COLORADO
Department of Transportation

Applied Research and Innovation Branch

Surface Chloride Levels in Colorado Structural Concrete

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Report No. CDOT-2018-05
January 2018

Technical Report Documentation Page

1. Report No. CDOT-2018-05	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Surface Chloride Levels in Colorado Structural Concrete		5. Report Date January 2018
		6. Performing Organization Code
7. Author(s) Yunping Xi, Yuxiang Jing, Renee Railsback		8. Performing Organization Report No. CDOT-2018-05
9. Performing Organization Name and Address Civil, Environmental and Architectural Engineering UCB 428, Boulder, CO 80309-0428		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address Colorado Department of Transportation - Research 4201 E. Arkansas Ave. Denver, CO 80222		13. Type of Report and Period Covered Final
		14. Sponsoring Agency Code 214-06

15. Supplementary Notes
Prepared in cooperation with the US Department of Transportation, Federal Highway Administration

16. Abstract

This project focused on the chloride-induced corrosion of reinforcing steel in structural concrete. The primary goal of this project is to analyze the surface chloride concentration level of the concrete bridge decks throughout Colorado. The study indicates three factors that can affect chloride concentration levels in bridge decks: age of the concrete, traffic, and weather. Samples were collected from decks and curbs of bridges in different climate regions with various concrete ages and traffic levels. Water-soluble chloride concentrations were tested for all samples. Chloride concentration profiles for all the locations were listed and plotted.

The deepest concrete powder was collected at a depth of 2 inches. The rebar level of the bridge was usually at or below this depth. The chloride concentrations of most bridge decks were below the critical values at the rebar level. The chloride concentrations of bridge decks are usually greater than that of bridge curbs. However, these bridge curbs showed deeper chloride penetration than the bridge decks. Younger bridges had much lower chloride concentrations, which is expected. Heavier traffic resulted in higher chloride concentrations. The bridges built in colder regions had a higher chloride concentration up to 2” depth (the rebar level). Climate may be the most significant influential factor among age, traffic, and climate when considering chloride concentration of bridge decks in Colorado. Corrosion protection should focus on the bridges decks who locate in the cold climate zone and with high traffic volume.

17. Keywords: Chloride Concentration, Bridge Deck, Age, Traffic, Climate.	18. Distribution Statement This document is available on CDOT’s website http://www.coloradodot.info/programs/research/pdfs

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 59	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGEMENTS

The University of Colorado at Boulder would like to acknowledge the financial support provided by the Colorado Department of Transportation for this study. The authors would like to thank the many CDOT personnel that assisted with this study. Special thanks are extended to Aziz Khan, Skip Outcalt, David Weld, Roberto DeDios who spent tremendous amount of time and effort for this project.

EXECUTIVE SUMMARY

In North America, ice and snow on bridges and roads are controlled using deicing salts, the application of deicing salts has been increasing significantly in recent years. The most commonly used deicers are chloride based, which can result in damage of the concrete bridge decks. Two types of damage mechanisms were introduced: direct damage due to the chemical reactions of chloride with some components in cement paste and corrosion damage of rebar triggered by high chloride concentration in the pore solution of concrete. This project focused on the chloride-induced corrosion of rebar. The primary goal of this project was to analyze the surface chloride concentration level of the concrete bridge decks throughout Colorado. A literature search showed that large-scale (statewide/nationwide) examinations/surveys in the published domain about deicer-induced chloride penetration in bridge decks is very limited. These studies indicate three factors that can affect chloride concentration levels in bridge decks: age of the concrete, traffic, and weather. These three factors were considered in this study and were used to categorize bridges and analyze results.

Field sampling was done by a Colorado Department of Transportation (CDOT) team. These samples were collected from decks and curbs of bridges in different climate regions with various concrete ages and traffic levels. The length of each concrete core was at least 2”, from which a sufficient amount of concrete powder was collected every 1/2” from the top of each drilling core. The samples were delivered to University of Colorado at Boulder (CU-Boulder). 88 samples were received in 2014 and 788 samples were received in 2016. The testing was done at CU-Boulder. Water-soluble chloride concentrations were tested using an RCT-500 kit by Germann Instruments.

Chloride concentration profiles for the locations were listed and plotted. Some of the samples from several bridges showed irregular chloride concentration profiles without any clear trends and they were eliminated in the analysis. A possible explanation is that most of these irregular samples were taken in late May and June. Heavy rain may have washed out some of the chloride ions from the sampling locations. Other possible explanations were also provided. In addition, the two sets of samples from the two deliveries are not comparable and were analyzed separately. Since the overall chloride concentration of each bridge is the main concern of the project, chloride concentrations of the three locations on the bridge deck and curb of each bridge were averaged for the samples in the second delivery. After processing the test data, the correlations among chloride levels and the selected influential factors were analyzed. The influential factors are four climate regions 4, 5, 6 and 7; three traffic levels, low (ADT<=7000), medium (7000<ADT<=40000) and high (ADT>40000); and three age ranges, 10 years, 11~30 years and 31+ years.

The deepest concrete powder was collected at a depth of 2 inches. The rebar level of the bridge was usually at or below this depth. Chloride concentration levels at a 2-inch depth for all the bridge decks and curbs were compared to the critical chloride concentrations.

The chloride concentrations of the decks and curbs at the same depth were compared and the ratios were obtained. The chloride concentrations of bridge decks are usually greater than that of bridge curbs, since deicers and traffic are applied directly onto the decks. However, these bridge curbs showed deeper chloride penetration than the bridge decks. This may be due to a lower concrete

quality of the bridge curbs compared to that of the bridge decks. In addition, snow mainly accumulates on the roadsides after snow removal. The resulting water from melting snow may have driven the chloride deeper into the concrete.

In climate zone 4 with different ages but similar traffic levels, younger bridges had much lower chloride concentrations, which is expected. However, no clear age effect was observed for the bridges in climate zone 5. There was not enough data to analyze the age effect in climate zones 6 and 7.

Chloride concentration profiles of the bridge decks in climate zones 4 and 7 with different traffic levels but similar ages were analyzed. Heavier traffic resulted in higher chloride concentrations. No clear traffic effect was observed for bridges in climate zone 5. There was not enough data to analyze the bridges in climate zone 6.

For the first delivery, the climate effects are not clear. For the second delivery, the chloride concentrations of the bridges vs. the climate zone at different depths were analyzed. The bridges built in colder regions had a higher chloride concentration up to 2” depth (the rebar level). This is because more deicers are usually used in cold regions than warm regions. Climate may be the most significant influential factor among age, traffic, and climate when considering chloride concentration of bridge decks in Colorado. Corrosion protection measures should be taken on the bridge decks in the cold climate zones with high traffic volumes. The chloride concentrations at the rebar level depend on not only the surface chloride concentrations (amount of deicers used on the deck) but also chloride permeability of the concrete cover. Therefore, repairing/replacing distressed concrete decks is equally important to prolonging service life.

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1 INTRODUCTION

Deicing salts are widely used for the control of ice and snow on roads and bridges in North America. In some areas, one mile of four-lane roadway requires the application of more than 100 metric tons of deicing salts each year. Approximately 15.4 million tons of deicing salts are used annually in the U.S. for deicing of highways and runways (Basu et al., 1999). The application rate of deicer application in the U.S. has dramatically increased over time (**Figure 1**). The most commonly used deicers are sodium chloride, calcium chloride, and magnesium chloride. Calcium magnesium acetate (CMA) and potassium acetate (KA) have been identified as better alternative deicer candidates because they are not chloride-based and are considered to be biodegradable and harmless to vegetation, concrete, bridges, and vehicles (Basu et al., 1999).

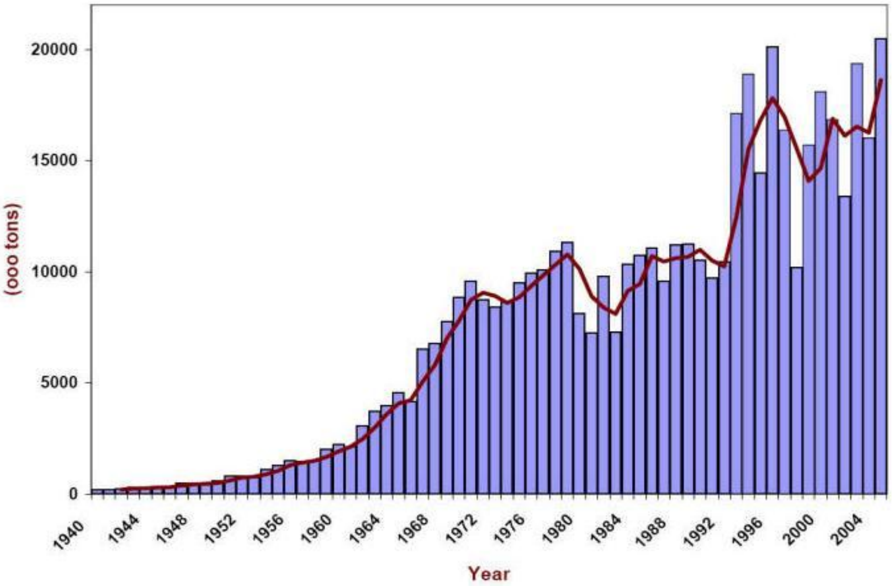


Figure 1. Increasing application rate of deicers in the U.S. (Data from the Salt Institute http://www.saltinstitute.org/)

There are two types of damage caused by chloride-base deicers in reinforced concrete structures: direct damage due to the chemical reactions of chloride with some components in cement paste and corrosion damage of rebar triggered by high chloride concentration in the pore solution of concrete.

1.1 Damage mechanisms

1.1.1 Chemical reactions of chloride with cement paste

Many studies suggest that the chloride-induced damage in concrete results primarily from chemical processes. Neville (1969) showed that saturated solutions of calcium chloride, even without freeze-thaw cycling, are deleterious to concrete. Chatterji (1978) and Berntsson (1982) confirmed that a chemical mechanism is responsible for scaling damage of concrete under concentrated calcium chloride solution. Collepardi and co-workers (1992) and Cody et al. (2000) found that the attack of chloride is accompanied by the formation of hydrated calcium oxychloride:

$$3Ca(OH)_2 + CaCl_2 + 12\ H_2O \rightarrow 3CaO \cdot CaCl_2 \cdot 15H_2O$$

This reaction involves a significant increase in the volume of the solid phases, mostly as a result of the incorporation of 15 water molecules in the reaction product. In this case, scaling may result from microfracturing of the surrounding matrix. According to Stix (1993), $CaCl_2$ can also react with the aluminate in cement paste to form chloroaluminate crystal or Friedel's salt, which results in reduced concrete strength:

$$CaCl_2 + C_3A + 10H_2O \rightarrow C_3A \cdot CaCl_2 \cdot 10H_2O$$

Again, this reaction involves an increase in the volume of the solid phase, which produces expansive forces that drive microfracturing and scaling of the concrete. Collepardi et al. (1994) pointed out that the deterioration of concrete caused by penetration of $CaCl_2$ occurs quickly under the temperature range of 5-10°C, which is higher than the freezing temperature of water. Therefore, the damage mechanism should be considered different from freezing/thawing deterioration.

Several reports clearly showed that long-term exposure of concrete to sodium chloride solution in different concentrations resulted in the leaching of $Ca(OH)_2$ (Gegout et al., 1992; Gagne et al., 1992; Dunker, 1993). The chemical reaction was described as:

$$2NaCl + Ca(OH)_2 \rightarrow CaCl_2 + NaOH$$

Note that this reaction is fundamentally different from those described above in that the volume of the reaction product is similar to or less than the reactants involved. Therefore, the damage mechanisms associated with this reaction involve increased porosity and softening rather than microfracturing.

Solutions of magnesium chloride have gained wide acceptance as important tools in winter maintenance programs. The amount of these materials being applied annually is rapidly increasing. Similar to calcium and sodium chloride, there are multitudes of suggested chemical reactions between magnesium chloride and cement paste. Kleinlogel (1950) considered that magnesium chloride reacts with the calcium compounds in hydrated cement to form insoluble colloidal magnesium compounds (hydrate, silicate, and aluminate) and soluble calcium chloride, which increase the permeability of the concrete. Oberste-Padtberg et al. (1986) reported that the damage caused by magnesium chloride was related to the formation of magnesium hydroxide, which results in cracking of concrete as well as a lowered pH value, which results in the decomposition of C-S-H.

Oberste-Padtberg et al. (1986) compared the relative damage of the four chlorides: sodium chloride, calcium chloride, potassium chloride, and magnesium chloride. They found that cement paste was severely damaged by over-saturated concentrations of magnesium chloride and calcium chloride, but the damage caused by sodium chloride and potassium chloride were less severe. The damage caused by magnesium chloride was related to the formation of magnesium hydroxide, which results in cracking of concrete as well as a lowered pH value, which causes the decomposition of C-S-H. For calcium chloride, the damage was associated with the dissolution of a large amount of Al, Fe and Si ions from the cement paste into the pore solution of concrete. McDonald and Perenchio (1997) found that salts containing potassium or magnesium are more likely to cause scaling damage to concrete.

In summary, the reaction products of chloride and certain components of cement paste may cause damage in concrete. Damage could take the form of cracking and scaling. However, this kind of damage is not the focus of this project.

1.1.2 Chloride-induced corrosion and surface chloride level

The chloride content at rebar level (on the surface of an embedded steel bar) in reinforced concrete structures is a very important indicator for the long-term performance of reinforced concrete bridges and bridge components. When the chloride content reaches the critical value, the corrosion of rebar starts. There are different suggestions for the critical chloride concentration as reviewed by Suwito and Xi (2008). The chloride content at the rebar level depends on two factors. One is the chloride permeability of concrete cover and the other is the surface chloride concentration.

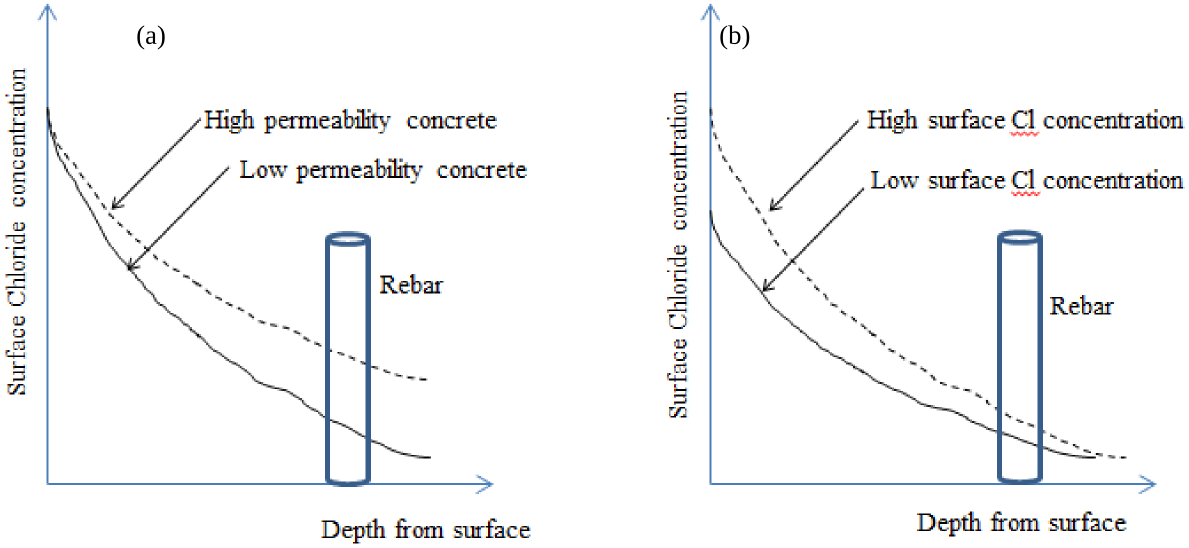


Figure 2. Internal chloride distributions of concrete with: (a) the same surface concentration and different permeabilities; (b) the same permeability and different surface concentrations

As shown in Figure 2(a), for the same surface chloride concentration, the internal chloride concentration distribution of concrete is determined by the permeability of concrete. At a fixed depth, (e.g., the rebar level) the concentration is high when the permeability is high. In this case, the onset of rebar corrosion in the concrete structure depends on the permeability of concrete.

As shown in Figure 2(b), for the same concrete, the two internal chloride distributions have similar shapes. In addition, the surface chloride concentration determines the internal chloride distribution (shifting up if the surface concentration is high, and down if it is low) and the surface chloride concentration determines the chloride concentration at the rebar level. Therefore, the surface chloride concentration is very important for the long-term performance of concrete structures.

There has been extensive research on the chloride permeability of concrete cover, such as the work concerning saturated concrete (Xi and Bazant, 1999), non-saturated concrete (Ababneh et al., 2003), distressed concrete (Xi and Nakhi, 2005), and concrete under low temperatures (Eskandari-Ghadi et al., 2013). However, there is a lack of research on surface chloride concentration, which will be the subject of this research project.

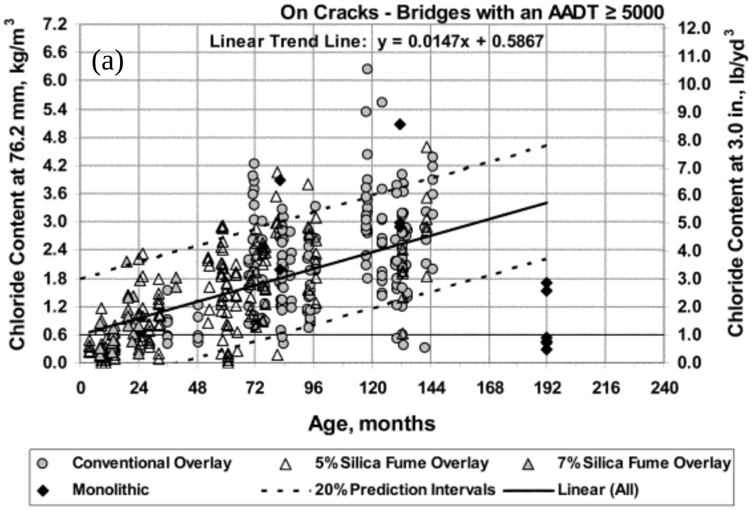
The surface chloride concentration depends mainly on two parameters: the dosage and type of deicers. They, in turn, depend on traffic and environmental conditions. The effect of deicer dosage is easily understood; with a higher dosage of deicers the surface chloride concentration will be higher. However, the effect of different types of deicers on the chloride distribution in concrete is not well understood. When different deicers are used on concrete bridges, the cations in the chloride solution can be Na^+, Ca^{++}, and Mg^{++} depending on the deicers used, such as sodium chloride, calcium chloride, or magnesium chloride. To keep electroneutrality in the material, the cations and Cl^- penetrate into concrete at the same time. Most of the previous research only focused on the chloride penetration. The multi-species transport of mixed deicing solution results in different rates of chloride penetration. Recent results showed a significant difference when different deicers are used on a concrete surface (Damrongwiriyanupap, 2010; Damrongwiriyanupap et al., 2011; Damrongwiriyanupap et al., 2013).

The focus of this project is the surface chloride concentration level. First, surface chloride concentration levels (water–soluble chlorides) from bridges throughout the state of Colorado need to be obtained. Then, the correlations among surface chloride concentrations and location-specific conditions can be obtained. The Colorado Department of Transportation (CDOT) can use the correlations to develop policy and corrosion protection strategies appropriate for different locations on the state highway system.

1.2 Influential factors

Large-scale (statewide/nationwide) examinations/surveys in the published domain about deicer induced chloride penetration in bridge decks are very limited. Lindquist et al. (2006) conducted field surveys on 59 bridges in Kansas to measure deck cracking, chloride ingress, and delamination. The effects of material properties, design specifications, construction practices, and environmental site conditions were evaluated. The data in Figure 3 shows a very large scattering. But in general, chloride content increases with the age of the bridge deck. The chloride contents are greater for bridges that are subjected to higher traffic counts, as demonstrated through the progressively higher chloride content with age shown in the two figures for bridges with annual average daily traffic (AADT) greater than 5000 and 7500, respectively.

Age and traffic are two factors which affect chloride concentration levels in bridge decks and are considered in this study. Obviously, chloride concentration of bridges should increase with time, since the chloride will accumulate in the concrete due to continuous usage of deicers every winter (Figure 4). Also, the possible deterioration of the concrete decks through time could also promote the penetration of chloride. A lot of research has indicated the time-dependent characteristic of coefficient diffusion of concrete (Luping and Gulikers, 2007; Stanish and Thomas, 2003; Xi and Nakhi, 2005). It has also been found that the surface chloride content increases with exposure time (Liu et al., 2014; Uji et al. 1990).



(b)

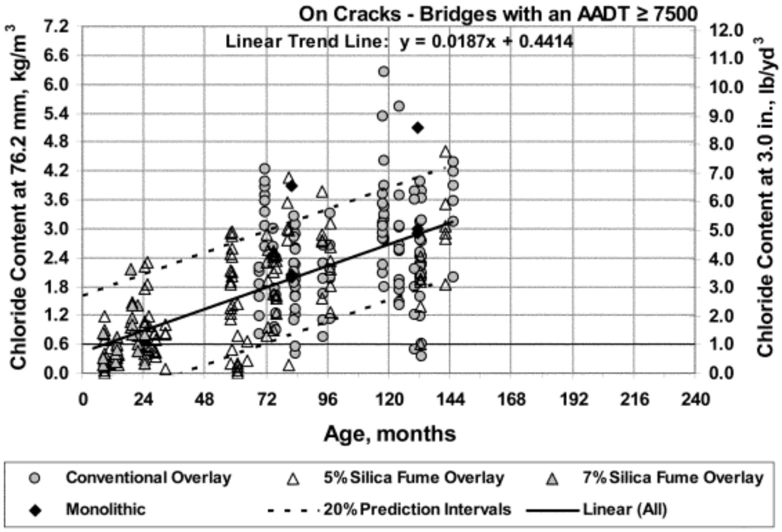


Figure 3. Chloride content taken on cracks interpolated at depth of 76.2 mm (3.0 in.) versus placement age for bridge decks with average annual daily traffic (AADT) (a) ≥ 5000; (b) ≥ 7500

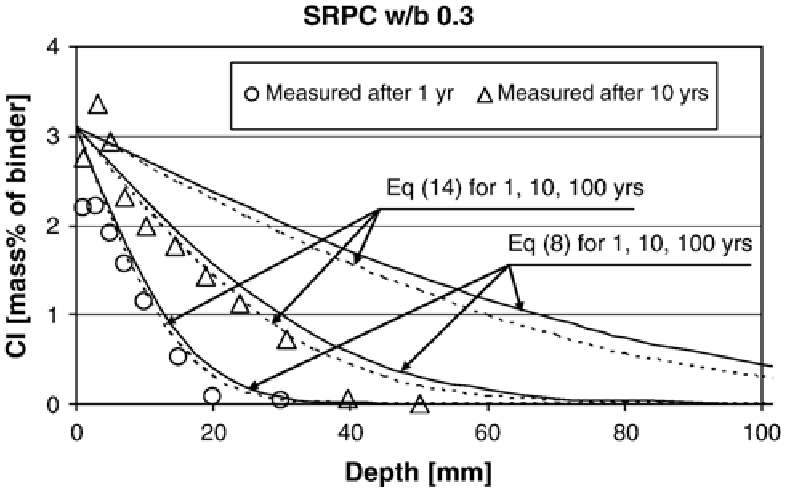


Figure 4. Measured and predicted chloride profiles in Portland cement concrete after 1 year and after 10 years (Luping and Gulikers, 2007)

Lower traffic volume roads are treated with deicing chemicals less often than higher volume roads. In addition, high traffic volume usually results in damage of the concrete, which could increase the chloride permeability of the concrete. In a previous CDOT project done by the PI (Liang et al., 2010), five bridges were selected for inspection. It was found that the chloride concentration level was lowest for the bridge with the lowest traffic volume. Traffic load on bridges can usually be considered as bending fatigue load. The concrete chloride diffusion coefficient would increase along load level. In addition, the concrete chloride diffusion coefficient is greater under bending fatigue load than under static load at the same load level (Figure 5). As a result, chloride concentration at the same depth of concrete will be higher under fatigue load than that under static load (Figure 6).

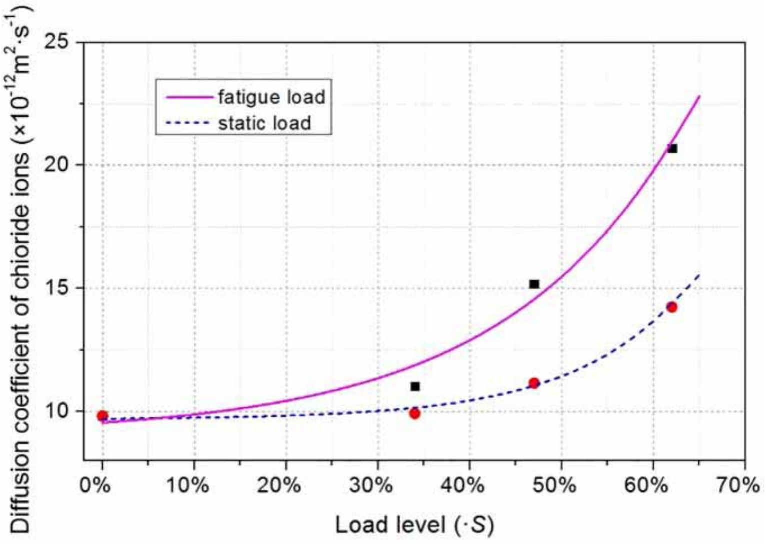


Figure 5. A relation schema of diffusion coefficient and load level (Ren et al., 2015)

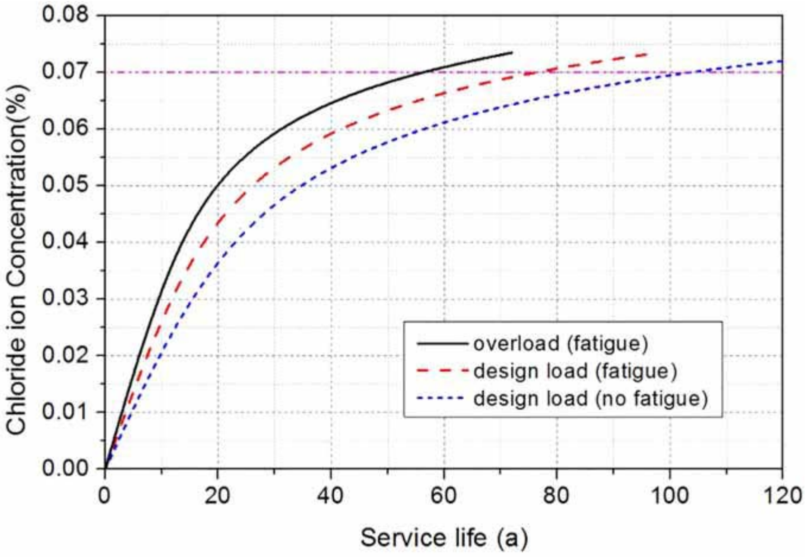


Figure 6. A relation schema of the chloride ion concentration and the time under different loads (Ren et al., 2015)

In addition to the age of concrete and traffic, weather also affects the use of deicers for winter maintenance, since colder weather (heavier snow) usually leads to greater deicer chemical use on bridge decks. Based on the International Energy Conservation Code (IECC), there are four different climate regions in Colorado - Zones 4, 5, 6, and 7 (Fig. 7).

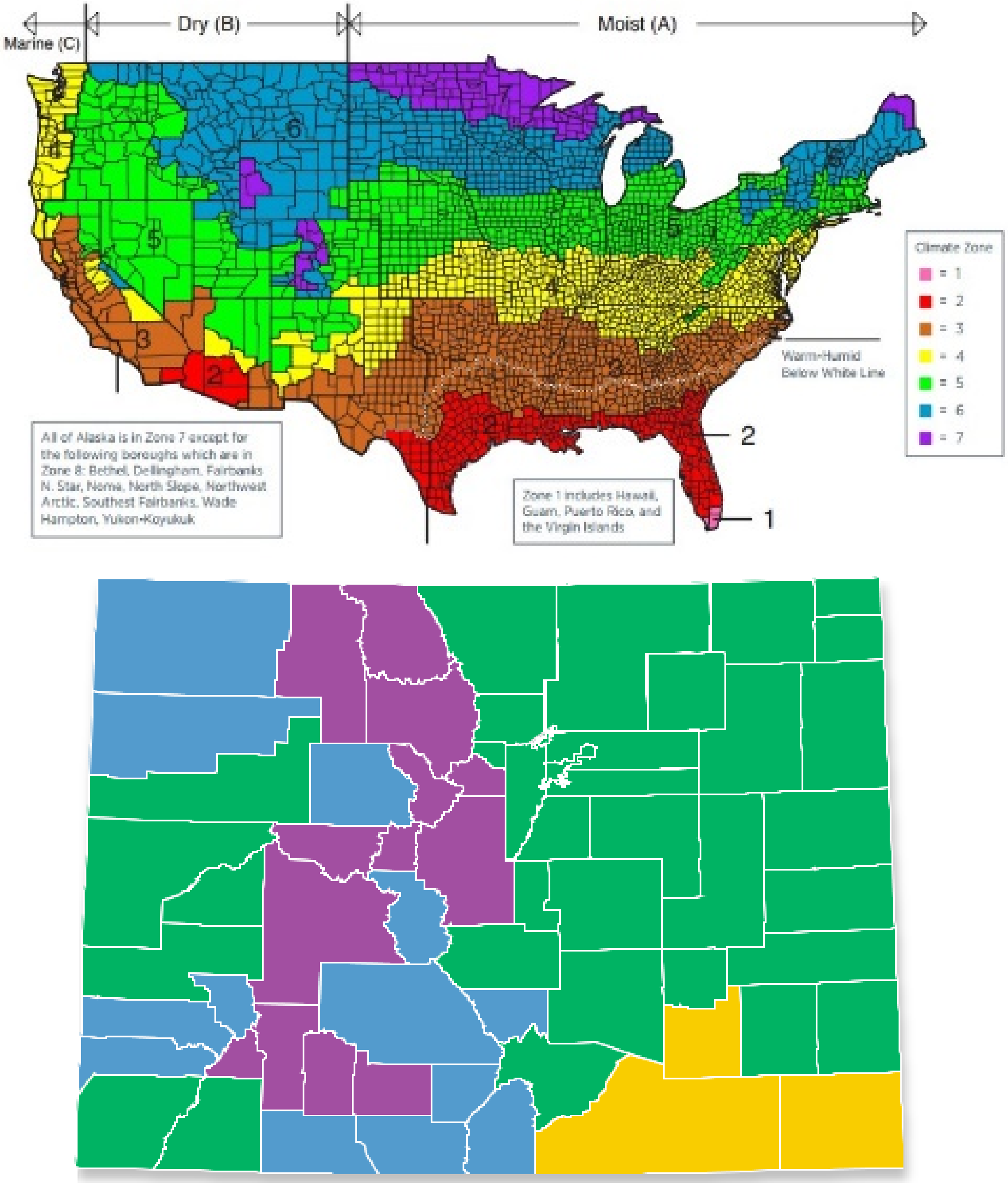


Figure 7. Climate regions (IECC) in Colorado (Baechler et al., 2010)

2 SAMPLING MATRIX AND LOCATIONS SELECTION

To determine which bridges should be sampled and analyzed, a representative number of indicators for the sampling matrix need to be selected. As discussed in the previous section, bridges should be selected based on three indicators: weather, traffic and age of the bridges.

Key locations on each bridge for sample collection also need to be identified. Samples should mainly be taken from within the wheel path. Additional samples can be taken from the shoulder, curb, sidewall, and concrete barriers while sampling the wheel path. Samples should be taken from bare concrete deck instead of concrete underneath waterproofing membranes and thin-bonded overlays, because topical protection measures block the deicers.

2.1 Proposed sampling plan

Based on the information in the Colorado bridge database provided by CDOT, bridges were categorized into different groups based on the weather, traffic and age of the bridges.

- Weather: There are four different climate regions (IECC) in Colorado (4, 5, 6, 7), each of which contains several counties. The corresponding column in the database is COUNTY which indicates the locations of the bridges.

- Traffic: The traffic of the bridges is described with three different levels: Low (ADT<=7000), Medium (7000<ADT<=40000), and High (ADT>40000). The column in the database is ADTTOTAL.

- Age: The age of the bridges is described with three different ranges: 10 years, 11~30 years, and 31+ years. The age should be determined based on the year it was built and reconstruction. No samples should be taken on bridges less than 10 years old to allow time for the surface chloride level to stabilize. No decks built before 1976 should be sampled because of a major change in the concrete mix standard that occurred that year. Columns in the database are YEARBUILT and YEARRECON.

Therefore, there are 4*3*3 = 36 groups to consider. In each group, at least two bridges should be randomly selected.

2.2 The bridge samples used in the project

Ultimately, the bridges selected for sampling were not the same as proposed. The bridges used for sampling were actually determined by the CDOT research branch at CDOT's convenience (e.g. coordinating with inspection schedules to reduce traffic control cost, and avoiding bridges in the Denver Metropolitan Area). Finally, the samples were taken by CDOT's sampling team and were categorized into different groups based on the weather, traffic and age.

3 FIELD SAMPLING

A sampling procedure and equipment/supply list were developed. A training session with CDOT research branch personnel was conducted. The sampling and testing procedures used were consistent with AASHTO T 260: “Standard Method of Test for Sampling and Testing for Chloride Ion in Concrete and Concrete Raw Materials”.

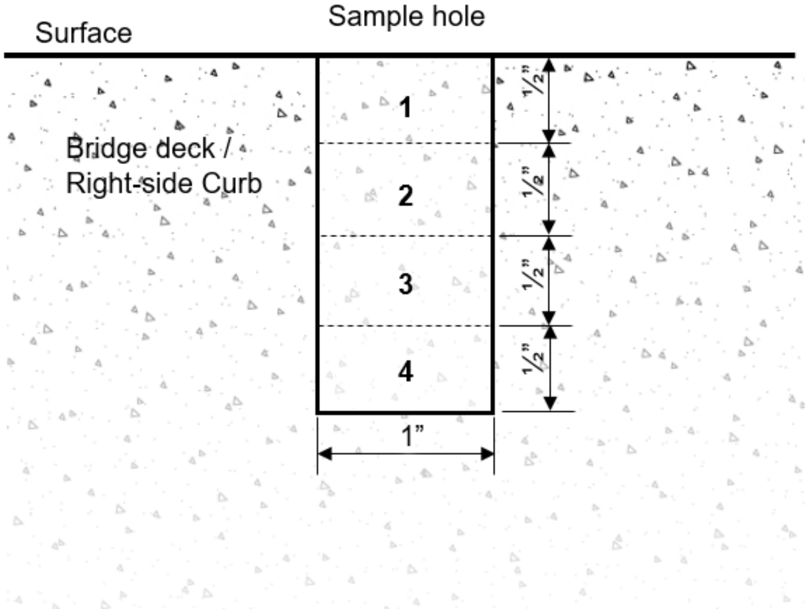


Figure 8. Sectional view of each drilling hole on the deck and curb.

Field sampling was done by the CDOT team. The length of the concrete cores was 2”.Concrete powder was collected every 1/2” from the top of each core (Figure 8). The CU-Boulder research team received samples from 2014 and 2016. 88 samples were received in the first delivery and 788 samples were received in the second delivery. Table 1 lists the samples received, their age, ADT, climate zone and location. Five bridges were sampled in both deliveries.

Table 1. Bridge samples received from CDOT

Brkey	Year built*	Age *	ADT	Climate zone	Location of samples	Received by
O-26-E	1966	48	2600	4	Deck	7/2014
M-23-F	1972	42	380	4	Deck	7/2014
M-21-F	2012	2	430	4	Deck	7/2014
P-18-AD	1959	55	621	4	Deck	7/2014
P-18-BS	1968	46	9499	4	Deck	7/2014
M-20-O	1985	29	630	4	Deck	7/2014

P-17-AE	1986	28	980	4	Deck	7/2014
P-18-AX	2005	9	7800	4	Deck	7/2014
N-26-Q	1975	39	3100	4	Deck	7/2014
N-26-G	2011	3	3100	4	Deck	7/2014
F-05-I	1975	39	8850	5	Deck and curb	7/2014
F-05-L	1975	39	8850	5	Deck and curb	7/2014
F-05-J	1975	39	8850	5	Deck and curb	7/2014
F-05-N	1975	39	11900	5	Deck and curb	7/2014
F-05-M	1975	39	11900	5	Deck and curb	7/2014
H-07-I	1978	36	1400	7	Deck	7/2014
G-09-I	2000	14	17900	7	Deck	7/2014
F-15-BZ	1999	17	936	7	A, B, C, D, E, F	10/2016
F-15-BX	1999	17	42900	7	A, B, C, D, E, F	10/2016
D-16-DK	1988	28	21350	5	A, B, C, D, E, F	10/2016
D-16-DF	1988	28	39700	5	A, B, C, D, E, F	10/2016
N-26-O	1976	40	3100	4	A, B, C, D, E, F	10/2016
O-26-P	1989	27	2600	4	A, B, C, D, E, F	10/2016
B-01-B	1976	40	260	6	A, B, C, D, E, F	10/2016
H-02-GK	1997	19	24900	5	A, B, C, D, E, F	10/2016
D-16-DJ	1988	28	21350	5	A, B, C, D, E, F	10/2016
F-16-SB	1995	21	24600	5	A, B, C, D, E, F	10/2016
E-17-PS	1994	22	13700	5	A, C, E	10/2016
F-05-P	1975	41	8850	5	A, B, C, D, E, F	10/2016
E-17-PT	1994	22	13700	5	A, C, E	10/2016
F-15-CR	1999	17	41800	7	A, B, C, D, E, F	10/2016
G-17-AM	1999	17	2100	5	A, B, C, D, E, F	10/2016
F-15-AA	1998	18	4900	7	A, B, C, D, E, F	10/2016
F-15-CY	1992	24	4900	7	A, B, C, D, E, F	10/2016
N-26-T	1992	24	2300	4	A, B, C, D, E, F	10/2016
N-26-R	1976	40	2300	4	A, B, C, D, E, F	10/2016
N-26-P	1976	40	3100	4	A, B, C, D, E, F	10/2016
G-17-BI	2003	13	34600	5	A, B, C, D, E, F	10/2016
F-17-CR	1999	17	95100	5	A, B, C, D, E, F	10/2016
G-17-T	1999	17	86500	5	A, B, C, D, E, F	10/2016
F-06-AA	1975	41	10100	5	A, B, C, D, E, F	10/2016

F-06-AE	1977	39	10100	5	A, B, C, D, E, F	10/2016
F-19-BG	1991	25	10500	5	A, B, C, D	10/2016
F-19-BI	1997	19	8500	5	A, B, C, D, E, F	10/2016
F-05-N†	1975	41	11900	5	A, B, C, D, E, F	10/2016
F-05-I†	1975	41	8850	5	A, B, C, D, E, F	10/2016
F-05-K	1975	41	8850	5	A, B, C, D, E, F	10/2016
F-06-AB	1975	41	10100	5	A, B, C, D, E, F	10/2016
F-05-L†	1975	41	8850	5	A, B, C, D, E, F	10/2016
F-06-AD	1977	39	10100	5	A, B, C, D, E, F	10/2016
F-05-O	1975	41	8850	5	A, B, C, D, E, F	10/2016
B-16-FX	1987	29	7500	5	A, B, C, D, E, F	10/2016
F-05-J†	1975	41	8850	5	A, B, C, D, E, F	10/2016
F-05-M†	1975	41	11900	5	A, B, C, D, E, F	10/2016
F-20-BW	1993	23	6200	5	A, B, C, D, E, F	10/2016
F-19-BF	1992	24	10500	5	A, C, E	10/2016
F-19-BH	1997	19	8500	5	A, B, C, F	10/2016
F-20-BX	1993	23	6200	5	A, B, C, D, E, F	10/2016

Note: *Combine year of built and reconstruction

† These 5 bridges were also sampled in the first delivery.

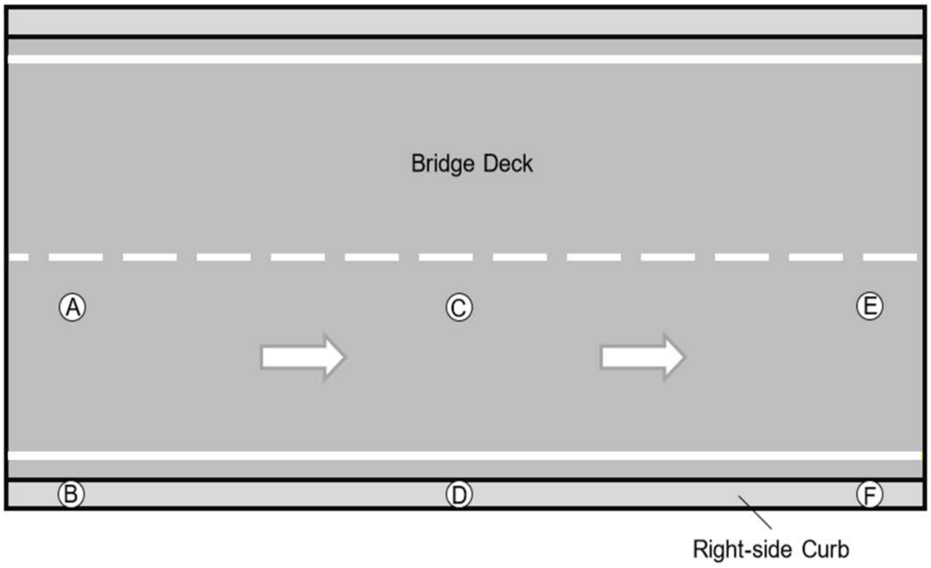


Figure 9. Drilling locations (plan view) on the deck and curb for both two-lane single direction and two-lane bi-directional bridges.

Most of the samples in the first delivery were taken from bridge decks; only a few samples were taken from the bridge curb. Samples in the second delivery were collected from six different locations on each bridge (Figure 9). Holes A, C, and E were located in the left wheel path of the right lane. Holes B, D, and F were located on the top of the curb directly to the right of the A-E row. Holes A and B were near the upstream end of the bridge. Holes E and F were near the downstream end of the bridge. Hole C and D were near the center of the length of the bridge.

4 LAB TESTING

Testing was done in the CU-Boulder lab. Water-soluble chloride concentration profiles of each sampling location were obtained by testing the concrete powder at 0.5, 1.0, 1.5 and 2.0 inches below the concrete surface following AASHTO T 260.

Chemical concentrations of other species, such as sodium, potassium, and magnesium were tested on selected samples. The selection is based on the chloride concentration at rebar level. Since the chloride concentration at rebar level is not very high (e.g. much lower than the critical value), the distributions of the other ions were not tested.

The equipment used for the water-soluble chloride concentration was an RCT-500 kit made by Germann Instrument (Figure 10). A 1.5-gram of powder was weighed and poured into a vial containing nine ml of extraction liquid. The vial was shaken vigorously for five min. A one ml of buffer solution was then added to the vial. The solution was filtered and tested for chloride concentration. The extraction liquid was <4% Hydrogen Peroxide. The buffer solution was <24% Hepes.

Figure 10. The RCT-500 Rapid Chloride Test Kit

5 ANALYSIS OF TEST RESULTS

The water-soluble chloride concentration (% Cl^- by concrete weight) of all the samples was obtained and the results are presented in Tables 2 and 3.

Table 2. Water-soluble chloride concentration of samples received 7/2014 (% Cl^- by concrete weight)

Brkey	O-26-E	M-23-F	M-21-F	P-18-AD	P-18-BS	M-20-O	P-17-AE	P-18-AX	N-26-Q
1	0.0218	0.0175	0.0032	0.0589	0.1495	0.0189	0.0907	0.1298	0.0278
2	0.0000	0.0189	0.0013	0.0131	0.0753	0.0212	0.0246	0.1314	0.0148
3	0.0000	0.0226	0.0000	0.0374	0.0747	0.0062	0.0000	0.0552	0.0074
4	0.0000	0.0091	0.0000	0.0264	0.0472	0.0000	0.0000	0.0095	0.0035
Brkey	**F-05-I (Deck)**	**F-05-L (Deck)**	**F-05-J (Deck)**	**F-05-N (Deck)**	**F-05-M (Deck)**	**N-26-G**	**H-07-I**	**G-09-I**	
1	0.1496	0.1658	0.1405	0.1684	0.0886	0.1229	0.0243	0.1638	
2	0.1181	0.1859	0.1556	0.1822	0.0192	0.0105	0.0310	0.1526	
3	0.0604	0.1303	0.1421	0.1496	0.0049	0.0060	0.0203	0.0932	
4	0.0332	0.0828	0.0932	0.0558	0.0000	0.0043	0.0139	0.0654	
Brkey	**F-05-I (Curb)**	**F-05-L (Curb)**	**F-05-J (Curb)**	**F-05-N (Curb)**	**F-05-M (Curb)**				
1	0.0628	0.0299	0.0398	0.1091	0.0434				
2	0.0476	0.0127	0.0478	0.0896	0.0230				
3	0.0259	0.0082	0.0604	0.0413	0.0107				
4	0.0122	0.0022	0.0429	0.0203	0.0016				

Table 3. Water-soluble chloride concentration of samples received 10/2016 (% Cl^- by concrete weight)

Brkey	F-15-BZ	F-15-BX	D-16-DK	D-16-DF	N-26-O	O-26-P	B-01-B	H-02-GK	D-16-DJ
A1*	0.0447	0.4751	0.0080	0.0024	0.2205	0.0372	0.0221	0.3155	0.0050
A2	0.0309	0.2571	0.1707	0.0213	0.0085	0.0024	0.0037	0.0115	0.0174
A3	0.0174	0.1256	0.1622	0.2997	0.0037	0.0020	0.0024	0.0044	0.1622
A4	0.0096	0.0464	0.1077	0.1464	0.0024	0.0020	0.0023	0.0031	0.1541
B1	0.2997	0.0972	0.1193	0.0316	0.0276	0.0247	0.0016	0.0185	0.0247
B2	0.1541	0.0526	0.0715	0.0256	0.0108	0.0096	0.0022	0.0080	0.0122
B3	0.0614	0.0431	0.0554	0.0102	0.0060	0.0053	0.0020	0.0115	0.0102
B4	0.0431	0.0229	0.0753	0.0085	0.0042	0.0042	0.0016	0.0091	0.0096

C1	0.2443	0.2205	0.0122	0.0050	0.1322	0.0431	0.0276	0.3678	0.0067
C2	0.1256	0.1322	0.0196	0.0247	0.0044	0.0063	0.0309	0.1891	0.0753
C3	0.0386	0.0554	0.0972	0.1622	0.0029	0.0019	0.0096	0.0464	0.1541
C4	0.0213	0.0287	0.0680	0.0924	0.0028	0.0022	0.0029	0.0050	0.0924
D1	0.4949	0.2443	0.0447	0.0792	0.0056	0.0174	0.0026	0.0256	0.0431
D2	0.2706	0.1134	0.0386	0.0400	0.0039	0.0063	0.0018	0.0213	0.0400
D3	0.1077	0.0500	0.0266	0.0297	0.0022	0.0037	0.0019	0.0213	0.0386
D4	0.0646	0.0614	0.0221	0.0229	0.0029	0.0035	0.0024	0.0174	0.0372
E1	0.2205	0.3678	0.0031	0.0309	0.1134	0.0526	0.0345	0.1891	0.0080
E2	0.0715	0.2571	0.0400	0.1464	0.0332	0.0080	0.0130	0.0256	0.0482
E3	0.0213	0.0680	0.0431	0.0680	0.0102	0.0050	0.0029	0.0047	0.0386
E4	0.0071	0.0266	0.0372	0.0447	0.0056	0.0029	0.0022	0.0024	0.0400
F1	0.3495	0.3320	0.0834	0.1891	0.0146	0.0276	0.0060	0.0256	0.0372
F2	0.1464	0.0614	0.0554	0.0792	0.0063	0.0047	0.0026	0.0196	0.0309
F3	0.0297	0.0431	0.0583	0.0431	0.0037	0.0060	0.0024	0.0115	0.0213
F4	0.0164	0.0155	0.0646	0.0256	0.0056	0.0047	0.0031	0.0067	0.0205

Brkey	**F-16-SB**	**E-17-PS**	**F-05-P**	**E-17-PT**	**F-15-CR**	**G-17-AM**	**F-15-AA**	**F-15-CY**	**N-26-T**
A1	0.0646	0.4288	0.1193	0.1891	0.3320	0.5000	0.2443	0.1322	0.0196
A2	0.0266	0.2321	0.0464	0.2321	0.0614	0.3155	0.0229	0.0372	0.0026
A3	0.0085	0.1256	0.0137	0.1391	0.0185	0.2095	0.0019	0.0196	0.0022
A4	0.0033	0.0834	0.0033	0.0792	0.0044	0.1797	0.0018	0.0085	0.0023
B1	0.0287		0.0297		0.2095	0.0464	0.1193	0.2205	0.0256
B2	0.0108		0.1464		0.0614	0.0164	0.1541	0.2205	0.0122
B3	0.0063		0.0256		0.0526	0.0053	0.0792	0.1707	0.0071
B4	0.0060		0.0060		0.0042	0.0028	0.0345	0.1077	0.0056
C1	0.3320	0.3320	0.1023	0.2571	0.2095	0.1797	0.3155	0.1023	0.0431
C2	0.0400	0.0972	0.0115	0.2997	0.0482	0.0309	0.0108	0.0400	0.0053
C3	0.0035	0.0715	0.0024	0.2571	0.0164	0.0035	0.0023	0.0213	0.0016
C4	0.0026	0.0415	0.0024	0.1797	0.0042	0.0029	0.0050	0.0085	0.0020
D1	0.0174		0.0102		0.1891	0.1193	0.1891	0.1464	0.0400
D2	0.0024		0.0753		0.0924	0.1134	0.0583	0.1134	0.0372
D3	0.0018		0.0415		0.0680	0.1464	0.0320	0.0792	0.0372
D4	0.0000		0.0146		0.0680	0.0972	0.0067	0.4075	0.0297
E1	0.2848	0.3320	0.0792	0.3155	0.1391	0.1391	0.4075	0.1322	0.0287
E2	0.0085	0.1991	0.0137	0.2321	0.0583	0.0238	0.0554	0.0583	0.0042
E3	0.0026	0.0415	0.0026	0.1464	0.0276	0.0056	0.0063	0.0320	0.0023
E4	0.0016	0.0115	0.0056	0.0878	0.0071	0.0020	0.0044	0.0196	0.0018
F1	0.0431		0.0164		0.1707	0.0309	0.2321	0.3320	0.0358
F2	0.0196		0.0583		0.0792	0.0266	0.1991	0.1991	0.0238
F3	0.0053		0.0056		0.0834	0.0221	0.0415	0.2095	0.0196

F4	0.0018		0.0026		0.0715	0.0238	0.0122	0.1193	0.0372
Brkey	**N-26-R**	**N-26-P**	**G-17-BI**	**F-17-CR**	**G-17-T**	**F-06-AA**	**F-06-AE**	**F-19-BG**	**F-19-BI**
A1	0.2321	0.4288	0.2443	0.0924	0.0715	0.0085	0.0130	0.1256	0.1134
A2	0.0076	0.0185	0.0924	0.0332	0.0174	0.1391	0.0091	0.0482	0.0878
A3	0.0017	0.0020	0.0071	0.0213	0.0044	0.0834	0.0080	0.0358	0.0482
A4	0.0022	0.0018	0.0022	0.0053	0.0026	0.0266	0.0060	0.0146	0.0345
B1	0.0130	0.0137	0.1256	0.0345	0.0554	0.0500	0.0526	0.0878	0.0526
B2	0.0039	0.0044	0.1023	0.0130	0.0386	0.0400	0.0056	0.0878	0.0447
B3	0.0028	0.0047	0.0415	0.0050	0.0320	0.0185	0.0024	0.0500	0.0287
B4	0.0024	0.0102	0.0164	0.0031	0.0205	0.0039	0.0015	0.0358	0.0287
C1	0.1622	0.3155	0.4288	0.0680	0.1707	0.0047	0.0174	0.1023	0.0834
C2	0.0091	0.0715	0.0500	0.0213	0.0358	0.0972	0.0792	0.0792	0.0646
C3	0.0037	0.0019	0.0029	0.0044	0.0229	0.0753	0.0256	0.0431	0.0309
C4	0.0031	0.0014	0.0028	0.0023	0.0115	0.0400	0.0108	0.0221	0.0332
D1	0.0174	0.0238	0.0753	0.0614	0.1622	0.0646	0.0320	0.1322	0.0482
D2	0.0247	0.0076	0.0715	0.0372	0.0646	0.0358	0.0044	0.0526	0.0680
D3	0.0071	0.0071	0.0431	0.0196	0.0345	0.0205	0.0017	0.0221	0.0320
D4	0.0039	0.0035	0.0146	0.0108	0.0238	0.0060	0.0015	0.0071	0.0205
E1	0.1707	0.2706	0.2571	0.1193	0.1622	0.0080	0.0031	0.1256	0.0526
E2	0.0102	0.0155	0.0972	0.0287	0.0583	0.0614	0.0108	0.0972	0.0297
E3	0.0024	0.0019	0.0146	0.0155	0.0205	0.0332	0.0091	0.0792	0.0164
E4	0.0017	0.0024	0.0022	0.0033	0.0122	0.0122	0.0067	0.0358	0.0063
F1	0.0115	0.0309	0.0878	0.0309	0.0464	0.0400	0.0256		0.0415
F2	0.0020	0.0332	0.0554	0.0080	0.0213	0.0155	0.0130		0.0247
F3	0.0000	0.0155	0.0122	0.0029	0.0155	0.0122	0.0035		0.0115
F4	0.0146	0.0164	0.0033	0.0022	0.0146	0.0039	0.0018		0.0063
Brkey	**F-05-N**	**F-05-I**	**F-05-K**	**F-06-AB**	**F-05-L**	**F-06-AD**	**F-05-O**	**B-16-FX**	**F-05-J**
A1	0.0358	0.0115	0.0056	0.0130	0.1391	0.0102	0.0164	0.2443	0.0115
A2	0.0526	0.0680	0.0482	0.0386	0.0878	0.0646	0.0924	0.0646	0.0386
A3	0.0715	0.0526	0.0646	0.0500	0.0320	0.0358	0.0320	0.0102	0.0972
A4	0.0447	0.0309	0.0238	0.0297	0.0080	0.0122	0.0091	0.0019	0.0415
B1	0.0266	0.0332	0.0122	0.0400	0.0130	0.0297	0.0146	0.0287	0.0213
B2	0.0067	0.0146	0.0037	0.0238	0.0050	0.0031	0.0020	0.0332	0.0185
B3	0.0024	0.0164	0.0031	0.0080	0.0056	0.0018	0.0022	0.0247	0.0185
B4	0.0037	0.0050	0.0029	0.0039	0.0039	0.0018	0.0022	0.0185	0.0108
C1	0.0102	0.0091	0.0060	0.0047	0.1193	0.0042	0.0056	0.0526	0.0053
C2	0.0792	0.0715	0.0646	0.0715	0.0372	0.0500	0.0047	0.0309	0.0646
C3	0.1797	0.0122	0.0924	0.0482	0.0108	0.0500	0.0044	0.0080	0.0753
C4	0.1256	0.0015	0.0309	0.0256	0.0060	0.0108	0.0060	0.0020	0.0060

D1	0.0221	0.0091	0.0213	0.0372	0.0415	0.0320	0.0320	0.1707	0.0332
D2	0.0023	0.0164	0.0164	0.0229	0.0229	0.0080	0.0155	0.0447	0.0102
D3	0.0020	0.0026	0.0155	0.0067	0.0063	0.0024	0.0205	0.0276	0.0042
D4	0.0047	0.0028	0.0146	0.0037	0.0035	0.0023	0.0091	0.0122	0.0029
E1	0.0096	0.0039	0.0067	0.0035	0.1023	0.0033	0.0164	0.0372	0.0037
E2	0.0400	0.1023	0.0044	0.0164	0.0431	0.0464	0.2706	0.0266	0.1134
E3	0.1193	0.0583	0.0044	0.0345	0.0256	0.0386	0.1891	0.0146	0.1193
E4	0.0431	0.0332	0.0042	0.0164	0.0115	0.0174	0.1134	0.0028	0.0400
F1	0.0213	0.0266	0.0924	0.0554	0.0063	0.0386	0.0056	0.2095	0.0386
F2	0.0108	0.0060	0.0196	0.0229	0.0029	0.0102	0.0309	0.1077	0.0266
F3	0.0060	0.0017	0.0067	0.0063	0.0026	0.0017	0.0026	0.0358	0.0122
F4	0.0022	0.0000	0.0102	0.0033	0.0033	0.0015	0.0023	0.0185	0.0076
Brkey	**F-05-M**	**F-20-BW**	**F-19-BF**	**F-19-BH**	**F-20-BX**				
A1	0.0071	0.1991	0.1193	0.1322	0.2848				
A2	0.0229	0.1541	0.0372	0.0878	0.1193				
A3	0.0715	0.2571	0.0102	0.0614	0.0358				
A4	0.0221	0.1023	0.0037	0.0332	0.0185				
B1	0.0276	0.1023		0.0924	0.1023				
B2	0.0031	0.0646		0.0646	0.0431				
B3	0.0020	0.0287		0.0386	0.0185				
B4	0.0020	0.0096		0.0196	0.0080				
C1	0.0071	0.2321	0.2571	0.2848	0.1256				
C2	0.0256	0.5539	0.0464	0.2443	0.0266				
C3	0.1541	0.2571	0.0085	0.1023	0.0071				
C4	0.0878	0.0447	0.0014	0.0332	0.0017				
D1	0.0130	0.0924			0.1256				
D2	0.0063	0.0878			0.0482				
D3	0.0033	0.0464			0.0415				
D4	0.0023	0.0164			0.0372				
E1	0.0047	0.3678	0.2997		0.2706				
E2	0.0155	0.2321	0.2321		0.0680				
E3	0.1256	0.2205	0.0447		0.0063				
E4	0.1077	0.0256	0.0035		0.0016				
F1	0.0276	0.1077		0.2571	0.1322				
F2	0.0071	0.1193		0.1797	0.0834				
F3	0.0023	0.0500		0.0500	0.0646				
F4	0.0000	0.0309		0.0229	0.0614				

Note: * The first letter means the location of that sample (Figure 9) and the number indicates its depth. For example, sample A1 is the top sample from Hole A.

5.1 Data processing methods

5.1.1 Irregular samples

To analyze the results, the chloride concentration profile needs to be obtained and their trends should be reasonable. However, some cores in several bridges showed irregular chloride concentration profiles without any clear trend; these are listed in Table 4. Some of these irregular profiles are plotted in Figure 11. In general, most of them had their lowest (instead of highest) chloride concentration at 0.5” depth and the highest concentration was observed at deeper levels. More than one location on the bridge showed this kind of trend. A similar trend was usually observed for all the locations on the deck or the curb of the bridge. The most probable explanation is that these irregular samples were taken in late May and June where heavy rain may have washed away chloride ions. In addition, some powder collected at different depths of concrete cores may come from aggregates, which may have a much lower chloride concentration level than the surrounding hardened cement paste. Some samples may have come from areas of repaired concrete, which can have a different chloride concentration profile compared with the surrounding concrete.

Table 4. Samples with irregular chloride concentration profiles

Brkey	Location
D-16-DK	A, C, E
D-16-DF	A, C, E
D-16-DJ	A, C, E
F-06-AA	A, C, E
F-05-N*	A, C, E
F-05-I	A, C, E
F-05-K	A, C, E
F-06-AB	A, C, E
F-06-AD	A, C, E
F-05-O	A, C, E
F-05-J*	A, C, E
F-05-M	A, C, E
B-01-B	B, D, F
F-05-P	B, D, F
F-15-CY	D
N-26-T	F
F-06-AE	C, E
F-20-BW	A, C
M-23-F	Deck
F-05-L	Deck
F-05-J	Deck and Curb

F-05-N	Deck
H-07-I	Deck

Note: *Bridges were also sampled in the first delivery.

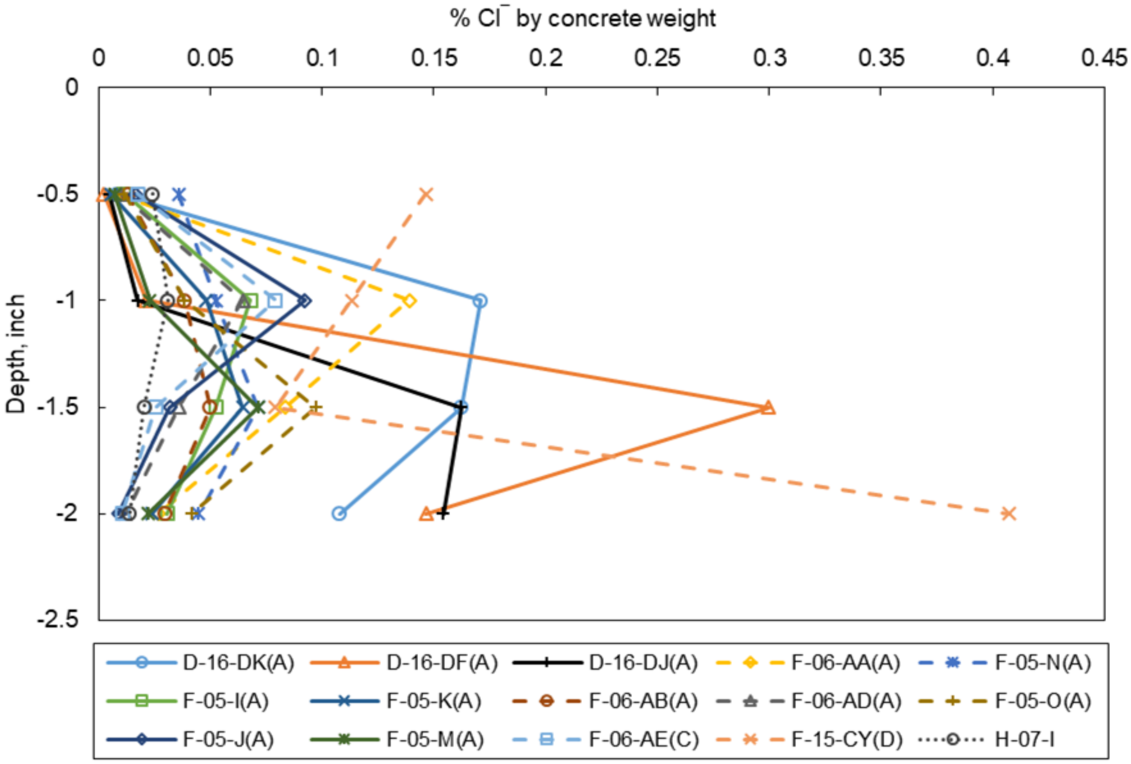
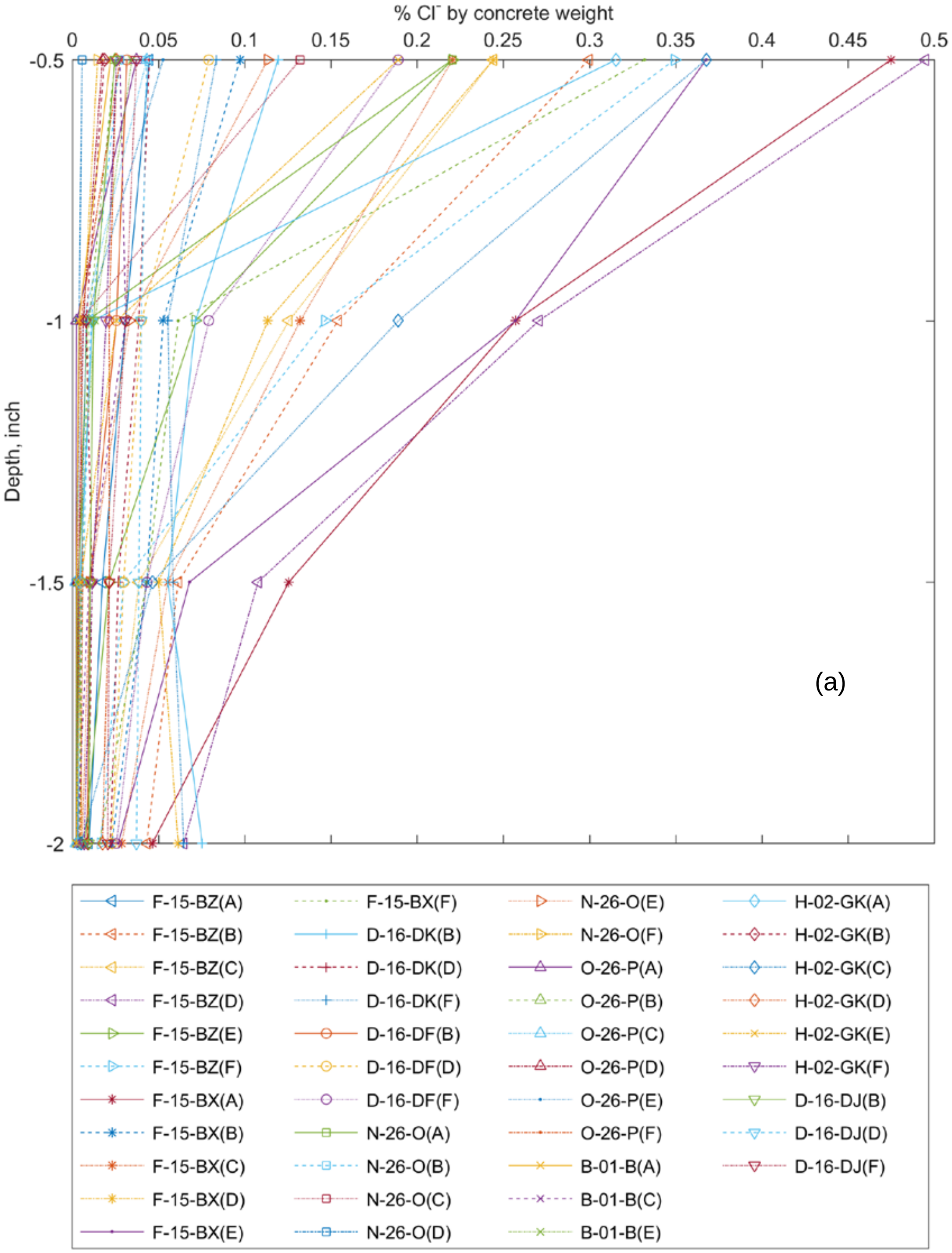
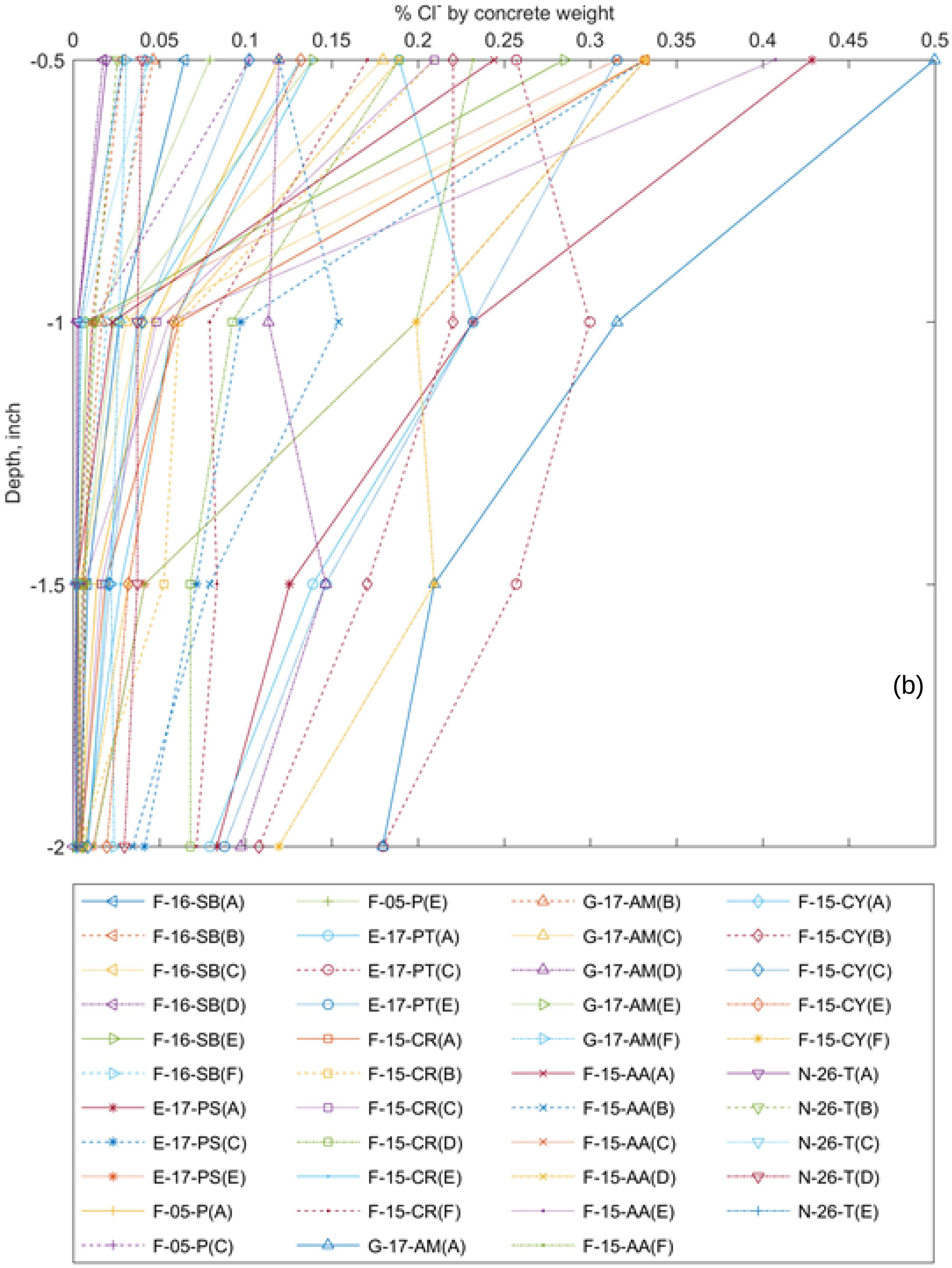


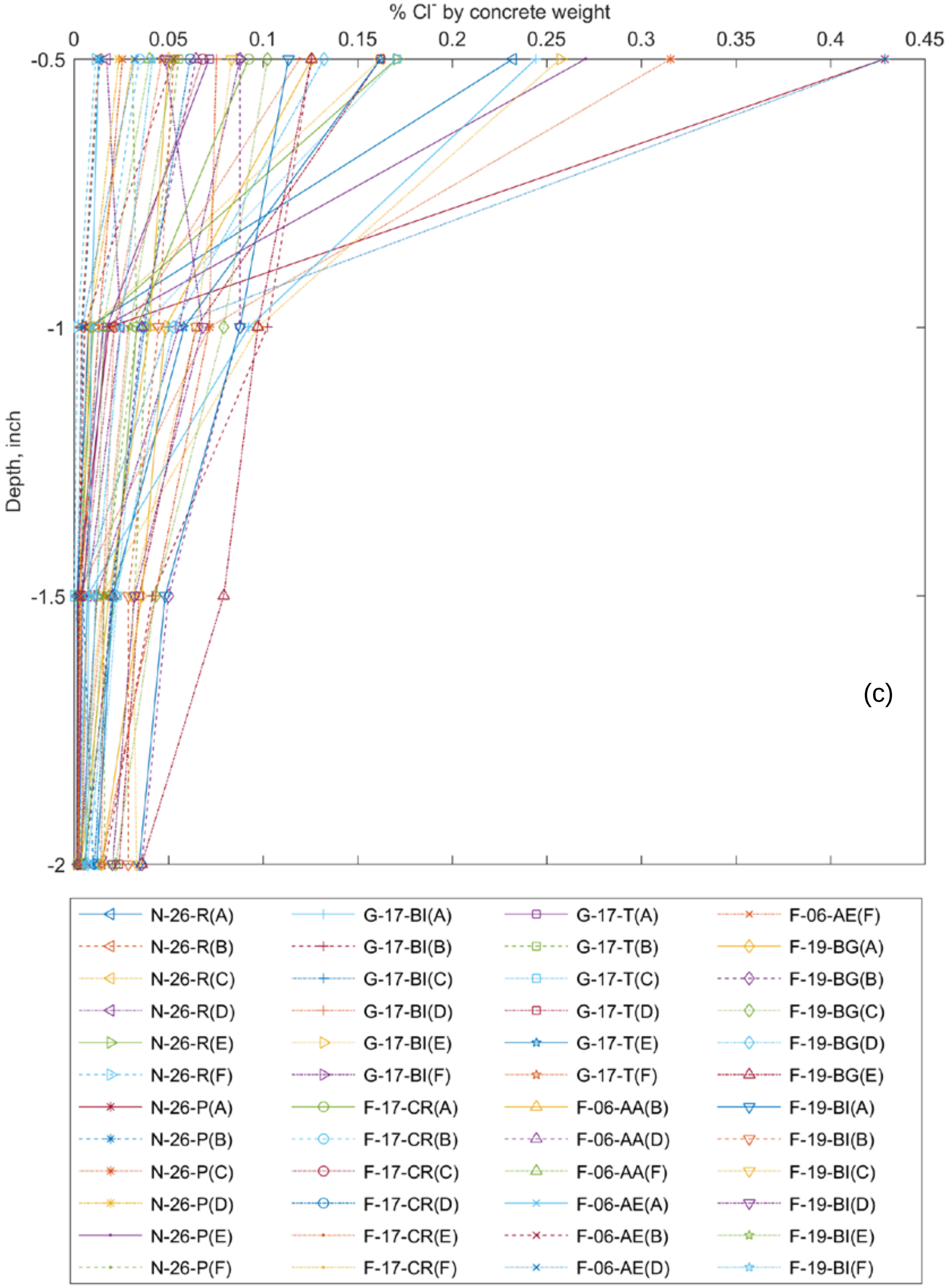
Figure 10. Chloride concentration profiles of irregular samples

5.1.2 Chloride concentration profiles

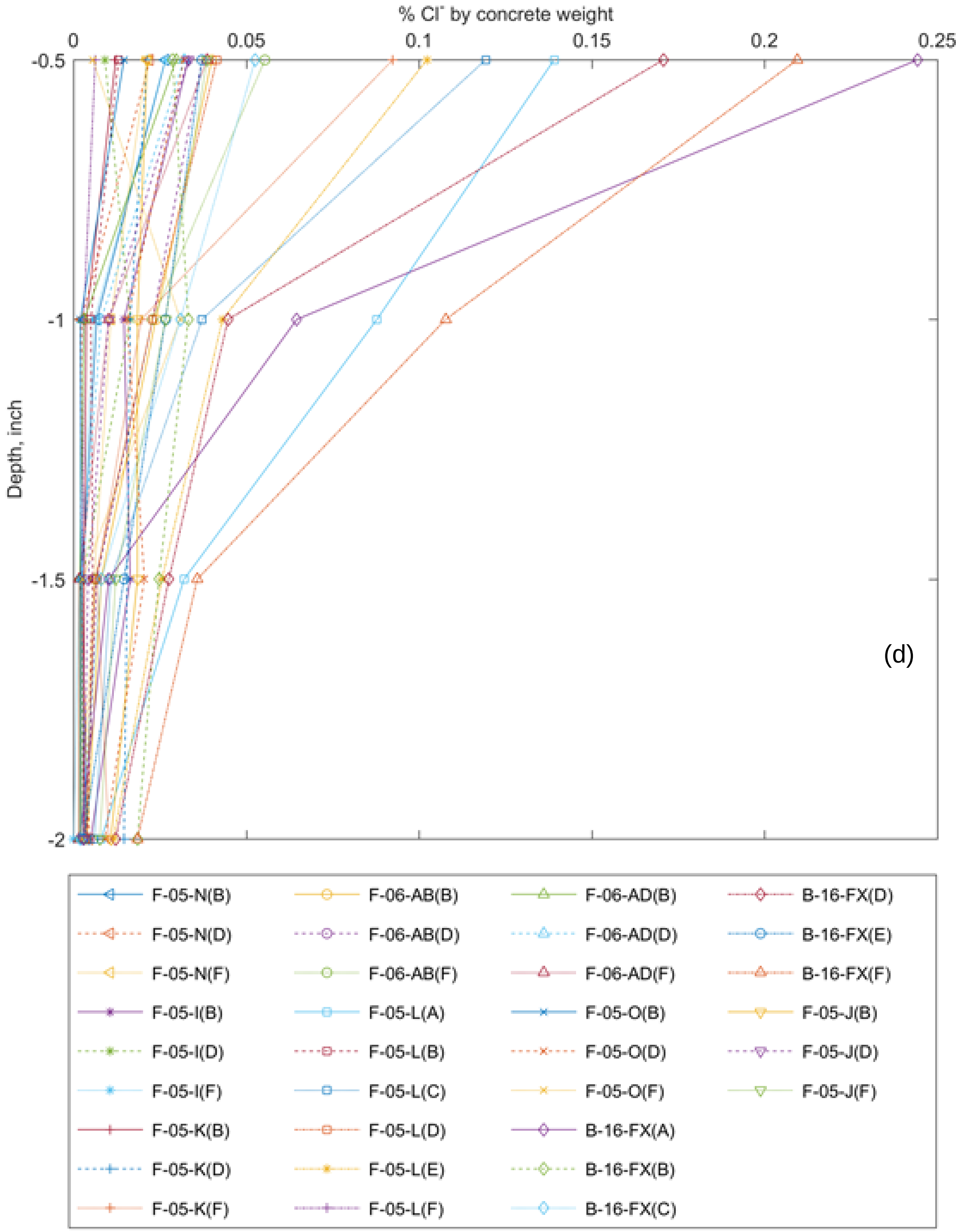
After excluding the irregular samples listed in Table 4, the chloride concentration profiles for the remaining locations were plotted (Figure 12). Most of the concrete cores had the highest chloride concentration at 0.5” depth and the lowest concentration at the 2.0” depth.


% Cl⁻ by concrete weight
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
-0.5
-1
-1.5
-2
Depth, inch
(a)
F-15-BZ(A)
F-15-BZ(B)
F-15-BZ(C)
F-15-BZ(D)
F-15-BZ(E)
F-15-BZ(F)
F-15-BX(A)
F-15-BX(B)
F-15-BX(C)
F-15-BX(D)
F-15-BX(E)
F-15-BX(F)
D-16-DK(B)
D-16-DK(D)
D-16-DK(F)
D-16-DF(B)
D-16-DF(D)
D-16-DF(F)
N-26-O(A)
N-26-O(B)
N-26-O(C)
N-26-O(D)
N-26-O(E)
N-26-O(F)
O-26-P(A)
O-26-P(B)
O-26-P(C)
O-26-P(D)
O-26-P(E)
O-26-P(F)
B-01-B(A)
B-01-B(C)
B-01-B(E)
H-02-GK(A)
H-02-GK(B)
H-02-GK(C)
H-02-GK(D)
H-02-GK(E)
H-02-GK(F)
D-16-DJ(B)
D-16-DJ(D)
D-16-DJ(F)


% Cl- by concrete weight
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Depth, inch
-0.5
-1
-1.5
-2
(b)
F-16-SB(A)
F-16-SB(B)
F-16-SB(C)
F-16-SB(D)
F-16-SB(E)
F-16-SB(F)
E-17-PS(A)
E-17-PS(C)
E-17-PS(E)
F-05-P(A)
F-05-P(C)
F-05-P(E)
E-17-PT(A)
E-17-PT(C)
E-17-PT(E)
F-15-CR(A)
F-15-CR(B)
F-15-CR(C)
F-15-CR(D)
F-15-CR(E)
F-15-CR(F)
G-17-AM(A)
G-17-AM(B)
G-17-AM(C)
G-17-AM(D)
G-17-AM(E)
G-17-AM(F)
F-15-AA(A)
F-15-AA(B)
F-15-AA(C)
F-15-AA(D)
F-15-AA(E)
F-15-AA(F)
F-15-CY(A)
F-15-CY(B)
F-15-CY(C)
F-15-CY(E)
F-15-CY(F)
N-26-T(A)
N-26-T(B)
N-26-T(C)
N-26-T(D)
N-26-T(E)



% Cl⁻ by concrete weight
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
Depth, inch
-0.5
-1
-1.5
-2
(c)
N-26-R(A)
N-26-R(B)
N-26-R(C)
N-26-R(D)
N-26-R(E)
N-26-R(F)
N-26-P(A)
N-26-P(B)
N-26-P(C)
N-26-P(D)
N-26-P(E)
N-26-P(F)
G-17-BI(A)
G-17-BI(B)
G-17-BI(C)
G-17-BI(D)
G-17-BI(E)
G-17-BI(F)
F-17-CR(A)
F-17-CR(B)
F-17-CR(C)
F-17-CR(D)
F-17-CR(E)
F-17-CR(F)
G-17-T(A)
G-17-T(B)
G-17-T(C)
G-17-T(D)
G-17-T(E)
G-17-T(F)
F-06-AA(B)
F-06-AA(D)
F-06-AA(F)
F-06-AE(A)
F-06-AE(B)
F-06-AE(D)
F-06-AE(F)
F-19-BG(A)
F-19-BG(B)
F-19-BG(C)
F-19-BG(D)
F-19-BG(E)
F-19-BI(A)
F-19-BI(B)
F-19-BI(C)
F-19-BI(D)
F-19-BI(E)
F-19-BI(F)


% Cl⁻ by concrete weight
0
0.05
0.1
0.15
0.2
0.25
Depth, inch
-0.5
-1
-1.5
-2
(d)
F-05-N(B)
F-05-N(D)
F-05-N(F)
F-05-I(B)
F-05-I(D)
F-05-I(F)
F-05-K(B)
F-05-K(D)
F-05-K(F)
F-06-AB(B)
F-06-AB(D)
F-06-AB(F)
F-05-L(A)
F-05-L(B)
F-05-L(C)
F-05-L(D)
F-05-L(E)
F-05-L(F)
F-06-AD(B)
F-06-AD(D)
F-06-AD(F)
F-05-O(B)
F-05-O(D)
F-05-O(F)
B-16-FX(A)
B-16-FX(B)
B-16-FX(C)
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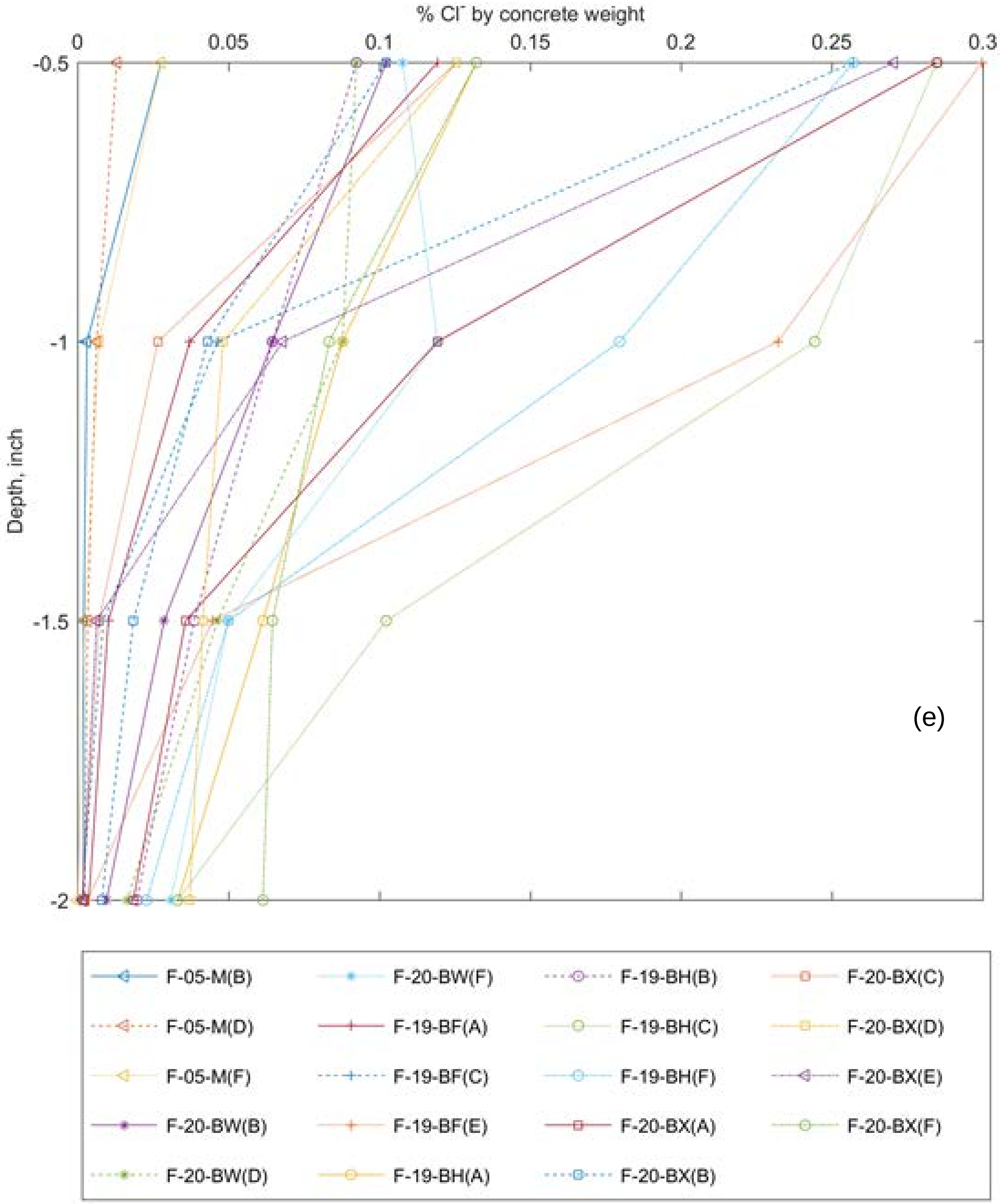
F-05-J(B)
F-05-J(D)
F-05-J(F)


% Cl⁻ by concrete weight
0
0.05
0.1
0.15
0.2
0.25
0.3
-0.5
-1
-1.5
-2
Depth, inch
(e)
F-05-M(B)
F-05-M(D)
F-05-M(F)
F-20-BW(B)
F-20-BW(D)
F-20-BW(F)
F-19-BF(A)
F-19-BF(C)
F-19-BF(E)
F-19-BH(A)
F-19-BH(B)
F-19-BH(C)
F-19-BH(F)
F-20-BX(A)
F-20-BX(B)
F-20-BX(C)
F-20-BX(D)
F-20-BX(E)
F-20-BX(F)

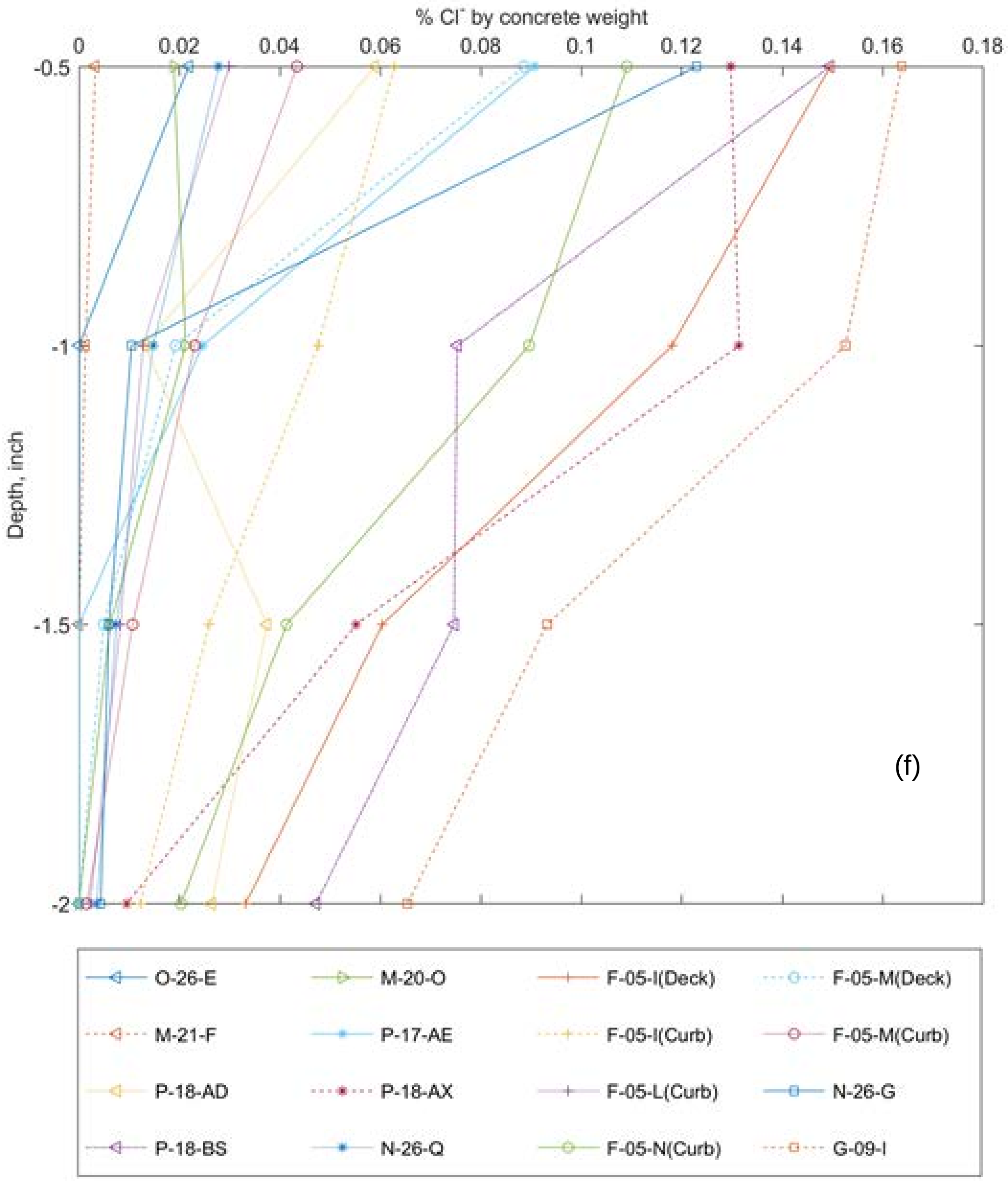


Figure 11. Bridge chloride concentration profiles (irregular concentration profiles excluded)

5.1.3 Comparison between the two deliveries

Five bridges were sampled twice in the two deliveries, as noted in Table 1. Each is plotted in Figure 13. Comparing the profiles from the same bridge (identical color) obtained from the samples in 2014 and 2016, the concentrations obtained from the first delivery (solid line) are much greater than those from the second delivery (dash line). Therefore, the two sets of data from these two deliveries are not comparable and should be analyzed separately.

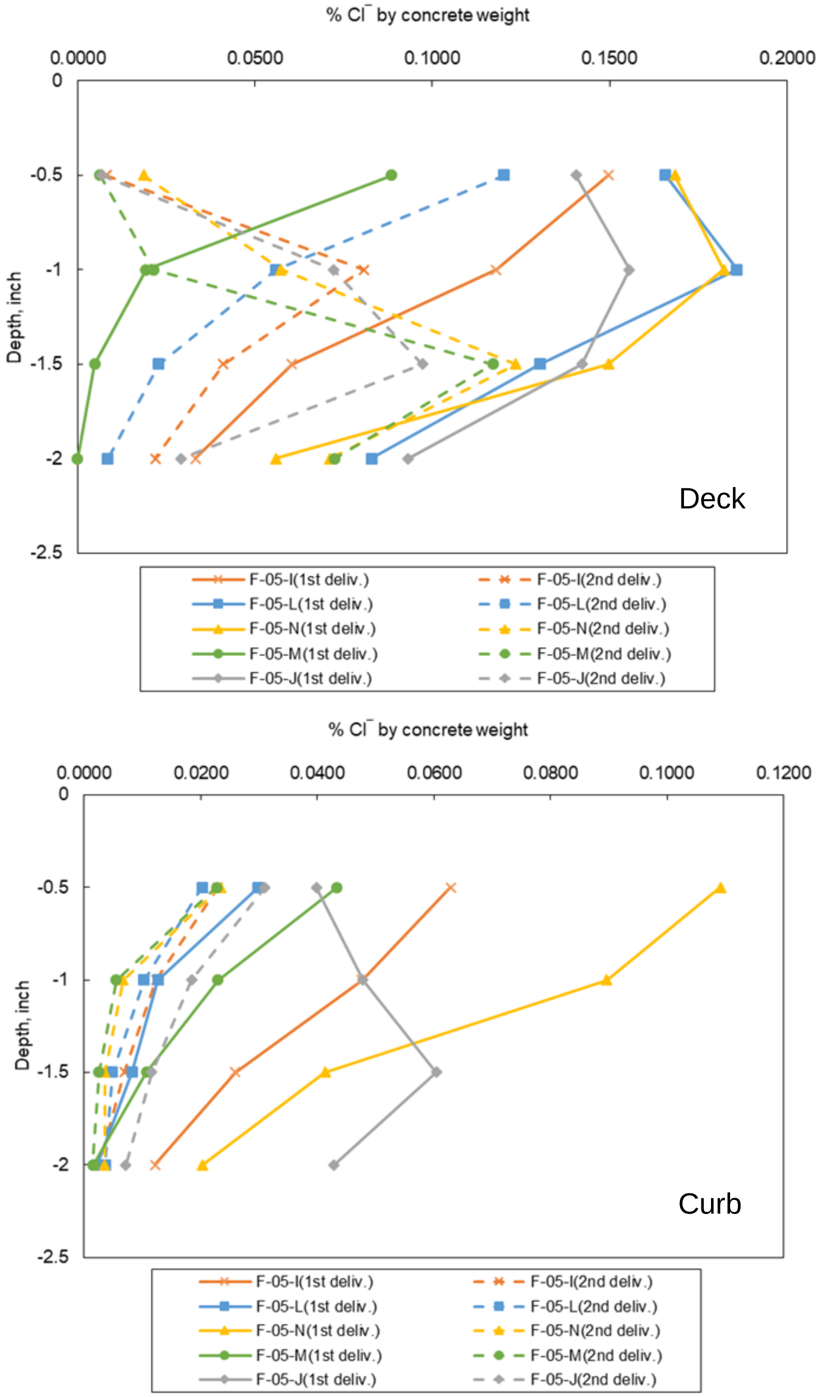


Figure 12. Comparison between chloride concentration profiles of the bridges sampled in both deliveries.

5.1.4 Average chloride concentrations

Since the primary concern of this project was the overall chloride concentration of each bridge at different depths, chloride concentrations of the three locations on the bridge deck and curb were averaged for the samples in the second delivery. The chloride concentrations at locations A, C, and E were averaged for the chloride concentrations of the decks. The chloride concentrations at locations B, D, and F were averaged for the chloride concentrations of the curbs. Irregular samples were excluded.

Final test data is listed in Table 5 and Table 6 as well as information from the bridge samples shown in Table 1, which was used to analyze the correlations among chloride levels and the selected influential factors. With the effect of multiple influential factors, evaluating the effect of a single factor on chloride concentrations was done by eliminating the effects of other factors. For instance, if samples from bridge decks in the same climate zone with the same age are selected, then the effect of traffic level can be analyzed. However, the sample sizes were not large enough for some of the influential factors.

Table 5. Water-soluble chloride concentration of bridges, 1st delivery in 2014 (% Cl^- by concrete weight)

Brkey	Deck				Curb			
	0.5	1	1.5	2	0.5	1	1.5	2
O-26-E	0.0218	0.0000	0.0000	0.0000				
M-21-F	0.0032	0.0013	0.0000	0.0000				
P-18-AD	0.0589	0.0131	0.0374	0.0264				
P-18-BS	0.1495	0.0753	0.0747	0.0472				
M-20-O	0.0189	0.0212	0.0062	0.0000				
P-17-AE	0.0907	0.0246	0.0000	0.0000				
P-18-AX	0.1298	0.1314	0.0552	0.0095				
N-26-Q	0.0278	0.0148	0.0074	0.0035				
N-26-G	0.1229	0.0105	0.0060	0.0043				
F-05-I	0.1496	0.1181	0.0604	0.0332	0.0628	0.0476	0.0259	0.0122
F-05-L					0.0299	0.0127	0.0082	0.0022
F-05-N					0.1091	0.0896	0.0413	0.0203
F-05-M	0.0886	0.0192	0.0049	0.0000	0.0434	0.0230	0.0107	0.0016
G-09-I	0.1638	0.1526	0.0932	0.0654				

Table 6. Average water-soluble chloride concentration of bridges, 2nd delivery in 2016 (% Cl^- by concrete weight)

Brkey	Deck Average				Curb Average			
	0.5	1	1.5	2	0.5	1	1.5	2
F-15-BZ	0.1698	0.0760	0.0258	0.0127	0.3814	0.1904	0.0663	0.0414
F-15-BX	0.3545	0.2155	0.0830	0.0339	0.2245	0.0758	0.0454	0.0333
D-16-DK					0.0825	0.0552	0.0468	0.0540
D-16-DF					0.1000	0.0483	0.0277	0.0190
N-26-O	0.1554	0.0154	0.0056	0.0036	0.0159	0.0070	0.0040	0.0042
O-26-P	0.0443	0.0056	0.0030	0.0024	0.0233	0.0069	0.0050	0.0041
B-01-B	0.0281	0.0158	0.0050	0.0025				
H-02-GK	0.2908	0.0754	0.0185	0.0035	0.0233	0.0163	0.0148	0.0111
D-16-DJ					0.0350	0.0277	0.0234	0.0224
F-16-SB	0.2271	0.0251	0.0049	0.0025	0.0297	0.0110	0.0045	0.0026
E-17-PS	0.3643	0.1761	0.0796	0.0455				
F-05-P	0.1003	0.0239	0.0063	0.0038				
E-17-PT	0.2539	0.2546	0.1809	0.1156				
F-15-CR	0.2269	0.0559	0.0209	0.0053	0.1898	0.0777	0.0680	0.0479
G-17-AM	0.2729	0.1234	0.0729	0.0616	0.0655	0.0521	0.0579	0.0413
F-15-AA	0.3224	0.0297	0.0035	0.0038	0.1802	0.1372	0.0509	0.0178
F-15-CY	0.1222	0.0452	0.0243	0.0122	0.2763	0.2098	0.1901	0.1135
N-26-T	0.0305	0.0040	0.0020	0.0021	0.0328	0.0247	0.0222	0.0177
N-26-R	0.1883	0.0090	0.0026	0.0023	0.0140	0.0102	0.0033	0.0070
N-26-P	0.3383	0.0352	0.0020	0.0019	0.0228	0.0151	0.0091	0.0100
G-17-BI	0.3101	0.0799	0.0082	0.0024	0.0962	0.0764	0.0323	0.0114
F-17-CR	0.0932	0.0277	0.0137	0.0036	0.0422	0.0194	0.0092	0.0054
G-17-T	0.1348	0.0372	0.0160	0.0088	0.0880	0.0415	0.0273	0.0196
F-06-AA					0.0515	0.0304	0.0171	0.0046
F-06-AE	0.0130	0.0091	0.0080	0.0060	0.0368	0.0077	0.0026	0.0016
F-19-BG	0.1178	0.0749	0.0527	0.0242	0.1100	0.0702	0.0361	0.0215
F-19-BI	0.0831	0.0607	0.0318	0.0247	0.0474	0.0458	0.0241	0.0185
F-05-I					0.0230	0.0123	0.0069	0.0026
F-05-N					0.0233	0.0066	0.0035	0.0035
F-05-K					0.0420	0.0133	0.0084	0.0092

F-06-AB					0.0442	0.0232	0.0070	0.0037
F-05-L	0.1203	0.0560	0.0228	0.0085	0.0203	0.0103	0.0049	0.0036
F-06-AD					0.0334	0.0071	0.0020	0.0019
F-05-O					0.0174	0.0161	0.0084	0.0045
B-16-FX	0.1114	0.0407	0.0110	0.0022	0.1363	0.0619	0.0294	0.0164
F-05-J					0.0310	0.0184	0.0116	0.0071
F-05-M					0.0227	0.0055	0.0026	0.0015
F-20-BW	0.3678	0.2321	0.2205	0.0256	0.1008	0.0906	0.0417	0.0190
F-19-BF	0.2254	0.1052	0.0212	0.0029				
F-19-BH	0.2085	0.1660	0.0819	0.0332	0.1747	0.1221	0.0443	0.0213
F-20-BX	0.2270	0.0713	0.0164	0.0073	0.1200	0.0582	0.0415	0.0355

5.2 Analyses of the influential factors

5.2.1 Chloride concentration level at 2” depth vs. the critical value

The deepest concrete powder collected was at a depth of 2-inches, with the rebar level of bridges usually at or below this depth. To evaluate possible corrosion damage of the rebar, the chloride concentration level at 2” depth should be compared to the critical chloride concentration. Table 7 lists several available critical chloride concentrations, C_{cri}, in the literature. C_{cri} is not a constant because the onset of rebar corrosion does not depend only on C_{cri}. This is because the corrosion process of rebar is an electrochemical process. Other influential parameters playing important roles in the electrochemical process consist of moisture content of the concrete and pH value of the pore solution near the rebar. Two different values for C_{cri} were used in this project. One is considered as the regular value, C_{cri} = 0.05%, which has been used widely in the research community. The other is considered as the conservative critical value, C_{cri} = 0.021 %. Histograms of chloride concentrations at 2” depth for all the bridge decks and curbs are shown in Figure 14. The chloride concentrations near rebar level of most of the bridge decks are below these critical values.

Table 7. Common critical chloride concentrations found in literature

Literature Source	Critical chloride content
Berke (1986)	0.039%-0.043%
Browne (1982)	0.055%
FHWA	0.0413%
ACI (1994)	0.021%
Cady and Weyers (1992)	0.025-0.05%

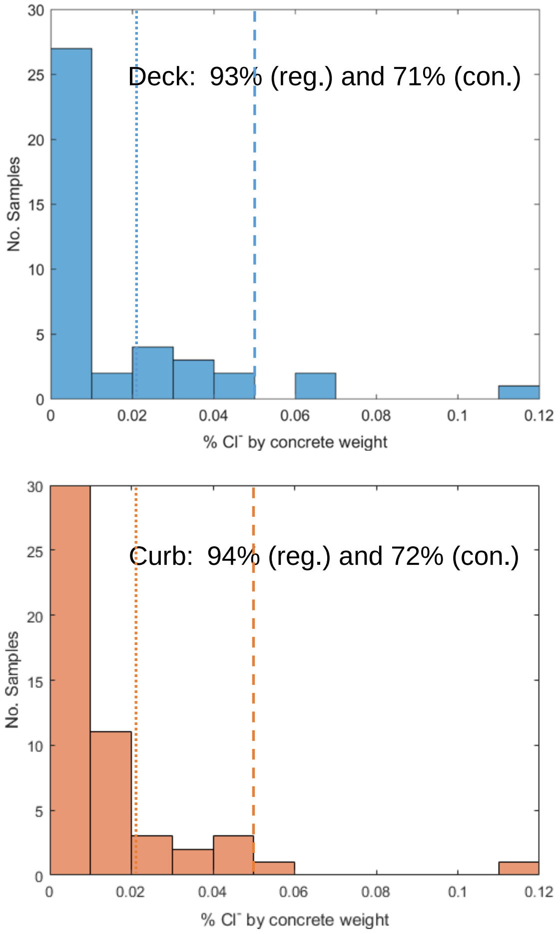


Figure 13. Histogram of chloride concentrations at 2” depth (dotted line and dashed line show the conservative critical value and regular critical value, respectively)

5.2.2 Effect of location on bridge structures: decks vs. curbs

The chloride concentrations of the decks and curbs at the same depth were compared and the ratios were plotted in Figure 15. In general, the chloride concentrations of the bridge decks were much greater than those of the bridge curbs since deicers and traffic are applied directly onto decks. However, the differences between decks and curbs decreased with increases in depth (Figure 15). At 2”, the average chloride concentration of the curb was even greater than that of the deck. This indicates that the bridge curbs suffered deeper chloride penetration than the bridge decks. This may be due to the lower concrete quality of the bridge curb compared to that of the bridge deck. In addition, snow accumulates on the roadsides after snow removal; resulting water from melting snow may drive the chloride deeper into the concrete. Curbs also contain water and deicer from draining off the bridge deck.

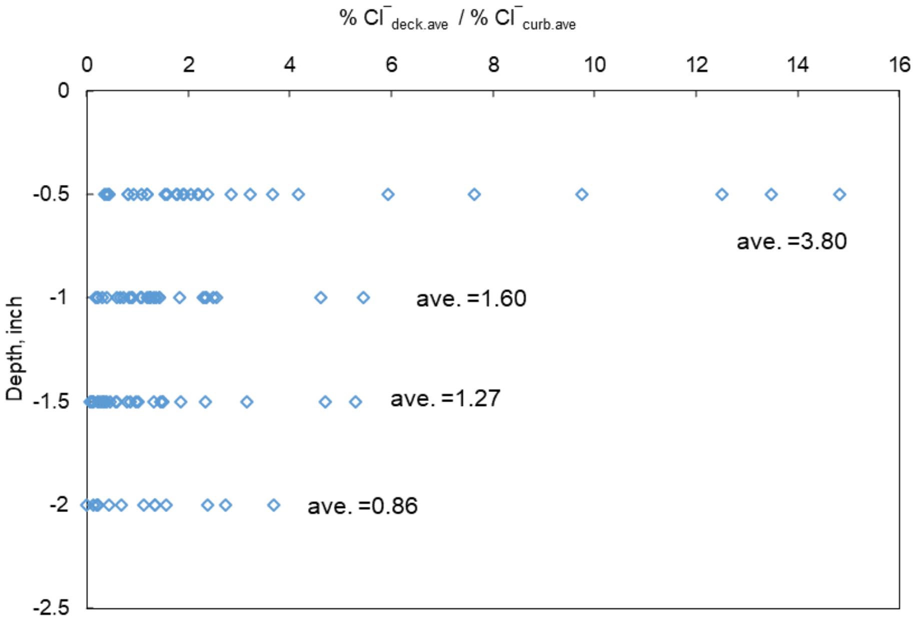


Figure 14. Ratios of chloride concentrations of decks to that of curbs at different depths

5.2.3 Effect of age

Chloride concentration profiles of the bridge decks with different ages were plotted in Figure 16 and Figure 17. The bridges plotted were all in climate zone 4 and have similar traffic levels. The younger bridges had much lower chloride concentrations, showing that the age of the concrete had a strong impact on the chloride concentrations of the bridges in climate zone 4. However, the age effect is getting weaker along the depth. As one can see in Table 5 and Table 6, chloride concentrations near rebar level of the very old bridges (up to 55 years) are still under regular critical value. No clear age effect was observed for bridges in climate zone 5. Not enough data was available to analyze the age effect in climate zones 6 and 7.

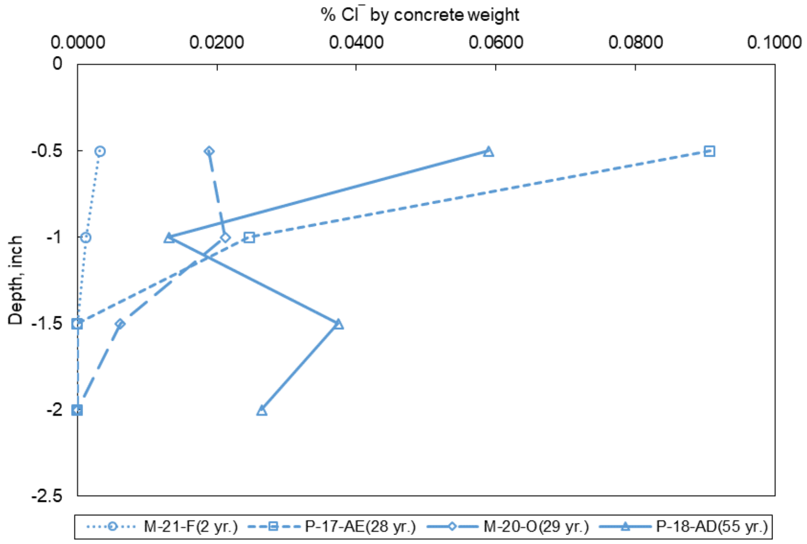


Figure 15. Chloride concentration profiles of bridges with different ages (1st delivery, deck, ADT<1000; climate zone 4)

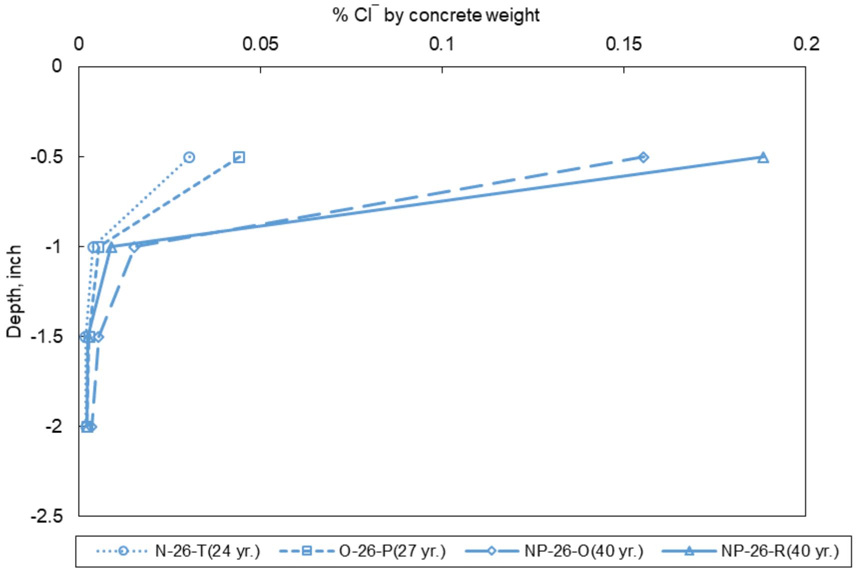


Figure 16. Chloride concentration profiles of bridges with different ages (2nd delivery, deck, 2300<ADT<3100; climate zone 4)

5.2.4 Effect of traffic level

Chloride concentration profiles of bridge decks with different traffic levels were plotted in Figure 18 and Figure 19. The bridges plotted were all in the same zone and had similar ages. Heavier traffic resulted in higher chloride concentrations for both ages in climate zone 4 (Fig. 18). Heavier traffic also led to higher chloride concentration for bridges with similar ages in climate zone 7 (Fig. 19). Therefore, traffic level has an apparent effect on the chloride concentration of the bridges in climate zones 4 and 7, since more deicer was used on roads with higher traffic volume. No clear traffic effect was observed for bridges in climate zone 5. There was not enough data available to analyze the bridges in climate zone 6.

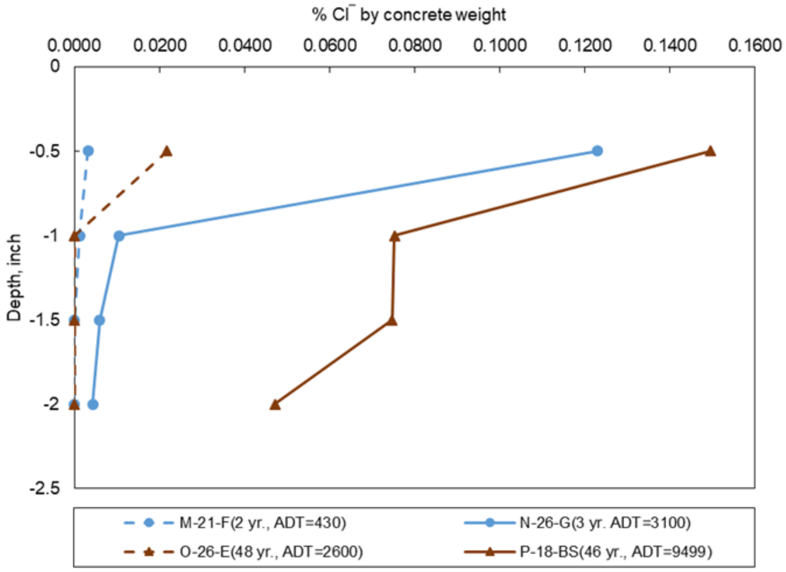


Figure 17. Chloride concentration profiles of bridges with different ADTs (1st delivery, deck; climate zone 4)

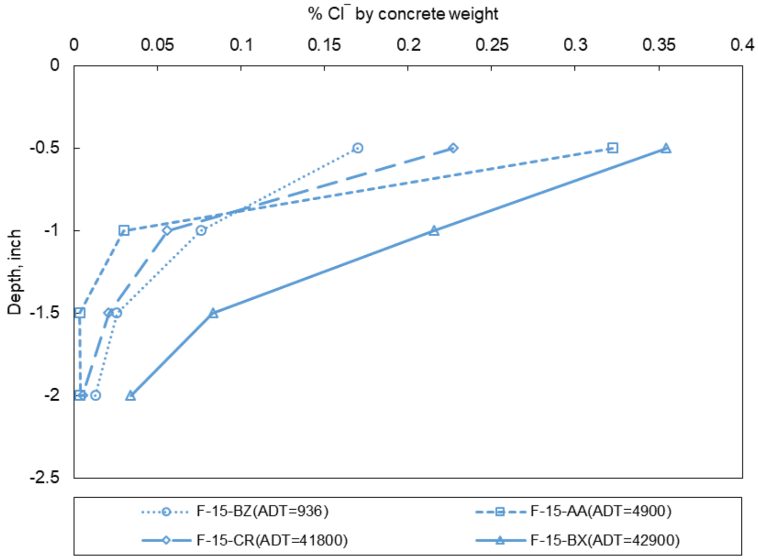


Figure 18. Chloride concentration profiles of bridges with different ADTs (2nd delivery, deck, age 17-18 yr; climate zone 7)

5.2.5 Effect of climate

Chloride concentration profiles of bridge decks with similar age and traffic levels but different weather were plotted in Figure 20 for the first delivery. Figure 21 shows the chloride concentration of the bridges vs. climate zone at different depths. Even though these bridges have different ages and traffic levels, very clear trends can be observed. Bridges built in colder regions have a higher chloride concentration up to 2” depth (the rebar level). This is because more deicing chemicals are usually used in cold regions than warm regions. Climate may be the most significant influential factor for chloride concentration of bridge decks in Colorado.

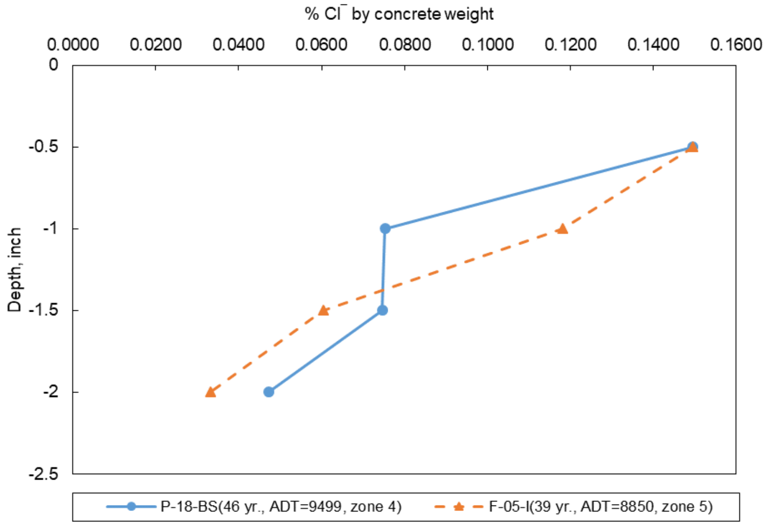


Figure 19. Chloride concentration profiles of the bridges with different weather (1st delivery, deck)

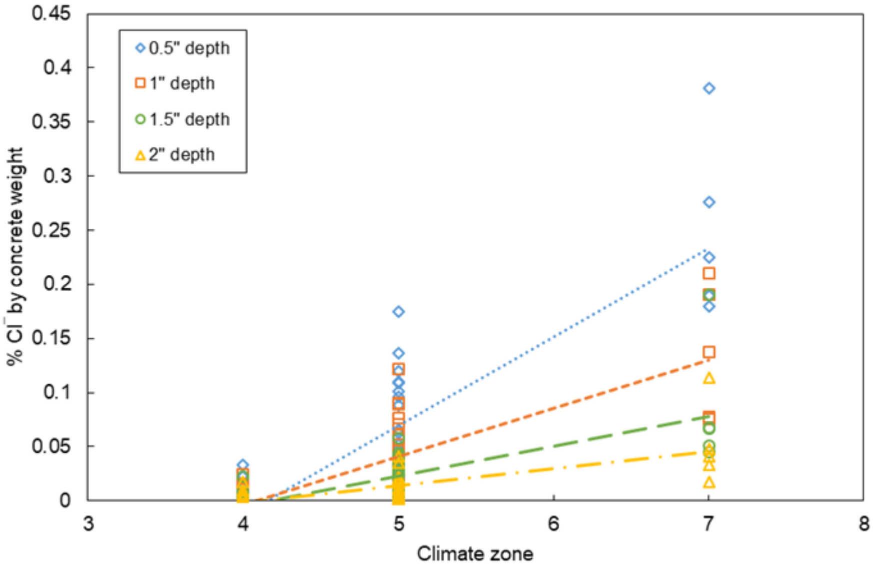


Figure 20. Chloride concentration of the bridges vs. climate zone at different depths (2nd delivery, variable ADT and age)

6 SUMMARY AND CONCLUSIONS

- A literature search showed that large-scale (statewide/nationwide) examinations/surveys in the published domain about deicer-induced chloride penetration in bridge decks are very limited. Available studies indicate that age of the concrete, traffic level, and weather condition are the three factors that can affect chloride concentration level in bridge decks significantly and should be considered in this study.

- The influential factors selected for this study are four climate regions 4, 5, 6 and 7; three traffic levels, low (ADT<=7000), medium (7000<ADT<=40000) and high (ADT>40000); and three age ranges, 10 years, 11~30 years and 31+ years.

- A representative number of bridges were proposed by CU-Boulder research team for field sampling, and the final sampling list was chosen by the CDOT Research Branch at CDOT's convenience. Field sampling was done by the CDOT team. Concrete powder was collected from the selected bridges at every 1/2" from the structural surface up to 2" depth. The CU-Boulder research team received two deliveries of concrete samples in 2014 and 2016, respectively. Eighty-eight samples were received in the first delivery and 788 samples were received in the second delivery.

- The samples were collected from decks and curbs of bridges in different climate regions with various ages and traffic levels.

- Testing was done at CU-Boulder after receiving the samples. The water soluble chloride concentrations were tested for all samples using an RCT-500 kit by Germann Instrument.

- Chloride concentration profiles for all the locations were listed and plotted. To analyze the correlations among chloride levels and the selected influential factors, the testing data obtained were processed by eliminating irregular samples and averaging among different locations at each bridge. The two sets of data from the two deliveries (in 2014 and 2016) were not comparable and were thus analyzed separately. The chloride concentrations of most of the bridge decks (even the very old ones) were below the critical values at the rebar level.

- Chloride concentrations of the bridge decks were higher than those of the bridge curbs. However, bridge curbs showed deeper chloride penetration.

- The age of the concrete had a strong impact on the chloride concentrations of bridges in climate zone 4. Younger bridges had lower chloride concentrations. However, the age effect decreases along the depth into the concrete. Chloride concentrations near rebar level of some of the very old bridges (up to 55 years) are still under the regular critical value.

- Traffic level affected the chloride concentrations in climate zones 4 and 7. Heavier traffic resulted in higher chloride concentrations, since more deicer was used on roads with higher traffic volume.

- Bridges built in colder regions had higher chloride concentrations up to 2” depth (the rebar level).

- Climate may be the most significant influential factor among age, traffic and climate for chloride concentration of bridge decks in Colorado.

- Corrosion protection measures should be taken on the bridges decks that locate in the cold climate zone and with high traffic volume.

- The chloride concentrations at the rebar level depend on not only the surface chloride concentrations but also chloride permeability of the concrete cover. Therefore, repairing/replacing distressed concrete decks is equally important to prolong service life of reinforced concrete bridges.

7 REFERENCES

Ababneh, A., Farid Benboudjema, and Xi, Y. (2003) “Chloride Penetration in Non-Saturated Concrete”, J. of Materials in Civil Engineering, ASCE, 15(2), 183-191.

ACI Committee 201 (1994), “Guide to durable concrete, Chapter 4 Corrosion of steel and other materials embedded in concrete,” Manual of Concrete Practice, Part I.

Baechler, M. C., Williamson, J., Gilbride, T., Cole, P., Hefty, M., & Love, P. M. (2010). High-performance home technologies: Guide to determining climate regions by county. US Department of Energy.

Basu, R., Breshears, J.S., and Clausen, E.C. (1999) "Calcium Magnesium Acetate at Lower Production Cost: Production of CMA Deicer from Biomass", Report No. FHWA-RD-98-055, Federal Highway Administration, Virginia.

Berke, N.S. (1986) "Corrosion Rates of Steel in Concrete", ASTM Standardization News, 14, 3, 57-61.

Berntsson, L., and Chandra, S. (1982) "Damage of Concrete Sleeper by Calcium Chloride", Cement and Concrete Research, Vol.12, pp. 87-92.

Browne, R. (1982) "Design Prediction of the Life for Reinforced Concrete in a Marine and Other Chloride Environment", Durability of Building Materials, 1, 2, 113-125.

Cady, P.D., and Weyers, R.E. (1992) “Predicting service life of concrete bridge decks subject to reinforcement corrosion,” In Corrosion Forms & Control for Infrastructure, San Diego, CA.

Chatterji, S. (1978) "Mechanism of CaCl2 attack on Portland Cement Concrete", Cement and Concrete Research, 8, pp. 461-468.

Cody, R. D, et al, (2000) "Concrete Deterioration by Deicing Salts: An Experimental Study", Project No. HR-355, Department of Transportation, Iowa.

Collepardi, M. et al. (1992), Proceeding of the 9th Congress on the Chemistry of Cement, Vol.5, New Delhi, pp. 389-395.

Collepardi, M., Coppola, L., and Pistolesi, C. (1994) "Durability of Concrete Structures Exposed to CaCl2 Based Deicing Salts", Durability of Concrete, ACI SP 145-5, pp. 107-120.

Damrongwiriyanupap, N. (2010) “Modeling the Penetration of Multi-Species Aggressive Chemicals into Concrete Structures”, Ph.D. Dissertation, University of Colorado at Boulder.

Damrongwiriyanupap, N., Li, L.Y., and Xi, Y. (2011) “Coupled Diffusion of Chloride and Other Ions in Saturated Concrete”, Journal of Frontiers of Architecture and Civil Engineering in China, 5(3), 267–277.

Damrongwiriyanupap, N., Li, L.Y., and Xi, Y. (2013) “Coupled Diffusion of Multi-Component Chemicals in Non-Saturated Concrete”, Computers and Concrete, 11(3), 201-222.

Dunker, K.F., and Rabbat, B.G. (1993) "Why America's Bridges are Crumbling," Scientific American, 268(4), pp. 102-112.

Eskandari-Ghadi, M., Zhang, W.P., Xi, Y., and Sture, S. (2013) “Modelling of Moisture Diffusivity of Concrete at Low Temperatures”, J. of Engineering Mechanics, ASCE, 139(7), 903-915.

Gagne, R. et al. (1992) "Chloride Ion Attack on Low Water/Cement Ratio Pastes Containing Silica Fume, ACI SP-132, pp. 1471-1490.

Gegout, P. et al. (1992) "Action of Chloride ions in Cement pastes: Influence of Cement Type and Loading Time Effect of the Concentration of Chloride", Cement Concrete Research, 22(2-3), pp. 451-457.

Kleinlogel, A. (1950) Influences on Concrete, Friderick Ungar Publishing Co. New York.

Liang, Y. C., Zhang, W., & Xi, Y. (2010). Strategic Evaluation of Different Topical Protection Systems for Bridge Decks and the Associated Life-Cycle Cost Analysis (No. CDOT-2010-6). Colorado Department of Transportation, DTD Applied Research and Innovation Branch.

Lindquist, W. D., Darwin, D., Browning, J., & Miller, G. G. (2006). Effect of cracking on chloride content in concrete bridge decks, ACI Materials Journal.

Liu, J., Tang, K., Pan, D., Lei, Z., Wang, W., & Xing, F. (2014). Surface chloride concentration of concrete under shallow immersion conditions. Materials, 7(9), 6620-6631.

Luping, T., and Gulikers, J. (2007). On the mathematics of time-dependent apparent chloride diffusion coefficient in concrete. Cement and concrete research, 37(4), 589-595.

McDonald, D. B., & Perenchio, W. F. (1997). Effects of salt type on concrete scaling. Concrete international, 19(7), 23-26.

Neville, A.M. (1969) "Behavior of Concrete in Saturated Solutions and weak Solutions of Magnesium Sulfate or Calcium Chloride", Journal of Materials, JMLSA, 4, pp. 781-816.

Ren, Y., Huang, Q., Liu, Q. Y., Sun, J. Z., & Liu, X. L. (2015). Chloride ion diffusion of structural concrete under the coupled effect of bending fatigue load and chloride. Materials Research Innovations, 19(sup1), S1-181.

Stanish, K., and Thomas, M. (2003). The use of bulk diffusion tests to establish time-dependent concrete chloride diffusion coefficients. Cement and Concrete Research, 33(1), 55-62.

Stix, G. (1993) "Concrete Solution", Scientific American, 268(4), pp. 102-112.

Suwito, A., and Xi, Y. (2008), “The Effect of Chloride-Induced Steel Corrosion on Service Life of Reinforced Concrete Structures”, Structure & Infrastructure Engineering, Vol. 4(3), pp. 177 – 192.

Uji, K., Matsuoka, Y., & Maruya, T. (1990). Formulation of an equation for surface chloride content of concrete due to permeation of chloride. Elsevier Applied Science,, 258-267.

Xi, Y. and Nakhi, A. (2005) “Composite Damage Models for Diffusivity of Distressed Materials”, J. of Materials in Civil Engineering, ASCE, May/June, 17(3), 286-295

Xi, Y., and Bazant, Z.P. (1999), “Modeling Chloride Penetration in Saturated Concrete”, Journal of Materials in Civil Engineering, ASCE, Vol. 11(1), 58–65.

Oberste-Padtberg, et al. (1986) "Corrosion of Brine Solutions on Hardened Cement", Proceeding of 8th International Congress of Cement Chemistry, Vol.3, Rio de Janeiro, Brazil.