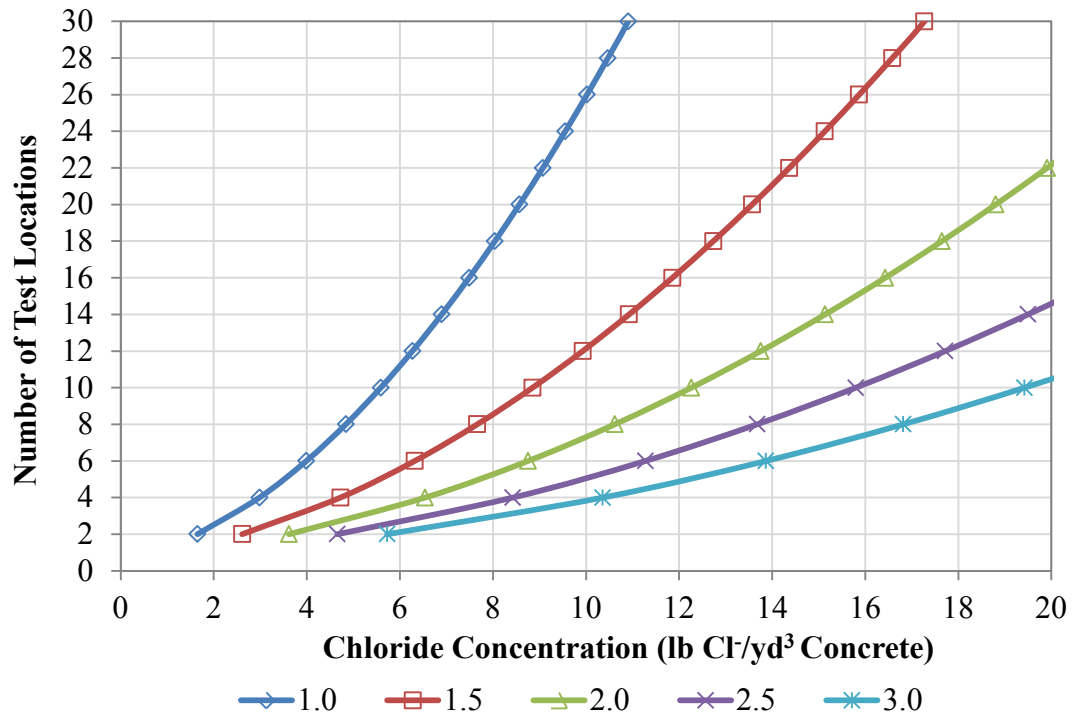
Figure 4-6: Number of chloride concentration test locations for 75% reliability.

48

selected chloride concentration should be the highest value associated with a decision pertaining to maintenance and rehabilitation of the given bridge deck.

For example, for a 95 percent reliability level, a user would refer to Figure 4-4; select a chloride concentration threshold from the x-axis, perhaps 2 lb Cl⁻/yd³ of concrete for a deck constructed using uncoated reinforcing steel; select a tolerance level, perhaps 1.0 lb Cl⁻/yd³ of concrete; and then read from the y-axis the recommended number of test locations, which would be six in this case. The user would then identify six random locations on the bridge deck for testing. If testing restrictions exist that prevent proper random sampling, pseudo-random sampling may be permitted instead.

After the testing is complete, the user may determine the actual tolerance associated with the data set using Equation 4.3, which is another form of Equation 3.2 presented previously:

$$\Delta x = \frac{t_{\alpha/2} \cdot s}{\sqrt{n}}$$

(4.3)

where Δx = tolerance in chloride concentration, lb Cl⁻/yd³ of concrete

$t_{\alpha/2}$ = two-tailed probability statistic

s = standard deviation in chloride concentration, lb Cl⁻/yd³ of concrete

n = number of test locations

The user would enter the value of the two-tailed probability statistic from Table B-1 in Appendix B, the standard deviation associated with the chloride concentration measurements, and the number of test locations from which samples were obtained. If the measured data were the same as that shown for bridge deck C-759 in Table B-2 in Appendix B, the average chloride concentration would be 6 lb Cl⁻/yd³ of concrete, and the associated standard deviation would be 1.4 lb Cl⁻/yd³ of concrete as measured for six test locations. The two-tailed probability statistic would be 2.447 for a 95 percent reliability level, and the computed tolerance would then be 1.4

49

lb Cl$^-$/yd^3 of concrete. The user would then be able to say with 95 percent confidence that the true chloride concentration was ±1.4 lb Cl$^-$/yd^3 of concrete from the measured average of 6.0 lb Cl$^-$/yd^3 of concrete, or in other words that the 95 percent confidence interval ranged from 4.6 to 7.4 lb Cl$^-$/yd^3 of concrete. This approach would be appropriate for testing across a single span or multiple spans of a bridge as long as the spatial variability in concrete properties associated with bridge construction, trafficking, and operational characteristics is consistent from span to span. Separate sampling plans would probably be required in cases where the spans were constructed at different times, by different contractors, and/or with different materials; traffic levels are different; and/or the operational characteristics, including deicing applications, are different.

4.4   Summary

The results of this research include data collected in the laboratory experiments on concrete drilling and powder collection, as well as the statistical analyses performed on field data to determine the number of chloride concentration test locations necessary for adequately characterizing the chloride concentration of a given bridge deck.

For the experiment on drilling, three of the eight lifts had p-values below 0.15, which was the threshold specified for distinguishing between chloride concentrations associated with the two drilling methods compared in this exploratory study, while the remaining five lifts had p-values greater than 0.15. The t-tests performed on the second and fifth lifts indicated statistically significant differences in the chloride concentrations, meaning that sufficient evidence exists to indicate that the chloride concentration associated with the constant drilling method was greater than the chloride concentration associated with the stepwise drilling method. The differences were also of practical importance, being greater than 1 lb Cl$^-$/yd^3 of concrete. Thus, because the

steel reinforcement is commonly placed at the depth associated with the fifth lift, between 2.0 and 2.5 in., measurements of chloride concentrations obtained using the constant drilling method may produce artificially high chloride concentrations at the typical depth of reinforcement.

For the experiment on powder collection, only the *p*-value associated with slab 3 was less than 0.15, which was the threshold specified for distinguishing between chloride concentrations associated with the two powder collection methods compared in this exploratory study. This result indicates that the null hypothesis could be rejected and the alternative hypothesis could be accepted. In this case, sufficient evidence exists to indicate that the chloride concentrations associated with the spoon collection method were not equal to the chloride concentrations associated with the vacuum collection method. However, for all the other cases, the *p*-values were greater than 0.15, meaning that insufficient evidence exists to indicate that the chloride concentrations associated with the spoon and vacuum collection methods were different.

Three charts were prepared for estimating the number of chloride concentration test locations necessary for adequately characterizing the chloride concentration of a given bridge deck depending on specified levels of reliability, tolerance, and chloride concentration. Specifically, reliability levels of 95, 85, and 75 percent were considered with tolerance levels of 1.0, 1.5, 2.0, 2.5, and 3.0 lb Cl^-/yd^3 of concrete and chloride concentrations up to 20 lb Cl^-/yd^3 of concrete. Examples were given to demonstrate the use of the charts for determining the number of chloride concentration test locations and to illustrate calculation of the actual tolerance associated with a data set after the testing is complete.

5   CONCLUSION

5.1   Summary

While reinforced concrete bridges can become structurally deficient or functionally obsolete through several mechanisms, corrosion of the steel reinforcement as a result of the application of chloride-based deicing salts is the primary cause of bridge deck deterioration in the United States. Chloride concentration testing is consequently among the most common techniques for evaluating the condition of a concrete bridge deck. Two ASTM standards and one AASHTO standard outline, in detail, specific procedures for analyzing concrete powder samples for chloride content; however, these standards lack specific protocols for the concrete sampling process, including procedures for concrete drilling and powder collection and determination of how many test locations should be sampled for adequately characterizing the chloride concentration of the bridge deck of interest. The objectives of this research were therefore to 1) compare concrete drilling and powder collection techniques to develop a sampling protocol for accurately measuring chloride concentrations and 2) determine the number of chloride concentration test locations necessary for adequately characterizing the chloride concentration of a given bridge deck.

Laboratory experiments on concrete drilling and powder collection were conducted to compare current concrete powder sampling techniques. The experiment on drilling involved preparation and testing of one large slab, comprising five separate layers designed to achieve a

chloride concentration gradient typical of concrete bridge decks in Utah. The experiment on

powder collection involved preparation and testing of five small slabs each corresponding to one

layer in the large slab. After all the samples for both the experiment on drilling and the

experiment on powder collection were collected, each concrete powder sample was analyzed

using laboratory titration. Statistical analyses were performed on the data collected in both the

experiment on drilling and the experiment on powder collection. In addition to sampling of

concrete powder, statistical analyses were performed on field data collected from concrete bridge

decks throughout the United States to determine the number of chloride concentration test

locations necessary for adequately characterizing the chloride concentration of a given bridge

deck. The number of samples is dependent on reliability, spatial variability in chloride

concentration, and an allowable difference between sample and population means.

5.2   Conclusions

For the experiment on drilling, the *t*-tests performed on the second and fifth lifts indicated

statistically significant differences in the chloride concentrations, meaning that sufficient

evidence exists to indicate that the chloride concentration associated with the constant drilling

method was greater than the chloride concentration associated with the stepwise drilling method.

The differences were also of practical importance, being greater than 1 lb Cl$^-$/yd^3 of concrete.

Thus, because the steel reinforcement is commonly placed at the depth associated with the fifth

lift, between 2.0 and 2.5 in., measurements of chloride concentrations obtained using the

constant drilling method may produce artificially high chloride concentrations at the typical

depth of reinforcement. Therefore, this research shows that the practice of decreasing the size of

the drill bit in a stepwise fashion with increasing sampling depth reduces the possibility of

abrading concrete from the sides of the hole above the sampling depth, where the chloride concentrations are higher, during the drilling of lower lifts.

For the experiment on powder collection, only one of the five *t*-tests performed indicated a statistically significant difference, meaning that sufficient evidence exists to indicate that the chloride concentrations associated with the spoon collection method were not equal to the chloride concentrations associated with the vacuum collection method. However, for all the other cases, the *t*-tests did not indicate statistically significant differences, meaning that insufficient evidence exists to indicate that the chloride concentrations associated with the spoon and vacuum collection methods were different. Therefore, this research demonstrates that representative samples of concrete powder can be collected with either a spoon or a vacuum.

To determine the number of chloride concentration test locations necessary for adequately characterizing the chloride concentration of a given bridge deck, three charts incorporating specified levels of reliability, tolerance, and chloride concentration were prepared. Specifically, reliability levels of 95, 85, and 75 percent were considered with tolerance levels of 1.0, 1.5, 2.0, 2.5, and 3.0 lb Cl^-/yd^3 of concrete and chloride concentrations up to 20 lb Cl^-/yd^3 of concrete. Examples were given to demonstrate the use of the charts for determining the number of chloride concentration test locations and to illustrate calculation of the actual tolerance associated with a data set after the testing is complete.

5.3   Recommendations

Based on the results of this research, a specific chloride concentration testing protocol is recommended. For bridge decks with properties similar to those investigated in this research, the stepwise drilling method and either the spoon or vacuum powder collection method are

recommended for application. In addition, the charts developed in this research are recommended for estimating the number of chloride concentration test locations required to adequately characterize a given bridge deck. This research is expected to be helpful in effectively assessing the condition of concrete bridge decks with respect to chloride-induced corrosion of the reinforcing steel and prioritizing bridge maintenance and rehabilitation projects.

REFERENCES

1. American Society of Civil Engineers (ASCE). (2013). "2013 Report Card for America's Infrastructure." American Society of Civil Engineers. <http://www.infrastructurereportcard.org/>. (May 14, 2013).

2. American Society for Testing and Materials (ASTM). (1978). "Significance of Tests and Properties of Concrete and Concrete-Making Materials." Committee C9 on Concrete and Concrete Aggregates, Baltimore, MD.

3. Arora, P., Popov, B. N., Haran B., Ramasubramanian, M., Popva, S., and White, R. E. (1997). "Corrosion Initiation Time of Steel Reinforcement in a Chloride Environment: A One Dimensional Solution." *Corrosion Science*, 39(4), 739-759.

4. Arup, H. (1983). *Corrosion of Reinforcement in Concrete Construction.* Ellis Horwood Limited, United Kingdom.

5. Austin, R. B. (1992). "Bridge Deck Distress and Repairs." *Proceedings of the Materials Engineering Congress: American Society of Civil Engineers*, 325-338.

6. Birdsall, A. W., Guthrie, W. S., and Bentz, D. P. (2007). "Effects of Initial Surface Treatment Timing on Chloride Concentrations in Concrete Bridge Decks." *Transportation Research Record: Journal of the Transportation Research Board*, 2028, 103-110.

7. Brigham Young University (BYU). (2010). *Civil Talk.* Annual Newsletter, Department of Civil and Environmental Engineering, Brigham Young University, Provo, UT. <http://ceen.et.byu.edu/sites/default/files/civiltalk/civiltalk-10.pdf>. (July 2, 2013).

8. Cady, P. D., and Weyers, R. E. (1984). "Deterioration Rates of Concrete Bridge Decks." *Journal of Transportation Engineering*, 110, 35-44.

9. Callahan, J. P., Lott, J. L., and Kesler, C. E. (1970). "Bridge Deck Deterioration and Crack Control." *Journal of the Structural Division*, 96, 2021-2036.

10. Carmen, A. (2002). "Analysis of Water Soluble Chloride Content in Concrete." *Materials and Structures*, 35, 586-588.

11. Cederberg, Inc. (2013). <http://www.cederberginc.com/Snow%20Plowing.html>. (May 29, 2013).

12. Climent, M. A., Viqueira, E., deVera, G., and Lopez-Atalaya, M. M. (1999). "Analysis of Acid-Soluble Chloride in Cement, Mortar, and Concrete by Potentiometric Titration Without Filtration Steps." *Cement and Concrete Research*, 29(6), 893-898.

13. Enright, M. P., and Frangopol, D. M. (2000). "Survey and Evaluation of Damaged Concrete Bridges." *Journal of Bridge Engineering*, 5, 31-38.

14. Freyermuth, C. L., Klieger, P., Stark, D. C., and Wenke, H. N. (1970). "Durability of Concrete Bridge Decks: A Review of Cooperative Studies." *Highway Research Record*, 328, 50-60.

15. Goodspeed, C. H., Vanikar, S., and Cook, R. A. (2002). "High Performance Concrete Defined for Highway Structures." *ACI Concrete International*, 18(2), 62-67.

16. Guthrie, W. S., Frost, S. L., Birdsall, A. W., Linford, E. T., Ross, L. A., Crane, R. A., and Eggett, D. L. (2006). "Effect of Stay-in-Place Metal Forms on Performance of Concrete Bridge Decks." *Transportation Research Record: Journal of the Transportation Research Board*, 1958, 33-41.

17. Guthrie, W. S., and Linford, E. T. (2006). *Development of an Index for Concrete Bridge Deck Management in Utah*. Report UT-06.05, Research Division, Utah Department of Transportation, Salt Lake City, UT.

18. Guthrie, W. S., Nolan, C. D., and Bentz, D. P. (2011). "Effect of Initial Scarification and Overlay Treatment Timing on Chloride Concentrations in Concrete Bridge Decks." *Transportation Research Record: Journal of the Transportation Research Board*, 2220, 66-74.

19. Guthrie, W. S., and Pinkerton, T. M. (2007). *Sensitivity of Half-Cell Potential Measurements to Properties of Concrete Bridge Decks*. Report UT-08.21, Research Division, Utah Department of Transportation, Salt Lake City, UT.

20. Hema, J., Guthrie, W. S., and Fonseca, F. (2004). *Concrete Bridge Deck Condition Assessment and Improvement Strategies*. Report UT-04.16, Research Division, Utah Department of Transportation, Salt Lake City, UT.

21. Herald, S. E., Weyers, R. E., and Cady, P. D. (1992). "Measuring the Chloride Content of Concrete." *Transportation Research Record: Journal of the Transportation Research Board*, 1347, 69-74.

22. Hurd, M. K. (2002). "Pressure on Wall and Column Forms." Publication #C02J043. <http://static.squarespace.com/static/51cc79a1e4b00280d0e5af80/t/51d06e1ee4b02caa00

3fb4f1/1372614174073/Concrete_Const_Article_W_ACI_Tables.pdf>. (February 4, 2014).

23. Kirkpatrick, T. J., Weyers, R. E., Anderson-Cook, C. M., and Sprinkel, M. M. (2002). "Probabilistic Model for the Chloride-Induced Corrosion Service Life of Bridge Decks." *Cement and Concrete Research*, 32, 1943-1960.

24. Mays, G. C. (1992). *Durability of Concrete Structures: Investigation, Repair, Inspection*. E & FN Spon, London, United Kingdom.

25. McCarthy, M., Giannakou, A., and Jones, M. (2004). "Comparative Performance of Chloride Attenuating and Corrosion Inhibiting Systems for Reinforced Concrete." *Materials and Structures*, 37, 671-679.

26. Melhem, H. G., and Cheng, Y. (2003). "Prediction of Remaining Service Life of Bridge Decks Using Machine Learning." *Journal of Computing in Civil Engineering*, 17(1), 1-9.

27. Mindess, S., Young, J. F., and Darwin, D. (2003). *Concrete*, Second Edition. Prentice Hall, Upper Saddle River, NJ.

28. Peterman, R. J., Ramirez, J. A., and Poston, R. W. (1999). "Durability Assessment of Bridges with Full-Span Prestressed Concrete Form Panels." *ACI Materials Journal*, 96(1) 11-19.

29. Peters Chemical Company. (2006). "Safe Winter Roads Start with Calcium Chloride." <http://www.peterschemical.com/safe-winter-roads-start-with-calcium-chloride>. (January 27, 2014).

30. Ott, R. L., and Longnecker, M. (2001). *An Introduction to Statistical Methods and Data Analysis*, Fifth Edition. Duxbury, Pacific Grove, CA.

31. Richardson, M. G. (2002). *Fundamentals of Durable Reinforced Concrete*. Spon Press, New York, NY.

32. Russell, H. G. (2004). *Concrete Bridge Deck Performance: A Synthesis of Highway Practice*. NCHRP Synthesis 333, National Cooperative Highway Research Program, Transportation Research Board of the National Academies, Washington, D.C.

33. Stewart, M. G., and Val, D. V. (2003). "Multiple Limit States and Expected Failure Costs for Deteriorating Reinforced Concrete Bridges." *Journal of Bridge Engineering*, 8(6), 405-415.

34. Suda, K., Misra, S., and Motohashi, K. (1993). "Corrosion Products of Reinforcing Bars Embedded in Concrete." *Corrosion Science*, 35, 1543-1549.

35. Sumsion, E. S., and Guthrie, W. S. (2013). *Physical and Chemical Effects of Deicers on Concrete Pavement: Literature Review*. Report UT-13.09, Research Division, Utah Department of Transportation, Salt Lake City, UT.

36. Sumsion, E. S. (2013). *Condition Assessment of Decommissioned Bridge Decks Treated with Waterproofing Membranes and Asphalt Overlays*. M.S. thesis, Department of Civil and Environmental Engineering, Brigham Young University, Provo, UT.

37. Thomas, C. D. (2013). *Deicer Usage on Concrete and Asphalt Pavements in Utah*. M.S. thesis, Department of Civil and Environmental Engineering, Brigham Young University, Provo, UT.

38. Young, J. F., Mindess, S., Gray, R. J., and Bentur, A. (1998). *The Science and Technology of Civil Engineering Materials*. Prentice Hall, Upper Sadde River, NJ.

APPENDIX A: SAMPLING OF CONCRETE POWDER

Tables showing the chloride concentration for each depth interval at each test location for both the experiment on drilling and the experiment on powder collection are provided in this appendix.

Table A-1: Data for Experiment on Drilling Using Constant Method

Repetition	Lift	Depth Interval (in.)	Chloride Concentration (lb Cl⁻/yd³ Concrete)
1	1	0.0-0.5	15.22
	2	0.5-1.0	14.06
	3	1.0-1.5	14.84
	4	1.5-2.0	11.19
	5	2.0-2.5	8.35
	6	2.5-3.0	4.66
	7	3.0-3.5	2.80
	8	3.5-4.0	2.01
2	1	0.0-0.5	17.85
	2	0.5-1.0	15.46
	3	1.0-1.5	19.87
	4	1.5-2.0	10.51
	5	2.0-2.5	9.64
	6	2.5-3.0	5.38
	7	3.0-3.5	3.15
	8	3.5-4.0	2.43
3	1	0.0-0.5	16.68
	2	0.5-1.0	15.25
	3	1.0-1.5	19.09
	4	1.5-2.0	12.76
	5	2.0-2.5	9.53
	6	2.5-3.0	5.72
	7	3.0-3.5	4.67
	8	3.5-4.0	2.34
4	1	0.0-0.5	15.47
	2	0.5-1.0	14.51
	3	1.0-1.5	14.43
	4	1.5-2.0	9.89
	5	2.0-2.5	10.33
	6	2.5-3.0	6.04
	7	3.0-3.5	2.81
	8	3.5-4.0	2.14

Table A-1 Continued.

Repetition	Lift	Depth Interval (in.)	Chloride Concentration (lb Cl⁻/yd³ Concrete)
5	1	0.0-0.5	15.88
	2	0.5-1.0	15.67
	3	1.0-1.5	15.35
	4	1.5-2.0	9.49
	5	2.0-2.5	7.34
	6	2.5-3.0	4.65
	7	3.0-3.5	2.99
	8	3.5-4.0	2.18
6	1	0.0-0.5	15.94
	2	0.5-1.0	17.37
	3	1.0-1.5	17.98
	4	1.5-2.0	12.03
	5	2.0-2.5	8.55
	6	2.5-3.0	5.25
	7	3.0-3.5	4.58
	8	3.5-4.0	2.47

Table A-2: Data for Experiment on Drilling Using Stepwise Method

Repetition	Lift	Depth Interval (in.)	Chloride Concentration (lb Cl⁻/yd³ Concrete)
1	1	0.0-0.5	16.26
	2	0.5-1.0	13.51
	3	1.0-1.5	16.08
	4	1.5-2.0	8.43
	5	2.0-2.5	9.26
	6	2.5-3.0	5.79
	7	3.0-3.5	2.79
	8	3.5-4.0	2.35
2	1	0.0-0.5	18.31
	2	0.5-1.0	14.86
	3	1.0-1.5	17.79
	4	1.5-2.0	12.15
	5	2.0-2.5	9.35
	6	2.5-3.0	5.14
	7	3.0-3.5	4.01
	8	3.5-4.0	2.13
3	1	0.0-0.5	16.89
	2	0.5-1.0	16.88
	3	1.0-1.5	13.00
	4	1.5-2.0	9.45
	5	2.0-2.5	5.94
	6	2.5-3.0	4.58
	7	3.0-3.5	2.17
	8	3.5-4.0	2.03
4	1	0.0-0.5	16.14
	2	0.5-1.0	14.54
	3	1.0-1.5	15.92
	4	1.5-2.0	10.32
	5	2.0-2.5	8.30
	6	2.5-3.0	6.00
	7	3.0-3.5	3.02
	8	3.5-4.0	1.98

Table A-2 Continued.

Repetition	Lift	Depth Interval (in.)	Chloride Concentration (lb Cl⁻/yd³ Concrete)
5	1	0.0-0.5	16.44
	2	0.5-1.0	14.28
	3	1.0-1.5	15.33
	4	1.5-2.0	9.11
	5	2.0-2.5	5.42
	6	2.5-3.0	4.32
	7	3.0-3.5	2.34
	8	3.5-4.0	1.67
6	1	0.0-0.5	18.79
	2	0.5-1.0	11.17
	3	1.0-1.5	18.48
	4	1.5-2.0	11.57
	5	2.0-2.5	8.12
	6	2.5-3.0	4.77
	7	3.0-3.5	4.31
	8	3.5-4.0	2.13

Table A-3: Data for Experiment on Powder Collection

Slab	Sampling Technique	Repetition	Chloride Concentration (lb Cl⁻/yd³ Concrete)
1	Spoon	1	13.49
		2	15.73
		3	14.71
	Vacuum	1	14.70
		2	16.48
		3	14.99
2	Spoon	1	8.60
		2	9.29
		3	7.35
	Vacuum	1	8.39
		2	8.85
		3	7.19
3	Spoon	1	4.56
		2	4.83
		3	4.60
	Vacuum	1	4.33
		2	4.31
		3	4.37
4	Spoon	1	2.31
		2	2.09
		3	1.97
	Vacuum	1	2.05
		2	2.22
		3	2.27
5	Spoon	1	0.23
		2	0.24
		3	0.26
	Vacuum	1	0.24
		2	0.21
		3	0.27

APPENDIX B: DETERMINATION OF NUMBER OF TEST LOCATIONS

This appendix provides tables showing values for the two-tailed probability statistic, the chloride concentration at the depth of the rebar at each test location for each bridge deck, and the number of chloride concentration test locations necessary for adequately characterizing a given bridge deck at specified levels of reliability and tolerance.

Table B-1: Values for Two-Tailed Probability Statistic

n	$t_{\alpha/2}$ Values for Specified Reliability Levels		
	95%	85%	75%
1	12.706	4.165	2.414
2	4.303	2.282	1.604
3	3.182	1.924	1.423
4	2.776	1.778	1.344
5	2.571	1.699	1.301
6	2.447	1.650	1.273
7	2.365	1.617	1.254
8	2.306	1.592	1.240
9	2.262	1.574	1.230
10	2.228	1.559	1.221
11	2.201	1.548	1.214
12	2.179	1.538	1.209
13	2.160	1.530	1.204
14	2.145	1.523	1.200
15	2.131	1.517	1.197
16	2.120	1.512	1.194
17	2.110	1.508	1.191
18	2.101	1.504	1.189
19	2.093	1.500	1.187
20	2.086	1.497	1.185
21	2.080	1.494	1.183
22	2.074	1.492	1.182
23	2.069	1.489	1.180
24	2.064	1.487	1.179
25	2.060	1.485	1.178
26	2.056	1.483	1.177
27	2.052	1.482	1.176
28	2.048	1.480	1.175
29	2.045	1.479	1.174
30	2.042	1.477	1.173

Table B-2: Chloride Concentrations at Depth of Rebar

Chloride Concentration (lb Cl⁻/yd³ Concrete)

Test No.	24 0287L	1074	5718	F-205	F-506	C-460	C-688	C-698	C-699	C-726	C-752	C-759	C-760	F-500	F-504	C-438	C-919
1	0.3346	5.2869	9.0567	0.2106	1.2168	3.5380	4.1244	22.1198	3.8095	18.3641	0.8385	6.9124	21.2429	0.0798	5.3239	1.0208	0.3819
2	0.1776	0.7006	3.0007	0.1370	3.1468	12.3680	13.8860	14.8571	23.3771	14.4263	0.2074	5.2850	16.0866	0.8949	8.5419	0.7397	0.0840
3	0.2005	6.8585	1.8176	0.1879	2.2481	16.9193	6.1148	24.1120	9.8606	19.6804	0.9590	3.8913	20.6334	0.0724	4.2227	1.2295	0.1147
4	0.1817	2.8972	9.8976	0.2212	3.7792	16.3396	2.9292	16.5933	20.9802	9.0409	0.5715	5.4893	23.4961	0.1729	3.0329	0.1477	0.0423
5	0.2027	0.7727	0.7613	0.1934	0.0484	10.8729	7.5073	9.1374	5.3772	11.4649	0.5939	6.4794	13.4484	0.9589	8.9265	0.7431	0.0719
6	0.2929	1.0056	11.5449	0.4235	3.2340	11.0458	3.0137	7.9628	14.4539	9.4074	0.2616	7.9427	9.1269	0.1517	5.7590	0.9480	0.0434
7	0.2923	1.3518	7.5664	0.7898	-	-	-	-	-	-	-	-	-	-	-	-	-
8	0.1314	5.6924	9.4363	0.1602	-	-	-	-	-	-	-	-	-	-	-	-	-
9	0.3188	5.1223	1.3181	0.4361	-	-	-	-	-	-	-	-	-	-	-	-	-
10	0.2019	7.5003	13.4959	-	-	-	-	-	-	-	-	-	-	-	-	-	-
11	0.1337	2.0549	3.2040	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12	0.3192	8.3074	0.8339	-	-	-	-	-	-	-	-	-	-	-	-	-	-
13	0.2217	4.8745	11.8648	-	-	-	-	-	-	-	-	-	-	-	-	-	-
14	0.1795	7.3460	0.5565	-	-	-	-	-	-	-	-	-	-	-	-	-	-
15	0.1373	4.5133	3.7607	-	-	-	-	-	-	-	-	-	-	-	-	-	-
16	0.3146	2.6289	10.0929	-	-	-	-	-	-	-	-	-	-	-	-	-	-
17	0.2188	5.0040	2.1940	-	-	-	-	-	-	-	-	-	-	-	-	-	-
18	0.1121	1.6964	9.5827	-	-	-	-	-	-	-	-	-	-	-	-	-	-
19	0.1816	3.4725	12.0739	-	-	-	-	-	-	-	-	-	-	-	-	-	-
20	0.1816	3.6130	2.3250	-	-	-	-	-	-	-	-	-	-	-	-	-	-
21	0.2037	5.0627	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
22	0.3187	3.4105	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
23	0.2738	5.9404	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
24	0.2024	5.1489	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Average	0.2	4.0	6.2	0.3	2.3	11.8	6.3	15.8	13.0	13.7	0.6	6.0	17.3	0.4	6.0	0.8	0.1
Std Dev	0.1	2.4	4.6	0.2	1.4	4.8	4.1	6.6	8.1	4.5	0.3	1.4	5.4	0.4	2.3	0.4	0.1

Table B-3: Number of Test Locations for 95% Reliability

n	$t_{\alpha/2}$	Chloride Concentrations for Specified Tolerances (lb Cl/yd^3 Concrete)				
		1.0	1.5	2.0	2.5	3.0
2	4.303	0.538	0.852	1.181	1.521	1.870
4	2.776	1.310	2.074	2.874	3.702	4.552
6	2.447	1.902	3.012	4.175	5.377	6.611
8	2.306	2.395	3.793	5.256	6.769	8.324
10	2.228	2.826	4.475	6.202	7.988	9.822
12	2.179	3.214	5.091	7.054	9.085	11.172
14	2.145	3.571	5.656	7.837	10.094	12.412
16	2.120	3.903	6.182	8.566	11.033	13.566
18	2.101	4.215	6.676	9.252	11.915	14.652
20	2.086	4.511	7.145	9.901	12.752	15.681
22	2.074	4.793	7.592	10.520	13.549	16.661
24	2.064	5.063	8.019	11.112	14.312	17.599
26	2.056	5.323	8.430	11.682	15.046	18.502
28	2.048	5.573	8.827	12.231	15.753	19.372
30	2.042	5.815	9.210	12.763	16.438	20.213
40	2.021	6.927	10.971	15.203	19.580	24.078
50	2.009	7.917	12.539	17.375	22.378	27.518
60	2.000	8.820	13.969	19.358	24.932	30.658
70	1.994	9.658	15.296	21.196	27.300	33.570
80	1.990	10.444	16.540	22.920	29.520	36.300
90	1.987	11.187	17.717	24.551	31.620	38.883
100	1.984	11.894	18.837	26.102	33.618	41.340
110	1.982	12.570	19.908	27.587	35.530	43.691

Table B-4: Number of Test Locations for 85% Reliability

n	$t_{\alpha/2}$	Chloride Concentrations for Specified Tolerances (lb CI^-/yd^3 Concrete)				
		1.0	1.5	2.0	2.5	3.0
2	2.282	1.104	1.749	2.424	3.121	3.838
4	1.778	2.171	3.438	4.764	6.136	7.545
6	1.650	2.973	4.709	6.526	8.405	10.335
8	1.592	3.645	5.773	8.000	10.303	12.669
10	1.559	4.236	6.709	9.297	11.973	14.724
12	1.538	4.771	7.556	10.471	13.486	16.583
14	1.523	5.265	8.338	11.554	14.881	18.299
16	1.512	5.725	9.068	12.565	16.183	19.900
18	1.504	6.160	9.755	13.518	17.411	21.410
20	1.497	6.572	10.408	14.423	18.576	22.843
22	1.492	6.965	11.031	15.287	19.688	24.210
24	1.487	7.343	11.629	16.115	20.755	25.522
26	1.483	7.706	12.204	16.912	21.781	26.784
28	1.480	8.056	12.759	17.681	22.772	28.002
30	1.477	8.396	13.296	18.425	23.731	29.181
40	1.468	9.957	15.769	21.852	28.143	34.607
50	1.462	11.350	17.975	24.909	32.081	39.450
60	1.458	12.623	19.992	27.703	35.680	43.875
70	1.456	13.805	21.864	30.297	39.021	47.983
80	1.453	14.914	23.620	32.731	42.156	51.838
90	1.452	15.964	25.282	35.035	45.123	55.486
100	1.451	16.963	26.865	37.228	47.947	58.960
110	1.450	17.919	28.379	39.326	50.650	62.283

Table B-5: Number of Test Locations for 75% Reliability

n	$t_{\alpha/2}$	Chloride Concentrations for Specified Tolerances (lb Cl/yd^3 Concrete)				
		1.0	1.5	2.0	2.5	3.0
2	1.604	1.648	2.609	3.616	4.657	5.727
4	1.344	2.981	4.721	6.542	8.426	10.361
6	1.273	3.990	6.318	8.756	11.277	13.867
8	1.240	4.838	7.663	10.619	13.676	16.817
10	1.221	5.588	8.851	12.264	15.796	19.424
12	1.209	6.269	9.929	13.759	17.720	21.790
14	1.200	6.898	10.925	15.139	19.498	23.976
16	1.194	7.486	11.856	16.430	21.161	26.021
18	1.189	8.041	12.735	17.648	22.729	27.950
20	1.185	8.569	13.570	18.805	24.220	29.782
22	1.182	9.072	14.368	19.910	25.643	31.533
24	1.179	9.555	15.133	20.971	27.009	33.213
26	1.177	10.021	15.870	21.992	28.325	34.830
28	1.175	10.470	16.582	22.978	29.595	36.392
30	1.173	10.905	17.271	23.933	30.825	37.905
40	1.167	12.909	20.445	28.331	36.489	44.870
50	1.164	14.699	23.280	32.260	41.549	51.092
60	1.162	16.336	25.873	35.853	46.177	56.782
70	1.160	17.857	28.281	39.190	50.474	62.067
80	1.159	19.284	30.541	42.322	54.509	67.028
90	1.158	20.635	32.681	45.287	58.327	71.723
100	1.157	21.921	34.718	48.110	61.963	76.195
110	1.156	23.153	36.668	50.812	65.443	80.474