EVALUATING CORROSIVE SITE PERFORMANCE, SERVICE LIFE, AND POLICY OF COASTAL BRIDGES

by

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ABSTRACT

TAISEER QAYS YOUSIF AL SALIHI. Evaluating Corrosive Site Performance, Service Life, and Policy of Coastal Bridge with Concrete Admixtures. (Under the direction of DR. BRETT Q. TEMPEST)

Many state-owned concrete structures, such as bridges, line the coast of North Carolina (NC), and these structures are vulnerable to corrosion and degradation in the aggressive, chloride-rich environments where they were built. The North Carolina Department of Transportation (NCDOT) created the Structures Management Unit (SMU) Design Manual in 2003 that contains different corrosion prevention requirements including the introduction of corrosive boundaries, increased concrete cover, epoxy coated steel and the addition of pozzolans and corrosion inhibitors to delay the corrosion-related deterioration of structural concrete in these environments. The Design Manual's specifications change depending on where the structure is built in relation to a corrosive boundary. It is the goal of the NCDOT policy to increase the service life of these new structures and to reduce the costs of maintenance and repair. The tidal zone was chosen for the structures in this study due to the diffusion is likely to be the dominant mode of mass transport in this zone.

Studying NCDOT corrosion policy and determining whether or not it is effective was the primary objective of this thesis research. To accomplish this goal the research was divided into three tasks: field visits and data collection (concrete powder samples), laboratory testing to analyze the data to estimate the diffusion coefficient using a nonlinear regression model (minimization of squared error), and service life modeling using the Life 365 software to predict the service life , and to model the effects of corrosion on the bridge components.

Given the research and results collected across the three tasks, it was concluded that the current NCDOT policy works in cases of lesser exposure, the severity of exposure was strongly related to proximity to the coast, service life modeling results indicated that the main factor impacting the service life is the tendency for the concrete member to be exposed to chloride rich waters, active corrosion was detected in the tidal zone of bridge piers and dropped off quickly at locations outside of the tidal zone, and some bridges constructed under the current corrosion policy will not have maintenance free service lives that exceed 75 or 100 years.

The conclusion was bridges close to the coastline need to be addressed by modifying the NCDOT policy, salinity distributions and the distance from the open water must be measured to determine the exposure severity, and to design for a predicted service life of 70 years, a targeted diffusion coefficient of 0.06 in^2 /yrs or less must be achieved.

ACKNOWLEDGEMENTS

This research would not have been possible without the assistance of a diligent set of individuals. As such result, there are several people I would like to thank for their significant contributions. It is with deep gratitude that I express my sincere thanks to my research supervisor, Dr. Brett Tempest, P.E., who has allowed and supported me throughout this research. His dynamism, vision, sincerity, and motivation have enthralled and inspired me to the fullest. To Dr. Tara Cavalline, P.E., I owe a debt of gratitude for the opportunity to learn and grow under her tutelage. I would like to thank Dr. Matthew Whelan, P.E., for serving on my committee.

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
C	Degrees Celsius
CEPRA	Connectionless Electronical Pulse Response Analysis
Cl	Chloride
cm	Centimeters
DOT	Department of Transportation
°F	Degrees Fahrenheit
gal	Gallon
in	Inch
in^2/yrs.	Square Inches per Year
kohm-cm	Kiloohm-Centimeter
m	Diffusion Decay Index
MHHW	Mean Higher High Water
MLLW	Mean Lower Low Water
NC	North Carolina
NCDOT	North Carolina Department of Transportation
pH	Potential Hydrogen
ppm	Parts-Per-Million
RCT	Rapid Chloride Test
SCMs	Supplementary Cementitious Materials

SMU	Structures Management Unit
SN	Structure Number
UNC	University of North Carolina
UNCC	University of North Carolina at Charlotte
US	United States
w/b	Water-to-Binder
w/c	Water-to-Cement
μm/year	Micrometers per Year

CHAPTER 1: INTRODUCTION

1.1 Background

Concrete structures that are located near or on the coast are subject to the corrosive effects of the marine environment, even if they do not come into direct contact with the ocean. In the marine environment, plain concrete without steel reinforcement is generally stable and durable, but when steel reinforcement is added, durability becomes a major consideration due to the steel's vulnerability to corrosion, the presence of chlorides in seawater is a major factor in the initiation of steel corrosion (Smith, 2016). There are numerous state-owned bridges along North Carolina's coastline, all of which are susceptible to chloride ingress, see Figure 1.1. The presence of oxygen and alternate wetting and drying of chloride-rich water are required for chloride ingress into concrete and reinforcement corrosion. Therefore, the tidal zone of a concrete element is the most aggressive zone because of the frequent wetting and the free availability of oxygen. Submerged or backfilled parts of the structure are less susceptible to corrosion because of the lack of oxygen (submerged zone). The atmospheric zone, is well-oxygenated, but its chloride supply is low because it is not exposed to splash or spray (Smith, 2016).

Figure 1.1: North Carolina's Coastal Plain (Based on (USGS, 2022)

1.1.1 NCDOT Structures Management Unit (SMU) Design Manual

North Carolina Department of Transportation (NCDOT) created the Structures Management Unit (SMU) Design Manual to provide general design policy and operating procedure guidance to Structures Management Unit personnel. The goals of this manual are to increase efficiency in both design and information transfer, as well as to ensure consistency in contract plan demonstration (NCDOT, 2019).

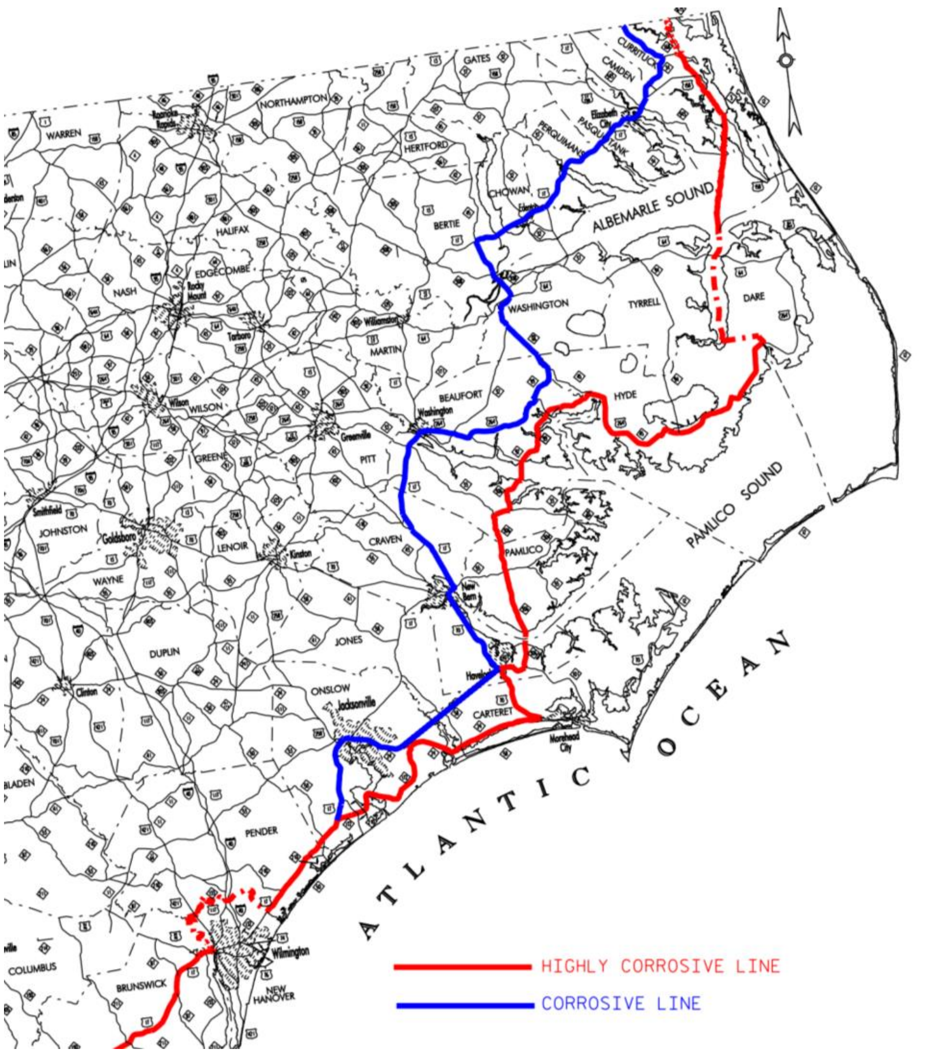


Figure 1.2: NCDOT Corrosive Areas Map

(Based on Figure 12-29, NCDOT (SMU) Design Manual)

1.1.2 NCDOT Corrosion Protection

In North Carolina, corrosion protection is accomplished by one or more of the following actions: increased clear cover for reinforcing steel, epoxy coating of reinforcing steel, addition of calcium nitrite corrosion inhibitor, silica fume, fly ash, or granulated blast furnace slag, specifying Class AA concrete for substructures, and limiting the use of uncoated structural steel (NCDOT, 2019). Corrosion protection is used to wide variations on bridges located on or east of the Corrosive Line (blue) in Figure 1.2 and in Divisions with significant road salt application (NCDOT, 2019).

Corrosion protection is more extensive for corrosive sites. Figure 1.2 defines the Corrosive Line (blue) as a stream crossing on or east of the Corrosive Line (blue). Mineral admixtures may be required in some or all of the bridge members for these structures. Calcium nitrite is also specified to increase the steel reinforcing's corrosion resistance (NCDOT, 2019).

The SMU Design Manual dictates the use of at least one corrosion-protection measure on all concrete on bridges located east of the Highly Corrosive Line (red). For bridges situated between the Highly Corrosive (red) and Corrosive (blue) lines shown in Figure 1.2, only those structural elements that are within 15 feet (4.5 m) of the mean high tide need to be provided with corrosion protection measures (NCDOT, 2019). Corrosion protection must be applied to all bridge elements that are within 15 feet (4.5 meters) of mean high tide (NCDOT, 2019). Corrosion protection requirements for bridges are depicted in flowchart form in Figure 1.3. The bridges east of the red line, as well as the area between the blue and red lines, are the subject of this thesis. Furthermore, bridges with reinforced concrete-element in the tidal zone will be the main focus.

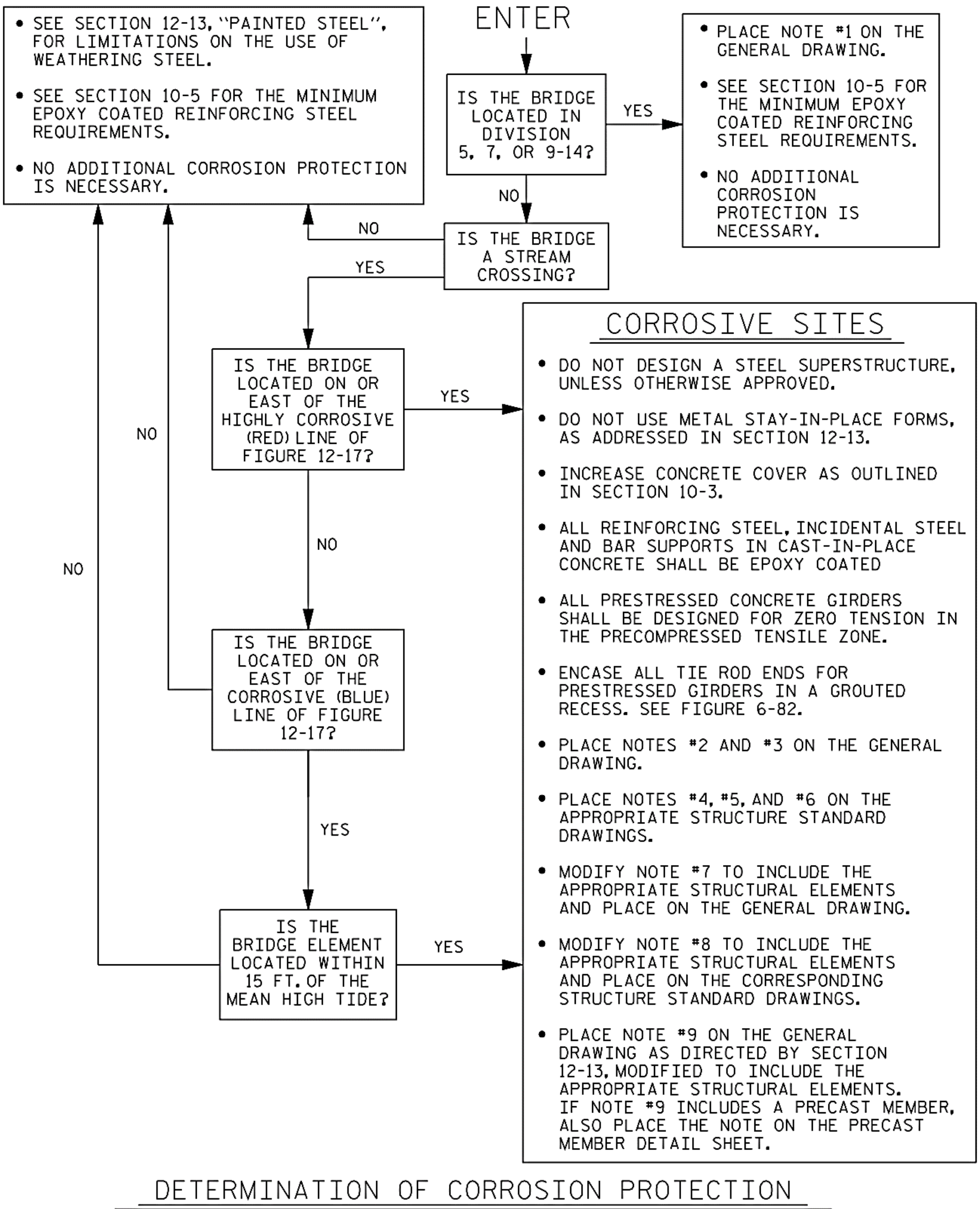


Figure 1.3: Flowchart for Determining the Required Level of Corrosion Protection

(Based on Figure 12-30, NCDOT (SMU) Design Manual)

1.2 Objectives and Scope

NCDOT's current corrosion prevention policies were established in 2003 to help mitigate the onset of corrosion in aggressive coastal environments. As of 2018, over 200 bridges within the corrosive boundary lines had been either newly constructed or replaced under the provisions of the policy. The primary objective of this thesis research is to examine the structures in the corrosive sites in order to determine the effectiveness of NCDOT's current corrosion prevention policies. The policy's objective is to extend the useful life of the new structures while reducing maintenance and repair costs. These structures are expected to have a service life of at least 50 years if the policy is successful.

To accomplish this primary objective, the research was divided into distinct tasks, each of which is specific to this thesis, see Figure 1.4. These tasks are as follows:

- Field visits and data collection
    - Select bridges from both the corrosive and highly corrosive zones.
    - Select bridges with an age of 10 to 15 years, giving them ample time to weather and develop corrosion.
    - Examine the chloride loading of each bridge's structural components by collecting concrete powder samples.
    - Measure active corrosion rate and concrete surface resistivity on site.
- Laboratory testing
    - Analyze the concrete powder samples in the lab and create a chloride content profile.
    - Use the chloride content to estimate a diffusion coefficient

- Service life modeling
    - Employ the diffusion coefficient and chloride surface concentration from the chloride content profile to estimate the service life or the maintenance free service life for the structural components of each bridge.

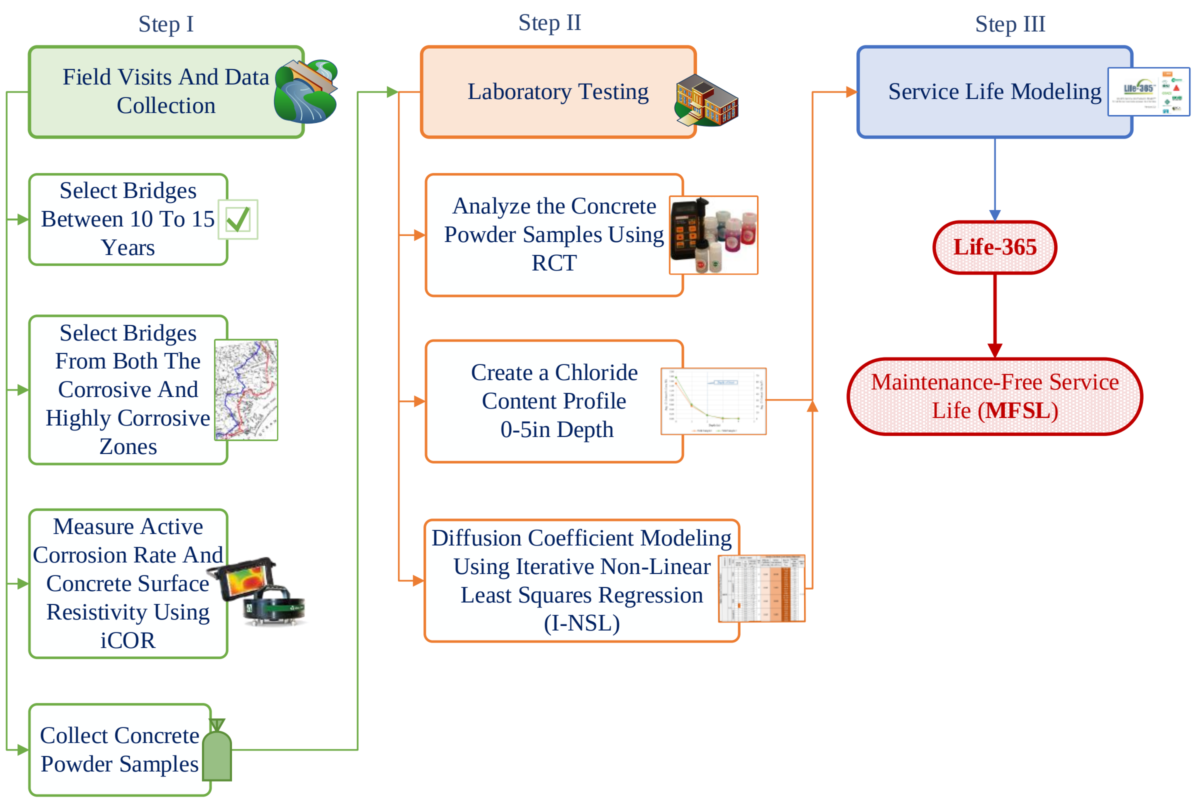


Figure 1.4: Summary of Research Tasks

CHAPTER 2: LITERATURE REVIEW

2.1 Corrosion in Reinforced Concrete in Marine Environment

In reinforced concrete (RC) structures, chloride in seawater generally poses the most significant risk to the durability and serviceability of structures because of the possibility for corrosion of the reinforcing steel (rebar). Engineers and designers understand and acknowledge the importance of marine concrete structural requirements, especially in terms of durability. The marine environment in this thesis refers to the area in proximity to the sea where concrete structures are in contact with seawater or brackish water or spray. Multiple terms refer to the marine environment, particularly the zone where concrete structures interact with the sea, including marine, coastal, and maritime (Alexander & Nganga, 2016).

Marine structures are frequently subjected to aggressive and corrosive sea salt conditions, in which tidal wetting and drying cycles promote chloride absorption and resulting in corrosion of reinforcing steel (Allen & Moore, 2016). The variability in concrete performance in different marine exposure environments is a major challenge. The change in the characteristics of different marine exposure environments, even those that are conventionally perceived to be similar in aggressivity, is why some concrete structures appear to last longer while others deteriorate in a relatively short period of time (Otieno & Thomas, 2016). As previously stated, the majority of current RC durability issues are related to reinforcing steel corrosion, which poses a significant threat to the service life and economic value of corrosion-affected structures (Alexander & Beushausen, 2019). A concrete structure's 'service life' can be defined as the 'assumed period for which a structure or part of it will be used for its intended purpose with expected maintenance but no major repair (Alexander & Beushausen, 2019).

Life-365 was used in this study to predict the onset of corrosion in reinforced concrete in marine environments and the time it takes for corrosion to reach a point where the effect of corrosion will require repair. The first step to estimate the maintenance-free service life was to measure the ongoing corrosion in structures in marine environment and the chloride content (a detailed description is in Chapter 3), see Figure 2.1. The cost of a structure's design life, including initial construction costs and predicted repair costs, can then be estimated using Life-365 (Violetta, 2002). Each project in Life-365 necessitates the following user inputs:

- Exposure Environment:
  - Temperature cycle
  - Location of structure geographically
  - Chloride (Cl-) max. surface concentration (at 0 in depth), and time to reach the max. chloride surface concentration (Age)
- Structure Type and Dimensions
- Concrete Mixture and Properties (prevention of chloride ingress and corrosion):
  - Water/Binder (Water-Cementitious Materials) Ratio (w/b or w/cm)
  - Supplementary Cementing Materials (SCMs) (fly ash, ground-granulated slag, silica fume)
  - Calcium Nitrite Inhibitor (CNI)
  - Chloride Threshold based on CNI
  - Type of steel
  - Depth of clear concrete cover to the reinforcing steel
  - Diffusion Coefficient at 28 days (D_{28})

This chapter will highlight all of these inputs and factors in determining the marine concrete performance and the maintenance-free service life, see Figure 2.2.

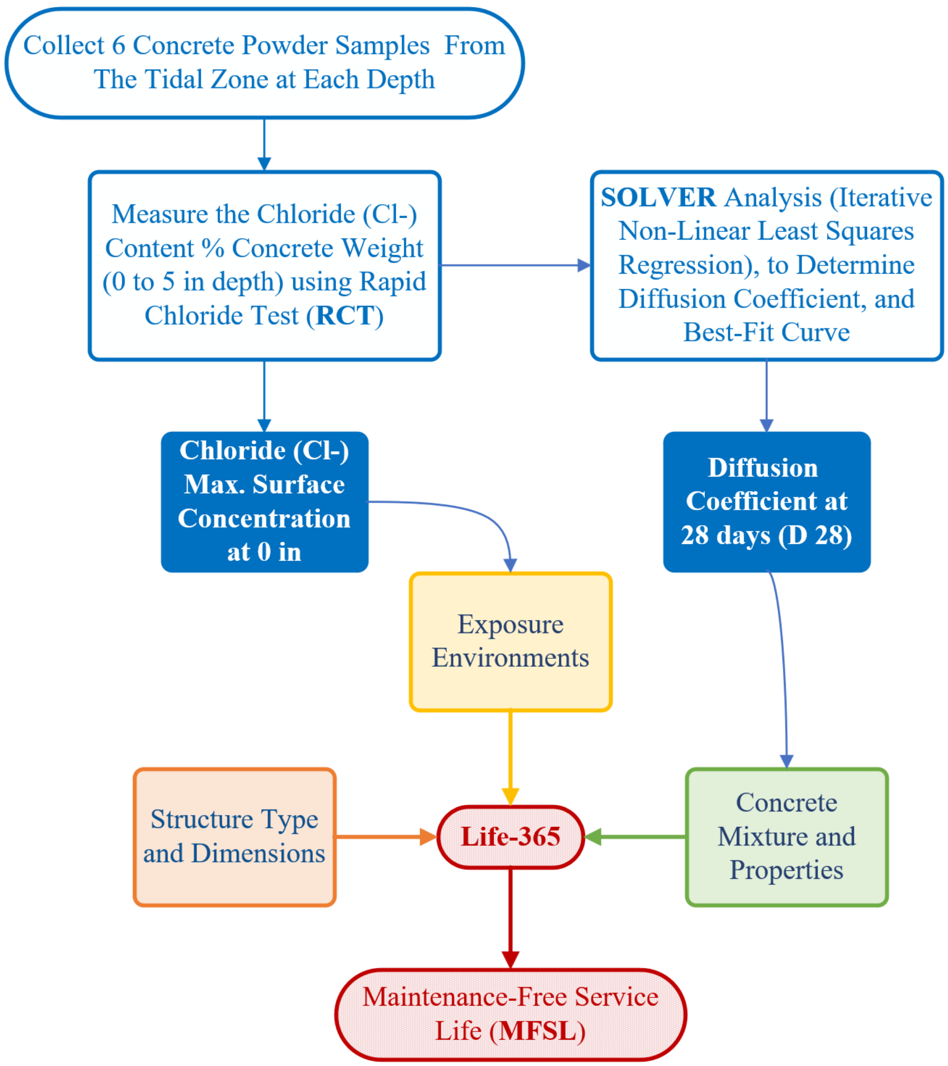


Figure 2.1: Schematic Representation of Service Life Modeling

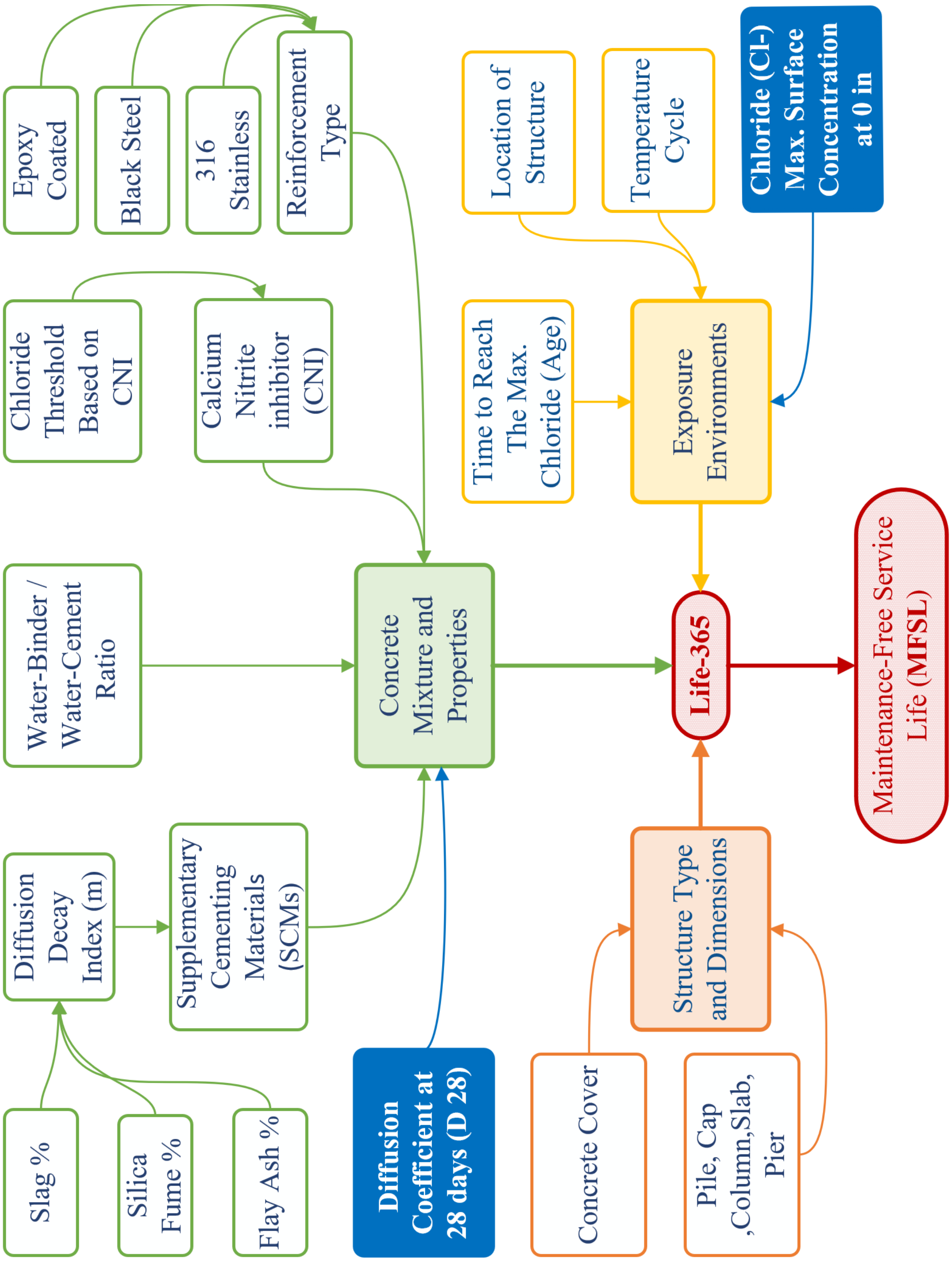


Figure 2.2: Life-365 Summary of Maintenance-Free Service Life Input

2.2 Chloride Transport Mechanisms in Concrete

The transport processes of concrete materials are critical for predicting their durability because deterioration mechanisms such as corrosion, leaching, or carbonation are all related to how easily a fluid or ion can move through the concrete microstructure (CSIRG, 2010). The distinct mechanisms of capillary action, fluid flow under pressure, flow under a concentration gradient, and movement due to an applied electric field are all involved in fluid and ion movement (Richardson, 2002). The material properties of absorption, migration, permeation, diffusion, convection, and sorption, characterize these mechanisms. Diffusion is likely to be the dominant mode of mass transport in the tidal zone, as the majority of the concrete member will remain saturated or near saturation due to the twice-daily submersion in water. Additionally, absorption contributes to the accumulation of chloride at the surface as a result of cyclic wetting and drying, with diffusion determining the rate of penetration below the surface (Thomas, 2016).

2.2.1 Diffusion

Diffusion is the mass transfer of chloride (or other) ions from high-concentration areas, such as a seawater-exposed surface, to low-concentration areas, such as the location of embedded reinforcing steel (Thomas, 2016). The concrete's diffusion coefficient, *D*, is a material property that influences the rate of chloride ingress due to a concentration gradient, with the intensity acting as the driving force (Thomas, 2016). Fick's first law of diffusion is commonly used to model gaseous and ionic diffusion in concrete (for steady-state diffusion). This law can be used to calculate the rate at which a gas or ion diffuses through a uniformly diffusible medium (Richardson, 2002):

$$J = -D_{eff}\frac{dC}{dx}$$

where J = mass transport rate

D_{eff} = effective (apparent) diffusion coefficient

dC/dx = concentration gradient

x = distance

In practice, this equation is only useful after steady-state conditions have been achieved, when there is no change in concentration over time. However, it can be used to derive Fick's Second Law for non-steady conditions, which considers the effect of concentration changing over time (t). (Stanish, et al., 1997):

$$\frac{\partial C}{\partial t} = D_{eff} \frac{\partial^2 C}{\partial x^2}$$

The solution is:

$$C_{(x,t)} = C_o \left(1 - \text{erf}\left(\frac{x}{\sqrt{4.D_{eff}.t}}\right)\right)$$

where $C_{(x,t)}$ = chloride concentration measured at x depth

C_o = initial chloride concentration measured

x = the depth below the exposed surface

D_{eff} = effective (apparent) diffusion coefficient

t = time

erf = the error function

Some factors make it difficult to interpret diffusion data. To begin with, chloride ions do not diffuse uniformly through a solution. Concrete is a porous matrix made up of both solid and liquid elements. When compared to the diffusion rate through the pore structure, diffusion through the solid portion of the matrix is insignificant. Therefore, the physical characteristics of the capillary pore structure control the rate of diffusion as well as the diffusion coefficient through the pore solution (Stanish, et al., 1997).

2.2.2 Absorption

The bulk uptake of water into a porous material such as concrete is referred to as absorption (Santhanam & Otieno, 2016). It usually occurs in unsaturated or partially saturated concrete that has been subjected to complete or partial immersion. This parameter is simple to measure but the measurement is imprecise due to the difficulty of penetrating all concrete pores. As a result, obtaining a true measure of porosity is impossible. However, the measured absorption does give a good indication of durability because the majority of the available capillary porosity is penetrated (Santhanam & Otieno, 2016).

2.2.3 Migration

Migration (also referred to as accelerated diffusion, electro-diffusion, or conduction) is the process by which ions move in the direction of an electrical gradient (negatively charged chloride cations are 'driven' toward the positively charged anode) (CSIRG, 2010). The migration rate is determined by the concrete's diffusion coefficient, *D*, and the potential gradient (Thomas, 2016). However, migration may not occur in the majority of cases under actual service conditions (Santhanam & Otieno, 2016). The Nernst-Planck equation governs this transport mechanism in laboratory-accelerated chloride tests (Andrade, 1993):

$$v = \left(D\,\frac{zF}{RT}\right)\left(\frac{dU}{dx}\right)$$

where v = velocity of the ionic species

D = diffusion coefficient of the ionic species

F = Faraday’s constant

z = electrical charge (ionic valence) of diffusing ions

T = absolute temperature

U = potential difference across the sample

x = distance variable

R = universal gas constant

2.2.4 Convection

As the bulk of water moves, solutes (e.g., chloride or sulfate ions) are carried away by convection (or advection) (Boddy, et al., 1999). The process is given by the following equation:

$$\frac{\partial C}{\partial t} = -\bar{v}\frac{\partial^2 C}{\partial x^2}$$

where C = Concentration of solute at depth x after time t

v = average velocity vector of fluid flow

The main transport mechanisms for chloride ingress in cracked concrete are convection and diffusion. Convection also plays a major role in how chloride ions move through the concrete during the wetting and drying cycles (Paulsson & Johan, 2002).

2.2.5 Permeation (Wick Action)

This mechanism operates as a measure of the capacity of concrete, where saturated liquid transfer controlled by a pressure gradient occurs across the concrete. (CSIRG, 2010). Ionic species dissolved in water can also move due to water permeation. When there are cracks and defects in the concrete, permeation is increased (Samaha & Hover, 1992). As a result of permeation, the average flow velocity (v) is calculated using D'Arcy's law:

$$\bar{v} = \left(\frac{k}{n}\right)\left(\frac{dh}{dx}\right)$$

where k = permeability coefficient

n = porosity

h = hydraulic head

x = distance

2.2.6 Sorption (Capillary Suction)

Sorption is the capillary suction uptake of liquids into an unsaturated or partially saturated solid. Bulk absorption and sorptivity, S, are two parameters used to measure it. Sorptivity is the movement of a wetting front in a porous medium that is either dry or partially saturated (Alexander & Mindess, 2005):

$$S = \frac{\Delta M_t}{t^{1/2}}\left[\frac{d}{M_{sat} - M_o}\right]$$

where $\Delta M_t / t^{1/2}$ = slope of the straight line produced when the mass of water absorbed is plotted against the square root of time

d = sample thickness

M_{sat} & M_o = saturated mass and dry mass of concrete specimen respectively

2.3 Chloride Threshold Level (CTL)

The concept of a corrosion inducing chloride threshold level (CTL) was developed after considering the role of chloride in steel corrosion in concrete. The CTL is the amount of chloride in the steel depth that is required to cause local passive film breakdown and, as a result, start the corrosion process (Schiessl & Raupach, 1990). CTL is usually expressed as a ratio of chloride to hydroxyl ions, the free chloride content, or a percentage of total chloride content to cement weight (Ann & Song, 2007). An assessment of the CTL is essential in predicting the service life for structures exposed to chlorides. One way to define service life is the time required for transport processes to raise the chloride level at the steel's depth to the CTL (Ann & Song, 2007). Despite the CTL's importance, conservative values such as 0.2 % or 0.4 % by weight of cement have been used to predict corrosion-free life due to the uncertainty surrounding the actual limits for chloride-induced corrosion in various environments (Ann & Song, 2007). At least ten design codes exist worldwide that specify the maximum allowable chloride content in concrete and grout. National publications include, three American Concrete Institute (ACI) codes, an American Association of State Highway and Transportation Officials (AASHTO) code, a Post-Tensioning Institute (PTI) code, and a Precast/Prestressed Concrete Institute (PCI) code, see Table 2.1 (Virmani & Ghasemi, 2012). Total (acid-soluble) chloride ions are limited to 0.08 percent by weight of cement in all domestic codes, while water-soluble chloride ions are limited to 0.06 percent. Water-soluble chloride ions are currently available for corrosion, whereas acid-soluble chloride represents the total amount of chloride ions that are available in the future (Virmani & Ghasemi, 2012). North Carolina Department of Transportation (NCDOT) chloride threshold limit is typically in the range of 0.03 to 0.04 percent weight of concrete (1.2 to 1.5 lbs./yd^3) depending on the cementitious content of the mix (Rochelle, 2000).

Table 2.1: Summary of Chloride Limit in U.S Design Codes

American Publications (Standard/ Design Code)	**Chloride Limit (Percent by mass of cementitious material*)**	
	Prestressed concrete	**Reinforced concrete**
Building Code Requirements for Structural Concrete and Commentary, ACI 318-19	0.06 (ASTM C1218)	0.15-0.3 (ASTM C1218)
Guide to Durable Concrete, ACI 201.2R-16	0.08 (ASTM C1152)	0.1 (ASTM C1152)
	0.06 (ASTM C1218)	0.08 (ASTM C1218)
Guide to Protection of Reinforcing Steel in Concrete against Corrosion, ACI 222R-19	0.08 (ASTM C1152)	0.2 (ASTM C1152)
	0.06 (ASTM C1218)	0.15 (ASTM C1218)
LRFD Bridge Construction Specifications, AASHTO 4th edition (2017)	0.08 (ASTM C1152)	-
Specifications for Grouting of Post Tensioned Structures, PTI M55.01-03	0.08 (ASTM C1152)	-
Design Handbook Precast and Prestressed Concrete, PCI 8th Edition 2018, MNL-120-17	0.06 (ASTM C1218)	0.15-0.3 (ASTM C1218)

*Total (acid-soluble) per ASTM C1152
*Water-soluble per ASTM C1218

NCDOT utilizes 0.037% weight of concrete[1] (1.4 lbs./yd^3) as a value for analyses. However, the chloride threshold limit increases when the concrete mix contains calcium nitrite. Thus, when calcium nitrite is specified in the range of 2 to 5 gal/yd^3, chloride threshold limits of 0.16 to 0.66 percent weight of concrete (1.2 to 1.5 lbs./yd^3) are used (Rochelle, 2000). It is preferable to have a reliable chloride threshold value to predict when corrosion can begin on metals embedded in a specific cementitious material, such as grout and concrete for chloride-induced corrosion. When corrosion begins, the corrosion propagation stage begins (Virmani & Ghasemi, 2012).

[1] One yd^3 of normal weight concrete is assumed to be 4,000 lbs. containing 600 lbs. of Portland cement.

2.3.1 Corrosion Initiation

Metals embedded in cementitious materials are protected from corrosion by the formation of a protective oxide film (passivity) on their surface in highly alkaline (typically pH > 13.2) environments (Virmani & Ghasemi, 2012). The corrosion initiation mechanism is the inverse of the corrosion protection mechanism: corrosion begins when the concentration of chloride ions in any metal/cementitious material exceeds a certain level (chloride threshold value) or when the cementitious medium's pH falls below 10 due to carbonation. As a result, the time required to initiate corrosion can be significantly extended for metals with significantly high chloride threshold values (Virmani & Ghasemi, 2012). For instance, corrosion initiation for high-grade stainless-steel rebar is different from mild carbon steel rebar in concrete. Carbon steel rebar is widely accepted to have a chloride threshold of approximately 1.2 lbs./yd^3 (0.71 kg/m^3), which equates to 0.03 percent by weight of concrete or 0.2 percent by weight of cement. The chloride threshold values for various grades of stainless steel are reported to be at least 12 times that of conventional rebar. Additionally, once corrosion begins, the stainless-steel bars exhibit a minimal corrosion rate (Virmani & Ghasemi, 2012). Chloride ions present in the marine environment can enter concrete cover through pores and cracks and cause rebar corrosion. As soon as the critical chloride ion concentration is reached on the surface of the steel, the passive state is lost (Morris & Vazquez, 2002).

2.3.2 Chloride Profile

After corrosion initiation, The chloride profile is measured to determine the CTL. The chloride profile is determined in two stages: sampling and analysis. Generally, sampling entails grinding the concrete and collecting dust samples from varying depths for analysis. It is critical to ensure that each sample contains an approximately equal amount of cement paste as the bulk concrete, as this avoids the sample being dominated by large aggregate sizes (Ann & Song, 2007). The most common method for analyzing and determining the total chloride content (profile) is acid-soluble extraction, which is predicated on the assumption that both bound and free chlorides are soluble in acid. The soluble acid chloride (total chloride) concentration can be determined either using a chloride ion-sensitive electrode or by titration (Ann & Song, 2007). Two measures of total chloride concentration were used to describe the chloride profiles in this thesis: (%) percent weight of concrete and lbs./yd3, see Figure 2.3.

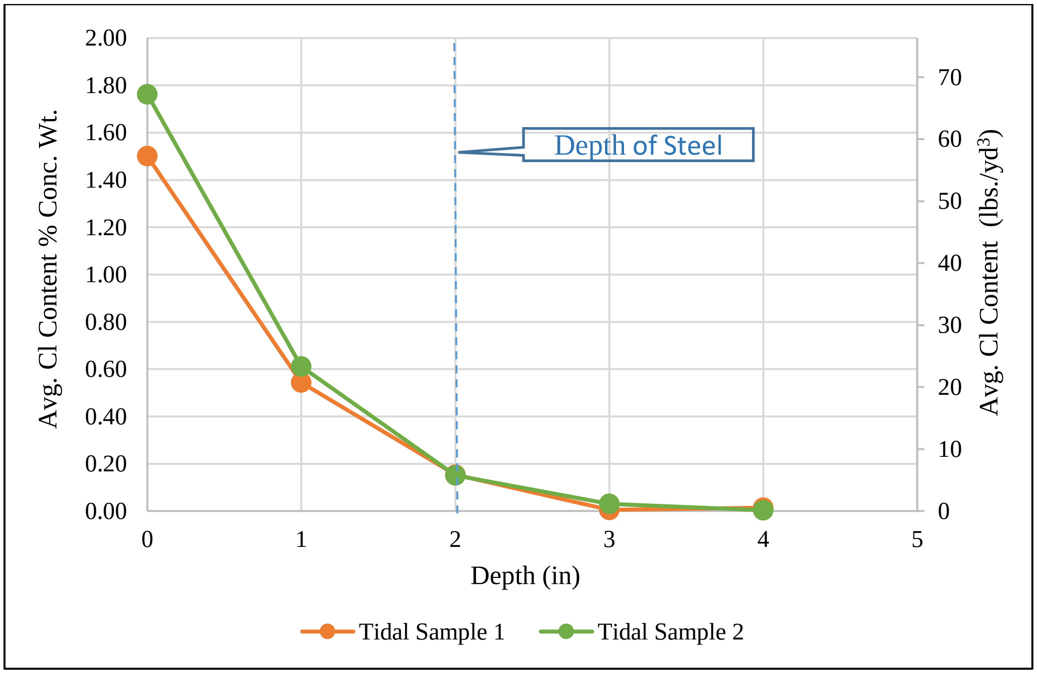


Figure 2.3: Representation of Chloride Profile (Structure #090206)

2.4 Marine Exposure Environments

There is a direct correlation between environmental exposure and the useful life of concrete structures. A combination of the chemical action of seawater components on cement hydration products, alkali-silica reaction, crystallization of salts in pores, cold climate frost action, corrosion of embedded steel in reinforced and prestressed members, physical erosion by waves, or a combination thereof, can also lead to the degradation of concrete in marine environments (coastal and offshore) (Otieno & Thomas, 2016). Fookes et al., (1986) classified marine environments according to how concrete behaves in different locations. The four basic categories used in the classification are: cool/cold, temperate, hot and dry, and wet. This classification is based on the climate of the maritime environment.

2.4.1 Cold Marine Environments

Near-freezing temperatures are found in cold marine environments, which are mostly located in far north or far south latitudes in which the climate usually has a significant difference in summer and winter, with annual average winter temperatures below 50º F (10° C) and summer temperatures below 68º F (20ºC); rainfall is usually not heavy in either season.

The ability of concrete to withstand freezing and thawing is an important durability requirement for concretes used in marine environments. Cool marine environments can be found in Canada, Denmark, Norway, northeast United Kingdom, Portugal, Scotland, Sweden, New Zealand, and parts of eastern Europe, Asia, Russia, and South America (Otieno & Thomas, 2016).

2.4.2 Temperate Marine Environments

In these marine environments the annual average temperature ranges between 50º F (10º C) and 68º F (20ºC), with only a few instances of freezing temperatures and only moderate rainfall. The absence of freezing and thawing in these climates means that the primary causes of physical and chemical deterioration of the concrete itself are wetting and drying cycles, as well as salt crystallization in the evaporation zone, which are present in all these regions (Otieno & Thomas, 2016). When reinforced concrete is exposed to saltwater, corrosion of the reinforcement is the most common cause of deterioration. Depending on how much concrete is used and how much wicking action occurs, the area affected by seawater may be higher than the actual area of contact (Otieno & Thomas, 2016). There are many examples of temperate marine environments, such as the coasts of San Diego, San Francisco, the Netherlands, and Cape Town.

2.4.3 Hot and Dry Marine Environments

Summer temperatures in these environments can reach 113º F (45º C), and there is little rainfall, allowing the surface zone to dry out significantly as a result of evaporation. In the presence of seawater, the dry surface zone exhibits increased sorptivity potential, which can result in rapid chloride penetration even in the presence of only infrequent interaction with seawater; this can cause deterioration in concrete well beyond the usual splash zone (Otieno & Thomas, 2016). After the chlorides de-passivate the steel, the rate of corrosion will also increase due to the increased availability of oxygen through the partially dry capillaries in the cover concrete. While aerosols are a common source of chlorides near the shore in hot and dry marine environments, wind-borne salty dust particles from the sea are a more common source because dew on cooled surfaces provides an ideal transport medium for chlorides to penetrate the concrete (BS-7527-2-3, 2014). Coastlines in the Middle East are typical examples of hot and dry marine environments (eg, Saudi Arabia, Turkey, UAE, Yemen, Iran, and Oman).

2.4.4 Hot and Wet Marine Environments

In tropical regions where conditions are common, the annual average temperature is between 75º F and 95º F (24º C and 35º C). While the seawater's salinity ranges from 26% to 32%, the annual average rainfall and relative humidity range from 1000 to over 1500 millimeters and 60% to 96%, respectively, and seasons are divided into wet and dry, with trade winds blowing year-round and carrying moisture from warm seas (Liam, et al., 1992; London, 1992; Wilson, 2005). There are a lot of variables in these marine environments, such as the amount of chlorides that can be accumulated on the structures (Castro, et al., 2001). Studying chloride ingress, researchers found that tropical climates promote the formation of two zones in a concrete member: one internal that is always damp (almost saturated) and one external that is constantly subjected to wet and dry cycles (Castro, et al., 2001). North Carolina, Bangkok, Calcutta, Hong Kong, Singapore, the Gulf of Mexico, coastal areas of Cuba, Yucatan, Mexico, and Shenyang and Wanning cities in China are examples of hot and moist marine environments.

In conclusion, when compared to the other zones, the rate of deterioration due to corrosion is typically higher in the hot-dry and hot-wet marine exposure environments than the other zones. As a result, it is important to recognize that marine exposure environments differ from one another around the world and that they must be treated as such. Moreover, due to the fact that sea temperatures and ocean currents close to the shore have a significant impact on coastal climate, the focus should be given to the localized coastal climate rather than the predominant inland weather conditions (Otieno & Thomas, 2016).

2.5 Marine Exposure Categories and Classes

Around the globe, various concrete design standards provide guidelines on exposure classes for concrete structures, particularly marine concrete structures. These exposure classes aim to classify the environment by employing a classification system that takes into account the magnitude of exposure, mainly in the area of chloride-induced corrosion (Alexander & Nganga, 2016). All of the standards under consideration provide descriptions of exposure conditions that are essentially the same. The severity of a structure's condition is determined by its location, with the most severe conditions occurring in the tidal and spray zones, see Table 2.2 (Alexander & Nganga, 2016).

The first step in figuring out the maintenance free service life (MFSL) of the concrete element properties is to figure out what type of exposure the concrete will encounter. Most standards have systems that help with the design process. For instance, BS EN 206:2013+A1:2016 has designations for environments that are likely to cause corrosion caused by carbonation (XC), chlorides from seawater (XS) (Figure 2.4) and freeze/thaw attack (XF) that may be important in a marine environment (Thomas, 2016). All three of these environments could be found in the same place at the same time. Moreover, seawater is usually thought of as having a moderate amount of sulphate exposure. More than one exposure class could affect the concrete's materials, proportions, and characteristics, so the concrete must be made to withstand all of exposure (Thomas, 2016). Furthermore, ACI 318 does not cover all of the possible exposures. Chemical or physical attacks can happen to concrete in such places as factories or farms. It is important to find out what is in the environment and how it was made. Also, if an aggregate reacts with alkalis, the standards need to make sure the concrete has enough fly ash, slag cement, and/or silica fume to keep the expansions in check. ASTM C1778 gives advice on how to achieve this (Detwiler, 2020).

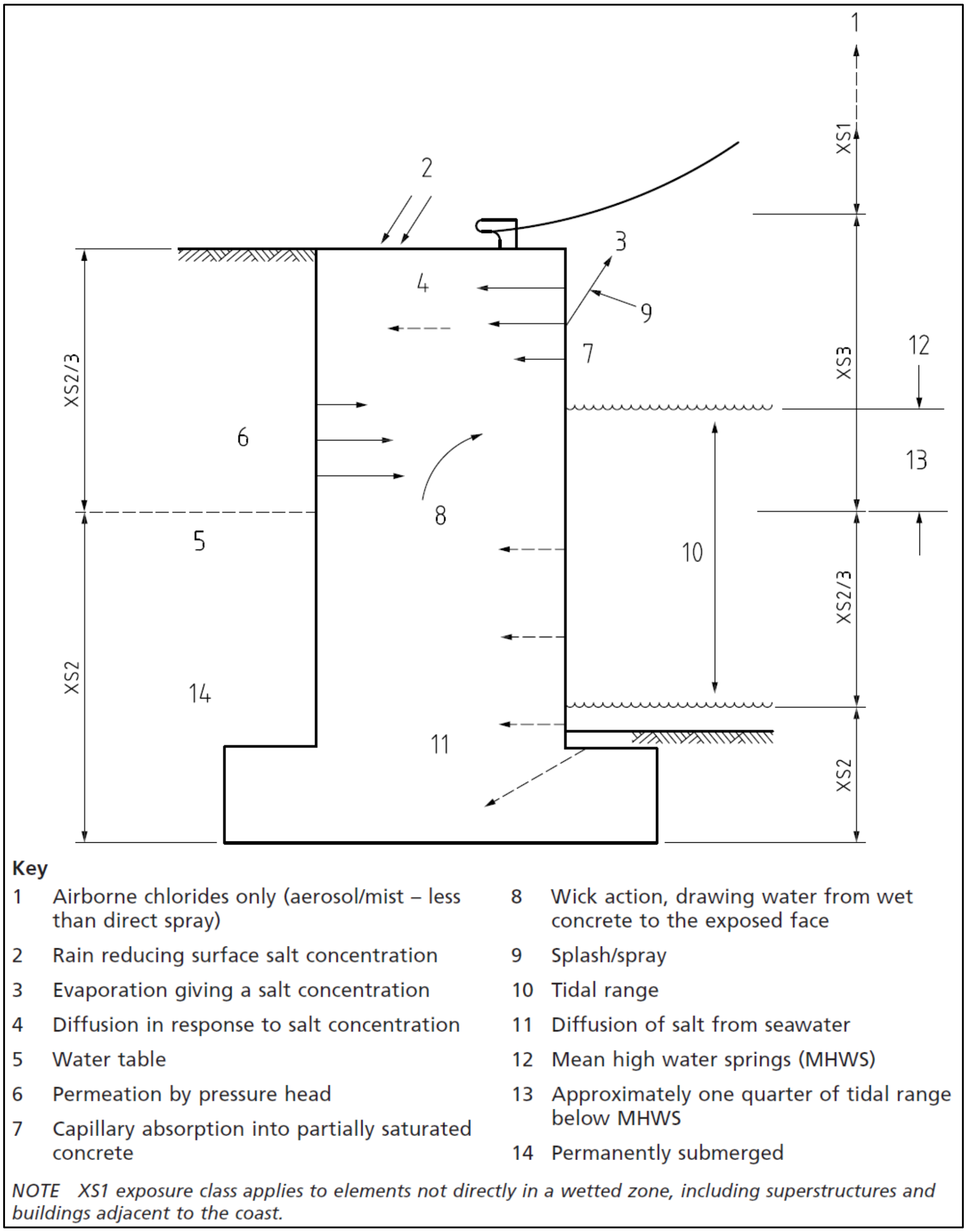


Figure 2.4: Schematic Diagram of the Chloride Transport Processes in a Maritime Structure (Based On (BS-6349-1-4, 2013)

Table 2.2 Exposure Classes for Marine Structures in Different Standards

Standard/ Design Code	Exposure class	Description
American ACI 318-19	C0: Negligible	Concrete dry and protected from moisture
	C1: Moderate	Concrete exposed to moisture, no external source of chlorides
	C2: Severe	Concrete exposed to moisture, and an external source of chlorides
British/European BS EN 206:2013+A1:2016	XS1: Exposed to airborne salt but not in direct contact with seawater	Surfaces near to or on the coast
	XS2: Permanently submerged	Parts of marine structures
	XS3: Tidal, splash and spray zone	Parts of marine structures
Australian AS 36000:2018	B-1: Near coastal	1-50 km from the coastline, and any climactic zone.
	B-2: Coastal	Up to 1 km from the coastline excluding tidal and splash zone, and any climactic zone.
	B-2: Seawater	Permanently submerged
	C1: Spray zone	The zone from 1 m above wave crest level
	C2:Tidal/Splash zone	The zone tidal/splash is immediately below spray zone
Canadian CSA A23.1:19/CSA A23.2:19	C-XL	Extreme chloride/severe environments with or without freeze-thaw
	C-1	Exposure to chlorides with or without freeze-thaw
	C-2	Exposure to chlorides with freeze-thaw
	C-3	Continuously submerged concrete exposed to chlorides but no freeze-thaw

2.5.1 Marine Exposure Zones

While a descriptive interpretation of the term would include structures that come into direct contact with marine conditions, other possibilities include structures that are close enough to the marine environment to be affected by seawater spray or airborne aerosols (Santhanam & Otieno, 2016). In the latter scenario, this could refer to marine conditions that exist well inland of the immediate marine zone. There are three primary conditions under which a reinforced concrete structure may be exposed in a marine environment: (1) atmospheric zone, (2) tidal zone (splash zone), and (3) the submerged zone (Santhanam & Otieno, 2016), see Figure 2.5.

2.5.1.1 Atmospheric Zone

In the atmospheric zone, the structure is exposed to chlorides carried by air. As a result, chloride-induced corrosion of steel may be a mechanism of deterioration in this zone. Additionally, depending on other factors, including relative humidity or temperature, the structure may be exposed to carbonation-induced corrosion. In comparison to carbonation-induced corrosion, chloride-induced corrosion will be the primary mechanism of deterioration (Santhanam & Otieno, 2016). Gaseous and water vapor diffusion are both possible transport mechanisms under these exposure conditions. Along with diffusion, sorption is a common mode of transport, as rain can cause alternate wetting and drying. Additionally, physical degrading of the structure may occur as a result of salt crystallization (Santhanam & Otieno, 2016). Bridge piers and the underside of decks on marine bridges are examples of structures placed in the atmosphere, which is above a level of +10 ft (+3 m) in relation to the highest possible water level. (Frederiksen, 2000).

2.5.1.2 Tidal Zone (Splash Zone)

Concrete exposed to the tidal or splash zone is typically regarded as having the worst deterioration of any exposure category. Diffusion, sorption, wick action, and permeation all play important roles in the transport of aggressive species in this zone. Furthermore, wave mechanical action can cause physical deterioration, such as abrasion and erosion, and drying cycles can cause salt crystallization (Santhanam & Otieno, 2016). Tidal zone structures include bridge pier shafts that are above -10 ft (-3 m) with respect to the lowest minimum water level and below +10 ft (+3 m) with respect to the highest maximum water level (Frederiksen, 2000).

2.5.1.3 Submerged Zone

There is no sorption effect on concrete that is fully submerged in the sea, but the absorption impact will be significant. Diffusion will also be an essential factor. Therefore, impermeability will be more important than strength in this scenario. Chemical deterioration processes, such as sulfate attack or leaching, and chloride-induced corrosion can cause concrete to degrade (Santhanam & Otieno, 2016). As there is no risk of freezing and limited oxygen available, Mg^{2+}, SO_4^{2-}, and/or CO_3^{2-} attack is the main deterioration process (Thomas, 2016). For example, caissons are submerged structures whose lowest minimum water level is below a depth of -10 ft (-3 m) (Frederiksen, 2000).

In conclusion, the exposure becomes less aggressive as the elevation above sea level increases as chloride loading declines and the concrete becomes less saturated. Wetting and drying cycles accelerate chloride penetration and corrosion risk due to the presence of oxygen and chlorides. Finally, it is not just the conditions of environmental exposure that determine how much deterioration occurs, but also the kind of structure and the element's location within the structure (Thomas, 2016).

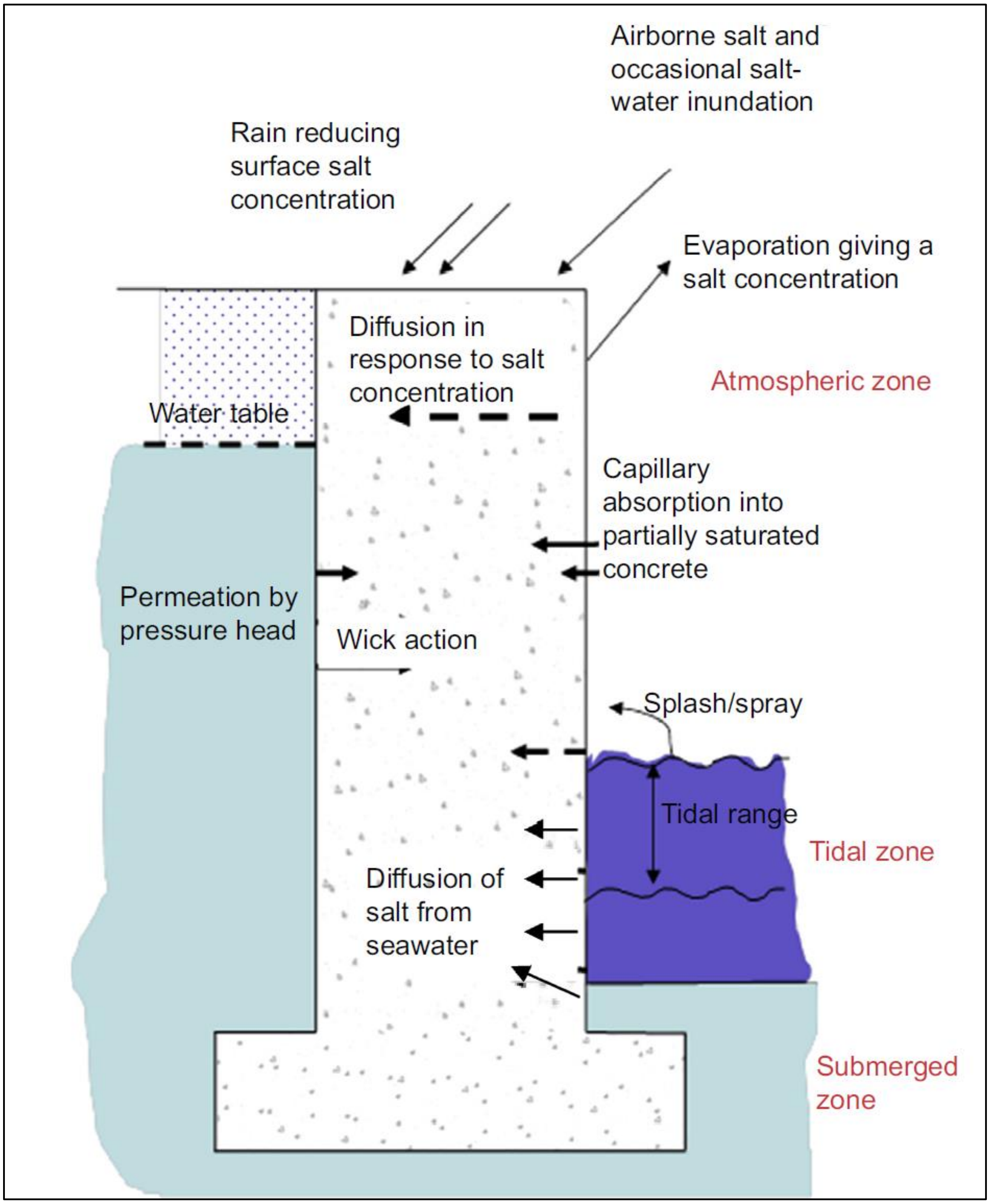


Figure 2.5: Marine Environment Exposure Zones. (Based on BS 6349-1, 2000)

2.6 Deterioration of Concrete in the Marine Environment

While it is obvious that concrete's performance in seawater is dependent on a complex interplay of physical and chemical mechanisms, it is critical to comprehend each of these mechanisms separately (Santhanam & Otieno, 2016). The amount of dissolved salts in seawater is approximately 35 g/l. However, this is subject to change and is dependent on specific geographical locations. Table 2.3 shows a variety of seawater compositions from different sources (Biczok, 1967; Skalny, et al., 2002). The data clearly shows that chloride ions are predominant.

Table 2.3: Seawater Composition from Across the Globe

(Based on (Biczok, 1967; Mehta, 1999)

Major	**Concentration (g/l)**					
	Mediterranean Sea	**North Sea**	**Atlantic Ocean**	**Arabian Gulf**	**Baltic Sea**	**Red Sea**
Na^+	12.400	12.200	11.100	20.700	2.190	11.350
Mg^{2+}	1.500	1.110	1.210	2.300	0.260	1.867
Cl^-	21.270	16.550	20.000	36.900	3.960	22.660
SO_3^-	2.596	2.220	2.180	5.12.	0.580	3.050
TDS*	38.795	33.060	35.370	66.650	7.110	40.960

*Total dissolved solids.

While permeation and sorption are both probable transport processes in a marine environment, the diffusion of chlorides into concrete requires special attention due to the corrosion of the reinforcing steel, which is the most debilitating feature of RC structures (Santhanam & Otieno, 2016). The severity of sulfate and carbon dioxide chemical attacks exacerbates the situation, resulting in faster depassivation of steel and eventual corrosion (Santhanam & Otieno, 2016). Although the chloride profiles, or the change in chloride concentration with depth in concrete, are well defined in the case of simulated exposures in laboratory conditions, the chemical alterations of the surface zone of concrete caused by the action of sulfate and carbon dioxide result in errors when using the error function to derive solutions to the chloride profile (Santhanam & Otieno, 2016). Furthermore, other effects in the tidal zones may cause a buildup of chloride concentration at the surface. Figure 2.6 shows an example of the differences in chloride profiles in different zones of a concrete bent cap.

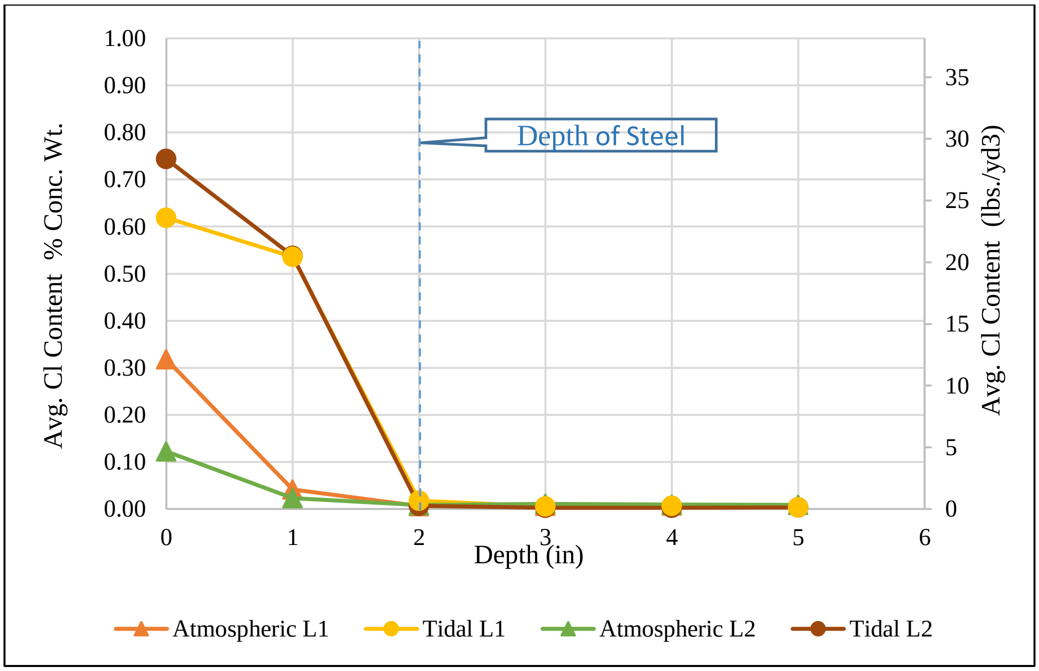


Figure 2.6: Chloride Content Profile in Different Zones

The total impact of the chemical attack is a gradual deterioration of the concrete's integrity. In other words, the splashing action of the waves weakens the surface concrete and makes it more prone to erosion. The chemical and physical mechanisms work together to cause deterioration (Santhanam & Otieno, 2016). In the end, the severity of deterioration is determined by the following factors:

2.6.1 pH Level

Although most seawaters are assumed to have a relatively uniform ionic concentration, and salinity of about 3.5 percent, variations in salinity are dependent on the balance between evaporation and precipitation, or freshwater inflow, as well as the degree of mixing between the surface and deeper waters. Furthermore, the amount of artificial pollution, that produced by processing industries, can have an impact on the ionic concentration of seawater (Otieno & Thomas, 2016). The pH of seawater typically ranges from 7.5 to 8.4, but values lower than 7.5 may be encountered due to high dissolved carbon dioxide concentrations, making the seawater more aggressive to particular concretes (Mehta & Monteiro, 2006).

2.6.2 Temperature and Relative Humidity

Chemical reactions are exacerbated by an increase in temperature in most deterioration processes in the marine environment. The temperature of the water and the temperature of the surrounding environment are important factors to consider. For instance, the surrounding air temperature may influence the duration of concrete wetness during low tides as well as the chloride threshold level for reinforcement corrosion initiation (Rincon, et al., 2007). Moreover, by causing evaporation, the temperature can raise the salinity and thus the aggressiveness of the seawater (Otieno & Thomas, 2016). Increased temperatures and high relative humidity can expedite the deterioration of various materials and aggravate existing deterioration processes. Furthermore, as the temperature rises, both the rate of chloride ion diffusion and the rate of steel corrosion increase (Otieno & Thomas, 2016).

2.6.3 Wetting and Drying Cycles

When it comes to durability, the amount of oxygen and moisture at the reinforcing steel level and the magnitude of capillary suction forces are directly influenced by concrete's moisture content (McCarter & Watson, 1997). Continuous moisture movement through concrete pores is caused by cyclic wetting and drying. By exposing concrete to harmful materials such as sulfates, alkalis, acids, and chlorides, this cyclic action accelerates durability problems (CSIRG, 2010). Depending on the expected mechanism of deterioration, the frequency of wetting and duration of low and high tides can significantly affect the rate of deterioration by affecting the degree of saturation of the concrete (Otieno & Thomas, 2016). Cyclic wetting and drying can accelerate the corrosion process in reinforced concrete structures in two stages. First, cyclic wetting and drying concentrates ions such as chlorides and can accelerate corrosion by enabling oxygen ingress during the drying stage. Second, once chloride thresholds are reached at the steel's depth, drying the concrete increases the availability of oxygen required for steel corrosion, as oxygen has a significantly lower diffusion coefficient in saturated concrete (Hong & Hooton, 1999). Therefore, tidal zone concrete structures are more susceptible to deterioration than those that are permanently submerged in seawater.

2.6.4 Salinity and the Distance from the Open Water

With a salinity of 3.5 percent (or 35 g/L dissolved salt), seawater is mostly made up of sodium chloride and magnesium sulfate; the major ions' concentrations are around 20.000 mg/L chloride (Cl^-), 11,000 mg/L sodium (Na^+), 2700 mg/L sulfate (SO_4^{-2}) and 1400 mg/L magnesium (Mg^{+2}), see Table 2.4 (Thomas, 2016).

Table 2.4: Water Salinity Parameters

Water Type	Part per Million	Percentage
Fresh water	< 1,000 ppm	< 0.1%
Slightly saline water	1,000 ppm - 3,000 ppm	0.1% - 0.3%
Moderately saline water	3,000 ppm - 10,000 ppm	0.3% - 1%
Highly saline water	10,000 ppm - 35,000 ppm	1% - 3.5%

* Based on USGS

The Coastal Salinity Index (CSI) shown in Figure 2.7 is a long-term monitoring tool used to characterize relative changes in coastal salinity regimes with salinity gages for long record periods (USGS, 2022). It is a probability index that has been standardized. A value of zero indicates that the gage data is equal to the historical mean salinity, while negative and positive values represent above and below normal salinity conditions, respectively. The CSI is site-specific and can be computed for multiple time intervals ranging from one to twenty-four months to assist users in evaluating responses at monthly to interannual time scales (USGS, 2022).

Coastal Salinity Classification	Description	CSI Values	Color	Cumulative Percentage
CD4	Exceptional salinity conditions	-2 or less		2
CD3	Extreme salinity conditions	-1.99 to -1.60		5
CD2	Severe salinity conditions	-1.59 to -1.30		10
CD1	Moderate salinity conditions	-1.29 to -0.80		20
CD0	Abnormal salinity conditions	-0.79 to -0.50		30
Normal	Normal salinity conditions	-0.49 to 0.50		70
CW0	Abnormal freshwater conditions	0.51 to 0.80		80
CW1	Moderate freshwater conditions	0.81 to 1.30		90
CW2	Severe freshwater conditions	1.31 to 1.60		95
CW3	Extreme freshwater conditions	1.61 to 2.00		98
CW4	Exceptional freshwater conditions	2.01 or more		100
Not Available	Missing Data			

CD = Coastal Drought
CW = Coastal Wet
Data last updated on 2022-03-30.

Operating Agency

○ U.S. Geological Survey (USGS)
□ National Estuarine Research Reserves (NERRS)
△ National Park Service (NPS)

Figure 2.7: Coastal Salinity Index (Based on USGS)

The distance of concrete structures from open water, such as the sea and ocean, is essential when determining the deleterious effect of water salinity in the marine environment. Estuaries are critical transitional zones where freshwater and seawater mix. The amount of freshwater inflows reaching an estuary varies according to their timing, frequency, duration, and distance. At the same time, the salinity of an estuary varies according to the amount of freshwater inflows, the tidal movement, and the estuary's location (Montagna, 2022).

The timing of freshwater inflows affects salinity levels in estuaries over time. Estuaries in the United States typically decrease in salinity during the spring months due to increased inflows, resulting in a positive estuarine system, see Figure 2.9. Furthermore, an increase in salinity during the summer as freshwater inflows decrease and evaporation increases due to higher temperatures, results in the system being classified as a negative estuarine system (Montagna, 2022). This increase in salinity results in higher chloride concentration, which can significantly affect the rate of deterioration and accelerate the onset and subsequent rate of corrosion due to increased temperature and oxygen availability, see Figure 2.10. Both Figure 2.9 and Figure 2.10 represent multiple coastal stations located along the coastline. These stations recorded the salinity readings. These stations took salinity readings throughout the year. The readings are for the multiple time interval of CSI from 1- to 24-months.

NCDOT Structures Management Unit (SMU) Design Manual divided the coastline of North Carolina into two corrosive zones: (1) Highly Corrosive (red) and (2) Corrosive (blue), see Figure 2.8 (NCDOT, 2019). A salinity test should be conducted during the summer and winter seasons to obtain an accurate assessment of these zones.

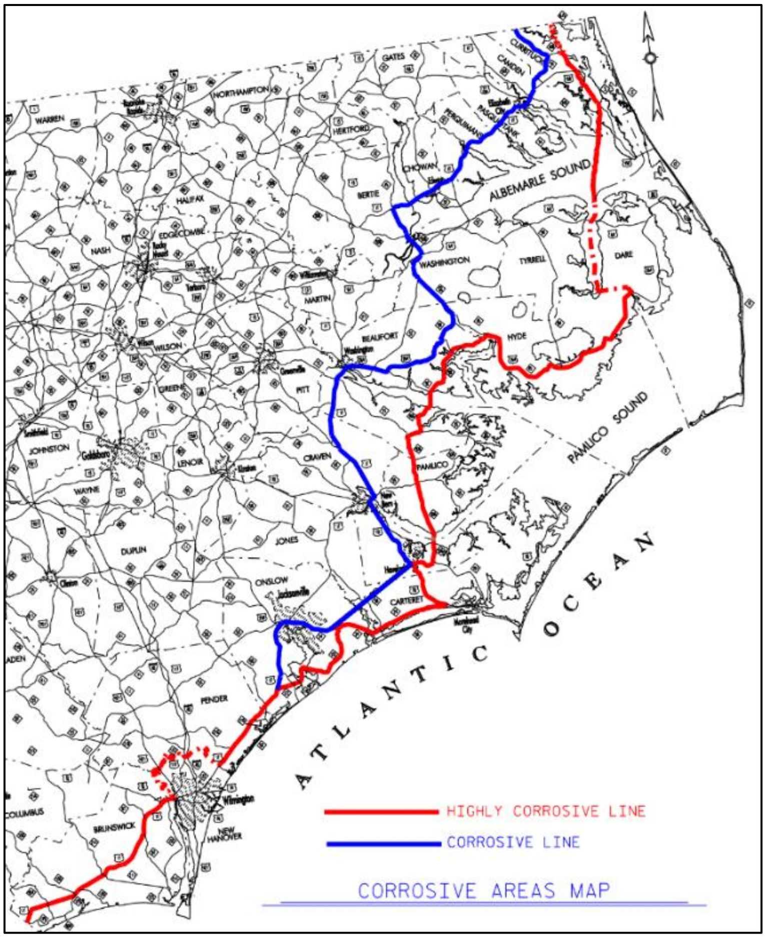


Figure 2.8: Corrosive Sites Dividing Lines (Based on NCDOT SMU Manual, Figure 12-29)

In conclusion, salinity distributions are determined by the driving force that mixes river and seawater flow into the estuary, the distance traveled by the tide, the strength of the tidal currents and waves, the time of year, and the rate of evaporation. All of these factors will contribute to chloride ingress and, consequently, to the corrosion process (Montagna, 2022).

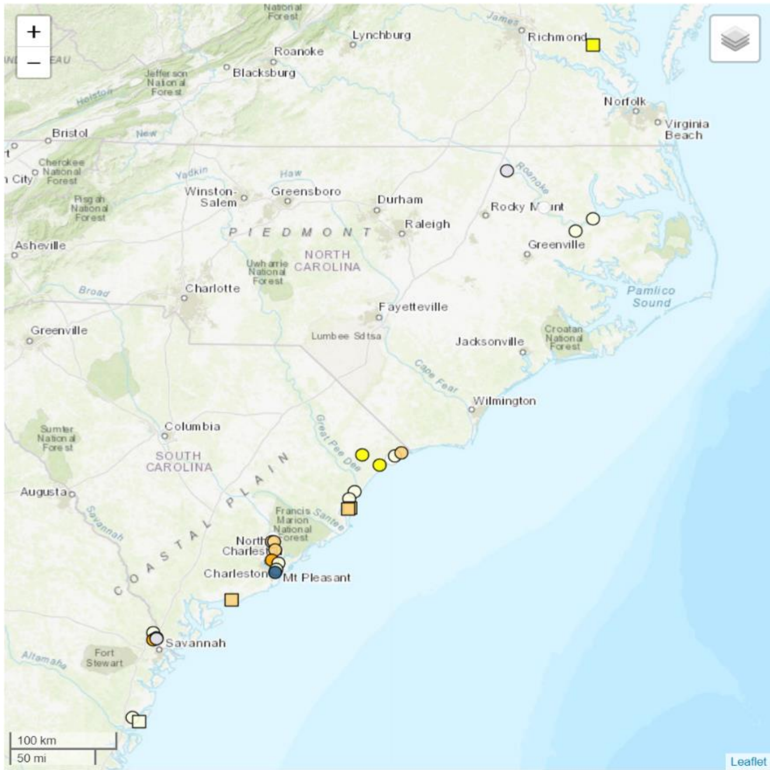


Figure 2.9: Time Interval of CSI Values: 6-month (Based on USGS CSI)

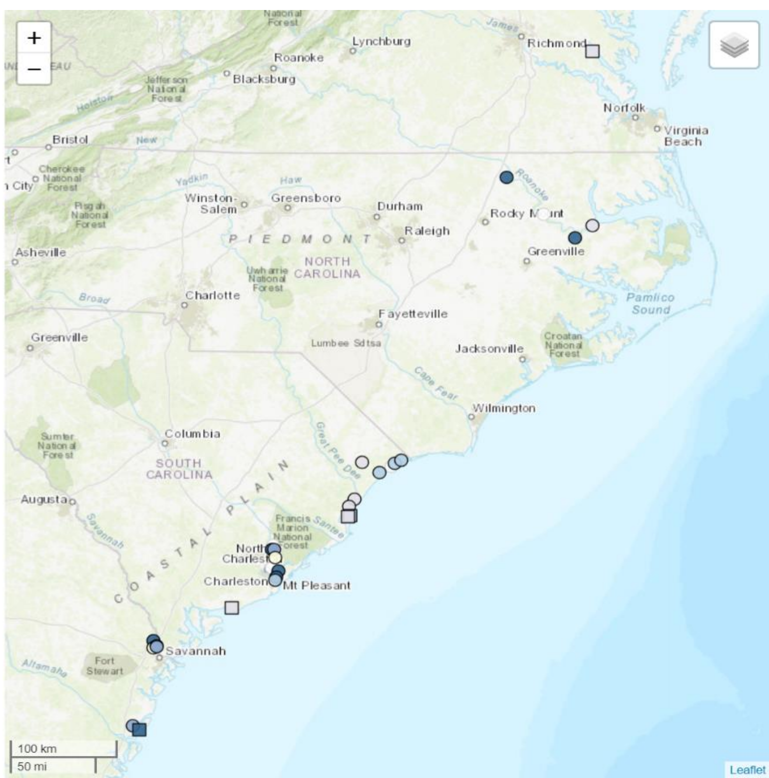


Figure 2.10: Time Interval of CSI Values: 24-month (Based on USGS CSI)

2.7 Prevention of Chloride Ingress and Corrosion

Concrete can be designed to be durable in even the most hostile marine environments, but special attention must be given to the exposure conditions. In other words, the materials and proportions chosen for one marine exposure condition may not be optimal for another. For instance, high levels of fly ash and slag produce concrete that is highly resistant to chlorides, making it ideal for use in tidal zones; however, high levels of these materials in sheltered elevated areas of a structure, such as the top of a pier beneath a bridge deck, may make the concrete more susceptible to carbonation (Thomas, 2016). There are numerous corrosion-prevention strategies, but one of the primary lines of defense is to provide concrete with a high resistance to chloride-ion penetration; of course, it is also critical to ensure that the depth of the concrete cover over the steel is sufficient and that cover concrete cracking is mitigated (Thomas, 2016). Concrete's chloride resistance is determined by the physical structure of the pore system as well as the chemical composition of the binder. A well-defined pore structure with small, disconnected pores will exhibit a high physical resistance to chloride penetration. This is typically accomplished by adjusting the water/binder ratio (w/b) of the concrete and selecting an appropriate binder. The binder selected is also critical for chemical resistance to chloride penetration, as some cementitious binders can bind a significant amount of penetrating chloride ions, preventing further ingress of the destined chlorides (Thomas, 2016). The addition of supplementary cementing materials (SCMs) such as fly ash, slag, silica fume, metakaolin, and other pozzolans can significantly improve the chloride resistance of concrete, as their proper use results in a much more refined pore structure and consequently reduced permeability, when compared to Portland cement (PC) concrete without SCMs. Additionally, many SCMs contain significant amounts of alumina (Al_2O_3), which increases the concrete's chloride-binding capacity (Zibara, 2001).

2.7.1 Types of Cement

Active corrosion of steel reinforcement is determined by the composition and availability of the pore solution, rather than by the concrete itself. Thus, the components of concrete that control the pH of the pore solution, the total porosity, and the pore-size distribution are critical in the corrosion process (ACI 222R-19, 2019). The best defense against chemical attack in a seawater environment is to use low-permeability concrete with a low w/b ratio; consideration should also be given to the use of SCMs to further reduce permeability (Thomas, 2016).

2.7.2 Supplementary Cementing Materials (SCMs)

Supplementary cementing materials have a very significant impact on the performance of marine concrete. The primary advantage is that SCMs decrease the permeability of concrete, making it less prone to chloride and other ion penetration. Additionally, the majority of SCMs reduce the risk of damage caused by the alkali-silica reaction (ASR) and delayed ettringite formation. (Thomas, 2013). The porosity and pore-size distribution for a given w/cm are determined by the fineness of the cement and the pozzolanic components. In general, supplementary cementitious materials, including fly ash, slag, and silica fume, reduce and refine the porosity of the concrete, as well as the rate at which aggressive chemicals are transported into the concrete and toward the steel reinforcement (ACI 222R-19, 2019). However, Thomas (1996) discovered that when the amount of fly ash (FA) in concrete exposed to seawater was increased, the CTL decreased. Nevertheless, as the amount of FA in the concrete increased, the mass loss of the steel embedded in concrete decreased. Moreover, Thomas & Matthews (2004) reported a reduction in the CTL of FA concrete based on its 10-year performance, which included chloride transport and embedded steel corrosion, both of which were reduced by FA replacement. They also demonstrated that, despite a lower CTL, the addition of FA can extend the time to corrosion and limit corrosion propagation. This difference in FA's impact on CTL could be due to the presence of other more dominant factors, such as the physical condition of the steel–concrete interface. The CTL appears to be influenced by external environmental factors, chloride source, and corrosion detection method (Ann & Song, 2007).

2.7.3 Aggregates

For aggregates exposed to marine environments, there are no specific properties or performance requirements. Aggregates should be well-graded, have suitable physical properties, be frost-resistant (if subjected to freeze-thaw in service), and meet the standard requirements for aggregates used in concrete construction. If the aggregates are alkali-silica reactive, precautions should be taken to reduce the risk of a negative reaction (Thomas, 2016).

2.7.4 Corrosion Inhibitors

The reason for using corrosion inhibitors for corrosion protection is that the inhibitor is evenly distributed throughout the concrete, protecting all of the steel. Corrosion inhibitors alter the chemical composition of steel's surface in order to slow or stop the corrosion process (Ann & Song, 2007). Since the mid-1970s, calcium nitrite has been widely used in concrete as a corrosion inhibitor due to its inhibitory effect and compatibility with the concrete. It increases compressive strength at a young age and accelerates the setting time to within the recommended values (Ann & Song, 2007). Numerous studies have demonstrated that calcium nitrite is extremely effective at mitigating chloride-induced corrosion in concrete, significantly reducing the rate and potential for corrosion while also substantially increasing the time to corrosion (Ann & Song, 2007). However, it is recommended to use high-quality concrete to maximize the inhibitory effect of calcium nitrite (Ann & Song, 2007). A recent series of studies on calcium nitrite discovered that calcium nitrite had no significant effect on the CTL in a beaker experiment using synthetic pore solution (Mammoliti, et al., 1999), Despite the fact that the time required for corrosion to occur was prolonged in mortar (Tre´panier, et al., 2001). Additionally, surface tomography performed by the same authors indicates that any inhibiting effect may be due to an increase in the electrolytic resistance of concrete induced by calcium nitrite, rather than a change in the steel surface's chemistry. Furthermore, it was recently discovered that nitrite ions in concrete may accelerate chloride transport, making it less effective at delaying corrosion despite the increased CTL (Ann & Buenfeld, 2007).

2.7.5 Alternative Reinforcement

Even in marine environments, steel-reinforced concrete is frequently reinforced with plain 'black' steel, largely for cost reasons (Thomas, 2016). Additionally, steel-reinforced concrete structures face chloride-induced corrosion of the embedded steel. Prestressed concrete, whether pre- or post-tensioned, is generally less prone to steel corrosion than conventionally reinforced concrete due to better crack control; nevertheless, the consequences of corrosion are typically more severe for prestressed concrete (Thomas, 2016). It may be necessary to use different types of reinforcement on occasion to ensure the structure's corrosion-resistant performance.

2.7.5.1 Epoxy-Coated Steels

The early 1960s saw the first recognition of the problem of premature deterioration of steel-reinforced concrete structures due to chloride-induced corrosion. About ten years later, epoxy-coated reinforcement (ECR) was developed as a potential solution to this problem, and the market grew rapidly to the point where ECR became the preferred corrosion-protection strategy in North American highway structures (Thomas, 2016). The first instances of ECR corrosion in marine structures were discovered in the Florida Keys in the mid- to late 1980s and were attributed to the epoxy debonding from the steel (Zayed, et al., 1989). Conversely, the high percentage of ECR structures exposed to deicing salts or seawater performed satisfactorily. At the moment, it is unknown how ECR will affect the service life of reinforced concrete structures exposed to marine environments (Thomas, 2016).

2.7.5.2 Corrosion-Resistant Steel

Many parts of the world have stainless steel reinforcement (SSR) for concrete. Stainless steel's superior corrosion resistance is well known, and it's been used in a variety of projects (Thomas, 2016). Stainless steel is an iron-based steel alloy that contains at least 12% chromium by weight (Hartt, et al., 2004). As a result, the composition of stainless steel varies considerably, and because the corrosion resistance of SSR is dependent on the alloy composition, the steel's performance in corrosive environments varies considerably as well. High-grade stainless steels, such as 316LN (which contains alloying elements such as chromium, nickel, molybdenum, and nitrogen), have been shown to be remarkably efficient in decreasing the risk of corrosion in reinforced concrete structures (Hansson, et al., 2009).

2.7.6 Cathodic Protection

Cathodic protection implies that the protected metal is polarized in a cathodic direction, effectively suppressing anodic reactions on the surface. This can be accomplished either through the use of sacrificial anodes or through the application of impressed current (Ahlström, 2015). A common method of utilizing impressed current in concrete structures is to apply a net made of titanium to the concrete surface and then cast a new layer of concrete over the net. The titanium net is anodically polarized to a potential where the oxygen evolution reaction occurs. In concrete with a high pH, the anodic reaction consumes hydroxides, whereas with a low pH, the anodic reaction consumes water (Ahlström, 2015). Therefore, the titanium is not consumed, and the formed electrons are transported to the rebar, which is then protected. Koleva, et al. (2007) studied the cathodic protection of concrete steel interfaces using impressed current. The impressed current was between 5 and 20 mA/m^2, and the results indicated a decrease in salinity at the rebar and the formation of a more uniform and protective passive layer on the steel surface

2.7.7 Maximum Water/Binder (Water-Cementitious Materials) Ratio (w/b or w/cm)

The expressions 'binder' and 'water/binder' are preferred over 'cement' and 'water/cement' ratios, as the cementitious materials currently used in marine concrete are typically blends of Portland cement and an extender. However, the word ‘cement’ has been used to match the terminology used in other standards. The w/cm is directly related to the porosity and penetration rate of deleterious materials. Corrosion resistance is generally improved with a lower w/cm, as long as the stiffness and reduced creep of the concrete do not lead to increased cracking (ACI 222R-19, 2019). This can be accomplished through the use of water-reducing admixtures, which typically reduce the required water content of a concrete mixture by approximately 5% to 10%. These admixtures should meet ASTM C494/C494M standards (ACI 357.3R-14, 2014). The various classifications for these types of admixtures are Type A through G (ACI 357.3R-14, 2014).

2.7.8 Minimum Depth of Cover

Both the depth of the concrete cover and the w/b (w/cm) ratio have an impact on corrosion protection provided by the minimum depth of cover. In order to reach the steel reinforcement, chloride or carbonation must first penetrate deeper into the uncracked concrete, which takes longer if the concrete cover is increased (ACI 357.3R-14, 2014). Chloride ions present in the marine environment can enter concrete cover through pores and cracks and cause rebar corrosion. As soon as the critical chloride ion concentration is reached on the surface of the steel, the passive state is lost (W. Morris, 2002). Increased concrete cover depth is one of the most effective ways to improve the corrosion protection of steel reinforcement. The amount of cover thickness appears to be primarily determined by the water to cementitious material ratio, the type of pozzolanic material replacement, and exposure conditions. The most severe condition is tidal zones, and the concrete cover must be increased to ensure an acceptable service life (Khaghanpour, et al., 2016). However, too much cover can increase cracking (ACI 201.2R-16, 2016). Cover thicknesses recommended by design codes will be addressed later.

The quality of the cover layer is determined not only by the ingredients and proportions of the mix, but also by the construction processes, specifically the effects of compaction, curing, early-age drying, and early penetration of aggressive environmental agents, see Figure 2.11 (Alexander & Beushausen, 2019).

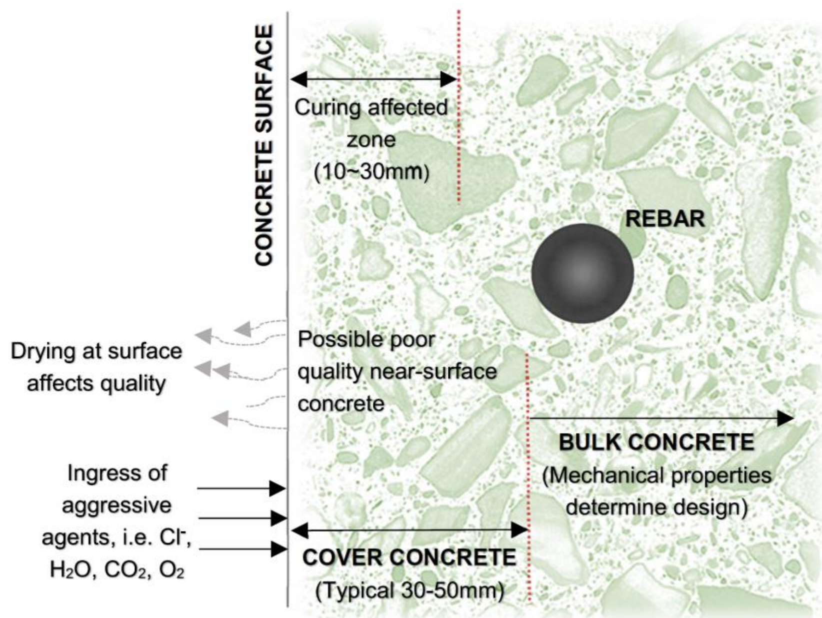


Figure 2.11: Schematic of Cover Layer of Concrete

(Based on Alexander & Beushausen, 2019)

2.8 Review of International Standards and Guide Manuals of Marine Concrete Structures

Several international standards and guide manuals address chloride ingress prevention, deterioration, marine exposure, and chloride content in reinforced concrete in the marine environment. Each code or publication takes a different approach to achieving durable design mix for concrete while protecting the steel in a corrosive environment. The NCDOT Structures Management Unit Manual contains policy and procedure guidelines that are similar with national and international standards. The standards and publications reviewing include U.S codes (ACI 318-19, ACI 357R-84, ACI 357.3R-14, ACI 222R-19, AASHTO LRFD-8, AASHTO LRFDCONS-4, PCI MNL-120-17), British and European codes (BS 6349-1-4:2013, BS 8500-1:2015+A2:2019, BS EN 206:2013+A1:2016), Australian Standards (AS 3600:2018, AS 4997-2005, AS 1379 Supp1-1997). A comparison summary of major durability requirements from different codes, standards, and design manuals with NCDOT SMU design manual are displayed in Table 2.5.a and 2.5.b. Seven parameters were selected that represent the best practice of preventing chloride ingress:

- Maintenance-free service life (MFSL)
- Definition of the tidal zone
- Requirement of concrete cover
- Maximum water/binder ratios (w/cm or w/b)
- Supplementary cementitious materials (SCMs)
- Maximum admixed chloride limits for new construction
- Distance from open water

Table 2.5.a: Comparison of International Standards and Guide Manuals

Parameter	American		British/European		Australian		NCDOT	
Maintenance-free service life (years)	Not specified		BS 6349-1-4:2013 (Table 1-3)		AS 4997-2005 (Table 6.1)		Not specified	
			30, 50, 100 years		25, 50, 100 years			
Definition of The Tidal Zone	ACI 357.3R-14 (5.2.2)		Not specified		AS 3600:2018 (Table 4.3)		SMU Manual (12-12)	
	Concrete is regularly wetted by tides.This is typically any element, or portion thereof, that is located between MLLW and mean higher high water (MHHW). In areas with minimal tides, this would be defined as the area located between MSL and mean high water (MHW)				Tidal/splash zone is the zone 1 m below lowest astronomical tide and up to 1 m above highest astronomical tide on vertical structures and all exposed soffits of horizontal structures over the sea; spray zone is the zone from 1 m above wave crest level		Not specified	
Requirement of Concrete Cover	AASHTO LRFD-8 (5.10.1-1)		BS 8500-1:2015+A2:2019		AS 3600:2018 (4.10.3.2)		SMU Manual (10.5.1)	
	"Prestressed piles crrosive environments"	3 in.	Table A.4: The concept of Dc introduced which is defined as an allowance in design for deviation; different compressive strengths specified for different exposures with various values of Dc		AS 4997-2005 (Table 6.4)		Columns (spiral)	3 in
	ACI 357.3R-14 (5.5.4)				Exposure classification C2:Tidal/Splash zone (fc'≥50 Mpa) for a design life of 25 years	2.5 to 3 in (65 to 70 mm)	SMU Manual (10.5.1)	
	Cast-in place splash and atmospheric zone subject to salt spray (tidal zone)	2.5-4 in.					End Bent & Bent Caps	3-4 in
Maximum water/binder ratios (w/cm or w/b)	ACI 318-19 (19.3.2.1)		BS 6349-1-4:2013 (Table 1-3)		AS 1379 Supp1—1997		SMU Manual (12-12)	
	Exposure class C2 (Cast-in place)	0.4	A.4.6		Exposure classification C2:Tidal/Splash zone	0.35	The water/cement ratio for concrete piles shall not exceed	0.4
	PCI MNL-120-17 (9.2.1.5)		Design life 30 year	0.55				
	Exposure class C2 (Prestressed)	0.37	Design life 50 year	0.45				
			Design life 100 year	0.35				

Table 2.5.b: Comparison of International Standards and Guide Manuals

Parameter	American		British/European		Australian	NCDOT	
Supplementary Cementitious Materials	ACI 232.2R-18 (8.8)		BS 6349-1-4:2013 (Table 1-3)		AS 1379 Supp1—1997	Standard Specifications1024-1	
	Prestressed fly ash type F	10-30 %	Cement type IIB-V+SR (fly ash)	25-35%	The code requirements are prescriptive, and they only give requirements for a 25-year design life.	fly ash type F (columns, bent caps, pile caps, footings, and/or piles)	20-30%
	ACI 232.2R-18 (5.1)						
	Reinforced fly ash type F	15-35%	Cement type IIB-V (fly ash)	21-24%			
	ACI 233R-17 (9.3)					Ground Granulated Blast Furnace Slag	35-50%
	Slag (Prestressed, ready mixed concret)	35-50%	Cement type IIIA (ggbs-slag)	46-65%			
	ACI 234R-06 (9.2)						
	Silica Fume	5-10%	Silica Fume	5-10%		Microsilica	4-8%
Maximum Admixed Chloride Limits for New Construction (by percent mass of cement)	ACI 222R-19 (4.2.3)		BS EN 206:2013 (5.2.8)		Not specified	Not specified	
	Prestressed concrete (ASTM C1218)	0.06	Containing prestressing steel reinforcement in direct contact with concrete	0.1-0.2			
	Prestressed concrete (ASTM C1152)	0.08					
	Reinforced concrete (ASTM C1218)	0.15	Containing steel reinforcement or other embedded metal	0.2-0.4			
	Reinforced concrete (ASTM C1152)	0.2					
Distance From Open Water	Not specified		Not specified		AS 3600:2018 (4.10.3.2) Distance from the coast is defined in three categories: (1) up to 1 km; (2) beyond 1 km and up to 50 km; (3) beyond 50 km with different exposure classifications	Tow corrosive zones lines: (1) Highly Corrosive (red) (2) Corrosive (blue)	

2.8.1 American Publications (Standard/ Design Code)

The American Concrete Institute (ACI) is one of the most comprehensive single sources of concrete design, construction, and materials information in dealing with corrosion mitigation, protection of reinforcing steel, SCMs, durability design, and requirement of concrete structures in the marine environment, as well as other publication like AASHTO, PCI. The U.S codes are as follows:

- ACI 201.2R-16 Guide to Durable Concrete
- ACI 222R-19 Guide to Protection of Reinforcing Steel in Concrete Against Corrosion
- ACI 222.2R-14 Report on Corrosion of Prestressing Steels
- ACI 222.3R-11 Practices to Mitigate Corrosion of Reinforcement in Concrete Structures
- ACI 232.2R-18 Report on The Use of Fly Ash in Concrete
- ACI 233R-17 Guide to The Use of Slag Cement in Concrete and Mortar
- ACI 234R-06 Guide for the Use of Silica Fume in Concrete
- ACI 318-19 Building Code Requirements for Structural Concrete
- ACI 357R-84 Guide for the Design and Construction of Fixed Offshore Concrete Structures
- ACI 357.3R-14 Design and Construction of Waterfront and Coastal Concrete Marine Structures
- AASHTO LRFD Bridge Design Specifications, 8th Edition
- AASHTO LRFD Bridge Construction Specifications, 4th Edition
- PCI Design Handbook Precast and Prestressed Concrete, 8th Edition, MNL-120-17

Chapter 19.3.1.1 of ACI 318-19 defined the exposure categories and classes in Table 2.6. Category C exposure refers to nonprestressed and prestressed concrete that is subjected to conditions that necessitate additional protection against reinforcement corrosion (ACI 318-19, 2019).

Table 2.6: Exposure Categories and Classes (Based on ACI 31-19, Table 19.3.1.1)

Category	Class	Condition	
Freezing and thawing (F)	F0	Concrete not exposed to freezing-and-thawing cycles	
	F1	Concrete exposed to freezing-and-thawing cycles with limited exposure to water	
	F2	Concrete exposed to freezing-and-thawing cycles with frequent exposure to water	
	F3	Concrete exposed to freezing-and-thawing cycles with frequent exposure to water and exposure to deicing chemicals	
Sulfate (S)		Water-soluble sulfate (SO_4^{2-}) in soil, percent by mass[1]	Dissolved sulfate (SO_4^{2-}) in water, ppm[2]
	S0	$SO_4^{2-} < 0.10$	$SO_4^{2-} < 150$
	S1	$0.10 \leq SO_4^{2-} < 0.20$	$150 \leq SO_4^{2-} < 1500$ or seawater
	S2	$0.20 \leq SO_4^{2-} \leq 2.00$	$1500 \leq SO_4^{2-} \leq 10,000$
	S3	$SO_4^{2-} > 2.00$	$SO_4^{2-} > 10,000$
In contact with water (W)	W0	Concrete dry in service	
	W1	Concrete in contact with water where low permeability is not required	
	W2	Concrete in contact with water where low permeability is required	
Corrosion protection of reinforcement (C)	C0	Concrete dry or protected from moisture	
	C1	Concrete exposed to moisture but not to an external source of chlorides	
	C2	Concrete exposed to moisture and an external source of chlorides from deicing chemicals, salt, brackish water, seawater, or spray from these sources	

ACI 357.3R-14 defines the tidal zone in chapter 5.2.2 as *"Concrete is regularly wetted by tides. This is typically any element, or portion thereof, that is located between MLLW and mean higher high water (MHHW). In areas with minimal tides, this would be defined as the area located between MSL and mean high water (MHW)"* (ACI 357.3R-14, 2014), Moreover, in a waterfront and coastal marine environment, ACI 357.3R-14 recommends a minimum concrete cover over principal reinforcement as shown in Table 2.7. However, AASHTO HB-17 recommends 4 in. (100 mm) of clear cover for reinforced concrete substructures that will be exposed to seawater for more than 40 years due to a higher risk of corrosion and concerns about public safety (ACI 357.3R-14, 2014).

Table 2.7: Recommended Minimum Concrete Cover

(Based on ACI 357.3R-14, Table 5.5.4)

Zone	Cover over principal reinforcing steel, in. (mm)
Atmospheric zone not subject to spray	2.0 (50)
Splash and atmospheric zone subject to salt spray (tidal zone)	2.5 (65)
Submerged zone	2.0 (50)

The maximum water/binder (w/cm) ratios have been reported in ACI 318-19 in chapter 19.3.2.1 for exposure class C2 in cast-in place concrete as 0.4 (ACI 318-19, 2019). For prestressed concrete PCI MNL-120-17 uses w/b of 0.4 in chapter 9.2.1.5 for the same exposure conditions, see Table 2.8. However, precast and prestressed concrete products are frequently used in many plants with a w/b material ratio of 0.37 or lower for added durability (PCI MNL-120-17, 2018).

Table 2.8: Water/Binder (w/cm) Ratios Requirements for Special Exposure Conditions

(Based on PCI MNL-120-17, Table 9.2.6)

Exposure condition	Maximum water–cementitious material ratio, by weight, normalweight concrete	Minimum concrete strength f'_c, psi, normalweight and lightweight concrete
Concrete in contact with water and low permeability is required (ACI 318-14 Class W1)	0.50	4000
Concrete exposed to cycles of freezing and thawing with frequent exposure to water (ACI 318-14 Class F2)	0.45	4500
Concrete exposed to cycles of freezing and thawing with frequent exposure to water and exposure to chlorides from deicing chemicals, salt, brackish water, seawater, or spray from these sources (ACI 318-14 Class F3/C2)	0.40	5000

Neither PCI nor ACI 318-19 have a specific requirement for the SCMs for concrete structures in the marine environment. However, both codes reference ACI 201.2R, which provides guidance on the durability of concrete, and ACI 222R, which provides guidance on the factors that affect metal corrosion in concrete. Moreover, ACI 201.2R and ACI 222 Reference ACI 232.2R, ACI 233R and ACI 234R for the SCMs requirements for concrete mixtures for prestressed and reinforced concrete, see Table 2.5.b.

The chloride ion limits for Exposure Classes C0, C1, and C2 (Table 2.6) apply to chlorides contributed by the concrete materials, not the environment surrounding the concrete. Water-soluble chlorides introduced from concrete materials, even in Exposure Class C0, can potentially cause reinforcement corrosion and must be limited for both nonprestressed and prestressed concrete, regardless of external exposure (ACI 318-19, 2019). To extend the service life of prestressed and reinforced concrete exposed to chlorides in service, the lowest possible chloride levels in the concrete mixture should be maintained, see Table 2.9. As a result, even if the chloride content of the constituent materials is less than the stated allowable limits, chlorides should not be intentionally added to the concrete mixture or its constituent materials. Additional protection against corrosion of embedded reinforcing steel may be required in many exposure conditions, such as highway and parking structures, marine environments, and industrial plants where chlorides are present (ACI 222R-19, 2019).

Table 2.9: Allowable Admixed Chloride Limits for New Construction

(Based on ACI 222R-19, Table 4.2.3)

Category	Chloride limit for new construction (percent by mass of cementitious material*)	
	Test method	
	Acid-soluble	Water-soluble
	ASTM C1152/ C1152M	ASTM C1218/ C1218M
Prestressed concrete	0.08	0.06
Reinforced concrete in wet conditions	0.20	0.15
Reinforced concrete in dry conditions†	0.30	0.25

*Portland-cement-based systems only Total cementitious material includes portland cement and SCM; however, for determining allowable admixed chloride level, the SCM content cannot exceed the portland cement content

†Typically interior concrete protected from moisture, high humidity, or both

2.8.2 British and European standards (BS-EN)

BS 6349 is the most comprehensive set of codes for the design of maritime civil engineering works available today, and it represents industry best practice. Because the BS 6349 codes are aligned with the Eurocodes, they present a unified picture. The BS 6349 Maritime Works code set covers a wide range of marine structures, as well as all of the common materials used in their construction (Smith, 2016). Besides BS 6349, other codes and practices used for the marine environment in Britain and Europe are as follows:

- BS 6349-1-1:2013 Maritime works – Part 1-1: General – Code of practice for planning and design for operations
- BS 6349-1-4:2013 Maritime works – Part 1-4: General – Code of practice for materials
- BS 8500-1:2015+A2:2019 Concrete – Complementary British Standard to BS EN 206 – Part 1: Method of specifying and guidance for the specifier
- BS 8500-2:2015+A1:2016 BS 8500-1:2015+A2:2019 Concrete – Complementary British Standard to BS EN 206 – Part 2: Specification for constituent materials and concrete
- BS EN 206:2013+A1:2016 Concrete — Specification, performance, production and conformity

In section 4.3.3.1, Chapter 4 of BS 6349-1-4:2013, durability design, deterioration processes, exposure classification, and particularly chloride ingress are discussed. Based on a systematic approach to durability design or on prescriptive limits, limiting values for reinforced concrete should be established for 30-, 50- and 100-year working lives, see Table 2.10. The limits are compressive strength, maximum water/cement ratio, minimum cement or combination content, and concrete cover (BS-6349-1-4, 2013). Table 2.10 shows the limiting values for a required design working life of 100 years. Chloride ingress is significantly reduced at higher levels of SCMs addition (e.g. 25–40% fly ash or 66–80% ggbs (slag)). The amount of fly ash or ggbs (slag) used is determined by climatic and site conditions (BS-6349-1-4, 2013). When used in conjunction with fly ash or ggbs (slag) and Portland cement, silica fume can be beneficial in doses up to 10% of the total cementitious content, or 5% in combination with fly ash or ggbs (slag) (BS-6349-1-4, 2013).

Table 2.10: Limiting Values for a Required Design Working Life of 100 Years

(Based on Table 3, BS 6349-1-4:2013)

Table 3 **Limiting values for composition and properties of concrete classes with normal weight aggregates of 20 mm maximum size exposed to risk of corrosion of reinforcement induced by UK seawater conditions for a required design working life of 100 years** *(1 of 2)*

Compressive strength class [A)], maximum water/cement ratio [B), C)] and minimum cement or combination content (kg/m³) [D)] — Nominal cover, in millimetres [E), F)]											Permissible cement and combination designations with additional restrictions (where appropriate)
30 + Δc	**35 + Δc**	**40 + Δc**	**45 + Δc**	**50 + Δc**	**55 + Δc**	**60 + Δc**	**65 + Δc**	**70 + Δc**	**75 + Δc**	**80 + Δc**	
XS1 – Airborne salt environment – exposed to airborne salt but not in contact with seawater or splash											
—	—	C35/45 0.40 360	C32/40 0.45 360	C28/35 0.50 360	C25/30 0.55 340	C20/25 0.55 340	C20/25 0.55 340	C20/25 0.55 340	C20/25 0.55 340	C20/25 0.55 340	IIIA with 46% to 65% ggbs IIIB IIB-V+SR (25% to 35% fly ash) [G)] IVB-V
—	—	C40/50 0.35 360	C35/45 0.40 360	C32/40 0.45 360	C28/35 0.50 360	C25/30 0.55 340	C20/25 0.55 340	C20/25 0.55 340	C20/25 0.55 340	C20/25 0.55 340	IIIA with 36% to 45% ggbs IIV-B with 21% to 24% fly ash [G)]
—	—	—	—	—	—	—	C40/50 0.35 360	C35/45 0.40 360	C32/40 0.45 360	C28/35 0.50 360	CEM I CEM II/A-L(LL), II/A, II/B-S
XS2 – Submerged environment – permanently submerged											
—	—	—	C40/50 0.35 360	C35/45 0.40 360	C32/40 0.45 360	C28/35 0.50 360	C25/30 0.55 340	C20/25 0.55 340	C20/25 0.55 340	C20/25 0.55 340	IIIA with 46% to 65% ggbs IIIB IIB-V+SR (25% to 35% fly ash) [G)] IVB-V
—	—	—	—	C40/50 0.35 360	C35/45 0.40 360	C32/40 0.45 360	C28/35 0.50 360	C28/35 0.50 360	C25/30 0.55 340	C20/25 0.55 340	IIIA with 36% to 45% ggbs IIV-B with 21% to 24% fly ash [G)]
XS2/3 – Frequently wetted lower tidal, backfilled											
—	—	—	—	—	—	C35/45 0.40 380	C32/40 0.45 360	C28/35 0.50 360	C25/30 0.55 340	C20/25 0.55 340	IIIA with 46% to 65% ggbs IIIB IIB-V+SR (25% to 35% fly ash) [G)] IVB-V
—	—	—	—	—	—	C40/50 0.35 380	C35/45 0.40 360	C32/40 0.45 360	C28/35 0.50 360	C28/35 0.50 360	IIIA with 36% to 45% ggbs IIB-V with 21% to 24% fly ash [G)]
XS3 – Infrequently wetted upper tidal, splash/spray, "dry" internal faces of submerged structures											
—	—	—	—	—	—	C40/50 0.35 380	C35/45 0.40 360	C32/40 0.45 360	C28/35 0.55 360	C25/30 0.55 340	IIIA with 46% to 65% ggbs IIIB IIB-V+SR (25% to 35% fly ash) [G)] IVB-V
—	—	—	—	—	—	—	C40/50 0.35 380	C35/45 0.40 360	C32/40 0.45 360	C28/35 0.50 360	IIIA with 36% to 45% ggbs IIB-V with 21% to 24% fly ash [G)]

A) Characteristic strength class: cylinder/cube (MPa). Lightweight aggregate concrete should conform to the equivalent strength classes.
B) Maximum free water/cement ratio in accordance with BS EN 206-1:2000.
C) Where there is difficulty in conforming to the strength required at 28 days because of the characteristics of the cement type or the combination then, provided that a systematic regime of checking is established to ensure conformity to the free water/cement ratio recommendation, the 28 day strength recommendation may be relaxed.
D) Minimum cement content depends on maximum aggregate size (see Notes on Table 1, Table 2 and Table 3).
E) Expressed as the minimum cover to reinforcement plus an allowance for deviation, Δc, to allow for workmanship and tolerance. An additional 10 mm should be allowed for prestressing strand.
F) A dash (—) signifies that greater cover is recommended.
G) The designation of cement type CEM IIB-V is deemed to contain 21% to 24% fly ash for the purposes of this table. The designation of IIB-V+SR contains 25% to 35% fly ash and is thus equivalent to a CEM IIB-V containing 25% to 35% fly ash as specified in BS EN 197-1.

2.8.3 Australian Standards

The Australian codes that apply to marine structures are as follows:

- AS 3600:2018 Concrete Structures
- AS 4997—2005 Guidelines for The Design of Maritime Structures
- AS 1379 Supp1—1997 Specification and Supply of Concrete
- AS 3972—2010 General Purpose and Blended Cements

A structure's or a structural element's design life is defined in AS 4997-2005 as the amount of time that it can be used for its intended purpose with proper maintenance. The design life of a maritime structure is determined by the facility's type and intended purpose, see Table 2.11 (AS 4997-2005, 2005).

Table 2.11: Design Life of Structures (Based on AS 4997, Table 6.1)

Facility category	**Type of facility**	**Design life (years)**
1	Temporary works	5 or less
2	Small craft facility	25
3	Normal commercial structure	50
4	Special structure/residential	100

Table 6.3 in AS 4997-2005 expands on Table 4.3 of AS 3600 in terms of exposure classifications. Only minor corrosion occurs in concrete reinforcement that is permanently submerged in seawater (AS 4997-2005, 2005). Rapid corrosion occurs in the splash (tidal) zone, where the concrete is alternately wet and dry, as a result of chloride concentration and

penetration, as well as the high availability of oxygen and moisture in the concrete, see Table 2.12 (AS 4997-2005, 2005).

Table 2.12: Exposure Classifications (Based on AS 4997-2005, Table 6.3)

Exposure environment	**Exposure classification**
	Reinforced or prestressed members
Members permanently 500 mm below the seabed	A2
Members permanently submerged 1 m below lowest sea water level to 500 mm below seabed level	B2
Spray zone, (i.e., exposed to airborne salt spray, but not in splash zone e.g., the top side of deck slabs)	C1
Splash zone, from 1 m below water level up to 1 m above wave crest levels on vertical structures, and all exposed soffits of structures over the sea	C2

Table 2.13 shows the coverage requirements for a period of 25 years. The AS 4997-2005 code does not provide explicit guidance on how to achieve a design life greater than that, instead recommending the use of corrosion-resistant reinforcement, as well as additives and coatings that improve durability (AS 4997-2005, 2005). A general requirement given in AS 1379 Supp1—1997 for w/b (w/c) and SCMs. The code requirements are prescriptive, and they only given for a 25-year design life.

Table 2.13 Minimum Cover to Reinforcing Steel (Based on AS 4997-2005, Table 6.4)

Exposure classification	**Minimum cover (mm)**	
	f'_c **= 40 MPa**	f'_c **= 50 MPa**
A2	40	30
B2	50	40
C1	70	50
C2	75	65

2.9 Concrete Corrosion Test Methods

In this study, two corrosion test methods were used to assess the presence and severity of ongoing corrosion. The first method was RCT laboratory testing to determine if corrosion has in fact initiated due to chloride ingress. The second method was field testing using non-invasive & non-destructive Giatec iCOR instrument to measure the corrosion rate and concrete resistivity onsite.

2.9.1 Rapid Chloride Test (RCT)

To ascertain whether corrosion is indeed caused by chloride ingress, powder samples of the concrete structure can be taken and tested in the laboratory for chloride content. A common method for determining this is to conduct a rapid chloride test on hardened concrete (RCT) (Newsome, 2020). A powder sample from hardened concrete drilling is required for this test. The chloride ions are separated by mixing it with an acidic extraction liquid. The ions can then be measured as a function of chloride percentage by mass of concrete using a calibrated electrode (Germann Instruments, 2022). The RCT is used to determine the amount of acid-soluble chlorides. A plot of the chloride profile can be generated using powder samples taken at various depths in the same location. By determining the chloride concentration in the concrete, it is possible to determine whether corrosion is caused by chloride ingress. If the chloride concentration is higher than the corrosion threshold value (CTV), corrosion is likely to occur or will occur (Newsome, 2020). Standard laboratory potentiometric titration methods such as AASHTO T 260, ASTM C114, DS 423.28, or NS 3671 were used to determine RCT test results and chloride ion content (Germann Instruments, 2022). The results of such correlations conducted by various laboratories in Scandinavia and the United States are shown in Figure 2.12.

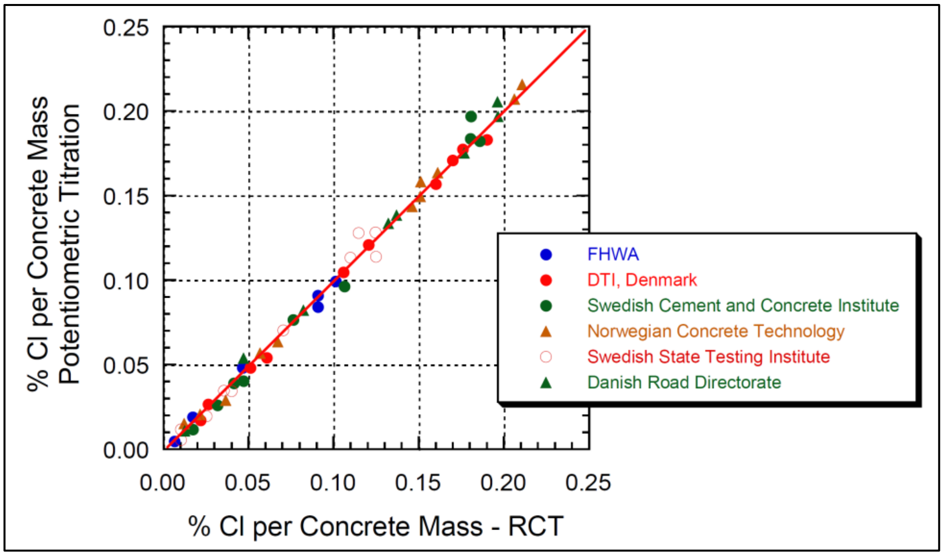


Figure 2.12: RCT VS Potentiometric Titration Method (Based on (Germann Instruments, 2022)

A diffusion coefficient can be calculated using these chloride concentration measurements at various depths. By quantifying how resistant the structure is to chloride ingress, this diffusion coefficient is useful in service-life prediction models like Life-365. In Chapter 4.1, this is explained in greater detail.

2.9.2 Noninvasive & Nondestructive Corrosion Detection (iCOR)

During field visits, a corrosion rate measurement device was used to collect data on ongoing corrosion. These devices are capable of performing a variety of measurements, including corrosion rate, rebar polarization resistance, electrical resistivity of concrete, and half-cell potential. iCOR complies with ASTM C876 (standard test method for corrosion potentials of uncoated reinforcing steel in concrete), and takes advantage of the patented CEPRA technology, which uses a noninvasive, nondestructive approach to estimate the rate of rebar corrosion. This means that, unlike other commercial devices, the iCOR does not require connecting the device to the rebar in order to obtain measurements (Giatec iCOR, 2022).

2.9.2.1 Giatec iCOR CEPRA Method

Giatec iCOR uses the concept of connection-less electrical pulse response analysis (CEPRA). With four probes, the electrical response of rebar inside concrete can be determined from the concrete surface, as shown in Figure 2.13. The voltage between the inner probes is measured while a constant AC current is applied between the outer probes. The corrosion state of reinforcement in concrete can be linked to the low frequency impedance of rebar in concrete (Giatec Scientific Inc., 2019).

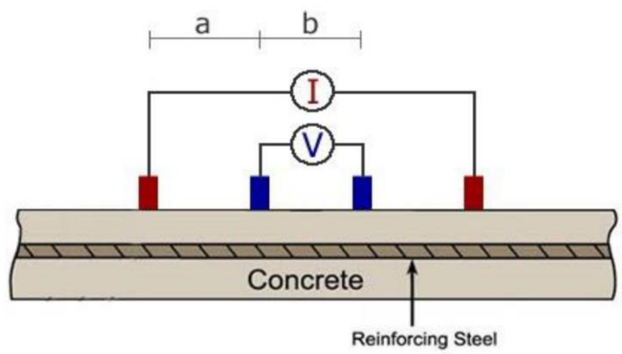


Figure 2.13: The Configuration of Four Probes on The Concrete Surface for Detecting Rebar Corrosion Inside the Concrete (Based on (Giatec Scientific Inc., 2019)

Nevertheless, because direct measurement of the low-frequency impedance of rebar in concrete is time consuming and subject to noise interruption, it is impractical to use this technique in the field to determine the corrosion rate of rebar within the concrete. The low-frequency behavior of reinforced concrete systems is determined in Giatec iCOR by applying a narrow current pulse or a step voltage/current for a brief period of time (a few seconds) and simultaneously recoding the system's voltage at a high sampling rate. The low-frequency impedance response of rebar in concrete can be extracted using the recorded voltage and current, which can be used to determine the state of corrosion in reinforced concrete structures (Giatec Scientific Inc., 2019).

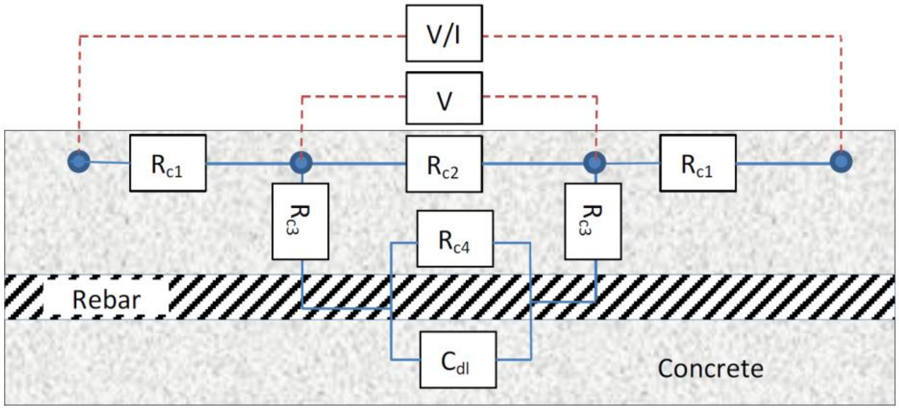


Figure 2.14: Electrical Circuit for Non-Contact Four-Probe Measurement of Reinforced Concrete Systems (Based on (Giatec Scientific Inc., 2019)

Giatec iCOR utilizes an intricate electrical circuit model to forecast the properties of various concrete materials and steel reinforcement. Figure 2.14 illustrates this electrical circuit schematically. The device's core software incorporates a sophisticated mathematical algorithm. This software processor is in charge of analyzing specific properties of reinforced concrete structures, such as the polarization resistance of embedded reinforcement and the “real” electrical resistivity of concrete (Giatec Scientific Inc., 2019).

2.9.2.2 Surface Resistivity

The ability of concrete to resist the ingress of chloride ions can be described using surface resistivity, which is a measure of the ability for an electrical current to flow within a material. Water content, cement type, water-to-binder ratio (w/b), and the presence of chlorides are all factors that affect resistivity. While some factors work to lower resistivity and thus increase the risk of corrosion, others, such as a low w/b ratio or the addition of a SCMs, work to raise resistivity and thus lower the risk of corrosion (Bertolini, et al., 2013). Surface resistivity is inversely proportional to electrical conductivity, which means that as conductivity decreases, resistivity rises (Violette, 2020).

Concrete's resistivity can range from less than ten to hundreds of kiloohm-centimeters (tens to thousands of ohm-meters), with lower values indicating a higher risk of chloride ingress and higher values indicating a lower or negligible risk (Bertolini, et al., 2013). The ranges listed Table 2.14 were used to interpret the surface resistivity data in the field (Feliu, et al., 1996; Polder, et al., 2000).

Table 2.14: Classification of Surface Resistivity

(Based on (Feliu, et al., 1996; Polder, et al., 2000; Violette, 2020)

Color Code	Surface Resistivity (kΩ·cm)	Classification
Green	>100	Very High
Yellow	30-100	High
Orange	10-30	Moderate
Red	<10	Low

2.9.2.3 Corrosion Rate

Corrosion rate is also known as penetration rate and is measured in μm/year (micrometers per year). Many factors, such as temperature and humidity, can have an impact on the magnitude of the corrosion rate (Bertolini, et al., 2013). For interpreting corrosion rate recordings for field work, Bertolini et al. (2013) recommend the ranges in

Table 2.15 that complies with Giatec iCOR User Manual (Bertolini, et al., 2013; Giatec Scientific Inc., 2020) l. In Chapter 5, the data collected from the field visits was analyzed using Table 2.14 and Table 2.15.

Table 2.15: Classification of Corrosion Rate Results

(Based on (Bertolini, et al., 2013; Giatec Scientific Inc., 2020; Violette, 2020)

Color Code	Corrosion Rate (μm/year)	Classification
Green	<10	Passive/Low
Yellow	10-30	Moderate
Orange	30-100	High
Red	>100	Severe

2.9.2.4 Giatec iCOR Complications and Limitations

Large cracks and delamination can have an impact on both corrosion rate and potential data. If the tendons are placed in protective tubes, these tests will not provide any useful information. Concrete structures with epoxy-coated or galvanized steel rebar are also exempt from these tests (Giatec Scientific Inc., 2020). Temperature, moisture, cover thickness, concrete properties, and oxygen availability are the most important parameters that can influence Giatec iCOR measurements (Giatec Scientific Inc., 2020).

CHAPTER 3: METHODOLOGY AND DATA COLLECTION

To determine whether the NCDOT's existing corrosion prevention policy is sufficient for extending the service life of concrete bridges in marine environment, the current condition of bridges constructed under this policy were be analyzed. The bridges evaluated during this phase of the research met a variety of parameters, such as:

- Located within corrosive or highly corrosive zones
- Crossed a brackish river or creek
- At least 10 years of coastal exposure
- Designed with current NCDOT corrosion policy specifications

These parameters allowed for the examination of potential correlations between the levels of corrosion mitigation strategies used and their performance in each environment. All of the bridges selected for evaluation were subjected to field and laboratory testing. During a field visit to each bridge, the following steps were usually followed:

- Visual inspection to identify and outline existing corrosion evidence, including cracks, spalls, stains, and efflorescence.
- Collection of concrete powder samples from relevant components
- Measurement of active corrosion rate to detect any onset of corrosion using iCOR
- Measurement of concrete surface resistivity to assess the resistance to chloride ingress using iCOR

3.1 Bridge Selection

The locations of the bridges selected for field visits are shown in Figure 3.1. The final selection of bridges was approved by the NCDOT Technical Advisory Committee assigned to the project. Nine bridges were selected for evaluation, as shown in Table 3.1. Depending on access, the sampled locations are described in Table 3.1 as either atmospheric or tidal, and this table also provides the bridge element type, age, and the distance from open water. The distance is measured by the stream or river's path for water to travel to reach open water, such as estuarine, sea, or ocean. The contamination of the concrete in the atmospheric zone comes from chloride ions in the marine air, delivered by spraying and splashing. In the tidal zone, the chloride is delivered by long daily wetting and drying cycles (Sun, et al., 2019).

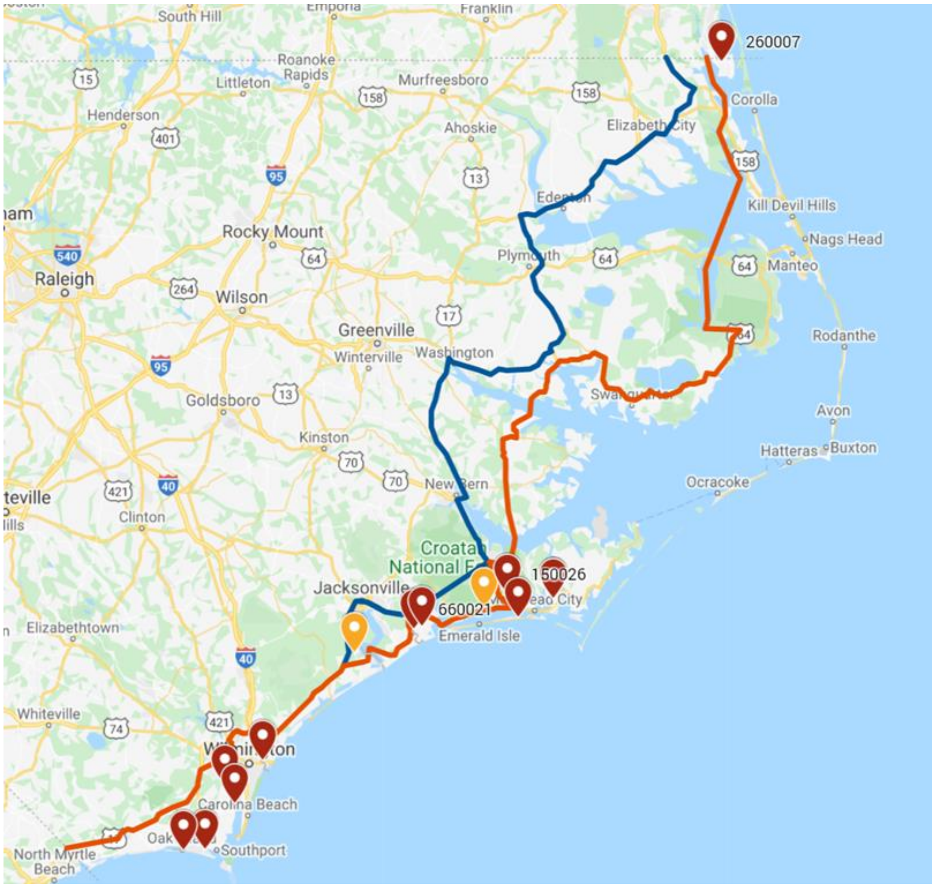


Figure 3.1 Locations of The Bridges Visited

Table 3.1: Selected Bridge Characteristics

Structure #	Zone		Bridge Element		Age (years)	Distance from open water (mi)
	Atmospheric	Tidal	Pier Cap	Pier		
090056	X	X	X		16	1.15
660021	X	X		X	15	6.42
090061		X		X	15	3.88
640010	X	X	X	X	14	3.87
150026	X		X		14	7.29
260007	X		X		13	0
090206		X		X	12	2.07
150020		X		X	12	2.5
660019	X	X		X	12	4.95

Data from the National Ocean and Atmospheric Administration (NOAA) was used to determine the time, water levels, tide and current predictions for all the bridges in the tidal zone (NOAA, 2021). NOAA employs multiple stations along the coastline for different monitoring and data collection purposes. Each station, when selected, gives a detailed report of the data it contains (in this case, tides height and water level). Figure 3.2 shows the date and the time during the day when the tide level at it is lowest point to conduct the field visit.

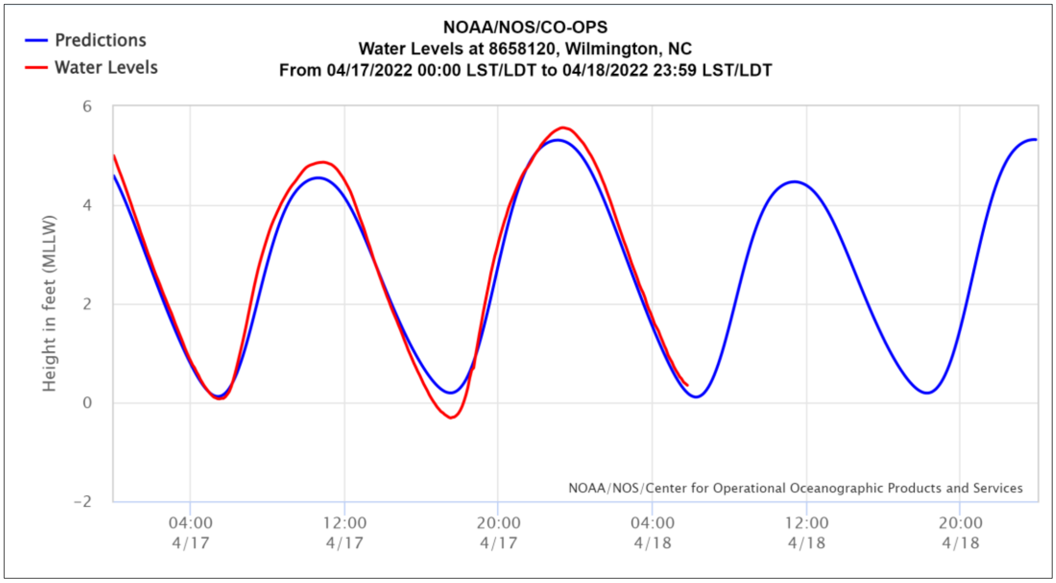


Figure 3.2: Example of Water/Tide levels at Wilmington, NC - Station ID: 8658120

3.2 Field Testing Procedures

Field testing and observations were carried out during each field visit. These included a visual survey, nondestructive testing (NDT) methods to determine the current corrosion rate and concrete resistivity, and the collection of powder samples for analysis at the UNC Charlotte laboratory (Newsome, 2020).

3.2.1 Visual Observations

Each bridge visited was visually inspected for corrosion-related deterioration. Corrosion-related deterioration manifested itself primarily through discoloration or staining, cracking, and spalling. Construction flaws that could increase the risk of corrosion or chloride ingress were also monitored and recorded as they were discovered, see (Table 3.2). Due to the relatively young age of the bridges chosen (10 to 15 years), it was recognized that many signs of corrosion would not be manifeste sufficiently to cause visual distress at the time of this study (Newsome, 2020).

Table 3.2: Structures Visual Observations

Structure #	Corrosive Zone	Bridge Element	Construction Flaws
090056	Highly Corrosive	Bent Cap	Honeycomb/Cracks
660021	Highly Corrosive	Prestressed Pile	Efflorescence/Honeycomb
090061	Highly Corrosive	Prestressed Pile	Efflorescence
640010	Highly Corrosive	Prestressed Pile	Marine Life/Honeycomb
150026	Highly Corrosive	Bent Cap	N/A
260007	Highly Corrosive	Bent Cap	Open Water
090206	Highly Corrosive	Prestressed Pile	Marine Life/Honeycomb
150020	Corrosive	Prestressed Pile	Efflorescence
660019	Corrosive	Prestressed Pile	Honeycomb

3.2.2 Corrosion Rate Testing and Concrete Surface Resistivity

Testing of the current corrosion rate and concrete resistivity were completed simultaneously with the Giatec iCOR NDT device. To begin this testing procedure, a flat reinforced concrete surface was selected to map the corrosion rates and concrete resistivity. A pachometer was also utilized to identify the location of reinforcing steel. A testing grid was drawn in chalk over the area to be evaluated and marked with an identifying code as shown in Figure 3.3. The testing locations were selected to obtain data at different levels of exposure. Data was collected at elevations within both the atmospheric and tidal exposure zones of the piers and pier caps. In several cases, the locations of greatest interest were fouled by oysters and other marine life. Fouling was removed with shovels and wire brushes and cleaned as much as possible before making measurements.

Figure 3.3: Corrosion Rate and Surface Resistivity Grid for iCOR

(Based on Structure #660021-L1)

A detailed description on how to use the Giatec iCOR NDT device in measuring corrosion rate and concrete surface resistivity can be found in Violette (2020) and Giatec Scientific Inc. (2020). One extra step was done differently from Violette, 2020. The default measurement time is 6 seconds for Giatec iCOR test. For the majority of measurements, polarizing the rebar for 6 or 10 seconds yields corrosion and resistance measurements (Giatec Scientific Inc., 2020). A 20 and 30 second duration test was utilized based on iCOR user manual "*If a large cover thickness exists and/or if the concrete is very dry, a longer measurement duration might be required*" (Giatec Scientific Inc., 2020). To ensure consistency of results at each structure, it was attempted to obtain a similar number of readings from each element of interest at each structure. This was not always possible due to accessibility challenges, such as excessive height above the water or piers that were mostly submerged. Structure number 660021 was selected to demonstrate the corrosion and concrete resistivity rates for tidal and atmospheric zones, see (Table 3.3). A similar result collected from all structures is provided Appendix A. The corrosion rate typically found in the atmospheric zone locations was relatively low and indicated a passive condition by the instrument manufacturer's guidelines, see (). In the tidal zone, measurements indicate substantial ongoing corrosion.

The heat maps shown in Figure 3.4 and Figure 3.5 are a representation of how corrosion rates and surface resistivity were distributed on elements. The highest rates of ongoing corrosion were often discovered within the splash or tidal zone where daily wetting cycles occur. Outside of the splash zone, values tended to be much lower. This same trend was seen with regard to surface resistivity. The classification and color coding for the corrosion rate and surface resistivity was mentioned in Chapter 2.9.9 Table 2.14 and Table 2.15.Because the moisture content of the concrete was not controlled during the field test, there was often considerable variability between wet and dry locations. A summary of the data collected from all structures is provided in Table 3.4.

Table 3.3: Corrosion Rate and Surface Resistivity Data (Based on Structure #660021)

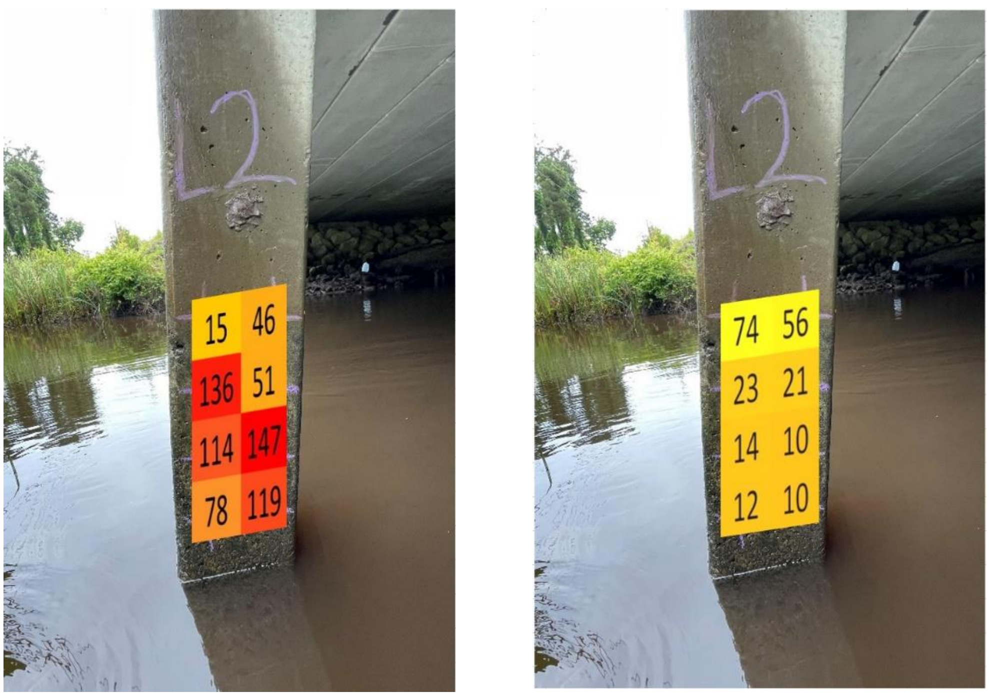
		Atmospheric Zone					**Tidal Zone**				
Structure #	**Location**	**Corrosion Rate**	**Avg. Corrosion Rate**	**Concrete Resist.**	**Avg. Concrete Resist.**	**R^2**	**Corrosion Rate**	**Avg. Corrosion Rate**	**Concrete Resist.**	**Avg. Concrete Resist.**	**R^2**
660021	L1	4	4	119	180	1	403	206	15	16	0.96
		5		112		0.97	13		28		0.99
		5		208		0.99	231		11		0.99
		1		204		0.99	336		9		0.98
		4		234		0.96	182		17		0.99
		7		200		0.89	153		22		0.98
							162		12		0.92
							172		11		0.99
	L2	0	4	257	198	0.97	15	88	74	28	1
		3		226		0.97	136		23		1
		3		178		1	114		14		0.98
		3		191		0.98	78		12		0.99
		3		177		0.99	46		56		0.95
		10		158		0.98	51		21		0.99
							147		10		0.99
							119		10		0.94

*Corrosion rates in (µm/year). Resistivity in (kΩ·cm)

(a) (b)

Figure 3.4: (a) Piers: Corrosion Rate Heat Map (b) Piers: Surface Resistivity Heat Map

(Based on Structure #660021-L1)



(a) (b)

Figure 3.5: (a) Piers: Corrosion Rate Heat Map (b) Piers: Surface Resistivity Heat Map

(Based on Structure #660021-L2)

Table 3.4: Summary of Surface Resistivity and Corrosion Rate Data Collected from All Structures

Structure #	Location	Bridge Element	SCMs	Zone	Corrosion Rate (μm/year)		Surface Resistivity (kΩ·cm)	
					Avg.	**Max.**	**Avg.**	**Min.**
660019	L1	Prestressed Pile	Silica Fume	Atmospheric	56	90	81	49
				Tidal	78	191	32	10
	L2	Prestressed Pile	Silica Fume	Atmospheric	38	136	96	51
				Tidal	64	218	57	7
090061	L1	Prestressed Pile	Silica Fume	Tidal	120	274	28	7
	L2	Prestressed Pile	Silica Fume	Tidal	154	251	23	7
640010	L1	Bent 1 Cap	Fly Ash/Silica Fume	Atmospheric	3	7	361	172
	L2	Prestressed Pile	Silica Fume	Atmospheric	42	77	118	91
				Tidal	26	45	61	32
	L3	Bent 3 Cap	Fly Ash/Silica Fume	Atmospheric	3	5	103	91
	L4	Prestressed Pile	Silica Fume	Atmospheric	-	-	-	-
				Tidal	30	40	52	32
660021	L1	Prestressed Pile	No SCMs	Atmospheric	4	7	212	200
				Tidal	197	403	28	9
	L2	Prestressed Pile	No SCMs	Atmospheric	5	10	176	158
				Tidal	88	147	35	10
090206	L1	Prestressed Pile	Silica Fume	Tidal	83	120	35	25
	L2	Prestressed Pile	Silica Fume	Tidal	103	138	30	13
090056	L1	Bent 2 Cap	Fly Ash/Silica Fume	Atmospheric	28	99	171	46
				Tidal	81	155	45	16
	L2	Bent 3 Cap	Fly Ash/Silica Fume	Tidal	30	87	90	24
150026	L2	Bent 1 Cap	Fly Ash	Tidal	-	-	-	-
	L3	Bent 1 Cap	Fly Ash	Tidal	9	28	305	199
260007	L1	Bent 3 Cap	Slag	Atmospheric	22	52	187	67
	L2	Bent 3 Cap	Slag	Atmospheric	31	52	137	67
150020	L1	Prestressed Pile	Fly Ash	Atmospheric	5	7	190	109
	L2	Prestressed Pile	Fly Ash	Atmospheric	4	11	518	407

3.2.3 Powder Sample Acquisition

Powder samples were removed from several locations on each bridge using a rotary hammer. Sampling locations were determined based on proximity to water, bridge elements, accessibility, and areas with a high corrosion rate as determined by the Giatec iCOR NDT device. Reinforcing steel locations were mapped with a pachometer prior to drilling to ensure that the hole avoided the reinforcing steel. At each location, powder samples were obtained at three to five depths in one-inch increments ranging from a depth of one inch to five inches, see (Figure: 3.6). The powder samples obtained for each one-inch drill depth are comprised of the concrete ½-inch above and below the representative depth (Newsome, 2020). The powder sample acquisition process and drilling can be found in detail in (Newsome, 2020) thesis.

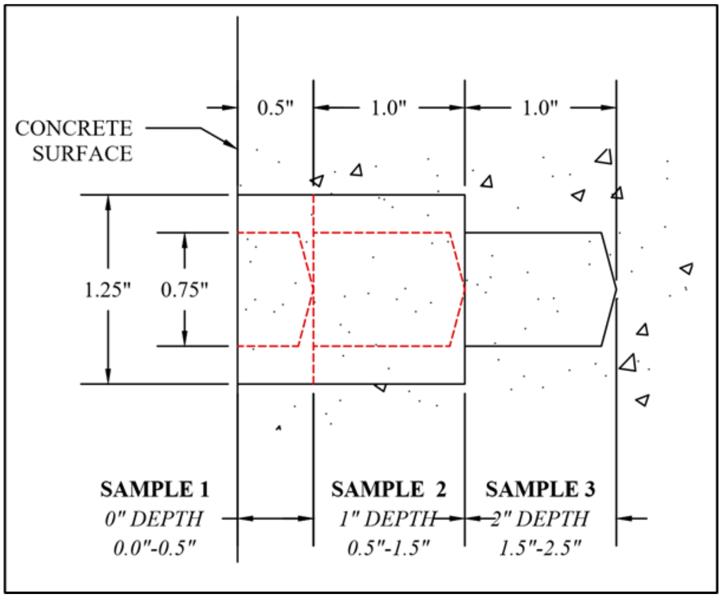


Figure: 3.6 Powder Sample Acquisition Process (Based on (Newsome, 2020)

3.3 Laboratory Testing Procedures

Laboratory testing of concrete powder samples included analysis of powder samples taken during the field-testing portion of the project. These powder samples were returned to the UNC Charlotte laboratory to be tested for chloride concentration content.

3.3.1 Rapid Chloride Test

Rapid Chloride Tests (RCT), developed and manufactured by Germann Instruments, were employed to determine the concentration of chlorides at various depths in the concrete elements. The tests were conducted in duplicate on separate powder samples from each depth at each location (Newsome, 2020). A full summary of the laboratory testing results of all RCT tests conducted is provided in Appendix A. An example of the rapid chloride test results is presented for structure number 660021. This structure is located in Bear Creek's highly corrosive zone. Bent 1's prestressed pile substructure was assessed. Powder samples were acquired from two piles at two zones: the tidal zone, where daily tides inundate and expose the concrete, and the atmospheric zone, where chlorides are deposited in the concrete by splashing, misting, and other forms of atmospheric deposition. The two locations are identified as L1 and L2 for both zones and are labeled in Figure 3.7. The chloride concentrations detected by RCT are shown in Table 3.5 and the chloride profile results are shown in Figure 3.8.

Figure 3.7 RCT Test Locations L1 and L2 (Based on Structure #660021)

Table 3.5: RCT Results for Test Locations L1 and L2 (Based on Structure #660021)

Structure #	Location	Zone	Chloride Content		
			Depth (in)	**% Conc. Wt.**	**Chlorides (lbs./yd³)**
660021	L1	Tidal	0	0.220	8.397
			1	0.243	9.252
			2	0.150	5.738
			3	0.094	3.592
			4	0.018	0.705
			5	0.012	0.443
		Atmospheric	0	0.115	4.404
			1	0.023	0.887
			2	0.004	0.156
			3	0.003	0.109
			4	0.003	0.105
			5	0.003	0.102
	L2	Tidal	0	0.412	15.718
			1	0.297	11.327
			2	0.161	6.157
			3	0.030	1.159
			4	0.006	0.247
			5	0.005	0.185
		Atmospheric	0	0.183	6.987
			1	0.043	1.628
			2	0.004	0.145
			3	0.004	0.142
			4	0.003	0.112
			5	0.003	0.116

As is apparent in these results, the chloride concentrations from the tidal zone are substantially greater than the atmospheric zone at shallow depths. At greater depths, the chloride concentrations become nearly zero, or background levels of the small amounts of naturally occurring chlorides in the aggregates and concrete mixing water. Another common observation is the considerable variability of surface chloride concentrations between different locations. The Tidal concentration at L1 (8.4 lbs./yd^3) is much less (nearly half) than the tidal concentration at L2 (15.7 lbs./yd^3). This is likely attributable to the fact that L1 is on an exterior pier that may be washed by rain, whereas L2 is in an interior area that is protected from freshwater washing. Also shown in Figure 3.8 is an indication of the depth of steel for the pier. In the tidal zone, the chloride concentrations are around 6 lbs./yd^3, which would typically be associated with a very elevated probability of corrosion. The steel-depth chloride concentrations in the atmospheric zone are barely above the background level. This observation demonstrates the degree to which exposure is highly variable at different locations on the same element. A summary of the chloride surface concentration from all structures is provided in Table 3.6.

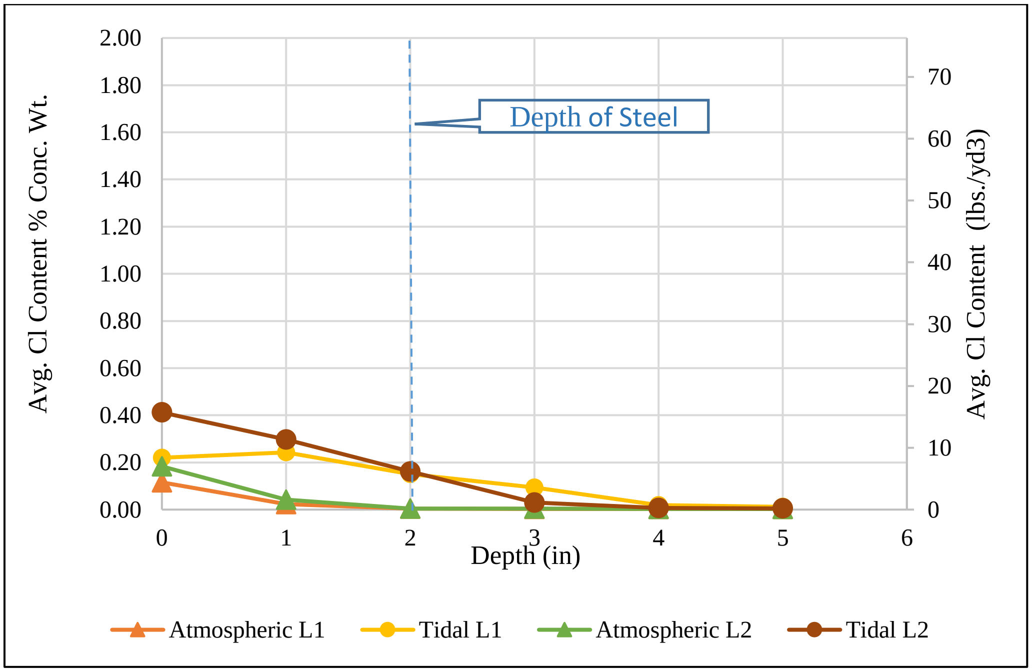


Figure 3.8: Chloride Profile for Locations L1 and L2 (Based on Structure #660021)

Table 3.6: Summary of The Chloride Surface Concentration from All Structures

Structure #	Location	Bridge Element	SCMs	Zone	Chloride Surface Concentration (lbs./yd^3)
660019	L1	Prestressed Pile	Silica Fume	Atmospheric	11.096
				Tidal	11.532
	L2	Prestressed Pile	Silica Fume	Atmospheric	13.001
				Tidal	17.429
090061	L1	Prestressed Pile	Silica Fume	Tidal	15.894
	L2	Prestressed Pile	Silica Fume	Tidal	28.972
640010	L1	Bent 1 Cap	Fly Ash/Silica Fume	Atmospheric	-
	L2	Prestressed Pile	Silica Fume	Atmospheric	8.044
				Tidal	11.237
	L3	Bent 3 Cap	Fly Ash/Silica Fume	Atmospheric	4.395
	L4	Prestressed Pile	Silica Fume	Atmospheric	14.532
				Tidal	22.424
660021	L1	Prestressed Pile	No SCMs	Atmospheric	4.404
				Tidal	8.397
	L2	Prestressed Pile	No SCMs	Atmospheric	6.987
				Tidal	15.718
090206	L1	Prestressed Pile	Silica Fume	Tidal	57.241
	L2	Prestressed Pile	Silica Fume	Tidal	67.231
090056	L1	Bent 2 Cap	Fly Ash/Silica Fume	Atmospheric	12.133
				Tidal	23.610
	L2	Bent 3 Cap	Fly Ash/Silica Fume	Tidal	28.370
150026	L2	Bent 1 Cap	Fly Ash	Tidal	18.062
	L3	Bent 1 Cap	Fly Ash	Tidal	13.603
260007	L1	Bent 3 Cap	Slag	Atmospheric	6.189
	L2	Bent 3 Cap	Slag	Atmospheric	3.608
150020	L1	Prestressed Pile	Fly Ash	Atmospheric	10.775
	L2	Prestressed Pile	Fly Ash	Atmospheric	11.817

CHAPTER 4: MODELING

4.1 Diffusion Coefficient Modeling

The chloride diffusion coefficient is an appropriate performance indicator for concrete in a marine tidal zone because diffusion is the primary mechanism of chloride transport (Alexander & Thomas, 2015). It is not uncommon for concrete's diffusion coefficient to decrease over time and surface concentration to fluctuate due to interactions between diffusant and matrix, such as the diffusion of chloride. These go against Fick's fundamental assumptions. However, apparent or effective diffusion coefficients or conductivity coefficients are defined and measured, and they can be useful as durability indicators if their limitations are understood (Alexander & Thomas, 2015). In this study a non-linear regression model will be used with an implementation of Microsoft Excel to calculate the diffusion coefficient and surface concentration.

4.1.1 Iterative Non-Linear Least Squares Regression (I-NSL)

A non-linear regression model uses an iterative process to calculate the optimal parameter values based on the robust and reliable generalized reduced gradient (GRG) method. This model was carried out using the SOLVER function in Microsoft Excel (Brown, 2000). SOLVER is being used to determine the diffusion coefficient and surface concentration at each bridge location in order to compare the estimated values with those obtained in the field. The SOLVER function is ideal for fitting data in a non-linear function via an iterative algorithm, minimizing the squared difference between the data point and the function that describes the data (Brown, 2000). The process the SOLVER function uses to fit the data is called iterative non-linear least-squares regression (I-NSL), and it involves a user input of a non-linear function.

4.1.2 Configuring Microsoft Excel and SOLVER For I-NSL

To perform the non-linear regression, a function is needed that contains a ‘dependent’ variable and an ‘independent’ variable. For this analysis, Fick’s second law relationship describing the change in chloride ions concentration as a function of depth and time is used (Tempest, et al., 2017). The function is as follows:

$$C_{(x,t)} = C_o \left(1 - \text{erf}\left(\frac{x}{\sqrt{4.D_c.t}}\right)\right)$$

where

$C_{(x,t)}$ =chloride concentration measured at x depth (dependent variable)

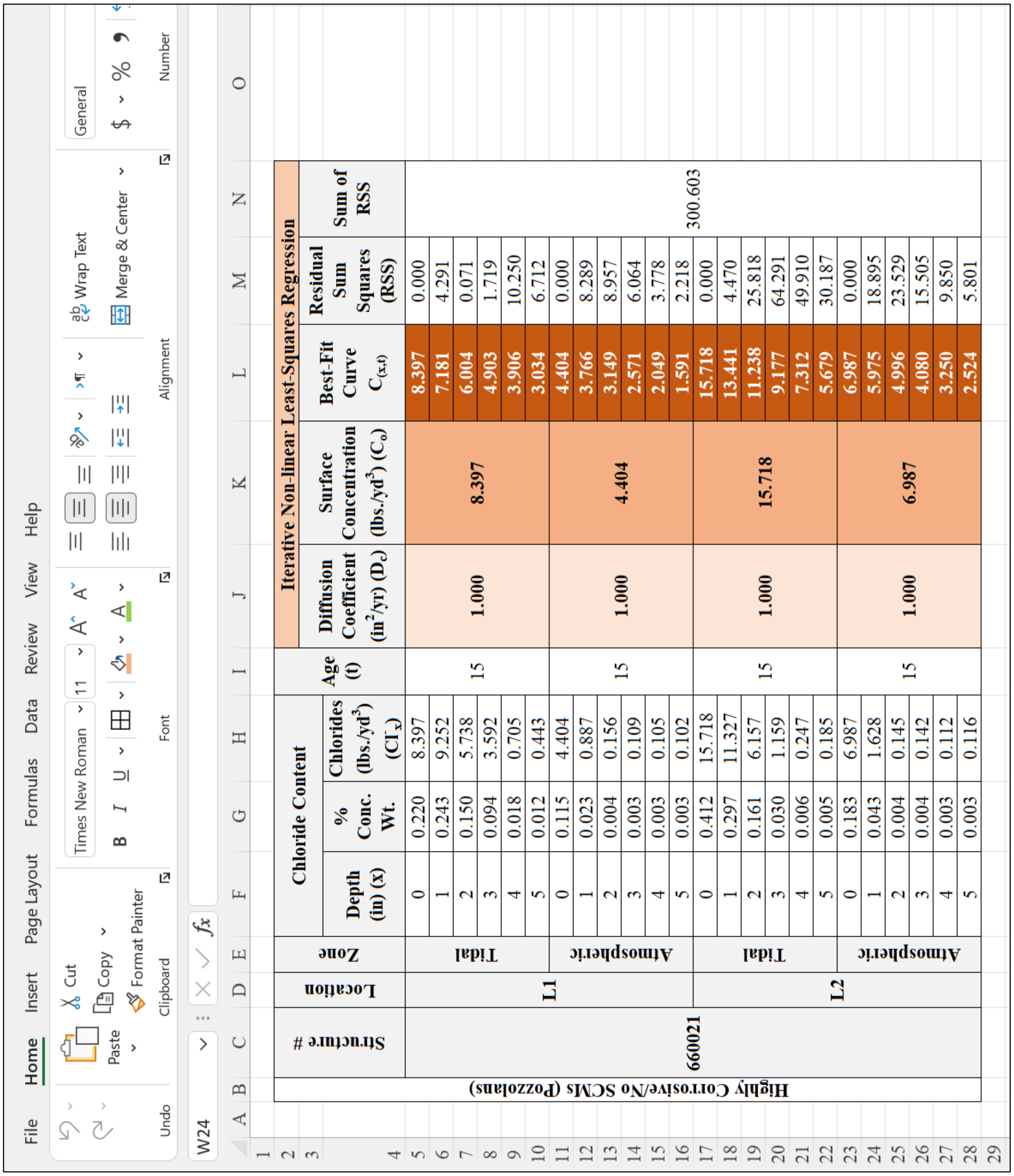
C_o = initial chloride concentration measured (independent variable)

x = the depth below the exposed surface (independent variable)

D_c = the apparent chloride transport coefficient (independent variable)

t = time (independent variable)

The 660021 bridge was used as an example to show how the model works. The data is arranged in the spreadsheet as shown in Figure 4.1: I-NSL Excel Implementation (Based on Microsoft 365). The field measured data from the RCT are shown in the column, “Chloride Content”. The first step is to set up the non-linear regression function for SOLVER by typing the Fick’s second law relationship in excel form under “Best-Fit Curve $C_{(x,t)}$”. The initial diffusion coefficient value will be seeded, and the surface concentration will be set as the chloride content at 0 in depth, see (Figure 4.1). The relationship will be applied to the whole column.



Highly Corrosive/No SCMs (Pozzolans)	Structure #	Location	Zone	Chloride Content: Depth (in) (x)	Chloride Content: % Conc. Wt.	Chloride Content: Chlorides (lbs./yd^3) (Cl^-_x)	Age (t)	Iterative Non-linear Least-Squares Regression: Diffusion Coefficient (in^2/yr) (D_c)	Surface Concentration (lbs./yd^3) (C_o)	Best-Fit Curve $C_{(x,t)}$	Residual Sum Squares (RSS)	Sum of RSS
	660021	L1	Tidal	0	0.220	8.397	15	1.000	8.397	8.397	0.000	300.603
				1	0.243	9.252				7.181	4.291	
				2	0.150	5.738				6.004	0.071	
				3	0.094	3.592				4.903	1.719	
				4	0.018	0.705				3.906	10.250	
				5	0.012	0.443				3.034	6.712	
			Atmospheric	0	0.115	4.404	15	1.000	4.404	4.404	0.000	
				1	0.023	0.887				3.766	8.289	
				2	0.004	0.156				3.149	8.957	
				3	0.003	0.109				2.571	6.064	
				4	0.003	0.105				2.049	3.778	
				5	0.003	0.102				1.591	2.218	
		L2	Tidal	0	0.412	15.718	15	1.000	15.718	15.718	0.000	
				1	0.297	11.327				13.441	4.470	
				2	0.161	6.157				11.238	25.818	
				3	0.030	1.159				9.177	64.291	
				4	0.006	0.247				7.312	49.910	
				5	0.005	0.185				5.679	30.187	
			Atmospheric	0	0.183	6.987	15	1.000	6.987	6.987	0.000	
				1	0.043	1.628				5.975	18.895	
				2	0.004	0.145				4.996	23.529	
				3	0.004	0.142				4.080	15.505	
				4	0.003	0.112				3.250	9.850	
				5	0.003	0.116				2.524	5.801	

Figure 4.1: I-NSL Excel Implementation (Based on Microsoft 365)

The second step is calculating the sum of the squared estimate of errors (sum of squared residuals) from the following formula:

$$RSS = \sum_{i=1}^{n} (y_i - f(x_i))^2$$

Where

RSS =Residual Sum of Squares

y_i =*i^th* value of the variable to be predicted

f(xi) =predicted value of y_i

n =upper limit of summation

Using the independent and dependent variable from the excel sheet table rewrite RSS equation to get the following formula:

$$RSS = \sum_{x=1}^{n} (Cl_x^- - C_{(x,t)})^2 \qquad Eq.1$$

where

Cl_x^- = Chloride Content at depth x

Following the same procedure before, typing the formula ($Eq.1$) in excel form under " Residual Sum Squares (RSS)". The formula will be applied to the whole column. The residual sum squares (RSS) will be the summation of all the cells under "Sum of RSS ".

The third step is using the SOLVER to find a solution for the diffusion coefficient (Dc), surface concentration (Co), and the Best-Fit Curve C(x,t) under "Iterative Non-linear Least-Squares Regression". A constraint is used in SOLVER under the assumption that the diffusion coefficient is the same in both tidal and atmospheric zone for the concrete elements that share the same properties.

I-NSL the SOLVER implementation is as follow:

I. Access the SOLVER function in Microsoft Excel under the “Data” tab, under “Analyze”.

II. Select the cell with the Residual Sum Square (RSS) and set it to “Min”. The dialogue box is shown in Figure 4.2, under “Set Objective”

III. Select all the cells for the diffusion coefficient (Dc) and surface concentration (Co), under “By Changing Variable Cells:”.

IV. Add a new constraint as shown in Figure 4.3, under “Subjected to the Constraints:” All the other options should not be changed and use the default settings for SOLVER as shown in Figure 4.2.

V. Chose default “GRG Nonlinear” under “Select a Solving Method:”

VI. Run the analysis by pressing “Solve”.

VII. Wait for SOLVER to finish running the analysis and finding the solution, see (Figure 4.4). Press “OK”, SOLVER found a solution, and all constraints and optimality condition are satisfied.

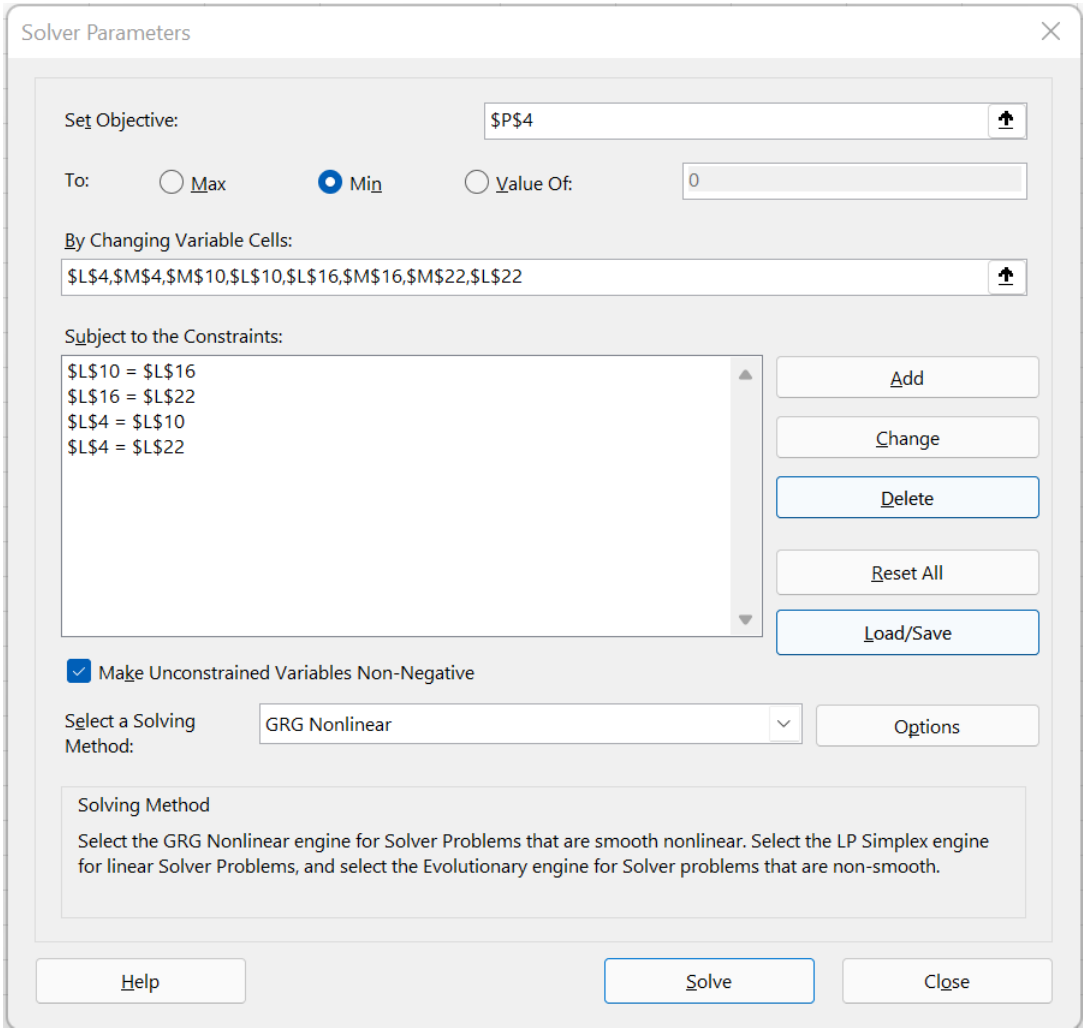


Figure 4.2: SOLVER Parameter (Based on Microsoft 365)

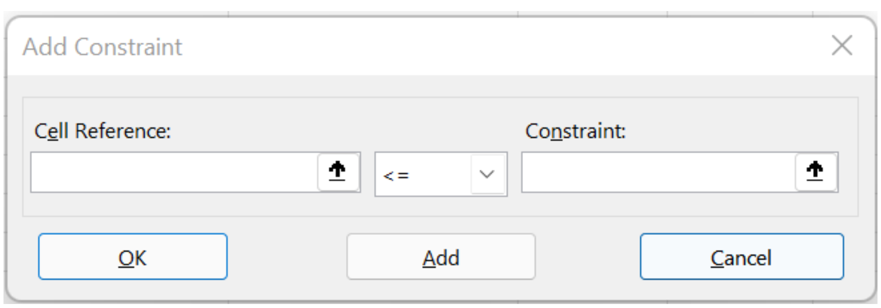


Figure 4.3: SOLVER Constraint (Based on Microsoft 365)

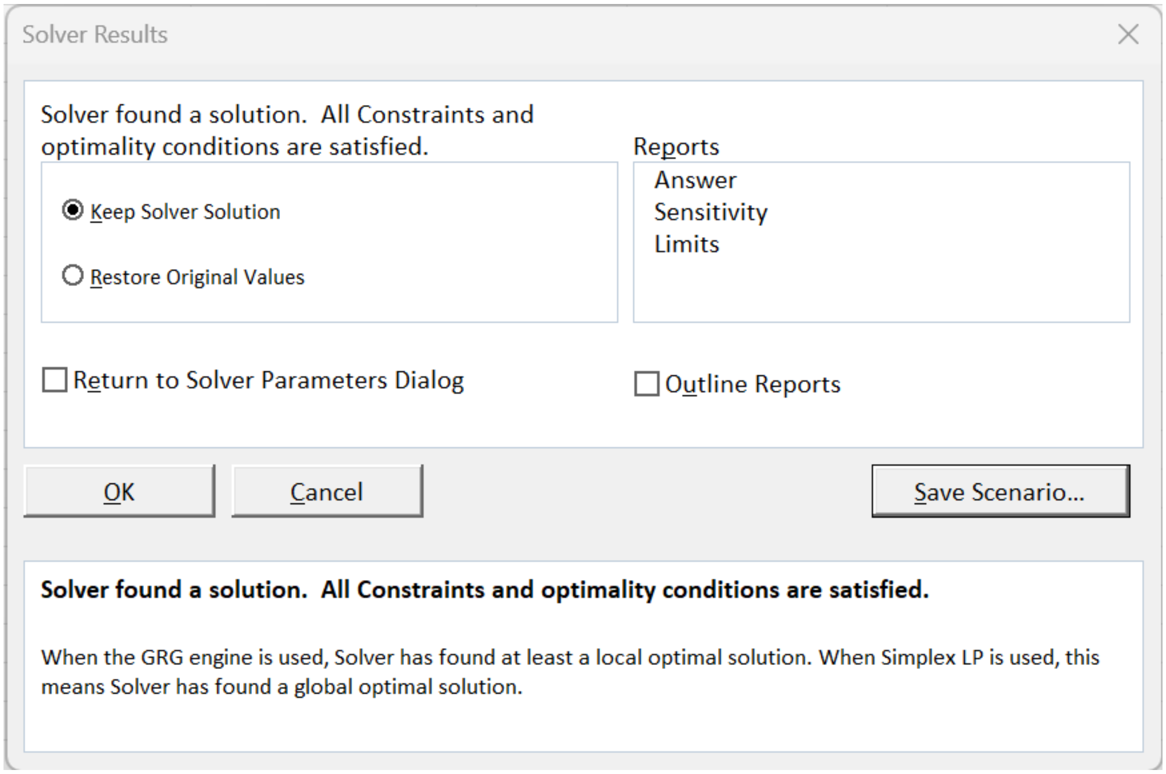


Figure 4.4: SOLVER Results (Based on Microsoft 365)

4.1.3 Iterative Non-linear Least-Squares Regression Results

As previously stated, bridge 660021 was used as an example to demonstrate how I-NSL with the SOLVER implementation can be used to calculate the diffusion coefficient and surface concentration. After running the I-NSL model, the values under the best-fit curve ($C_{(x,t)}$) are changed (since they are dependent variable) depending on the value of diffusion coefficients, see (Table 4.2). Figure 4.5 shows the best-fit curve ($C_{(x,t)}$) comparing it to the field measured chloride concentration. A full set of the I-NSL model results for each structure is listed in Appendix A . A summary of the diffusion coefficient and surface concentration for all the structures from I-NSL is included in Table 4.3. The range of the diffusion coefficient for all structures depending on their SCMs from I-NSL can be summarized in Table 4.1

Table 4.1: Diffusion Coefficient Range

SCMs	Diffusion Coefficient (in^2/yrs.)
Silica Fume	0.025-0.045
Fly Ash	0.025-0.045
Slag	0.045-0.065
Silica Fume/Fly Ash	0.045-0.075
No SCMs (Pozzolans)	>0.2

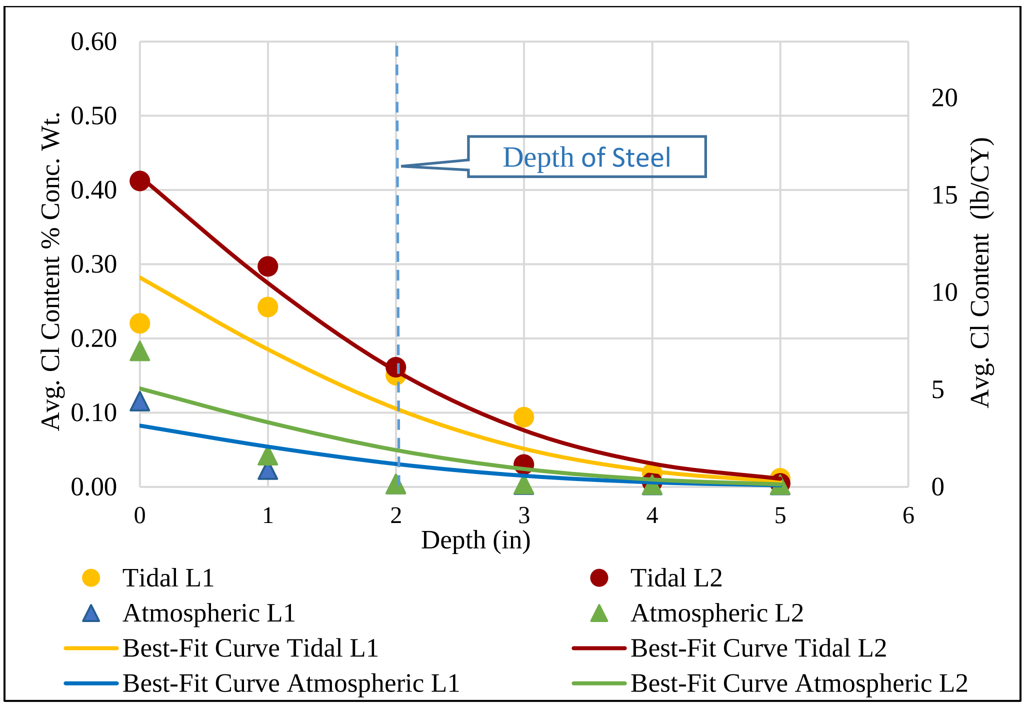


Figure 4.5: I-NSL Model Best-Fit Curve ($C_{(x,t)}$)

Table 4.2: Iterative Non-linear Least-Squares Model Results (Based on Structure 660021)

	Structure #	Location	Zone	Chloride Content			Age (t)	Iterative Non-linear Least-Squares Regression				
				Depth (in) (x)	% Conc. Wt.	Chlorides (lbs./yd^3) (Cl^-_x)		Diffusion Coefficient (in^2/yr) (D_c)	Surface Concentration (lbs./yd^3) (C_o)	Best-Fit Curve $C_{(x,t)}$	Residual Sum Squares (RSS)	Sum of RSS
Highly Corrosive/No SCMs (Pozzolans)	**660021**	**L1**	**Tidal**	0	0.220	8.397	15	**0.169**	**10.765**	**10.765**	5.606	35.408
				1	0.243	9.252				**7.068**	4.769	
				2	0.150	5.738				**4.025**	2.936	
				3	0.094	3.592				**1.962**	2.656	
				4	0.018	0.705				**0.811**	0.011	
				5	0.012	0.443				**0.282**	0.026	
			Atmospheric	0	0.115	4.404	15	**0.169**	**3.151**	**3.151**	1.569	
				1	0.023	0.887				**2.069**	1.397	
				2	0.004	0.156				**1.178**	1.045	
				3	0.003	0.109				**0.574**	0.217	
				4	0.003	0.105				**0.237**	0.018	
				5	0.003	0.102				**0.083**	0.000	
		L2	**Tidal**	0	0.412	15.718	15	**0.169**	**15.953**	**15.953**	0.055	
				1	0.297	11.327				**10.475**	0.726	
				2	0.161	6.157				**5.965**	0.037	
				3	0.030	1.159				**2.908**	3.057	
				4	0.006	0.247				**1.202**	0.911	
				5	0.005	0.185				**0.418**	0.055	
			Atmospheric	0	0.183	6.987	15	**0.169**	**5.059**	**5.059**	3.717	
				1	0.043	1.628				**3.322**	2.869	
				2	0.004	0.145				**1.892**	3.050	
				3	0.004	0.142				**0.922**	0.609	
				4	0.003	0.112				**0.381**	0.072	
				5	0.003	0.116				**0.133**	0.000	

Table 4.3: Summary of Estimated Diffusion Coefficients and Surface Concentrations

Structure #	Location	Bridge Element	SCMs	Zone	C_o (lbs./yd^3) I-NSL Estimated	C_o (lbs./yd^3) Field Measured	D_c (in^2/yrs.)
660019	L1	Prestressed Pile	Silica Fume	Atmospheric	10.560	11.096	0.0443
				Tidal	11.805	11.532	
	L2	Prestressed Pile	Silica Fume	Atmospheric	12.613	13.001	
				Tidal	17.866	17.429	
090061	L1	Prestressed Pile	Silica Fume	Tidal	18.484	15.894	0.2587
	L2	Prestressed Pile	Silica Fume	Tidal	28.419	28.972	
640010	L1	Bent 1 Cap	Fly Ash/Silica Fume	Atmospheric	0.233	-	0.0439
	L2	Prestressed Pile	Silica Fume	Atmospheric	8.153	8.044	0.0454
				Tidal	11.125	11.237	
	L3	Bent 3 Cap	Fly Ash/Silica Fume	Atmospheric	4.382	4.395	0.0439
	L4	Prestressed Pile	Silica Fume	Atmospheric	15.707	14.532	0.0454
				Tidal	21.684	22.424	
660021	L1	Prestressed Pile	No SCMs	Atmospheric	3.151	4.404	0.1686
				Tidal	10.765	8.397	
	L2	Prestressed Pile	No SCMs	Atmospheric	5.059	6.987	
				Tidal	15.952	15.718	
090206	L1	Prestressed Pile	Silica Fume	Tidal	57.248	57.241	0.0513
	L2	Prestressed Pile	Silica Fume	Tidal	66.845	67.231	
090056	L1	Bent 2 Cap	Fly Ash/Silica Fume	Atmospheric	10.084	12.133	0.0695
				Tidal	26.433	23.610	
	L2	Bent 3 Cap	Fly Ash/Silica Fume	Tidal	30.095	28.370	
150026	L2	Bent 1 Cap	Fly Ash	Tidal	18.375	18.062	0.0365
	L3	Bent 1 Cap	Fly Ash	Tidal	13.257	13.603	
260007	L1	Bent 3 Cap	Slag	Atmospheric	6.012	6.189	0.0472
	L2	Bent 3 Cap	Slag	Atmospheric	3.900	3.608	
150020	L1	Prestressed Pile	Fly Ash	Atmospheric	10.686	10.775	0.0261
	L2	Prestressed Pile	Fly Ash	Atmospheric	19.097	11.817	

"- " Indicates Data was not collected or technical issues

The feasibility of the values generated by the curve fitting routine were verified by two benchmarking techniques. Figure 4.6 provides a comparison of the surface chloride concentration measured in the field with the value predicted by the modeling parameters determined by curve fitting. As is evident in the Figure as well as by comparing the rightmost two columns of Table 4.3, the values are very similar, indicating the reliability of the model to relate surface concentration with diffusion coefficient and predict the current conditions.

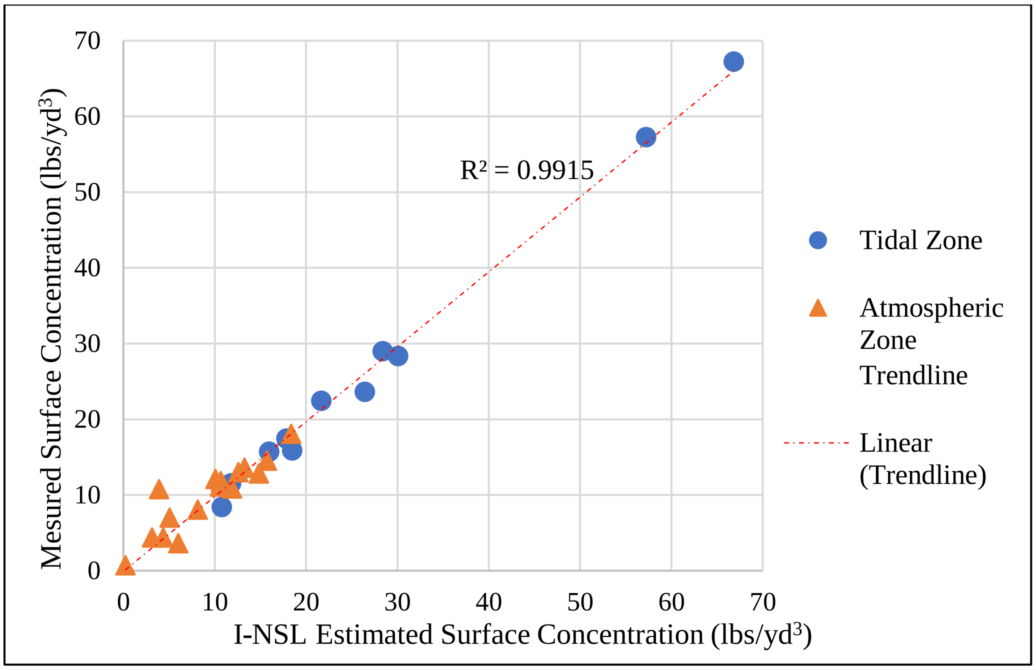


Figure 4.6: Measured vs I-NSL Model Surface Concentration (lbs./yd^3)

Table 4.1 provides the range of values determined for concretes containing various SCMs. These may be compared with a second set of reference point values that were developed by Rochelle (2000) for NCDOT for use with coastal bridge service life modeling. The model was used in the design of the Manteo Bypass. For comparative purposes, the values estimated from field data collected during this project are shown alongside the typical values based on

Rochelle's work. Most values are either consistent with the ranges that Rochelle prepared for various concrete elements, or slightly lower. Only two were found to be higher, however these structures had either physical defects or did not contain pozzolans, see (Table 4.4).

Table 4.4: I-NSL Model VS Manteo Bypass Model Diffusion Coefficient Range Comparison (Tidal Zone) (Based on Rochelle, 2000)

		I-NSL Model				**Manteo Bypass Model**				
Structure #	**Bridge Element**	**Diffusion Coefficient (in^2/yrs.)**	**Corrosion Inhibitor (gal/yd^3)**	**Fly Ash %**	**Silica Fume %**	**Diffusion Coefficient (in^2/yrs.)**	**Check the range**	**Corrosion Inhibitor (gal/yd^3)**	**Fly Ash %**	**Silica Fume %**
660019	Prestressed Pile	0.044	3	0	5	0.0392 - 0.1225	In Range	3	20	5
090061	Prestressed Pile	0.259	3	0	5	0.0392 - 0.1225	Above Range (High)	3	20	5
640010	Bent 1 Cap	0.045	3	25	5	0.0784 - 0.147	Below Range (Low)	3	20	5
	Prestressed Pile	0.045	3.5	0	5	0.0392 - 0.1225	In Range	3	20	5
660021	Prestressed Pile	0.169	3.5	0	0	0.0392 - 0.1225	Above Range (High)	3	20	5
090206	Prestressed Pile	0.051	3	0	5	0.0392 - 0.1225	In Range	3	20	5
090056	Bent 2 Cap	0.070	3	25	5	0.0784 - 0.147	Below Range (Low)	3	20	5
150026	Bent 1 Cap	0.037	3	30	0	0.0784 - 0.147	Below Range (Low)	3	20	5
260007	Bent 3 Cap	0.047	3	0	0	0.0784 - 0.147	Below Range (Low)	3	20	5
150020	Prestressed Pile	0.026	3	30	0	0.0392 - 0.1225	Below Range (Low)	3	20	5

4.2 Service Life Modeling

The Life-365 software was used to model the effects of corrosion on the bridge components chosen for this study. Modeling can be used to predict how long a bridge will last before major repairs or reconstruction are required. A life cycle analysis is a term used to describe this type of analysis (LCA). Life-365 allows you to evaluate the impact of various corrosion mitigation techniques on service life (Newsome, 2020). Environmental conditions, concrete performance properties, and corrosion mitigation practices can all be investigated using input values specific to each structural element tested. Data from field and laboratory testing was used to complete the modeling effort with as few as possible assumptive inputs (Newsome, 2020). Life-365 software uses two separate methods for the service life modeling:

1. The first method is based on concrete mixture design, such as SCMs (fly ash, silica fume and slag), w/b ratio and the amount of corrosion inhibitor. These properties were determined using mixture designs reports provided by the committee of the NCDOT research project, see Table 4.5.
2. The second method is user defined based on data obtained from the field study, such as surface concentration and diffusion coefficient.

This study used the second method, which was identical to the procedure Ross Newsome, a fellow UNC Charlotte graduate student, used for Life-365 modeling and was discussed in detail in his thesis (Newsome, 2020). Since this procedure was detailed in previous work, it will not be discussed further here. For each project, Life-365 requires three general user inputs:

- Structure type and dimensions
- Exposure environments
- Concrete mixture and properties

Table 4.5: Corrosion Protection in Concrete Mixtures

Structure Number	Location	Corrosion Inhibitor (gal/cy)	Fly Ash	Slag	Silica Fume	w/b
660019	L1	3	-	-	5%	0.35
	L2	3	-	-	5%	0.35
090061	L3	3	-	-	5%	0.35
	L4	3	-	-	5%	0.35
640010	L1*	3	25%	-	5%	0.32
	L2	3.5	-	-	5%	0.32
	L3*	3	25%	-	5%	0.32
	L4	3.5	-	-	5%	0.32
660021	L1	3.5	-	-	-	0.32
	L2	3.5	-	-	-	0.32
090206	L1	3	-	-	5%	0.38
	L2	3	-	-	5%	0.38
090056	L1	3	25%	-	5%	0.37
	L2	3	25%	-	5%	0.37
150026	L2	3	30%	-	-	0.36
	L3	3	30%	-	-	0.36
260007*	L1*	3	-	43%	-	0.35
	L2*	3	-	43%	-	0.35
150020*	L1*	3	30%	-	-	0.36
	L2*	3	30%	-	-	0.36
*	Atmospheric					

4.2.1 Structure Type and Dimensions

The first step in the modeling process was to determine the type of structural element and its geometry. The type of element, its dimensions, and the cover used on each modeled component are shown in Table 4.6. The exposure conditions were calculated using as many data points as possible.

Table 4.6: Geometry and Element Type Inputs of Modeled Locations (Tidal Zone)

Structure Number	Location	Vertical Distance from High Tide Elevation (ft)	Bridge Element	Dimensions (in)	Cover (in)
660019	L1	-1	Prestressed Pile	16x16	2
	L2	-1	Prestressed Pile	16x16	2
090061	L3	-1	Prestressed Pile	20x20	2
	L4	-1	Prestressed Pile	20x20	2
640010	L1*	5	Bent 1 Cap	30x33	2
	L2	-1	Prestressed Pile	16x16	2
	L3*	5	Bent 3 Cap	30x33	2
	L4	-1	Prestressed Pile	16x16	2
660021	L1	-1	Prestressed Pile	12x12	2
	L2	-1	Prestressed Pile	12x12	2
090206	L1	-1	Prestressed Pile	16x16	2
	L2	-1	Prestressed Pile	16x16	2
090056	L1	-1	Bent 2 Cap	30x33	2
	L2	-1	Bent 3 Cap	30x33	2
150026	L2	-1	Bent 1 Cap	42x44	2
	L3	-1	Bent 1 Cap	42x44	2
260007*	L1*	2	Bent 3 Cap	33x50	2
	L2*	2	Bent 3 Cap	33x50	2
150020*	L1*	2	Prestressed Pile	20x20	2
	L2*	2	Prestressed Pile	20x20	2

* Atmospheric

4.2.2 Exposure Environments

The second step was to input the exposure conditions based on as many field measurements as could be gathered. This includes the estimated surface concentration and the buildup period, which is the bridge's age, as summarized in Table 4.7. Temperature data from the three North Carolina cities of Jacksonville, Wilmington, and Nags Head were used to populate the average monthly temperatures, see (Table 4.8).

Table 4.7: Exposure Condition Inputs of Modeled Locations (Tidal Zone)

Structure Number	Location	Vertical Distance from High Tide Elevation (ft)	Age (yrs.)	Surface Con. (% wt. conc)	Temperature Region
660019	L1	-1	12	0.309	Jacksonville
	L2	-1		0.468	
090061	L3	-1	15	0.485	Wilmington
	L4	-1		0.745	
640010	L1*	5	14	0.006	Wilmington
	L2	-1		0.292	
	L3*	5		0.115	
	L4	-1		0.568	
660021	L1	-1	15	0.282	Jacksonville
	L2	-1		0.418	
090206	L1	-1	12	1.501	Wilmington
	L2	-1		1.752	
090056	L1	-1	16	0.693	Wilmington
	L2	-1		0.789	
150026	L2	-1	14	0.482	Jacksonville
	L3	-1		0.347	
260007*	L1*	2	13	0.158	Nags Head
	L2*	2		0.102	
150020*	L1*	2	12	0.280	Jacksonville
	L2*	2		0.501	

* Atmospheric

To determine an approximate value for the vertical distance from high tide elevation at each location, the elevation where high tide was last observed on the day of testing was used. Because so many variables affect the high tide elevation on a daily basis, the reported value can only be approximated to the nearest half-foot. The sampling location was below the structure's high tide mark, as indicated by negative values. All structures in the tidal zone were sampled at least one foot below the high tide markings.

Table 4.8: Monthly average temperatures utilized for LCA modeling

(Based on U.S. Climate Data)

Month	**Average Temperature (ºF)**		
	Jacksonville	**Wilmington**	**Nags Head**
January	43.5	46.0	45.0
February	45.5	49.0	46.0
March	53.0	55.0	51.5
April	61.0	63.0	61.0
May	69.0	70.5	69.0
June	77.0	78.0	77.5
July	80.5	81.5	80.5
August	79.0	79.5	80.5
September	73.0	75.0	76.0
October	63.0	65.5	67.0
November	54.5	56.5	56.0
December	46.5	48.5	50.0

4.2.3 Concrete Mixture and Properties

The third step was to input the measured concrete properties (concrete properties based off of field measured data), such as diffusion coefficient at 28 days from Chapter 4.1.3, diffusion decay index (m) (Alexander & Thomas, 2015), which is calculated based on the following formula:

$$m = 0.26 + 0.4\,(\%FA/50 + \%SG/70)$$

chloride threshold value (Ct), and constant values, including the length of the hydration process (recommended to be set to 25 years) and propagation period, see Table 4.9 (Newsome, 2020).

Table 4.9: Measured Concrete Properties Used as Inputs to Life-365

<table>
<tr><th rowspan="2">Structure Number</th><th rowspan="2">Location</th><th colspan="3">Constant Values</th><th colspan="3">Field Measured</th></tr>
<tr><th>Hydration (yrs.)</th><th>Propagation Period (yrs.)</th><th>Ct (% wt. conc.)</th><th>Diffusion Coefficient at 28 days (in²/sec)</th><th>Diffusion Coefficient (in²/sec)</th><th>m</th></tr>
<tr><td rowspan="2">660019</td><td>L1</td><td rowspan="22">25</td><td rowspan="22">6</td><td rowspan="2">0.24</td><td>2.33E-09</td><td>0.0443</td><td rowspan="2">0.26</td></tr>
<tr><td>L2</td><td>2.33E-09</td><td>0.0443</td></tr>
<tr><td rowspan="2">090061</td><td>L3</td><td rowspan="2">0.24</td><td>1.45E-08</td><td>0.2587</td><td rowspan="2">0.26</td></tr>
<tr><td>L4</td><td>1.45E-08</td><td>0.2587</td></tr>
<tr><td rowspan="4">640010</td><td>L1*</td><td>0.24</td><td>4.89E-09</td><td>0.0454</td><td>0.40</td></tr>
<tr><td>L2</td><td>0.28</td><td>2.49E-09</td><td>0.0454</td><td>0.26</td></tr>
<tr><td>L3*</td><td>0.24</td><td>4.89E-09</td><td>0.0454</td><td>0.40</td></tr>
<tr><td>L4</td><td>0.28</td><td>2.49E-09</td><td>0.0454</td><td>0.26</td></tr>
<tr><td rowspan="2">660021</td><td>L1</td><td rowspan="2">0.28</td><td>2.15E-08</td><td>0.1686</td><td rowspan="2">0.26</td></tr>
<tr><td>L2</td><td>2.15E-08</td><td>0.1686</td></tr>
<tr><td rowspan="2">090206</td><td>L1</td><td rowspan="2">0.24</td><td>7.65E-09</td><td>0.0513</td><td rowspan="2">0.26</td></tr>
<tr><td>L2</td><td>7.65E-09</td><td>0.0513</td></tr>
<tr><td rowspan="2">090056</td><td>L1</td><td rowspan="2">0.24</td><td>8.17E-09</td><td>0.0695</td><td rowspan="2">0.40</td></tr>
<tr><td>L2</td><td>8.17E-09</td><td>0.0695</td></tr>
<tr><td rowspan="2">150026</td><td>L2</td><td rowspan="2">0.24</td><td>1.14E-08</td><td>0.0365</td><td rowspan="2">0.44</td></tr>
<tr><td>L3</td><td>1.14E-08</td><td>0.0365</td></tr>
<tr><td rowspan="2">260007</td><td>L1*</td><td rowspan="2">0.24</td><td>1.47E-08</td><td>0.0472</td><td rowspan="2">0.45</td></tr>
<tr><td>L2*</td><td>1.47E-08</td><td>0.0472</td></tr>
<tr><td rowspan="2">150020</td><td>L1*</td><td rowspan="2">0.24</td><td>7.65E-09</td><td>0.0261</td><td rowspan="2">0.44</td></tr>
<tr><td>L2*</td><td>7.65E-09</td><td>0.0261</td></tr>
</table>

* Atmospheric

4.2.4 Life-365 Service Life Predictions

The output results of the service life modeling process utilizing second method have been summarized in Table 4.10. The component service life was estimated based on exposure conditions for each individual element modeled. Because these can vary substantially based on individual conditions, the total maintenance free bridge service life is reported as the minimum service life of any of the components modeled on the bridge. Because of the large number of assumptions made in the software when using the first method, the second method, which uses field measured values, should be more accurate and reliable. Utilizing the field measured input method, 67% of structural concrete bridge elements observed were predicted to have a maintenance free service life greater than 50 years, and 33% of structural concrete bridge elements observed were predicted to have a maintenance free service life less than 50 years.

The most important factor that influenced the expected service life was surface concentration. According to the modeling results, the frequency with which the concrete element is exposed to chloride-rich water appears to be the most important factor influencing the service life. The maximum service life of 506 years was estimated for all locations in the atmospheric zone. This indicates that the risk of corrosion-related deterioration is low in locations where concrete elements do not receive heavy chloride loading from regular exposure to chloride-rich waters. The predicted service lives were significantly shorter in tidal areas subjected to frequent wetting and drying cycles, with some structures having less than 50 years of predicted maintenance-free service life.

The variation in surface concentration between multiple locations for the same structure can be seen in Table 4.11. The chloride concentration is a direct measurement of the severity of exposure to chloride. Rochelle (2000) estimated that severe exposures at the NC coast would have chloride concentrations in the range of 15 to 25 lbs./yd^3. In fact, chloride concentrations were found to be approximately 31 lbs./yd^3, however the average surface concentration in the tidal zone locations sampled was 0.515% by weight of concrete or 19.6 lbs./yd^3.

Table 4.10: Summary of Service Life Modeling

Structure Number	Location	Corrosive Zone	Bridge Element	Vertical Distance from High Tide Elevation (ft)	Distance from open water (mi)	Field Measured	
						Component Service life (yrs.)	Total Maintenance Free Life (yrs.)
660019	L1	Corrosive	Prestressed Pile	-1	4.95	337	141
	L2		Prestressed Pile	-1		141	
090061	L3	Highly Corrosive	Prestressed Pile	-1	3.88	31	24
	L4		Prestressed Pile	-1		24	
640010	L1*	Highly Corrosive	Bent 1 Cap	5	3.87	506	111
	L2		Prestressed Pile	-1		506	
	L3*		Bent 3 Cap	5		506	
	L4		Prestressed Pile	-1		111	
660021	L1	Highly Corrosive	Prestressed Pile	-1	6.42	506	33
	L2		Prestressed Pile	-1		33	
090206	L1	Highly Corrosive	Prestressed Pile	-1	2.07	22	21
	L2		Prestressed Pile	-1		21	
090056	L1	Highly Corrosive	Bent 2 Cap	-1	1.15	57	52
	L2		Bent 3 Cap	-1		52	
150026	L2	Highly Corrosive	Bent 1 Cap	-1	7.29	-	134
	L3		Bent 1 Cap	-1		134	
260007	L1*	Highly Corrosive	Bent 3 Cap	2	0	506	506
	L2*		Bent 3 Cap	2		506	
150020	L1*	Corrosive	Prestressed Pile	2	2.5	409	104
	L2*		Prestressed Pile	2		104	

* Atmospheric

Table 4.11: Summary of Surface Concentration and Service Life

Structure Number	Location	Surface Con. (lbs./yd^3)	Field Measured			
			Diffusion Coefficient at 28 days (in^2/sec)	Diffusion Coefficient (in^2/sec)	Component Service life (yrs.)	Total Maintenance Free Life (yrs.)
660019	L1	11.805	2.33E-09	0.0443	337	141
	L2	17.866	2.33E-09	0.0443	141	
090061	L3	18.484	1.45E-08	0.2587	31	24
	L4	28.419	1.45E-08	0.2587	24	
640010	L1*	0.233	4.89E-09	0.0454	506	111
	L2	11.125	2.49E-09	0.0454	506	
	L3*	4.382	4.89E-09	0.0454	506	
	L4	21.684	2.49E-09	0.0454	111	
660021	L1	10.765	2.15E-08	0.1686	506	33
	L2	15.952	2.15E-08	0.1686	33	
090206	L1	57.248	7.65E-09	0.0513	22	21
	L2	66.845	7.65E-09	0.0513	21	
090056	L1	26.433	8.17E-09	0.0695	57	52
	L2	30.095	8.17E-09	0.0695	52	
150026	L2	18.375	1.14E-08	0.0365	-	134
	L3	13.257	1.14E-08	0.0365	134	
260007	L1*	6.012	1.47E-08	0.0472	506	506
	L2*	3.900	1.47E-08	0.0472	506	
150020	L1*	10.686	7.65E-09	0.0261	409	104
	L2*	19.097	7.65E-09	0.0261	104	

* Atmospheric

CHAPTER 5: ANALYSIS OF RESULTS

The field portion of this research project collected material samples from several coastal NC bridges that were built in "corrosive" and "highly corrosive" designated areas. These samples enabled the team to estimate current levels of exposure and chloride permeability (diffusion coefficients) for locations on the piers and bent caps that are within the tidal zone. The team also measured rates of ongoing corrosion. This chapter presents an analysis that combines the findings of data collected in the field with the results of the service life modeling in order to describe correlations between exposure and durability.

5.1 Minimum Service Life (MFSL) VS. Maximum Surface Concentration (Tidal Zone)

High chloride surface concentrations were consistently associated with shorter predicted service life. This relationship can be seen in Figure 5.1. Although an expected maintenance free service life was predicted for about one third of the bridges sampled from in the tidal zone, the remainder of bridges in the tidal zone have a predicted service life less than 100 years. The linkage between service life and exposure showed that bridges with a chloride surface concentration greater than 25 lbs./yd^3 were predicted to have a service life less than 75 years on their current track. Bridge number 660021 was excluded from the relationship because its mix design did not include SCMs (pozzolans). Bridge number 090206 was found to have an unusually high surface chloride concentration (66.8 lbs./yd^3), which indicates that its exposure conditions may have been unique. There was heavy fouling from oysters and also the presence of honeycombs on the surface of the piers, see (Figure 5.2). The effects of marine organisms, such as algae, mollusks, bacteria, and crustaceans, on marine structures can increase exposure to chlorides (BS 6349-1-1, 2013). Some marine mollusks living in warm coastal waters bore into the concrete surface and lessen the protective role of concrete cover (PIANC, 1990).

As was described, Figure 5.1 depicts a general trend of decreasing service life with increasing surface concentration (or exposure). Also shown in this Figure are general curves associated with representative diffusion coefficients for typical mix designs with diffusion coefficients between 0.04 and 0.120 in^2/yr. Although the strong correlation between these curves to individual bridge results is simply a product of the fact that they were derived from the same model, the Figure highlights the importance of diffusion coefficient to achieving particular service life under various exposure conditions.

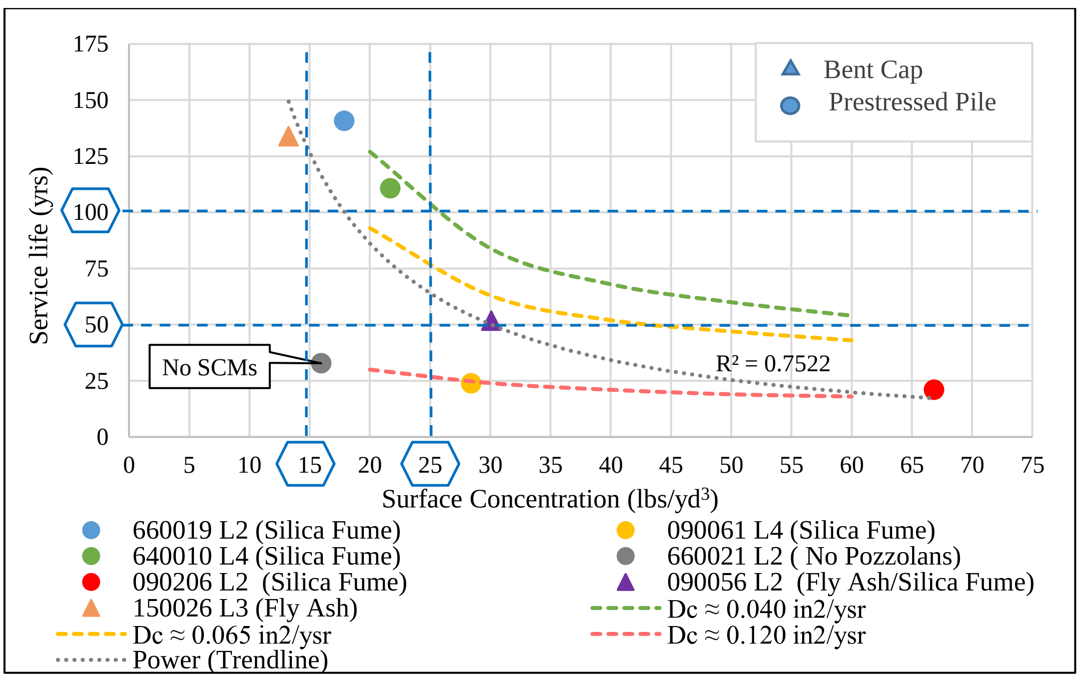


Figure 5.1: Minimum Service Life (MFSL) VS. Maximum Surface Concentration

Figure 5.2: Structure 090206 Heavy Fouling Presence (Marine life)

5.2 Distance from Open Water (Tidal Zone)

The distance of structures from the coastline significantly impacts the surface chloride concentration of locations within the tidal zone. Bridges that were further from open water had much lower surface chloride concentration. This relationship can be seen in Figure 5.3. Structure number 090206 was an outlier due to its very high chloride surface chloride concentration. However, the cause of this seemed to be related to heavy fouling by marine life and honeycombing in the concrete.

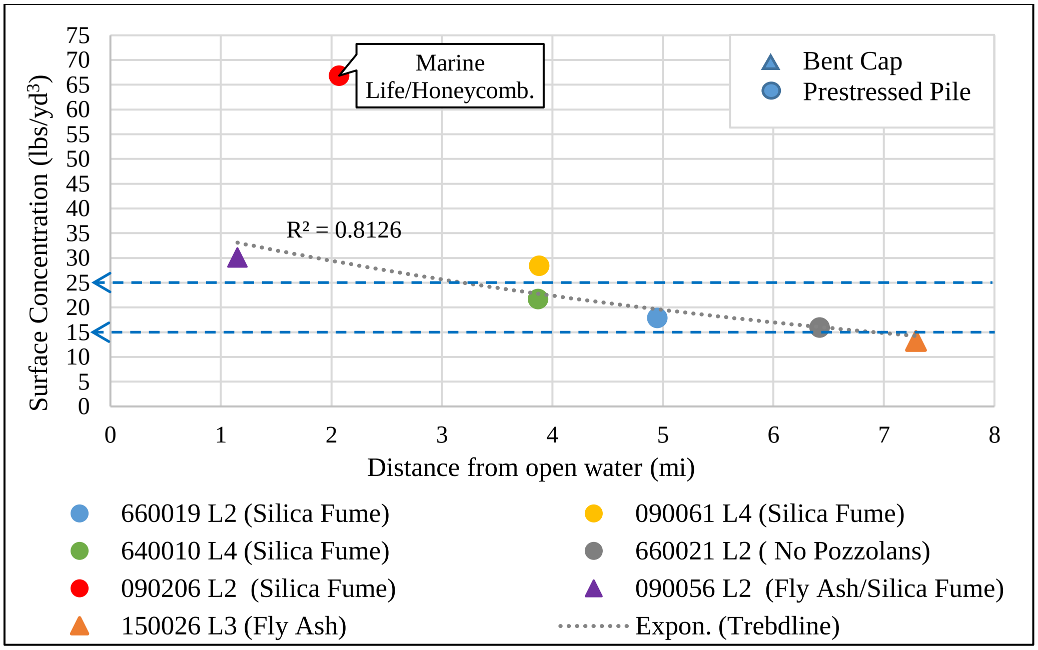


Figure 5.3: Max. Surface Concentration vs Distance from open water (Tidal Zone)

The data also show a strong correlation between the distance from open water (proximity to the coastline) and service life, which can be seen in Figure 5.4. The expected service life increases with distance from open water. Two bridges with outlying conditions were excluded from the relationship. Structure number 660021 did not follow the trend because its concrete did not contain SCMs (pozzolans) like the others and its diffusion coefficient (0.169 in2/yr.) was substantially higher than those typical of bridges that adhered to the corrosion policy. Structure number 090061 was an outlier to this relationship. Although it contained silica fume, the diffusion coefficient was exceptionally high.

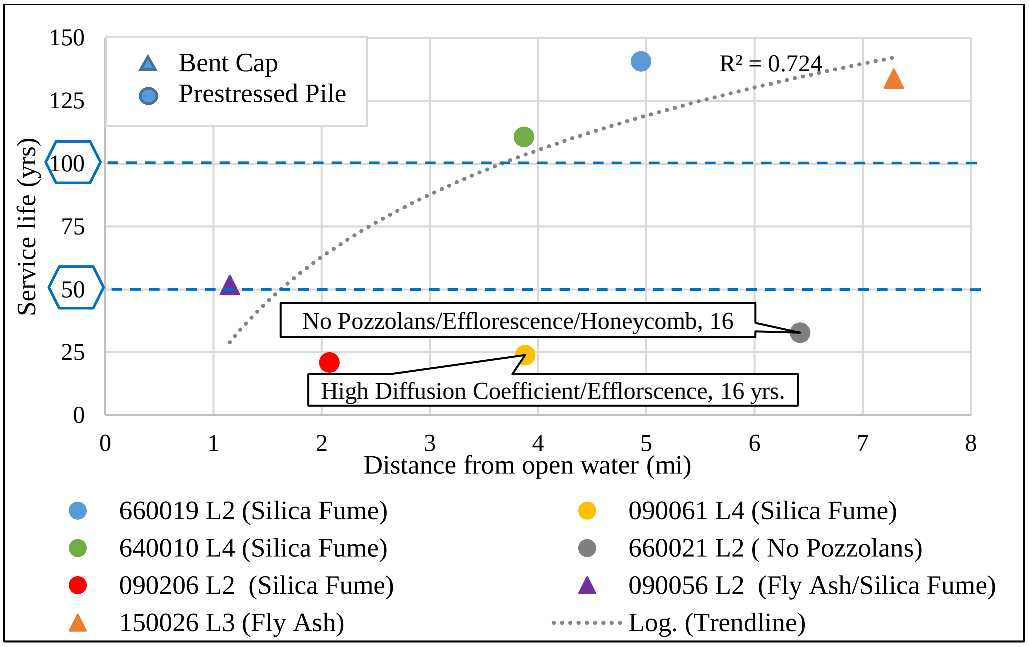


Figure 5.4: Min. Service life vs Distance from Open Water (Tidal Zone)

5.3 2-in Chloride Concentration vs. Avg. Corrosion Rate (Tidal Zone)

Figure 5.5 shows a strong correlation between the chloride concentrating at 2in depth and the rate of ongoing corrosion. Low corrosion rates were associated with chloride concentration below the threshold of approximately 1.4 lbs./yd^3. In previously published information about corrosion modeling, NCDOT has utilized a chloride threshold for non-carbonated concrete at a steel depth (2-in) of 1.4 lbs/yd^3 and 9 lbs/yd^3 for concrete mixtures with 3 gal/yd^3 of calcium nitrite as a corrosion-inhibiting admixture (Rochelle, 2000). All of the concrete elements that were tested contained corrosion-inhibiting admixture between 3-3.5 gal/yd^3, yet ongoing corrosion was detected in several structures with chloride concentration above 1.4 lbs/yd^3 and less than 9.0 lbs/yd^3. Some studies on calcium nitrite have found that calcium nitrite does not have a significant effect on increasing the chloride threshold, despite the delayed corrosion time of the concrete mix. This finding indicates that the corrosion inhibiting admixture may not be providing adequate protection to bridge components.

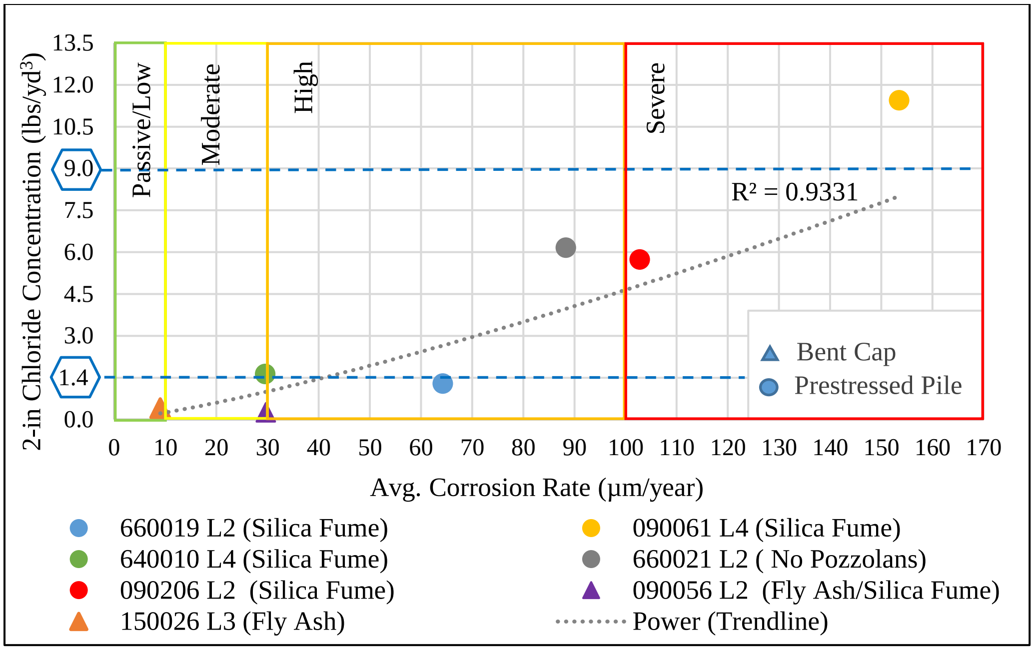


Figure 5.5: 2-in Chloride Concentration vs Avg. Corrosion Rate (Tidal Zone)

5.4 Concrete Diffusion Coefficient and Resistivity

Concrete Diffusion Coefficient and Resistivity

Concrete Diffusion Coefficient and Resistivity

The diffusion coefficient describes the permeability of concrete to chloride ions. It is utilized in the estimation of corrosion-related service life for bridges that are exposed to chlorides. As was described in Chapter 4, the diffusion coefficient was estimated by collecting samples of concrete from the field and measuring the existing chloride concentration at various depths within the concrete. A second, indirect measurement of permeability and general concrete quality is resistivity. Although resistance to electron flow is a surrogate for permeability to chloride ions, there is a strong relationship between the two. In the following plots, these quantities are related to each other and to ongoing corrosion that was measured in-situ in the structures. Based on published data, corrosion rate, surface resistivity, and diffusion coefficient were assigned to a color-coded classification system. This classification system is displayed in and (Erdogdu, et al., 2004; Giatec Scientific Inc., 2020).

Table 5.1: Interpretation of Corrosion Rate and Surface Resistivity Measurements

(Based on (Giatec Scientific Inc., 2020)

Corrosion Rate (µm/year)	Classification
<10	Passive/Low
10-30	Moderate
30-100	High
>100	Severe

Surface Resistivity (kΩ·cm)	Classification
>100	Very High
50-100	High
10-50	Moderate
<10	Low

Table 5.2: Interpretation of Diffusion Coefficient Measurements

(Based on (Erdogdu, et al., 2004)

Diffusion Coefficient (in^2/yrs.)	Classification
< 0.3	Passive/Low
0.3 - 0.6	Moderate
> 0.6	High

In , the diffusion coefficient is related to the predicted service life of the bridges considered in the study. With strong correlation, higher diffusion coefficients were related to shorter service life. Bridges with predicted service life greater than 100 years were associated with diffusion coefficient less than 0.05 in^2/year. These concrete mixtures were achieved both with silica fume and fly ash addition to the mixtures. They were also achieved in cast-in-place bent cap mixtures (ie. in structure 150026).

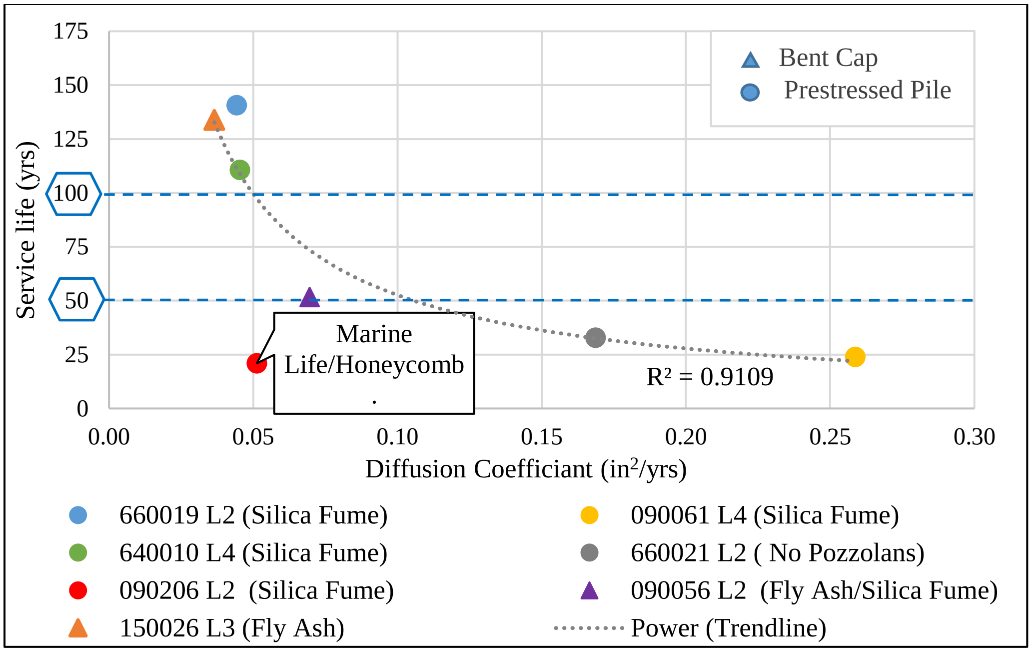


Figure 5.6: Min. Service life vs Diffusion Coefficient (Tidal Zone)

As was previously described in Figure 5.5, the rate of ongoing corrosion was strongly related to the chloride concentration at 2 inch depth within the concrete. This depth is typically close to the first layer of steel within reinforced concrete components. High levels of chlorides were found at 2 inch depth within concrete components with low surface resistivity. This relationship is shown in . similarly relates the rate of active corrosion with the surface resistivity measured in the field. Low corrosion rates were associated with high surface resistivity and high corrosion rates were associated with low surface resistivity. Not only is the concrete resistivity an indication of low permeability to chloride ion, but it also impedes the progress of corrosion once chlorides build up near the steel reinforcing. Although this correlation is strong, the values of surface resistivity measured in the field are not standardized to methods that would be used in the lab to measure resistivity. Due to the field conditions, the concrete was not at a standard temperature or moisture content and was also heavily contaminated with chlorides. Therefore, although these results are a good justification to incorporate surface resistivity into the corrosion polity specification for concrete, the appropriate threshold may not be determined from this data.

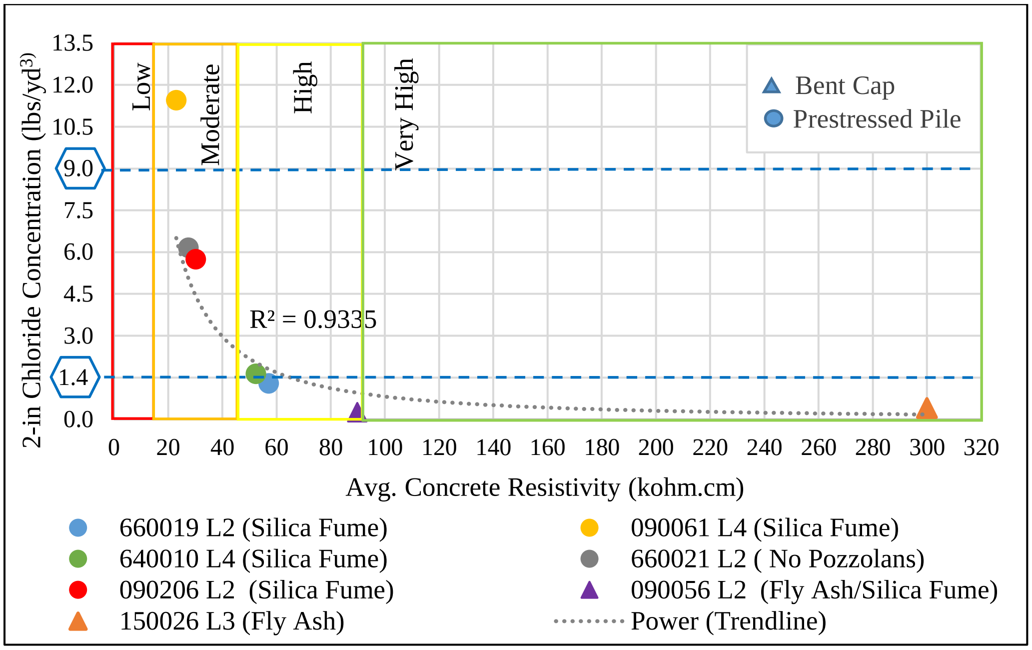


Figure 5.7: 2-in Chloride Concentration vs Avg. Concrete Resistivity (Tidal Zone)

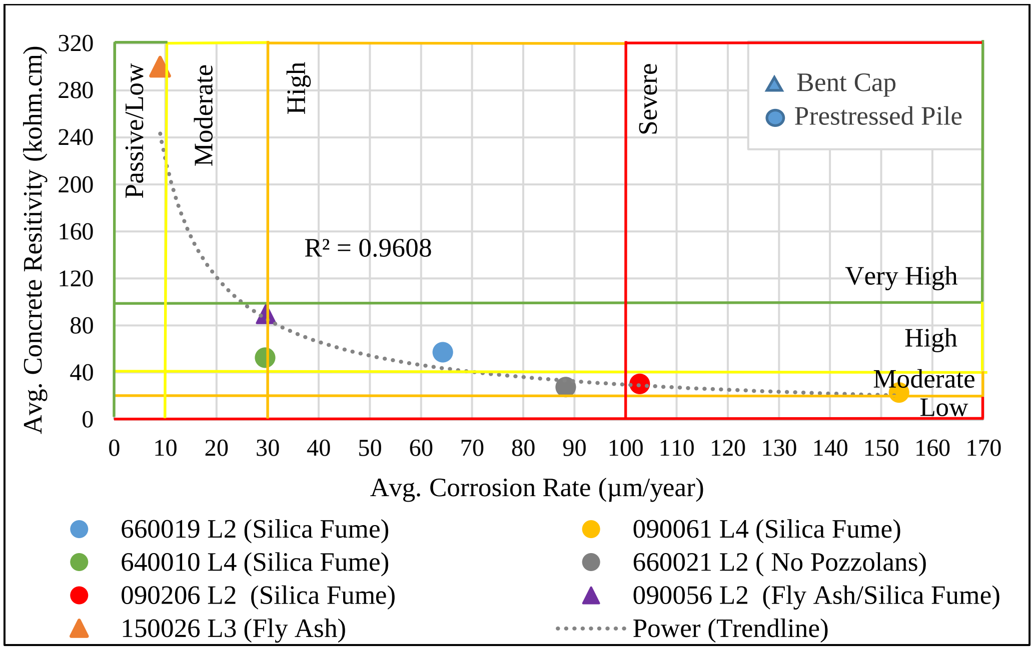


Figure 5.8: Avg. Concrete Resistivity Vs. Avg. Corrosion Rate (Tidal Zone)

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

During this study, field measurements and concrete samples were taken from the piers and pier caps of nine bridges that crossed waterways in the corrosive and highly corrosive zones of the North Carolina coast. Ongoing corrosion was detected in all the structures that were sampled. The team used the data collected in the field to prepare service life models of the bridges and determined that three of the bridges had expected service life greater than 100 years, one just over 50 years and three significantly less than 50 years. The three bridges with expected service live less than 50 years were all characterized by high chloride exposure and loading (ie. less than 3 miles from the ocean) and problems with concrete quality that likely increased the diffusion coefficient. These problems included honeycombing, cracking, and excessive fouling by oysters. Some highlighted findings are summarized below:

- Although most bridges did not feature significant visual signs of corrosion, the team identified exposed prestressing strands and large, unfilled honeycomb (SN 660091), concrete spalling, and exposed steel bar of the bent cap of (SN 090056) and frequent examples of consolidation problems and efflorescence on most structures.
- Active corrosion was detected in the tidal zone of bridge piers, although it dropped off quickly at locations outside of the tidal zone. The significant contamination of chloride is mostly limited to the portions of the structure that are frequently wetted. Limited evidence of corrosion was detected or observed on the portions of the bridges that receive only atmospheric contact with chlorides through spray, splashing, and mist.

- Chloride concentration tests indicated a rapid decrease of chloride contamination between the surface and two inches below the surface on almost all elements. Although the chloride levels were high at the level of the steel (above typical corrosion inducing thresholds), they were low towards the interior of the elements. This is most likely due to the limited exposure most structures have experienced because of their young age.
- Most concrete was found to have diffusion coefficients less than the typical/target values proposed for 100-year service life by NCDOT (Rochelle). However, structures were found to have more severe exposure than anticipated by those models. Service life modeling results indicated that the main factor impacting the service life is the tendency for the concrete member to be exposed to (or intermittently exposed to) chloride rich waters. The severity of exposure was strongly related to proximity to the coast. Factors such as fouling, and construction defects increased the vulnerability to high rates of chloride ingress.
- In all cases where locations experienced infrequent wetting, corrosion was not predicted to be the predominant or significant deterioration mechanism.
- Generally, the concentration of calcium nitrite in powder samples collected in the field was equal to or greater than the NCDOT-required minimum (Newsome, 2020). There is no doubt that calcium nitrite is being used in the correct proportions. The dosage rate did not have the expected effect of raising the corrosion causing threshold of chloride concentration to 9 lbs./yd^3. Active corrosion was detected at moderate to high rates in components that contained corrosion inhibiting admixture and had less than 9 lbs./yd^3 of chloride.

- The NC corrosion policy has similar features to many other national and international standards and codes. However, the police need to address some parameters, such as the tidal zone, the proximity from open water, and maximum admixed chloride limits for new construction. The British standard used criteria, including mixes design (SCMs), type of concrete (compressive strength), and concrete clear cover to design for a specific service life (30-, 50-, 100 years) that can be utilized in future designs.

The findings of this research project suggest that many bridges constructed under the current corrosion policy will not have maintenance free service lives that will exceed 75 or 100 years. Bridges that meet the current specified requirements of the corrosion policy for including silica fume, proper concrete cover and corrosion inhibiting admixture, may have maintenance free service lives of less than 50 years. Bridges constructed over brackish water within three miles of the coast are especially likely to be vulnerable to corrosion. Therefore, there is an opportunity to revise the corrosion policy to address these particular conditions.

6.2 Recommendations to Current Specifications

The surface concentration and diffusion coefficient are the most important factors in predicting the service life in this study. A surface concentration greater than 15 lbs./yd3 will result in a shorter service life based on the exposure. Two table were created as part of the Life-365 implementation to address various scenarios that can predict service life, see Table 6.1, and Table 6.2. As an example, a prestressed concrete pile with 15 years of chloride buildup (age) was chosen. The parameters for these tables are:

- Three possible mix designs,
- Two depths of concrete cover (2 in, 3 in)
- Six different surface concentrations
- Two types of reinforcing steel (black steel, epoxy coated)
- Three different diffusion coefficients (0.04 in^2/yrs., 0.08 in^2/yrs., 0.12 in^2/yrs.) based on D_c range 0.0392 - 0.1225 in^2/yrs., see (Table 4.4).
- 3 gal/yd^3 of corrosion inhibitor (Ct)

Tables 6.1 and 6.2 can assist in determining what type of concrete design mix to use, as well as other factors such as concrete cover and steel type, to achieve a 50, 75, or 100-year service life. When compared to 2 in. concrete cover and black steel, using 3 in. cover will double the service life, while using epoxy coated steel will add 14 years to the service life. These proposed practices may provide insight to NCDOT regarding future design projects.

For example, SN 090206 is a prestressed pile with a service life of 22 years, C_o = 50 lbs./yd^3, D_c = 0.05 in^2/yrs., SF = 5%, and concrete cover = 2in. To achieve a higher service life, the Dc must be decreased by using a mix design with known Dc, while modifying the concrete cover, SCMs, and steel type, see Figure 5.1.

The models used to predict service life are based on permeability to chloride (as measured by the diffusion coefficient), exposure (as measured by surface concentration) and corrosion threshold concentration of chloride. Diffusion coefficient and exposure were measured directly in this study, however the third parameter, corrosion threshold, was only measured indirectly (as is shown in Figure 5.5). Only one data point confirmed passive conditions at chloride concentrations below 1.4 lbs/yd^3, which is frequently taken as a general value for corrosion threshold. A more detailed study of corrosion threshold would enhance the reliability of the modeled results.

Table 6.1: Predicted Service life for a Prestressed Concrete Pile (16x16) Using Black Steel With 2-inch Cover

	Targeted Service Life (yrs.)		
C_o (lbs./yd^3)	**Dc ≈ 0.04 in^2/ysr**	**Dc ≈ 0.065 in^2/ysr**	**Dc ≈ 0.12 in^2/ysr**
20	127	93	30
30	84	63	24
40	68	52	21
50	60	47	19
60	54	43	18

Dc ≈ 0.040 in^2/ysr [2" cover + 25% FA + 5%SF + 3 gal/yd^3 Ct]
Dc ≈ 0.065 in^2/ysr [2" cover + 5%SF + 3 gal/yd^3 Ct]
Dc ≈ 0.120 in^2/ysr [2" cover + No SCMs + 3 gal/yd^3 Ct]

Table 6.2: Predicted Service life for a Prestressed Concrete Pile (16x16) Using Black Steel With 3-inch Cover

	Targeted Service Life (yrs.)		
C_o (lbs./yd^3)	**Dc ≈ 0.04 in^2/ysr**	**Dc ≈ 0.065 in^2/ysr**	**Dc ≈ 0.12 in^2/ysr**
20	254	186	60
30	168	126	48
40	136	104	42
50	120	94	38
60	108	86	36

Dc ≈ 0.040 in^2/ysr [3" cover + 25% FA + 5%SF + 3 gal/yd^3 Ct]
Dc ≈ 0.065 in^2/ysr [3" cover + 5%SF + 3 gal/yd^3 Ct]
Dc ≈ 0.120 in^2/ysr [3" cover + No SCMs + 3 gal/yd^3 Ct]

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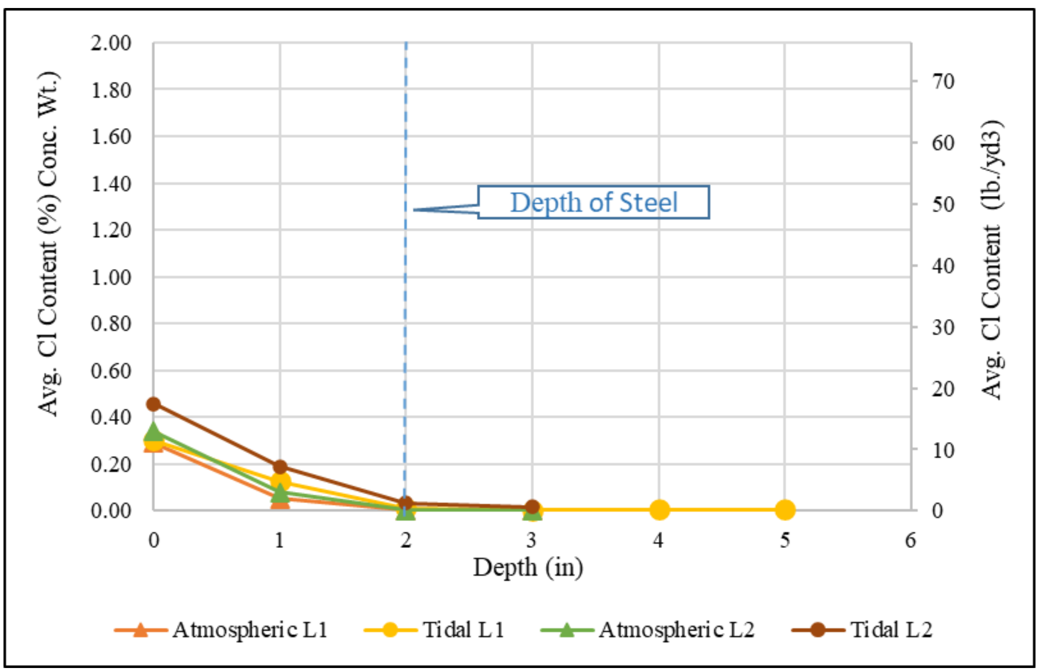
APPENDIX A - BRIDGE EVALUATION RESULTS AND MODEL INPUTS

A.1Structure 660019 Results Summary

A.1.1 RCT Test Results (Chloride Content Profile)

Structure #	Location	Zone	Chloride Content		
			Depth (in)	% Conc. Wt.	Chlorides (lbs./CY)
660019	L1	Tidal	0	0.302	11.532
			1	0.125	4.768
			2	0.011	0.436
			3	0.004	0.154
			4	0.005	0.193
			5	0.005	0.183
		Atmospheric	0	0.291	11.096
			1	0.051	1.963
			2	0.003	0.109
			3	0.003	0.098
	L2	Tidal	0	0.457	17.429
			1	0.188	7.186
			2	0.034	1.281
			3	0.018	0.692
		Atmospheric	0	0.341	13.001
			1	0.081	3.096
			2	0.004	0.167
			3	0.004	0.171


L2
L1

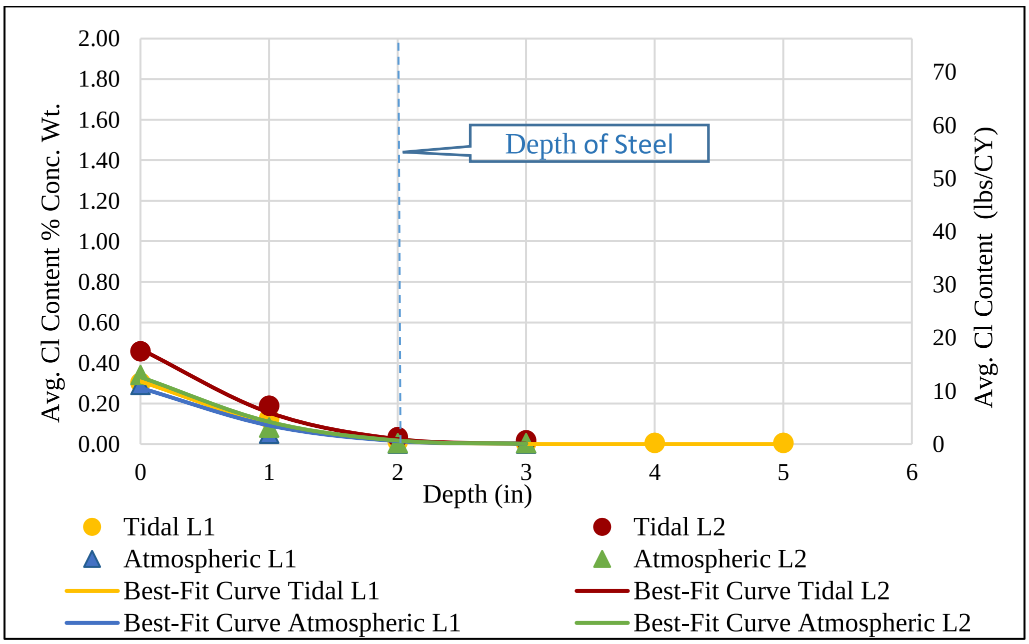

Avg. Cl Content (%) Conc. Wt.)
Avg. Cl Content (lb./yd3)
Depth of Steel
Depth (in)
Atmospheric L1
Tidal L1
Atmospheric L2
Tidal L2

A.1.2 COR Test Results (Corrosion Rate & Surface Resistivity)

		Atmospheric Zone					Tidal Zone				
Structure #	Location	Corrosion Rate	Avg. Corrosion Rate	Concrete Resist.	Avg. Concrete Resist.	R^2	Corrosion Rate	Avg. Corrosion Rate	Concrete Resist.	Avg. Concrete Resist.	R^2
660019	L1	8.1	31.2	133.0	115.6	1	48.4	77.7	38.0	32.0	0.92
		8.4		99.0		1	67.6		28.0		0.95
		2.7		130.0		1	191.1		12.0		0.51
		5.0		187.0		1	35.3		37.0		0.98
		4.6		161.0		1	122.0		10.0		0.92
		10.0		190.0		0.95	1.9		67.0		0.8
		40.0		102.0		0.99					
		36.0		95.0		0.99					
		49.0		133.0		0.98					
		90.0		49.0		0.99					
		73.0		52.0		0.94					
		47.0		56.0		0.99					
	L2	2.9	22.9	104.0	99.6	1	12.1	64.3	37.0	57.2	0.98
		5.5		57.0		1	217.8		7.0		0.87
		0.8		129.0		1	2.5		84.0		0.99
		13.0		78.0		1	4.4		115.0		0.99
		3.6		147.0		0.99	84.6		43.0		0.98
		19.0		104.0		1					
		17.0		105.0		1					
		5.0		138.0		0.99					
		10.0		108.0		1					
		39.0		51.0		1					
		136.0		75.0		0.95					

A.1.3 Iterative Non-linear Least-Squares Regression

			Chloride Content				Iterative Non-linear Least-Squares Regression				
Structure #	Location	Zone	Depth (in) (x)	% Conc. Wt.	Chlorides (lbs./yd^3) (Cl^-_x)	Age (t)	Diffusion Coefficient (in*in/yr) (D_c)	Surface Concentration (lbs./yd^3) (C_o)	Best-Fit Curve $C_{(x,t)}$	Residual Sum Squares (RSS)	Sum of RSS
Corrosive/Silica Fume 660019	L1	Tidal	0	0.302	11.5320	12	0.044	11.805	11.805	0.074	7.661
			1	0.125	4.7684				3.920	0.720	
			2	0.011	0.4364				0.618	0.033	
			3	0.004	0.1541				0.043	0.012	
			4	0.005	0.1931				0.001	0.037	
			5	0.005	0.1831				0.000	0.034	
		Atmospheric	0	0.291	11.0959	12	0.044	10.560	10.560	0.287	
			1	0.051	1.9626				3.507	2.384	
			2	0.003	0.1092				0.553	0.197	
			3	0.003	0.0975				0.038	0.004	
										0.000	
	L2	Tidal	0	0.457	17.4292	12	0.044	17.866	17.866	0.191	
			1	0.188	7.1863				5.933	1.572	
			2	0.034	1.2813				0.936	0.119	
			3	0.018	0.6924				0.065	0.394	
										0.000	
		Atmospheric	0	0.341	13.0012	12	0.044	12.613	12.613	0.151	
			1	0.081	3.0959				4.188	1.193	
			2	0.004	0.1674				0.661	0.243	
			3	0.004	0.1712				0.046	0.016	
										0.000	



Avg. Cl Content % Conc. Wt.
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Avg. Cl Content (lbs/CY)
70
60
50
40
30
20
10
0
Depth of Steel
0
1
2
3
4
5
6
Depth (in)
Tidal L1
Tidal L2
Atmospheric L1
Atmospheric L2
Best-Fit Curve Tidal L1
Best-Fit Curve Tidal L2
Best-Fit Curve Atmospheric L1
Best-Fit Curve Atmospheric L2

A.1.4 Corrosion Modeling Service Life Reports

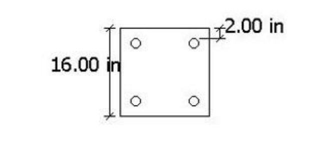
Life-365 v2.2 - Concrete Mixes and Service Lives

Project: 660019 L1

Description: Bent Cap\Highly Corrosive Zone

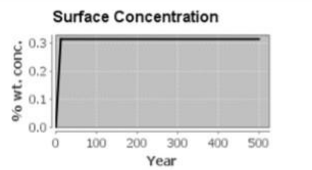
Analyst: Taiseer Al Salihi

Date: 07/30/2021



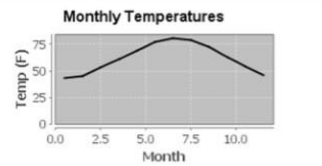
square column/beams (2-D)

Outer dim: 16in; clear cover: 2in



Max surface: 0.312 % wt. conc.

Years to buildup: 12



Loc: user-defined

Type: user-defined

Concrete Mixes

Alt name	User?	w/cm	SCMs	Inhib.	Barrier	Reinf.
Assumed Concret Properties		0.35	Silica Fume (5%);	Ca Nitrite - 3 gal/cub. yd.		Black Steel
Measured Concrete Properties	yes	n/a	n/a	n/a		Black Steel

"n/a" indicates that, since the user is specifying the diffusion properties of this mix, this value is not specified.

Diffusion Properties and Service Lives

Alt name	D28	m	Ct	Init.	Prop.	Service life
Assumed Concret Properties	4.09E-9 in*in/sec	0.2	0.24 % wt. conc.	136.7 yrs	6 yrs	**142.7 yrs**
Measured Concrete Properties	-> 2.33E-9 in*in/sec	-> 0.26	-> 0.24 % wt. conc.	330.8 yrs	-> 6 yrs	**336.8 yrs**

"->" indicates that the user has directly specified this value; "+" indicates the service life exceeds the study period.

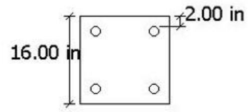
Life-365 v2.2 - Concrete Mixes and Service Lives

Project: 660019 L2

Description: Bent Cap\Highly Corrosive Zone

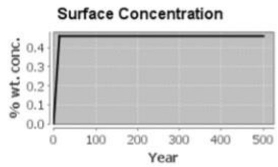
Analyst: Taiseer Al Salihi

Date: 07/30/2021



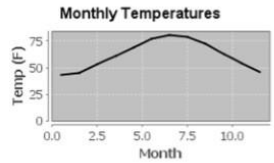
square column/beams (2-D)

Outer dim: 16in; clear cover: 2in



Max surface: 0.457 % wt. conc.

Years to buildup: 12



Loc: user-defined

Type: user-defined

Concrete Mixes

Alt name	User?	w/cm	SCMs	Inhib.	Barrier	Reinf.
Assumed Concret Properties		0.35	Silica Fume (5%);	Ca Nitrite - 3 gal/cub. yd.		Black Steel
Measured Concrete Properties	yes	n/a	n/a	n/a		Black Steel

"n/a" indicates that, since the user is specifying the diffusion properties of this mix, this value is not specified.

Diffusion Properties and Service Lives

Alt name	D28	m	Ct	Init.	Prop.	Service life
Assumed Concret Properties	4.09E-9 in*in/sec	0.2	0.24 % wt. conc.	57.2 yrs	6 yrs	**63.2 yrs**
Measured Concrete Properties	-> 2.33E-9 in*in/sec	-> 0.26	-> 0.24 % wt. conc.	134.7 yrs	-> 6 yrs	**140.7 yrs**

"->" indicates that the user has directly specified this value; "+" indicates the service life exceeds the study period.

A.1.5 Materials and Tests Unit Statement of Concrete Mix Design

Form 312U
3-96

North Carolina Department of Transportation, Division of Highways, Materials and Tests Unit
Statement of Concrete Mix Design and Source of Materials

Project	**Date Expires** 12/31/2075
Mix Design Status Active	**Concrete Producer** S & G PRESTRESS CONCRETE
County	**Plant Location & DOT No.** LELAND, NC - 2
Resident Engr.	**Contractor**
Class of Concrete PRESTRESS	**Date Assigned**
Mix Design No. 2PVU13CIMSE	**Contractor's Signature**
Note Mix Design Units (English or Metric) ENGLISH	

Mix Design Proportions Based on SSD Mass of Aggregates

Material	Producer	Source	Qty. per Cu. Yard
Cement	ARGOS USA	BARRANQUILLA PLANT - (FORMERLY CEMENT(	665 lbs.
Pozzolan	Degussa Rheomac SF 100 silica fume		35 lbs.
Fine Aggregate	MARTIN MARIETTA	ROCKY POINT QUARRY - ROCKY POINT	1244 lbs.
Coarse Aggregate	MARTIN MARIETTA	GARNER QUARRY - GARNER	1700 lbs.
Total Water		WELL	29.4 gals.
Air. Entr. Agent	BASF CONSTRUCTION CHEMICALS, LLC	MASTERAIR AE 90 (AKA MB AE 90)	As recommended
Retarder	BASF CONSTRUCTION CHEMICALS, LLC	POZZOLITH 122R	As recommended
Water Reducer			
Superplasticizer	BASF CONSTRUCTION CHEMICALS, LLC	MASTERGLENIUM 3030 (AKA GLENIUM 3030NS	As recommended
Corrosion Inhibitor	BASF CONSTRUCTION CHEMICALS, LLC	MASTERLIFE CI 30 (AKA RHEOCRETE CNI)	As recommended

Mix Properties and Specifications

Slump	7.00 in.	**Mortar Content**	16.60 cu. ft.
Max Water	31.0 gals.	**Air Content**	5.0 %

Material	Specific Gravity	% Absorption	Unit Mass	Fineness Modulus
Fine Aggregate	2.65	1.0	NA	2.40
Coarse Aggregate, #67	2.62	0.5	93.5	NA

Comment Mix is designed for 6000 psi. Mix contains 3.0 gals. CNI and 35 lbs. Rheomac SF 100 silica fume. (Silica fume quantity is listed on Form 312 under "pozzolan.") Max. water-cement ratio is 0.4.

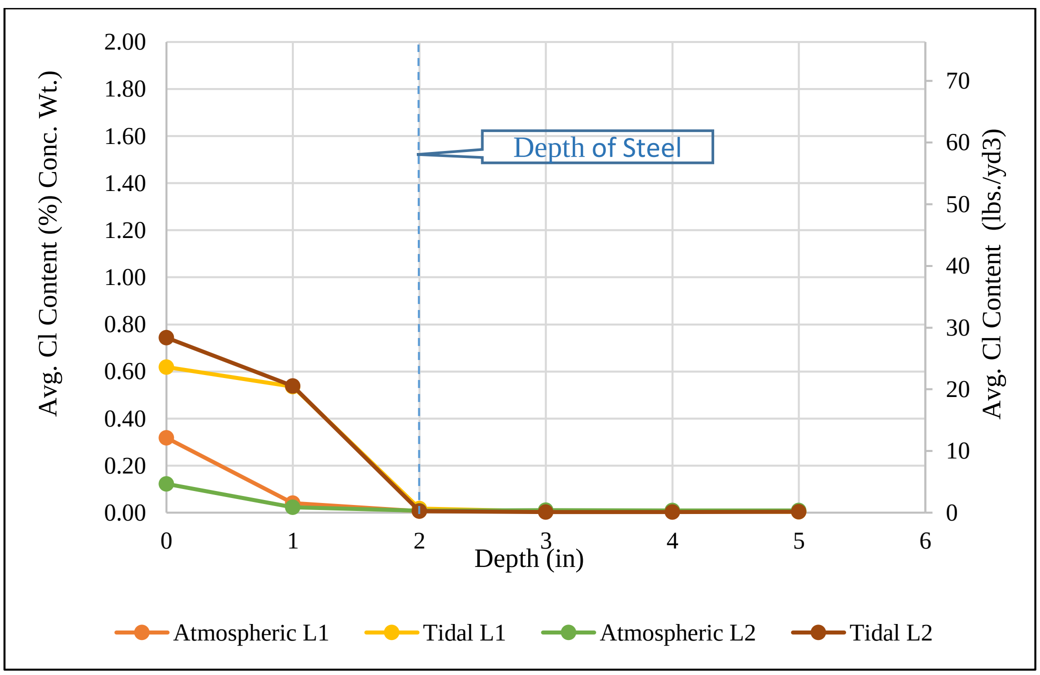
Cast-in-place concrete shall conform to Section 1000, precast concrete to Section 1077, and prestressed concrete to Section 1078 of the applicable edition of the Standard Specifications for Roads and Structures plus all applicable Special Provisions.

A.2 Structure 090056 Results Summary

A.1.1 RCT Test Results (Chloride Content Profile)

Structure #	Location	Zone	Chloride Content		
			Depth (in)	% Conc. Wt.	Chlorides (lbs/CY)
090056	**L1**	**Tidal**	0	0.619	23.610
			1	0.536	20.450
			2	0.017	0.659
			3	0.005	0.200
			4	0.007	0.269
			5	0.004	0.135
		Atmospheric	0	0.318	12.133
			1	0.041	1.569
			2	0.006	0.240
			3	0.007	0.261
			4	0.007	0.283
	L2	**Tidal**	0	0.744	28.370
			1	0.538	20.510
			2	0.007	0.257
			3	0.003	0.113
			4	0.003	0.100
			5	0.004	0.135
		Atmospheric	0	0.122	4.668
			1	0.023	0.890
			2	0.008	0.321
			3	0.011	0.406
			4	0.010	0.363
			5	0.009	0.339


L2
L1

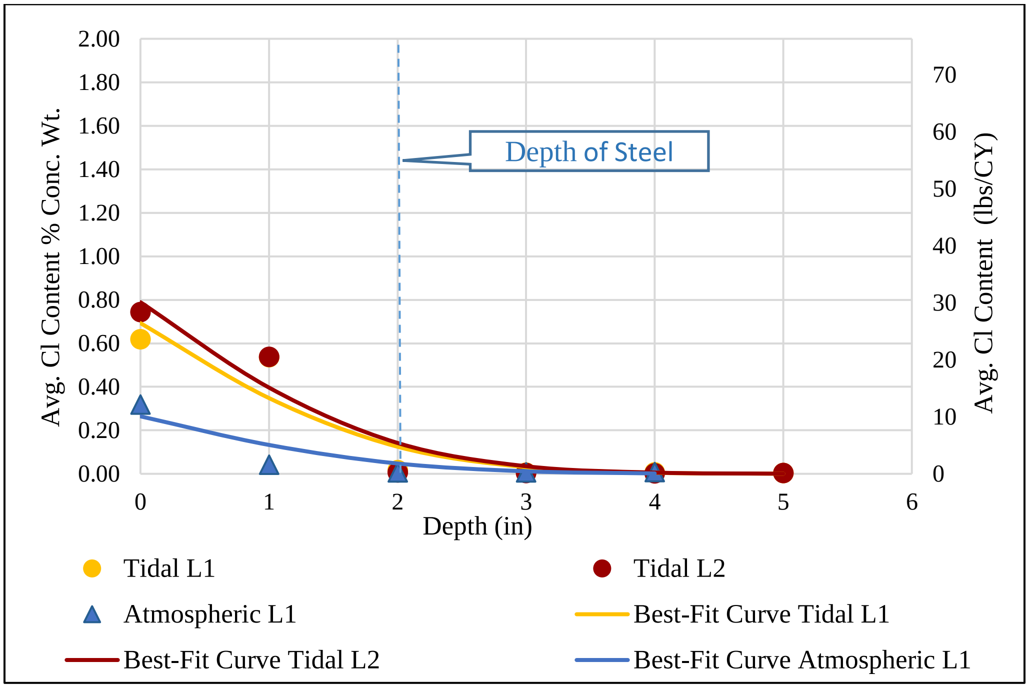

Avg. Cl Content (%) Conc. Wt.)
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Avg. Cl Content (lbs./yd3)
70
60
50
40
30
20
10
0
Depth of Steel
0
1
2
3
4
5
6
Depth (in)
Atmospheric L1
Tidal L1
Atmospheric L2
Tidal L2

iCOR Test Results (Corrosion Rate & Surface Resistivity)

		Atmospheric Zone					Tidal Zone				
Structure #	**Location**	**Corrosion Rate**	**Avg. Corrosion Rate**	**Concrete Resist.**	**Avg. Concrete Resist.**	**R2**	**Corrosion Rate**	**Avg. Corrosion Rate**	**Concrete Resist.**	**Avg. Concrete Resist.**	**R2**
090056	L1	7.86	27.98	151	171.35	0.98	71	81	21	45	0.98
		3.22		188		1	119		17		0.95
		98.98		46.4		0.95	155		18		0.94
		1.86		300		1	148		17		0.95
							83		16		0.98
							147		18		0.93
							65		33		0.96
							27		101		0.96
							32		96		0.96
							15		78		0.98
							29		79		0.97
	L2	Data Not Collected					48	30	38	90	0.93
							87		31		0.94
							84		31		0.98
							63		24		0.97
							60		39		0.96
							4		55		0.94
							24		72		0.96
							11		64		0.99
							11		111		0.98
							7		154		0.97
							4		159		0.98
							2		209		0.96
							1		210		0.99
							10		134		0.95
							40		64		0.96
							37		67		0.96
							20		86		0.99
							22		69		0.99

Iterative Non-linear Least-Squares Regression

Highly Corrosive/Silica Fume-Fly Ash												
Structure #	Location	Zone	Chloride Content			Age (t)	Iterative Non-linear Least-Squares Regression				
			Depth (in) (x)	% Conc. Wt.	Chlorides (lbs./yd^3) (Cl^-_x)		Diffusion Coefficient (in*in/yr) (D_c)	Surface Concentration (lbs./yd^3) (C_o)	Best-Fit Curve $C_{(x,t)}$	Residual Sum Squares (RSS)	Sum of RSS
090056	**L1**	**Tidal**	0	0.619	23.610	16	**0.070**	**26.433**	**26.433**	7.966	156.164
			1	0.536	20.450				**13.283**	51.367	
			2	0.017	0.659				**4.755**	16.777	
			3	0.005	0.200				**1.170**	0.940	
			4	0.007	0.269				**0.193**	0.006	
			5	0.004	0.135				**0.021**	0.013	
		Atmospheric	0	0.318	12.133	16	**0.070**	**10.084**	**10.084**	4.195	
			1	0.041	1.569				**5.068**	12.242	
			2	0.006	0.240				**1.814**	2.479	
			3	0.007	0.261				**0.446**	0.034	
			4	0.007	0.283				**0.074**	0.044	
	L2	**Tidal**	0	0.744	28.370	16	**0.070**	**30.095**	**30.095**	2.974	
			1	0.538	20.510				**15.123**	29.019	
			2	0.007	0.257				**5.414**	26.595	
			3	0.003	0.113				**1.332**	1.486	
			4	0.003	0.100				**0.220**	0.014	
			5	0.004	0.135				**0.024**	0.012	



Avg. Cl Content % Conc. Wt.
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Avg. Cl Content (lbs/CY)
70
60
50
40
30
20
10
0
Depth of Steel
0
1
2
3
4
5
6
Depth (in)
Tidal L1
Tidal L2
Atmospheric L1
Best-Fit Curve Tidal L1
Best-Fit Curve Tidal L2
Best-Fit Curve Atmospheric L1

Corrosion Modeling Service Life Reports

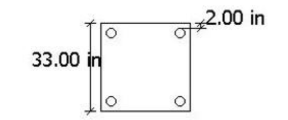
Life-365 v2.2 - Concrete Mixes and Service Lives

Project: 090056 L1

Description: Bent Cap\Highly Corrosive Zone

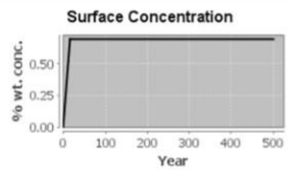
Analyst: Taiseer Al Salihi

Date: 07/30/2021



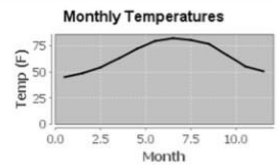
square column/beams (2-D)

Outer dim: 33in; clear cover: 2in



Max surface: 0.690 % wt. conc.

Years to buildup: 16



Loc: user-defined

Type: user-defined

Concrete Mixes

Alt name	User?	w/cm	SCMs	Inhib.	Barrier	Reinf.
Assumed Concret Properties		0.37	Class F Fly Ash (25%); Silica Fume (5%);	Ca Nitrite - 3 gal/cub. yd.		Black Steel
Measured Concrete Properties	yes	n/a	n/a	n/a		Black Steel

"n/a" indicates that, since the user is specifying the diffusion properties of this mix, this value is not specified.

Diffusion Properties and Service Lives

Alt name	D28	m	Ct	Init.	Prop.	Service life
Assumed Concret Properties	4.57E-9 in*in/sec	0.4	0.24 % wt. conc.	88.4 yrs	6 yrs	**94.4 yrs**
Measured Concrete Properties	-> 8.17E-9 in*in/sec	-> 0.4	-> 0.24 % wt. conc.	51.4 yrs	-> 6 yrs	**57.4 yrs**

"->" indicates that the user has directly specified this value; "+" indicates the service life exceeds the study period.

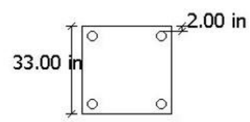
Life-365 v2.2 - Concrete Mixes and Service Lives

Project: 090056 L2

Description: Bent Cap\Highly Corrosive Zone

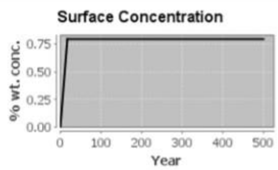
Analyst: Taiseer Al Salihi

Date: 07/30/2021



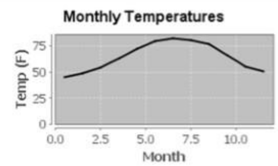
square column/beams (2-D)

Outer dim: 33in; clear cover: 2in



Max surface: 0.792 % wt. conc.

Years to buildup: 16



Loc: user-defined

Type: user-defined

Concrete Mixes

Alt name	User?	w/cm	SCMs	Inhib.	Barrier	Reinf.
Assumed Concret Properties		0.37	Class F Fly Ash (25%); Silica Fume (5%);	Ca Nitrite - 3 gal/cub. yd.		Black Steel
Measured Concrete Properties	yes	n/a	n/a	n/a		Black Steel

"n/a" indicates that, since the user is specifying the diffusion properties of this mix, this value is not specified.

Diffusion Properties and Service Lives

Alt name	D28	m	Ct	Init.	Prop.	Service life
Assumed Concret Properties	4.57E-9 in*in/sec	0.4	0.24 % wt. conc.	78.4 yrs	6 yrs	**84.4 yrs**
Measured Concrete Properties	-> 8.17E-9 in*in/sec	-> 0.4	-> 0.24 % wt. conc.	45.7 yrs	-> 6 yrs	**51.7 yrs**

"->" indicates that the user has directly specified this value; "+" indicates the service life exceeds the study period.

Materials and Tests Unit Statement of Concrete Mix Design

Form 312U
3-96

North Carolina Department of Transportation, Division of Highways, Materials and Tests Unit
Statement of Concrete Mix Design and Source of Materials

Project	**Date Expires** 02/28/2011
Mix Design Status Expired	**Concrete Producer** ARGOS USA LLC
County	**Plant Location & DOT No.** LELAND, NC - 15
Resident Engr.	**Contractor**
Class of Concrete CLASS AA	**Date Assigned**
Mix Design No. 152VF6034E	**Contractor's Signature**
Note Mix Design Units (English or Metric) ENGLISH	

Mix Design Proportions Based on SSD Mass of Aggregates

Material	Producer	Source	Qty. per Cu. Yard
Cement	CEMEX	KNOXVILLE, TN (TYPE I/II)	540 **lbs.**
Pozzolan	THE SEFA GROUP	WINYAH GENERATING STATION/GEORGETOWN	135 **lbs.**
Fine Aggregate	CAPE FEAR PAVING, LLC	WILMINGTON MATERIALS - OAK RIDGE PIT #1	1160 **lbs.**
Coarse Aggregate	MARTIN MARIETTA	CASTLE HAYNE QUARRY - CASTLE HAYNE	1540 **lbs.**
Total Water		WELL	30.0 **gals.**
Air. Entr. Agent	BASF CONSTRUCTION CHEMICALS, LLC	MASTERAIR AE 90 (AKA MB AE 90)	**As recommended**
Retarder	BASF CONSTRUCTION CHEMICALS, LLC	POZZOLITH 122R	**As recommended**
Water Reducer			
Superplasticizer			
Corrosion Inhibitor	BASF CONSTRUCTION CHEMICALS, LLC	MASTERLIFE CI 30 (AKA RHEOCRETE CNI)	**As recommended**

Mix Properties and Specifications

Slump	3.50 **in.**	**Mortar Content**	16.84 **cu. ft.**
Max Water	32.3 **gals.**	**Air Content**	6.0 **%**

Material	Specific Gravity	% Absorption	Unit Mass	Fineness Modulus
Fine Aggregate	2.65	1.0	**NA**	2.40
Coarse Aggregate, #57	2.43	3.1	76.5	**NA**

Comment Mix also contains 35 lbs. Elkim silica fume and 3 gals. CNI corrosion inhibitor. Use of 5 % silica fume and 1:1 cement:fly ash replacement rate are in accordance with a note on the plans for 8.1231503. Mix is for caps on bent #s 1 - 4.

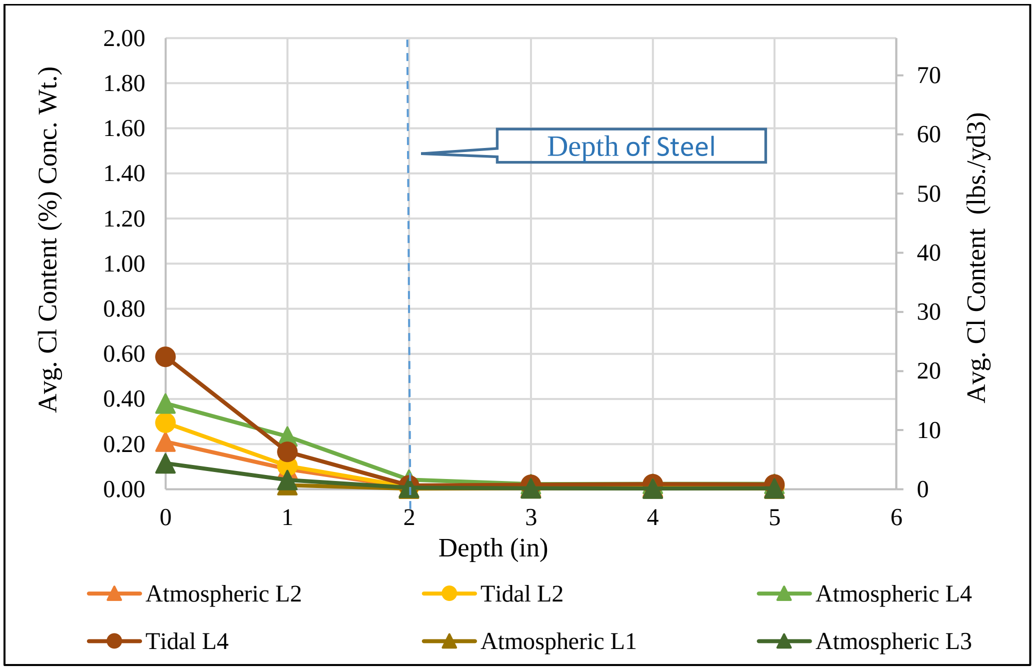
Cast-in-place concrete shall conform to Section 1000, precast concrete to Section 1077, and prestressed concrete to Section 1078 of the applicable edition of the Standard Specifications for Roads and Structures plus all applicable Special Provisions.

Structure 660021 Results Summary

RCT Test Results (Chloride Content Profile)

Structure #	Location	Zone	Chloride Content		
			Depth (in)	% Conc. Wt.	Chlorides (lbs/CY)
660021	L1	Tidal	0	0.220	8.397
			1	0.243	9.252
			2	0.150	5.738
			3	0.094	3.592
			4	0.018	0.705
			5	0.012	0.443
		Atmospheric	0	0.115	4.404
			1	0.023	0.887
			2	0.004	0.156
			3	0.003	0.109
			4	0.003	0.105
			5	0.003	0.102
	L2	Tidal	0	0.412	15.718
			1	0.297	11.327
			2	0.161	6.157
			3	0.030	1.159
			4	0.006	0.247
			5	0.005	0.185
		Atmospheric	0	0.183	6.987
			1	0.043	1.628
			2	0.004	0.145
			3	0.004	0.142
			4	0.003	0.112
			5	0.003	0.116


L2
L1

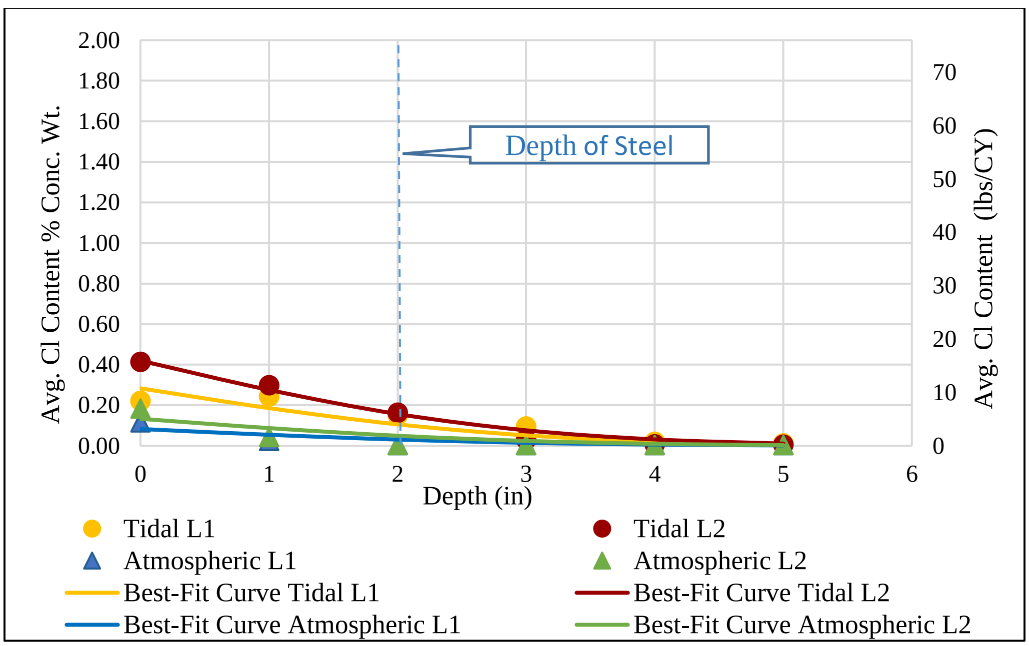

Avg. Cl Content (%) Conc. Wt.)
Avg. Cl Content (lbs./yd3)
Depth of Steel
Depth (in)
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
Atmospheric L2
Tidal L2
Atmospheric L4
Tidal L4
Atmospheric L1
Atmospheric L3

iCOR Test Results (Corrosion Rate & Surface Resistivity)

		Atmospheric Zone					Tidal Zone				
Structure #	**Location**	**Corrosion Rate**	**Avg. Corrosion Rate**	**Concrete Resist.**	**Avg. Concrete Resist.**	**R2**	**Corrosion Rate**	**Avg. Corrosion Rate**	**Concrete Resist.**	**Avg. Concrete Resist.**	**R2**
660021	L1	4		119		1	403		15		0.96
		5		112		0.97	13		28		0.99
		5	4	208	180	0.99	231		11		0.99
		1		204		0.99	336	206	9	16	0.98
		4		234		0.96	182		17		0.99
		7		200		0.89	153		22		0.98
							162		12		0.92
							172		11		0.99
	L2	0		257		0.97	15		74		1
		3		226		0.97	136		23		1
		3	4	178	198	1	114		14		0.98
		3		191		0.98	78	88	12	28	0.99
		3		177		0.99	46		56		0.95
		10		158		0.98	51		21		0.99
							147		10		0.99
							119		10		0.94

Iterative Non-linear Least-Squares Regression

	Structure #	Location	Zone	Chloride Content: Depth (in) (x)	Chloride Content: % Conc. Wt.	Chloride Content: Chlorides (lbs./yd^3) (Cl^-_x)	Age (t)	Iterative Non-linear Least-Squares Regression: Diffusion Coefficient (in^2/yr) (D_c)	Surface Concentration (lbs./yd^3) (C_o)	Best-Fit Curve $C_{(x,t)}$	Residual Sum Squares (RSS)	Sum of RSS
Highly Corrosive/No SCMs (Pozzolans)	**660021**	**L1**	**Tidal**	0	0.220	8.397	15	**0.169**	**10.765**	**10.765**	5.606	35.408
				1	0.243	9.252				**7.068**	4.769	
				2	0.150	5.738				**4.025**	2.936	
				3	0.094	3.592				**1.962**	2.656	
				4	0.018	0.705				**0.811**	0.011	
				5	0.012	0.443				**0.282**	0.026	
			Atmospheric	0	0.115	4.404	15	**0.169**	**3.151**	**3.151**	1.569	
				1	0.023	0.887				**2.069**	1.397	
				2	0.004	0.156				**1.178**	1.045	
				3	0.003	0.109				**0.574**	0.217	
				4	0.003	0.105				**0.237**	0.018	
				5	0.003	0.102				**0.083**	0.000	
		L2	**Tidal**	0	0.412	15.718	15	**0.169**	**15.953**	**15.953**	0.055	
				1	0.297	11.327				**10.475**	0.726	
				2	0.161	6.157				**5.965**	0.037	
				3	0.030	1.159				**2.908**	3.057	
				4	0.006	0.247				**1.202**	0.911	
				5	0.005	0.185				**0.418**	0.055	
			Atmospheric	0	0.183	6.987	15	**0.169**	**5.059**	**5.059**	3.717	
				1	0.043	1.628				**3.322**	2.869	
				2	0.004	0.145				**1.892**	3.050	
				3	0.004	0.142				**0.922**	0.609	
				4	0.003	0.112				**0.381**	0.072	
				5	0.003	0.116				**0.133**	0.000	



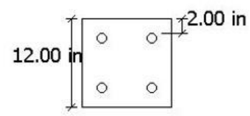
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Avg. Cl Content % Conc. Wt.
70
60
50
40
30
20
10
0
Avg. Cl Content (lbs/CY)
0
1
2
3
4
5
6
Depth (in)
Depth of Steel
Tidal L1
Tidal L2
Atmospheric L1
Atmospheric L2
Best-Fit Curve Tidal L1
Best-Fit Curve Tidal L2
Best-Fit Curve Atmospheric L1
Best-Fit Curve Atmospheric L2

Corrosion Modeling Service Life Reports

Life-365 v2.2 - Concrete Mixes and Service Lives

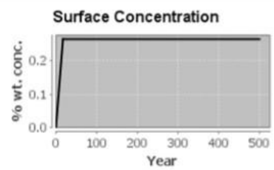
Project: 660021 L1 | Description: Bent Cap\Highly Corrosive Zone

Analyst: Taiseer Al Salihi | Date: 07/30/2021



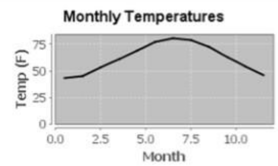
square column/beams (2-D)

Outer dim: 12in; clear cover: 2in



Max surface: 0.263 % wt. conc.

Years to buildup: 15



Loc: user-defined

Type: user-defined

Concrete Mixes

Alt name	User?	w/cm	SCMs	Inhib.	Barrier	Reinf.
Assumed Concrete Properties		0.32		Ca Nitrite - 3.5 gal/cub. yd.		Black Steel
Measured Concrete Properties	yes	n/a	n/a	n/a		Black Steel

"n/a" indicates that, since the user is specifying the diffusion properties of this mix, this value is not specified.

Diffusion Properties and Service Lives

Alt name	D28	m	Ct	Init.	Prop.	Service life
Assumed Concrete Properties	7.91E-9 in*in/sec	0.2	0.28 % wt. conc.	500+ yrs	6 yrs	**506+ yrs**
Measured Concrete Properties	-> 2.15E-8 in*in/sec	-> 0.26	-> 0.28 % wt. conc.	500+ yrs	-> 6 yrs	**506+ yrs**

"->" indicates that the user has directly specified this value; "+" indicates the service life exceeds the study period.

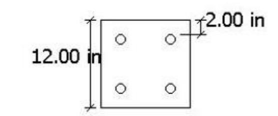
Life-365 v2.2 - Concrete Mixes and Service Lives

Project: 660021 L2

Description: Bent Cap\Highly Corrosive Zone

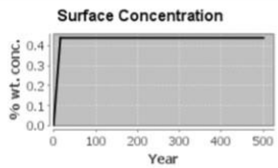
Analyst: Taiseer Al Salihi

Date: 07/30/2021



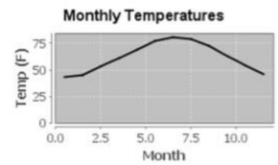
square column/beams (2-D)

Outer dim: 12in; clear cover: 2in



Max surface: 0.436 % wt. conc.

Years to buildup: 15



Loc: user-defined

Type: user-defined

Concrete Mixes

Alt name	User?	w/cm	SCMs	Inhib.	Barrier	Reinf.
Assumed Concret Properties		0.32		Ca Nitrite - 3.5 gal/cub. yd.		Black Steel
Measured Concrete Properties	yes	n/a	n/a	n/a		Black Steel

"n/a" indicates that, since the user is specifying the diffusion properties of this mix, this value is not specified.

Diffusion Properties and Service Lives

Alt name	D28	m	Ct	Init.	Prop.	Service life
Assumed Concret Properties	7.91E-9 in*in/sec	0.2	0.28 % wt. conc.	46.5 yrs	6 yrs	**52.5 yrs**
Measured Concrete Properties	-> 2.15E-8 in*in/sec	-> 0.26	-> 0.28 % wt. conc.	26.8 yrs	-> 6 yrs	**32.8 yrs**

"->" indicates that the user has directly specified this value; "+" indicates the service life exceeds the study period.

Materials and Tests Unit Statement of Concrete Mix Design

Form 312U
3-96

North Carolina Department of Transportation, Division of Highways, Materials and Tests Unit
Statement of Concrete Mix Design and Source of Materials

Project	**Date Expires** 12/31/2075
Mix Design Status Active	**Concrete Producer** FLORENCE CONCRETE PROD.
County	**Plant Location & DOT No.** SUMTER, SC - 10
Resident Engr.	**Contractor**
Class of Concrete PRESTRESS	**Date Assigned**
Mix Design No. 10PVO6167935E	**Contractor's Signature**
Note Mix Design Units (English or Metric) ENGLISH	

Mix Design Proportions Based on SSD Mass of Aggregates

Material	**Producer**	**Source**	**Qty. per Cu. Yard**
Cement	HOLCIM (US) INC.	HOLLY HILL, SC (TYPE I/II)	752 lbs.
Pozzolan			lbs.
Fine Aggregate	AMERICAN MATERIALS CO.	SUMTER COUNTY SAND PIT	1005 lbs.
Coarse Aggregate	MARTIN MARIETTA	CAYCE QUARRY - CAYCE, SC	1866 lbs.
Total Water		CITY	28.4 gals.
Air. Entr. Agent	SIKA CORPORATION	SIKA AEA-14	As recommended
Retarder	SIKA CORPORATION	PLASTIMENT	As recommended
Water Reducer			
Superplasticizer	SIKA CORPORATION	SIKA VISCOCRETE-6100	As recommended
Corrosion Inhibitor	SIKA CORPORATION	SIKA-CNI	As recommended

Mix Properties and Specifications

Slump	8.00 **in.**	**Mortar Content**	15.59 **cu. ft.**
Max Water	33.0 **gals.**	**Air Content**	5.0 **%**

Material	**Specific Gravity**	**% Absorption**	**Unit Mass**	**Fineness Modulus**
Fine Aggregate	2.62	0.5	NA	
Coarse Aggregate, #67	2.62	0.4		NA

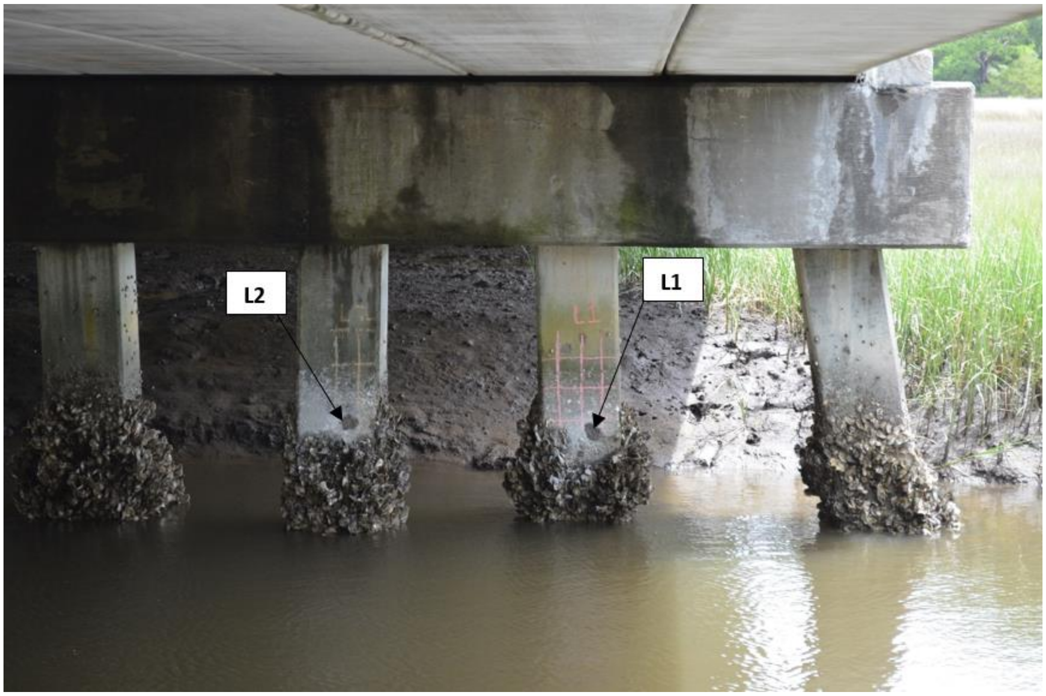
Comment Designed for 6000 psi at 28 days. Contains 3.5 gals. corrosion inhibitor. Max. w/c = 0.40.

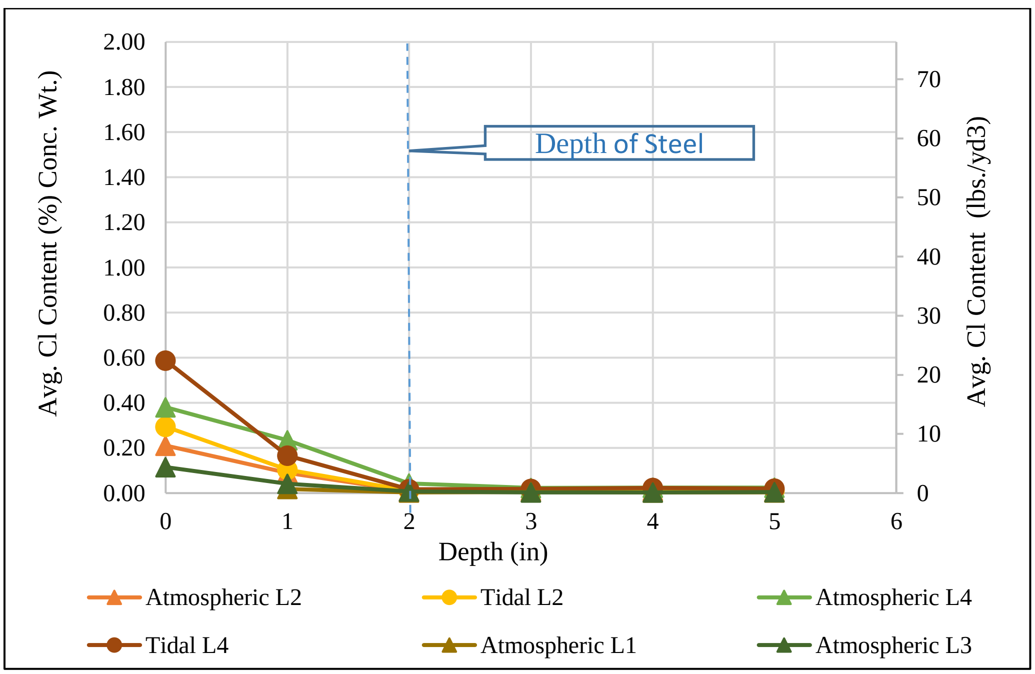
Cast-in-place concrete shall conform to Section 1000, precast concrete to Section 1077, and prestressed concrete to Section 1078 of the applicable edition of the Standard Specifications for Roads and Structures plus all applicable Special Provisions.

Structure 640010 Results Summary

RCT Test Results (Chloride Content Profile)

Structure #	Location	Zone	Chloride Content		
			Depth (in)	% Conc. Wt.	Chlorides (lbs/CY)
640010	L1	Atmospheric	0		
			1	0.018	0.69240
			2	0.004	0.13930
			3	0.004	0.15010
			4	0.004	0.14460
			5	0.003	0.13160
	L2	Atmospheric	0	0.211	8.0443
			1	0.089	3.4037
			2	0.008	0.3142
			3	0.010	0.3771
			4	0.010	0.3861
			5	0.008	0.3052
		Tidal	0	0.295	11.237
			1	0.104	3.957
			2	0.010	0.391
			3	0.011	0.408
			4	0.013	0.504
			5	0.012	0.468
	L3	Atmospheric	0	0.115	4.3951
			1	0.041	1.5741
			2	0.007	0.2814
			3	0.004	0.1416
			4	0.003	0.1251
			5	0.004	0.1573
	L4	Tidal	0	0.381	14.5323
			1	0.234	8.9158
			2	0.043	1.6317
			3	0.023	0.8800
			4	0.024	0.9211
			5	0.024	0.9322
		Atmospheric	0	0.588	22.424
			1	0.166	6.347
			2	0.017	0.648
			3	0.019	0.738
			4	0.023	0.860
			5	0.021	0.793


L2
L1

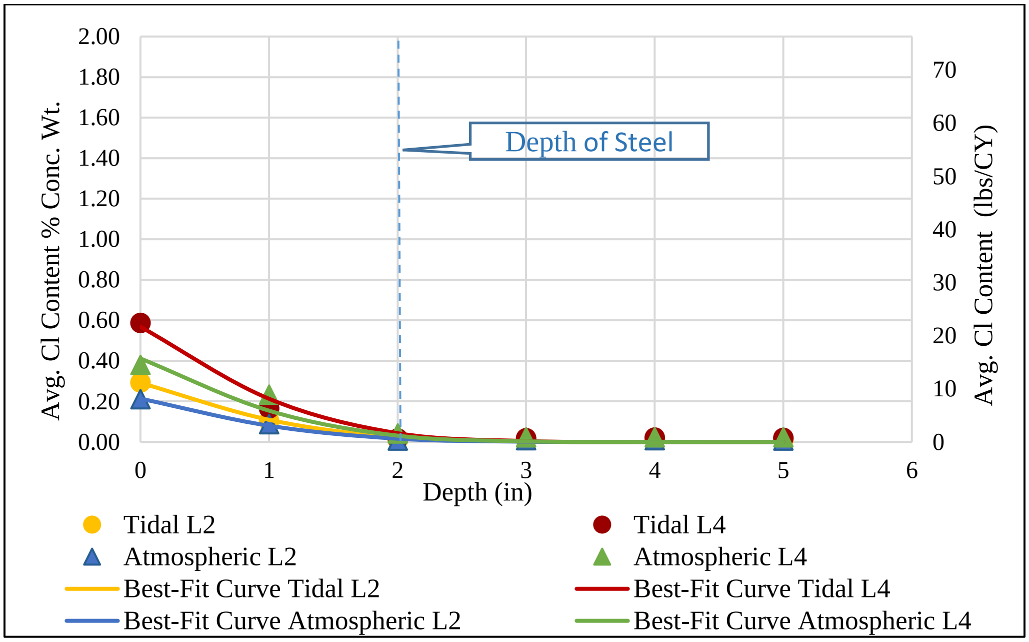

Avg. Cl Content (%) Conc. Wt.)
Avg. Cl Content (lbs./yd3)
Depth of Steel
Depth (in)
Atmospheric L2
Tidal L2
Atmospheric L4
Tidal L4
Atmospheric L1
Atmospheric L3

iCOR Test Results (Corrosion Rate & Surface Resistivity)

		Atmospheric Zone					Tidal Zone				
Structure #	**Location**	**Corrosion Rate**	**Avg. Corrosion Rate**	**Concrete Resist.**	**Avg. Concrete Resist.**	**R2**	**Corrosion Rate**	**Avg. Corrosion Rate**	**Concrete Resist.**	**Avg. Concrete Resist.**	**R2**
640010	L1	2.7	2.2725	159	242.38	1					
		2.5		161		1					
		3.8		162		0.99					
		1.6		182		1					
		3		62		0.96					
		1.8		364		0.96					
		0.88		352		1					
		1.9		497		0.99					
	L2	8.7	7.4333	72	90.889	1	17.7	26.493	71	60.5	0.95
		6		65		1	14.37		93		0.98
		4.3		13		1	21.18		61		0.97
		9.2		189		1	21.78		67		0.91
		7		50		1	39.22		32		0.97
		5.4		57		1	44.71		39		0.83
		1.7		160		0.99					
		17		88		1					
		7.6		124		1					
	L3	0.83	2.104	173	390.6	1					
		3.3		127		1					
		2.9		186		1					
		7		172		1					
		3		350		0.99					
		0.46		442		1					
		0.37		801		1					
		0.76		624		1					
		0.92		461		1					
		1.5		570		0.99					
	L4	19	31.4	172	128.44	1	23.43	29.538	74	52.444	0.97
		4.1		144		0.98	17.59		85		0.98
		6.5		130		1	30.69		43		0.93
		77		91		0.97	31.03		40		0.97
		14		136		1	39.8		33		0.86
		67		134		0.96	34.44		32		0.97
		36		107		0.99	33.27		34		0.96
		44		111		0.96	17.16		87		0.97
		15		131		0.97	38.43		44		0.94

Iterative Non-linear Least-Squares Regression

Highly Corrosive/Silica Fume											
Structure #	Location	Zone	Chloride Content			Age (t)	Iterative Non-linear Least-Squares Regression				
			Depth (in) (x)	% Conc. Wt.	Chlorides (lbs./yd^3) (Cl^-_x)		Diffusion Coefficient (in*in/yr) (D_c)	Surface Concentration (lbs./yd^3) (C_o)	Best-Fit Curve $C_{(x,t)}$	Residual Sum Squares (RSS)	Sum of RSS
640010	L2	Atmospheric	0	0.211	8.0443	14	0.045	8.153	8.153	0.012	20.818
			1	0.089	3.4037				3.057	0.120	
			2	0.008	0.3142				0.619	0.093	
			3	0.010	0.3771				0.063	0.098	
			4	0.010	0.3861				0.003	0.147	
			5	0.008	0.3052				0.000	0.093	
		Tidal	0	0.295	11.237	14	0.045	11.125	11.125	0.013	
			1	0.104	3.957				4.171	0.046	
			2	0.010	0.391				0.845	0.206	
			3	0.011	0.408				0.086	0.103	
			4	0.013	0.504				0.004	0.250	
			5	0.012	0.468				0.000	0.219	
	L4	Atmospheric	0	0.381	14.5323	14	0.045	15.707	15.707	1.379	
			1	0.234	8.9158				5.889	9.164	
			2	0.043	1.6317				1.193	0.192	
			3	0.023	0.8800				0.122	0.574	
			4	0.024	0.9211				0.006	0.837	
			5	0.024	0.9322				0.000	0.869	
		Tidal	0	0.588	22.424	14	0.045	21.684	21.684	0.547	
			1	0.166	6.347				8.130	3.178	
			2	0.017	0.648				1.647	0.998	
			3	0.019	0.738				0.168	0.324	
			4	0.023	0.860				0.008	0.725	
			5	0.021	0.793				0.000	0.629	

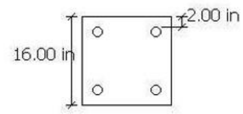

2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Avg. Cl Content % Conc. Wt.
70
60
50
40
30
20
10
0
Avg. Cl Content (lbs/CY)
Depth of Steel
0
1
2
3
4
5
6
Depth (in)
Tidal L2
Tidal L4
Atmospheric L2
Atmospheric L4
Best-Fit Curve Tidal L2
Best-Fit Curve Tidal L4
Best-Fit Curve Atmospheric L2
Best-Fit Curve Atmospheric L4

Corrosion Modeling Service Life Reports

Life-365 v2.2 - Concrete Mixes and Service Lives

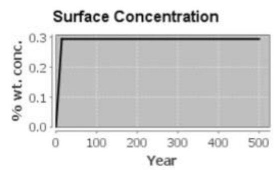
Project: 640010 L2 | Description: Prestressed Pile\Highly Corrosive Zone

Analyst: Taiseer Al Salihi | Date: 07/30/2021



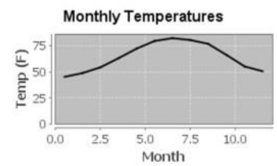
square column/beams (2-D)

Outer dim: 16in; clear cover: 2in



Max surface: 0.295 % wt. conc.

Years to buildup: 14



Loc: user-defined

Type: user-defined

Concrete Mixes

Alt name	User?	w/cm	SCMs	Inhib.	Barrier	Reinf.
Assumed Concret Properties		0.32	Silica Fume (5%);	Ca Nitrite - 3.5 gal/cub. yd.		Black Steel
Measured Concrete Properties	yes	n/a	n/a	n/a		Black Steel

"n/a" indicates that, since the user is specifying the diffusion properties of this mix, this value is not specified.

Diffusion Properties and Service Lives

Alt name	D28	m	Ct	Init.	Prop.	Service life
Assumed Concret Properties	3.47E-9 in*in/sec	0.2	0.28 % wt. conc.	500+ yrs	6 yrs	**506+ yrs**
Measured Concrete Properties	-> 2.49E-9 in*in/sec	-> 0.26	-> 0.28 % wt. conc.	500+ yrs	-> 6 yrs	**506+ yrs**

"->" indicates that the user has directly specified this value; "+" indicates the service life exceeds the study period.

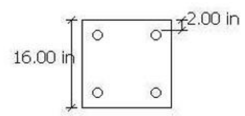
Life-365 v2.2 - Concrete Mixes and Service Lives

Project: 640010 L4

Description: Prestressed Pile\Highly Corrosive Zone

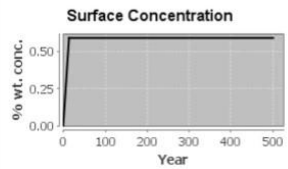
Analyst: Taiseer Al Salihi

Date: 07/30/2021



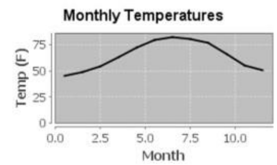
square column/beams (2-D)

Outer dim: 16in; clear cover: 2in



Max surface: 0.588 % wt. conc.

Years to buildup: 14



Loc: user-defined

Type: user-defined

Concrete Mixes

Alt name	User?	w/cm	SCMs	Inhib.	Barrier	Reinf.
Assumed Concret Properties		0.32	Silica Fume (5%);	Ca Nitrite - 3.5 gal/cub. yd.		Black Steel
Measured Concrete Properties	yes	n/a	n/a	n/a		Black Steel

"n/a" indicates that, since the user is specifying the diffusion properties of this mix, this value is not specified.

Diffusion Properties and Service Lives

Alt name	D28	m	Ct	Init.	Prop.	Service life
Assumed Concret Properties	3.47E-9 in*in/sec	0.2	0.28 % wt. conc.	56.5 yrs	6 yrs	**62.5 yrs**
Measured Concrete Properties	-> 2.49E-9 in*in/sec	-> 0.26	-> 0.28 % wt. conc.	104.7 yrs	-> 6 yrs	**110.7 yrs**

"->" indicates that the user has directly specified this value; "+" indicates the service life exceeds the study period.

Materials and Tests Unit Statement of Concrete Mix Design

Form 312U
3-96

North Carolina Department of Transportation, Division of Highways, Materials and Tests Unit
Statement of Concrete Mix Design and Source of Materials

Project	**Date Expires** 12/31/2075
Mix Design Status Active	**Concrete Producer** ARGOS USA LLC
County	**Plant Location & DOT No.** WILMINGTON, NC - 192
Resident Engr.	**Contractor**
Class of Concrete CLASS AA	**Date Assigned**
Mix Design No. 1922VF6034CE	**Contractor's Signature**
Note Mix Design Units (English or Metric) ENGLISH	

Mix Design Proportions Based on SSD Mass of Aggregates

Material	Producer	Source	Qty. per Cu. Yard
Cement	ARGOS USA	BARRANQUILLA PLANT - (FORMERLY CEMENT(	540 lbs.
Pozzolan	SOUTHEASTERN FLY ASH	SEFA - WINYAH GENERATING STATION/GEORG	135 lbs.
Fine Aggregate	CAPE FEAR PAVING, LLC	WILMINGTON MATERIALS - OAK RIDGE PIT #1	1160 lbs.
Coarse Aggregate	MARTIN MARIETTA	CASTLE HAYNE QUARRY - CASTLE HAYNE	1540 lbs.
Total Water		WELL	30.0 gals.
Air. Entr. Agent	BASF CONSTRUCTION CHEMICALS, LLC	MASTERAIR AE 90 (AKA MB AE 90)	As recommended
Retarder	BASF CONSTRUCTION CHEMICALS, LLC	POZZOLITH 122R	As recommended
Water Reducer			
Superplasticizer			
Corrosion Inhibitor	BASF CONSTRUCTION CHEMICALS, LLC	MASTERLIFE CI 30 (AKA RHEOCRETE CNI)	As recommended

Mix Properties and Specifications

Slump	3.50 **in.**	**Mortar Content**	16.84 **cu. ft.**
Max Water	32.3 **gals.**	**Air Content**	6.0 **%**

Material	Specific Gravity	% Absorption	Unit Mass	Fineness Modulus
Fine Aggregate	2.65	1.0	NA	2.40
Coarse Aggregate, #57	2.43	3.1	76.5	NA

Comment Mix contains 35 lbs. Elkim silica fume and 3 gals. CNI corrosion inhibitor. Use of 5 % silica fume and 1:1 cement:fly ash replacement rate are in accordance with a plan note for 8.1231503. Mix is for caps on bent #s 1 - 4. Cement imported by Port Royal.

Cast-in-place concrete shall conform to Section 1000, precast concrete to Section 1077, and prestressed concrete to Section 1078 of the applicable edition of the Standard Specifications for Roads and Structures plus all applicable Special Provisions.

Form 312U
3-96

North Carolina Department of Transportation, Division of Highways, Materials and Tests Unit
Statement of Concrete Mix Design and Source of Materials

Project	**Date Expires** 12/31/2075
Mix Design Status Active	**Concrete Producer** S & G PRESTRESS CONCRETE
County	**Plant Location & DOT No.** LELAND, NC - 2
Resident Engr.	**Contractor**
Class of Concrete PRESTRESS	**Date Assigned**
Mix Design No. 2PVU13CIMSE	**Contractor's Signature**
Note Mix Design Units (English or Metric) ENGLISH	

Mix Design Proportions Based on SSD Mass of Aggregates

Material	Producer	Source	Qty. per Cu. Yard
Cement	ARGOS USA	BARRANQUILLA PLANT - (FORMERLY CEMENT(	665 lbs.
Pozzolan	Degussa Rheomac SF 100 silica fume		35 lbs.
Fine Aggregate	MARTIN MARIETTA	ROCKY POINT QUARRY - ROCKY POINT	1244 lbs.
Coarse Aggregate	MARTIN MARIETTA	GARNER QUARRY - GARNER	1700 lbs.
Total Water		WELL	29.4 gals.
Air. Entr. Agent	BASF CONSTRUCTION CHEMICALS, LLC	MASTERAIR AE 90 (AKA MB AE 90)	As recommended
Retarder	BASF CONSTRUCTION CHEMICALS, LLC	POZZOLITH 122R	As recommended
Water Reducer			
Superplasticizer	BASF CONSTRUCTION CHEMICALS, LLC	MASTERGLENIUM 3030 (AKA GLENIUM 3030NS	As recommended
Corrosion Inhibitor	BASF CONSTRUCTION CHEMICALS, LLC	MASTERLIFE CI 30 (AKA RHEOCRETE CNI)	As recommended

Mix Properties and Specifications

Slump	7.00 **in.**	**Mortar Content**	16.60 **cu. ft.**
Max Water	31.0 **gals.**	**Air Content**	5.0 **%**

Material	Specific Gravity	% Absorption	Unit Mass	Fineness Modulus
Fine Aggregate	2.65	1.0	NA	2.40
Coarse Aggregate, #67	2.62	0.5	93.5	NA

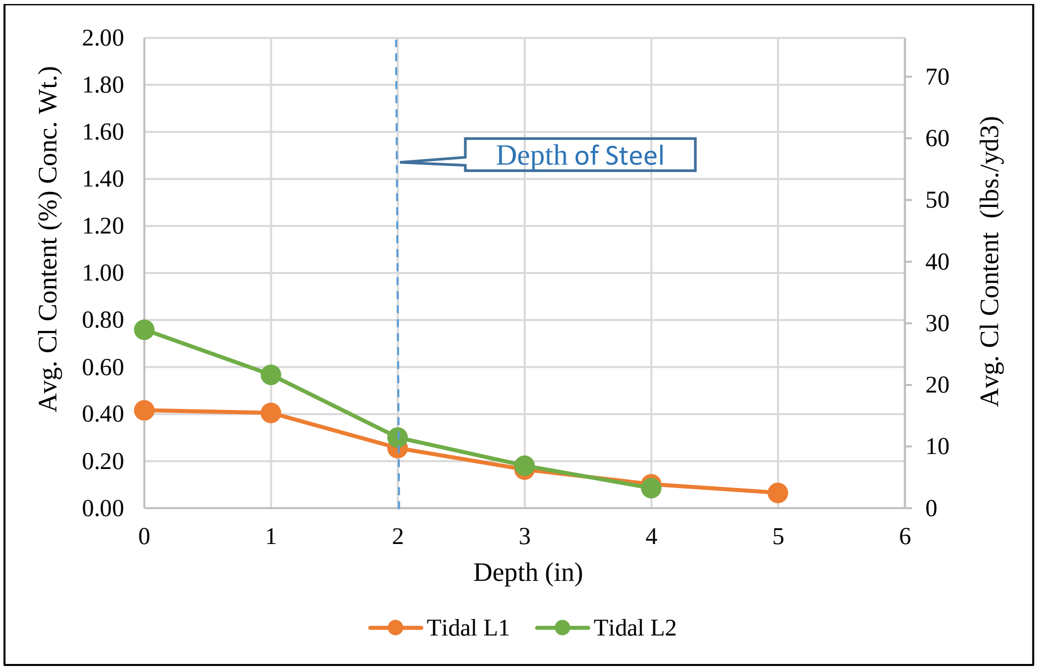
Comment Mix is designed for 6000 psi. Mix contains 3.0 gals. CNI and 35 lbs. Rheomac SF 100 silica fume. (Silica fume quantity is listed on Form 312 under "pozzolan.") Max. water-cement ratio is 0.4.

Cast-in-place concrete shall conform to Section 1000, precast concrete to Section 1077, and prestressed concrete to Section 1078 of the applicable edition of the Standard Specifications for Roads and Structures plus all applicable Special Provisions.

Structure 090061 Results Summary

RCT Test Results (Chloride Content Profile)

Structure #	Location	Zone	Chloride Content		
			Depth (in)	% Conc. Wt.	Chlorides (lbs/CY)
090061	L1	Tidal	0	0.417	15.894
			1	0.405	15.463
			2	0.256	9.762
			3	0.164	6.268
			4	0.102	3.908
			5	0.065	2.498
	L2	Tidal	0	0.759	28.972
			1	0.567	21.638
			2	0.300	11.451
			3	0.181	6.905
			4	0.085	3.249

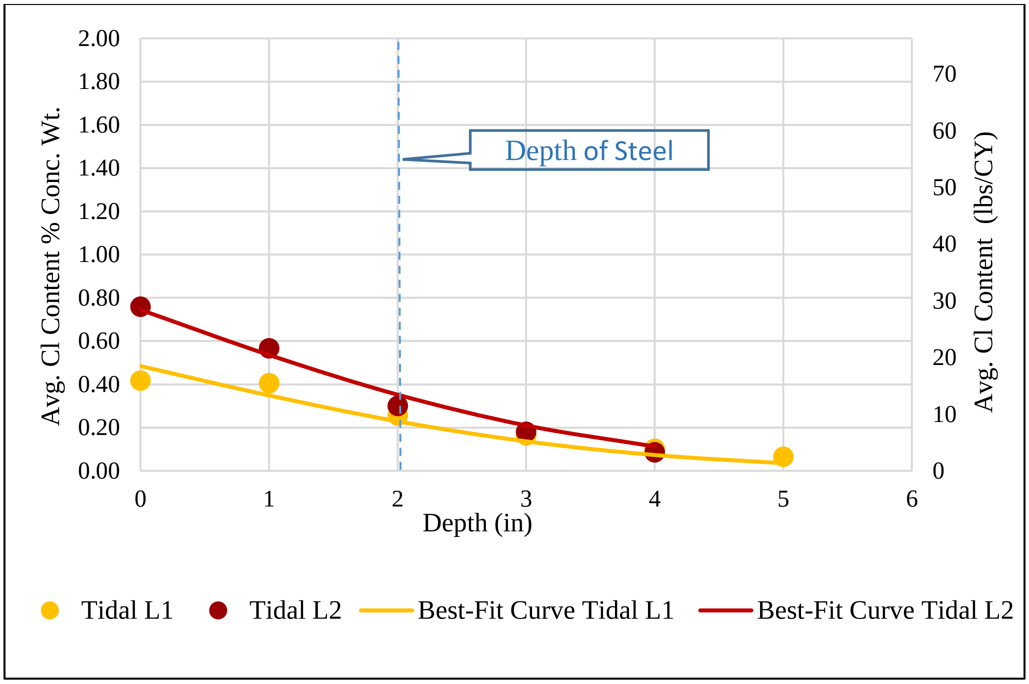

Avg. Cl Content (%) Conc. Wt.)
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Depth of Steel
70
60
50
40
30
20
10
0
Avg. Cl Content (lbs./yd3)
0
1
2
3
4
5
6
Depth (in)
Tidal L1
Tidal L2

iCOR Test Results (Corrosion Rate & Surface Resistivity)

		Tidal Zone				
Structure #	**Location**	**Corrosion Rate (Y)**	**Avg. Corrosion Rate**	**Concrete Resist. (Y)**	**Avg. Concrete Resist.**	**R2**
090061	L2	9	76	73	84	0.93
		9		144		0.98
		4		283		1
		88		30		0
		104		40		97
		1		176		0.96
		47		44		1
		13		59		0.99
		1		403		0.99
		37		11		0.98
		65		29		0.99
		61		73		0.99
		251		6.7		0.99
		209		14		0.98
		4.2		49		0.98
		203		6.8		0.99
		238		14		0.99
		16		49		1
	L3	5.1	63	70	58	0.96
		0.6		185		0.92
		3.6		128		1
		7.2		52		0.98
		16		51		1
		4.5		35		1
		61		58		0.93
		15		73		0.99
		7.4		103		1
		130		9.9		1
		139		40		1
		31		72		0.99
		274		7.2		0.99
		35		27		1
		112		31		1
		233		7.8		1
		53		41		0.99
		15		55		0.99

Iterative Non-linear Least-Squares Regression

Silica Fume							Iterative Non-linear Least-Squares Regression				
Structure #	Location	Zone	Chloride Content			Age (t)	Diffusion Coefficient (in*in/yr) (D_c)	Surface Concentration (lbs./yd^3) (C_o)	Best-Fit Curve $C_{(x,t)}$	Residual Sum Squares (RSS)	Sum of RSS
			Depth (in) (x)	% Conc. Wt.	Chlorides (lbs./yd^3) (Cl^-_x)						
090060	L1	Tidal	0	0.417	15.8939	15	0.259	18.484	18.484	6.709	24.084
			1	0.405	15.4630				13.302	4.671	
			2	0.256	9.7618				8.740	1.044	
			3	0.164	6.2677				5.204	1.131	
			4	0.102	3.9075				2.792	1.243	
			5	0.065	2.4984				1.344	1.333	
	L2	Tidal	0	0.759	28.972	15	0.259	28.419	28.419	0.305	
			1	0.567	21.638				20.452	1.407	
			2	0.300	11.451				13.438	3.946	
			3	0.181	6.905				8.002	1.204	
			4	0.085	3.249				4.293	1.091	



Corrosion Modeling Service Life Reports

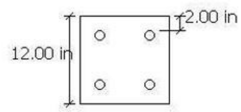
Life-365 v2.2 - Concrete Mixes and Service Lives

Project: 090061 L3

Description: Bent Cap\Highly Corrosive Zone

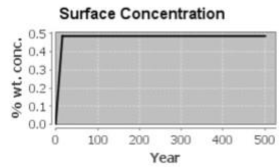
Analyst: Taiseer Al Salihi

Date: 07/30/2021



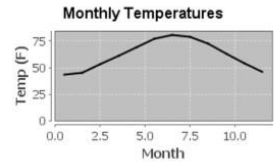
square column/beams (2-D)

Outer dim: 12in; clear cover: 2in



Max surface: 0.485 % wt. conc.

Years to buildup: 15



Loc: user-defined

Type: user-defined

Concrete Mixes

Alt name	User?	w/cm	SCMs	Inhib.	Barrier	Reinf.
Assumed Concrete Properties		0.35	Silica Fume (5%);	Ca Nitrite - 3 gal/cub. yd.		Black Steel
Measured Concrete Properties	yes	n/a	n/a	n/a		Black Steel

"n/a" indicates that, since the user is specifying the diffusion properties of this mix, this value is not specified.

Diffusion Properties and Service Lives

Alt name	D28	m	Ct	Init.	Prop.	Service life
Assumed Concrete Properties	4.09E-9 in*in/sec	0.2	0.24 % wt. conc.	54.6 yrs	6 yrs	**60.6 yrs**
Measured Concrete Properties	-> 1.45E-8 in*in/sec	-> 0.26	-> 0.24 % wt. conc.	25.3 yrs	-> 6 yrs	**31.3 yrs**

"->" indicates that the user has directly specified this value; "+" indicates the service life exceeds the study period.

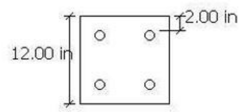
Life-365 v2.2 - Concrete Mixes and Service Lives

Project: 090061 L4

Description: Bent Cap\Highly Corrosive Zone

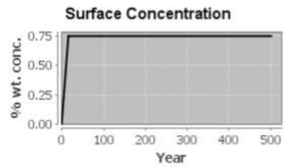
Analyst: Taiseer Al Salihi

Date: 07/30/2021



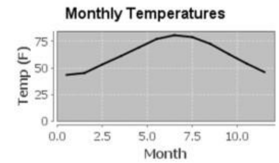
square column/beams (2-D)

Outer dim: 12in; clear cover: 2in



Max surface: 0.745 % wt. conc.

Years to buildup: 15



Loc: user-defined

Type: user-defined

Concrete Mixes

Alt name	User?	w/cm	SCMs	Inhib.	Barrier	Reinf.
Assumed Concret Properties		0.35	Silica Fume (5%);	Ca Nitrite - 3 gal/cub. yd.		Black Steel
Measured Concrete Properties	yes	n/a	n/a	n/a		Black Steel

"n/a" indicates that, since the user is specifying the diffusion properties of this mix, this value is not specified.

Diffusion Properties and Service Lives

Alt name	D28	m	Ct	Init.	Prop.	Service life
Assumed Concret Properties	4.09E-9 in*in/sec	0.2	0.24 % wt. conc.	35.7 yrs	6 yrs	**41.7 yrs**
Measured Concrete Properties	-> 1.45E-8 in*in/sec	-> 0.26	-> 0.24 % wt. conc.	17.9 yrs	-> 6 yrs	**23.9 yrs**

"->" indicates that the user has directly specified this value; "+" indicates the service life exceeds the study period.

Materials and Tests Unit Statement of Concrete Mix Design

Form 312U
3-96

North Carolina Department of Transportation, Division of Highways, Materials and Tests Unit
Statement of Concrete Mix Design and Source of Materials

Project	**Date Expires** 12/31/2075
Mix Design Status Active	**Concrete Producer** S & G PRESTRESS CONCRETE
County	**Plant Location & DOT No.** LELAND, NC - 2
Resident Engr.	**Contractor**
Class of Concrete PRESTRESS	**Date Assigned**
Mix Design No. 2PVU13CIMSE	**Contractor's Signature**
Note Mix Design Units (English or Metric) ENGLISH	

Mix Design Proportions Based on SSD Mass of Aggregates

Material	Producer	Source	Qty. per Cu. Yard
Cement	ARGOS USA	BARRANQUILLA PLANT - (FORMERLY CEMENT(	665 lbs.
Pozzolan	Degussa Rheomac SF 100 silica fume		35 lbs.
Fine Aggregate	MARTIN MARIETTA	ROCKY POINT QUARRY - ROCKY POINT	1244 lbs.
Coarse Aggregate	MARTIN MARIETTA	GARNER QUARRY - GARNER	1700 lbs.
Total Water		WELL	29.4 gals.
Air. Entr. Agent	BASF CONSTRUCTION CHEMICALS, LLC	MASTERAIR AE 90 (AKA MB AE 90)	As recommended
Retarder	BASF CONSTRUCTION CHEMICALS, LLC	POZZOLITH 122R	As recommended
Water Reducer			
Superplasticizer	BASF CONSTRUCTION CHEMICALS, LLC	MASTERGLENIUM 3030 (AKA GLENIUM 3030NS	As recommended
Corrosion Inhibitor	BASF CONSTRUCTION CHEMICALS, LLC	MASTERLIFE CI 30 (AKA RHEOCRETE CNI)	As recommended

Mix Properties and Specifications

Slump	7.00 in.	**Mortar Content**	16.60 cu. ft.
Max Water	31.0 gals.	**Air Content**	5.0 %

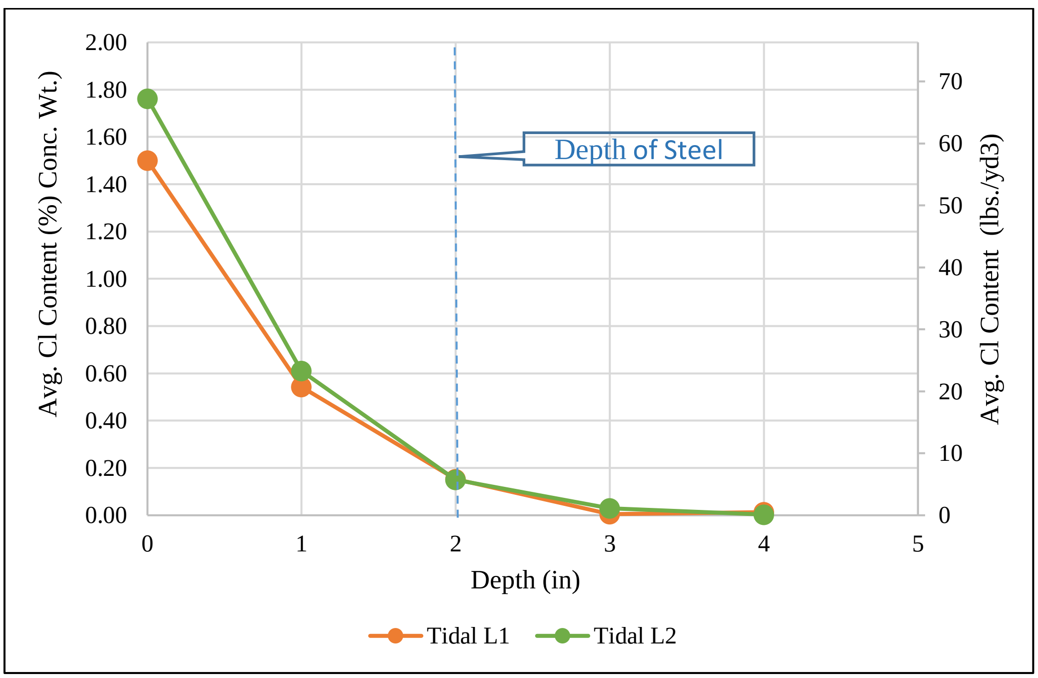
Material	Specific Gravity	% Absorption	Unit Mass	Fineness Modulus
Fine Aggregate	2.65	1.0	NA	2.40
Coarse Aggregate, #67	2.62	0.5	93.5	NA

Comment Mix is designed for 6000 psi. Mix contains 3.0 gals. CNI and 35 lbs. Rheomac SF 100 silica fume. (Silica fume quantity is listed on Form 312 under "pozzolan.") Max. water-cement ratio is 0.4.

Cast-in-place concrete shall conform to Section 1000, precast concrete to Section 1077, and prestressed concrete to Section 1078 of the applicable edition of the Standard Specifications for Roads and Structures plus all applicable Special Provisions.

RCT Test Results (Chloride Content Profile)

Structure #	Location	Zone	Chloride Content		
			Depth (in)	% Conc. Wt.	Chlorides (lbs/CY)
090206	L1	Tidal	0	1.500	57.241
			1	0.543	20.711
			2	0.153	5.844
			3	0.005	0.185
			4	0.013	0.508
	L2	Tidal	0	1.762	67.231
			1	0.611	23.305
			2	0.150	5.741
			3	0.030	1.143
			4	0.003	0.119

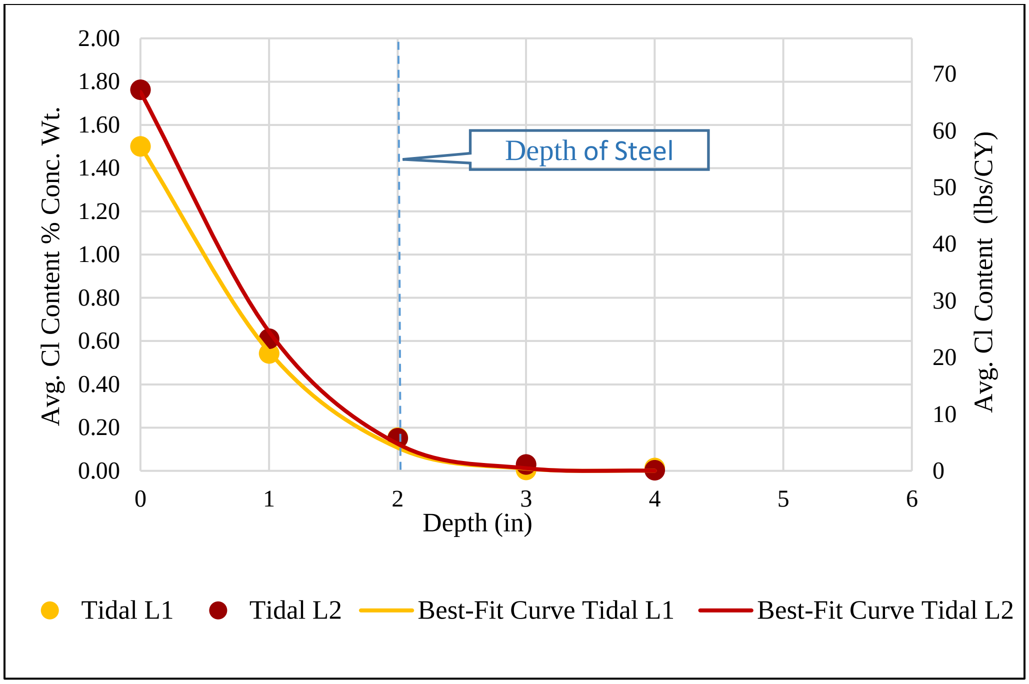


iCOR Test Results (Corrosion Rate & Surface Resistivity)

		Tidal Zone				
Structure #	**Location**	**Corrosion Rate (Y)**	**Avg. Corrosion Rate**	**Concrete Resist. (Y)**	**Avg. Concrete Resist.**	**R2**
090206	L1	48	83	42	35	0.98
		49		39		0.98
		90		38		0.92
		110		31		0.98
		120		25		0.98
	L2	79	103	43	30	0.98
		119		36		0.98
		93		33		0.92
		98		32		0.98
		89		24		0.98
		138		13		0.99

Iterative Non-linear Least-Squares Regression

Silica Fume/Fly Ash								Iterative Non-linear Least-Squares Regression				
Structure #	Location	Zone	Chloride Content			Age (t)	Diffusion Coefficient (in*in/yr) (D_c)	Surface Concentration (lbs./yd^3) (C_o)	Best-Fit Curve $C_{(x,t)}$	Residual Sum Squares (RSS)	Sum of RSS
			Depth (in) (x)	% Conc. Wt.	Chlorides (lbs./yd^3) (Cl^-_x)						
090206	**L1**	Tidal	0	1.500	57.2408	12	**0.051**	**57.248**	**57.248**	0.000	6.597
			1	0.543	20.7113				**21.031**	0.102	
			2	0.153	5.8441				**4.088**	3.084	
			3	0.005	0.1847				**0.392**	0.043	
			4	0.013	0.5079				**0.018**	0.240	
	L2	Tidal	0	1.762	67.231	12	**0.051**	**66.845**	**66.845**	0.149	
			1	0.611	23.305				**24.556**	1.565	
			2	0.150	5.741				**4.773**	0.935	
			3	0.030	1.143				**0.458**	0.470	
			4	0.003	0.119				**0.021**	0.010	


2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Avg. Cl Content % Conc. Wt.
70
60
50
40
30
20
10
0
Avg. Cl Content (lbs/CY)
Depth of Steel
0
1
2
3
4
5
6
Depth (in)
Tidal L1
Tidal L2
Best-Fit Curve Tidal L1
Best-Fit Curve Tidal L2

Corrosion Modeling Service Life Reports

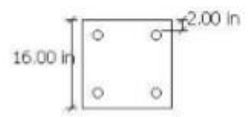
Life-365 v2.2 - Concrete Mixes and Service Lives

Project: 090206 L1

Description: Prestressed Pile\Highly Corrosive Zone

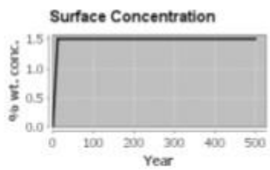
Analyst: Taiseer Al Salihi

Date: 02/16/2021



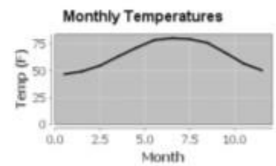
square column/beams (2-D)

Outer dim: 16in; clear cover: 2in



Max surface: 1.501 % wt. conc.

Years to buildup: 12



Loc: user-defined

Type: user-defined

Concrete Mixes

Alt name	User?	w/cm	SCMs	Inhib.	Barrier	Reinf.
Assumed Concret Properties		0.38	Silica Fume (5%);	Ca Nitrite - 3 gal/cub. yd.		Black Steel
Measured Concrete Properties	yes	n/a	n/a	n/a		Black Steel

"n/a" indicates that, since the user is specifying the diffusion properties of this mix, this value is not specified.

Diffusion Properties and Service Lives

Alt name	D28	m	Ct	Init.	Prop.	Service life
Assumed Concret Properties	4.83E-9 in*in/sec	0.2	0.24 % wt. conc.	18.5 yrs	6 yrs	**24.5 yrs**
Measured Concrete Properties	-> 7.65E-9 in*in/sec	-> 0.26	-> 0.24 % wt. conc.	16.2 yrs	-> 6 yrs	**22.2 yrs**

"->" indicates that the user has directly specified this value; "+" indicates the service life exceeds the study period.

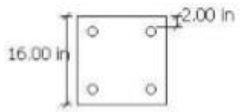
Life-365 v2.2 - Concrete Mixes and Service Lives

Project: 090206 L2

Description: Prestressed Pile\Highly Corrosive Zone

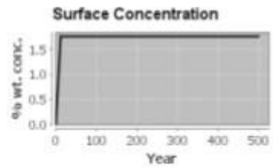
Analyst: Taiseer Al Salihi

Date: 02/16/2021



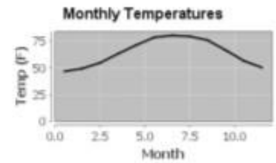
square column/beams (2-D)

Outer dim: 16in; clear cover: 2in



Max surface: 1.752 % wt. conc.

Years to buildup: 12



Loc: user-defined

Type: user-defined

Concrete Mixes

Alt name	User?	w/cm	SCMs	Inhib.	Barrier	Reinf.
Assumed Concret Properties		0.38	Silica Fume (5%);	Ca Nitrite - 3 gal/cub. yd.		Black Steel
Measured Concrete Properties	yes	n/a	n/a	n/a		Black Steel

"n/a" indicates that, since the user is specifying the diffusion properties of this mix, this value is not specified.

Diffusion Properties and Service Lives

Alt name	D28	m	Ct	Init.	Prop.	Service life
Assumed Concret Properties	4.83E-9 in*in/sec	0.2	0.24 % wt. conc.	17.2 yrs	6 yrs	**23.2 yrs**
Measured Concrete Properties	-> 7.65E-9 in*in/sec	-> 0.26	-> 0.24 % wt. conc.	15 yrs	-> 6 yrs	**21 yrs**

"->" indicates that the user has directly specified this value; "+" indicates the service life exceeds the study period.

Materials and Tests Unit Statement of Concrete Mix Design

Form 312U
3-96

North Carolina Department of Transportation, Division of Highways, Materials and Tests Unit
Statement of Concrete Mix Design and Source of Materials

Project	**Date Expires** 12/31/2075
Mix Design Status Active	**Concrete Producer** S & G PRESTRESS CONCRETE
County	**Plant Location & DOT No.** LELAND, NC - 2
Resident Engr.	**Contractor**
Class of Concrete PRESTRESS	**Date Assigned**
Mix Design No. 2PVU13CIMSE	**Contractor's Signature**
Note Mix Design Units (English or Metric) ENGLISH	

Mix Design Proportions Based on SSD Mass of Aggregates

Material	Producer	Source	Qty. per Cu. Yard
Cement	ARGOS USA	BARRANQUILLA PLANT - (FORMERLY CEMENTC	665 **lbs.**
Pozzolan	Degussa Rheomac SF 100 silica fume		35 **lbs.**
Fine Aggregate	MARTIN MARIETTA	ROCKY POINT QUARRY - ROCKY POINT	1244 **lbs.**
Coarse Aggregate	MARTIN MARIETTA	GARNER QUARRY - GARNER	1700 **lbs.**
Total Water		WELL	29.4 **gals.**
Air. Entr. Agent	BASF CONSTRUCTION CHEMICALS, LLC	MASTERAIR AE 90 (AKA MB AE 90)	**As recommended**
Retarder	BASF CONSTRUCTION CHEMICALS, LLC	POZZOLITH 122R	**As recommended**
Water Reducer			
Superplasticizer	BASF CONSTRUCTION CHEMICALS, LLC	MASTERGLENIUM 3030 (AKA GLENIUM 3030NS)	**As recommended**
Corrosion Inhibitor	BASF CONSTRUCTION CHEMICALS, LLC	MASTERLIFE CI 30 (AKA RHEOCRETE CNI)	**As recommended**

Mix Properties and Specifications

Slump	7.00 **in.**	**Mortar Content**	16.60 **cu. ft.**
Max Water	31.0 **gals.**	**Air Content**	5.0 **%**

Material	Specific Gravity	% Absorption	Unit Mass	Fineness Modulus
Fine Aggregate	2.65	1.0	**NA**	2.40
Coarse Aggregate, #67	2.62	0.5	93.5	**NA**

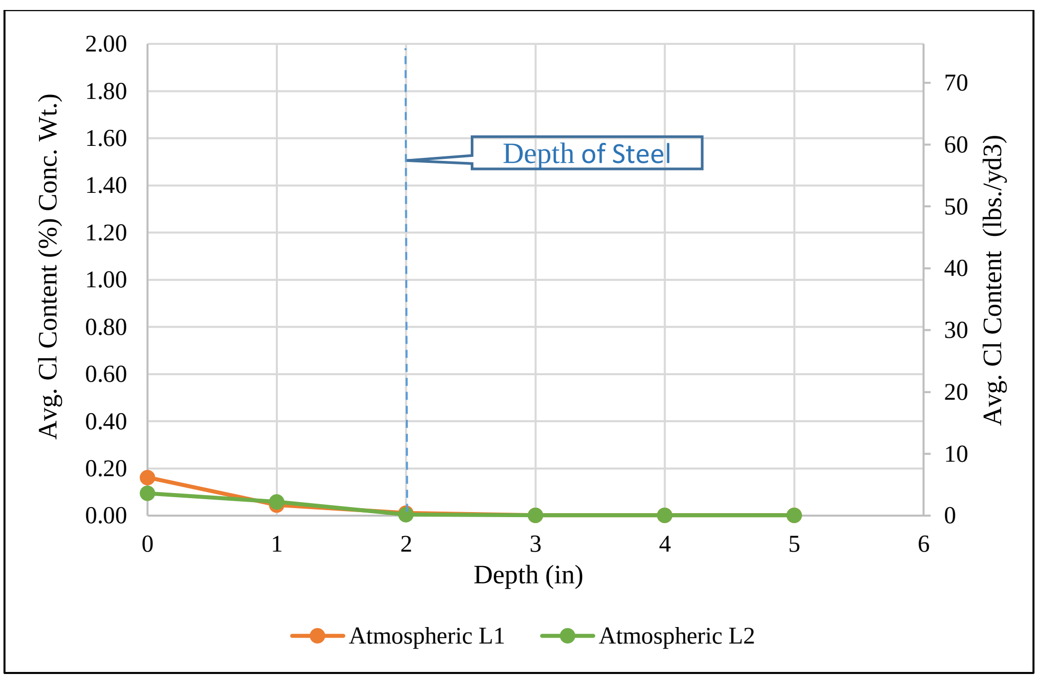
Comment Mix is designed for 6000 psi. Mix contains 3.0 gals. CNI and 35 lbs. Rheomac SF 100 silica fume. (Silica fume quantity is listed on Form 312 under "pozzolan.") Max. water-cement ratio is 0.4.

Cast-in-place concrete shall conform to Section 1000, precast concrete to Section 1077, and prestressed concrete to Section 1078 of the applicable edition of the Standard Specifications for Roads and Structures plus all applicable Special Provisions.

Structure 260007 Results Summary

RCT Test Results (Chloride Content Profile)

Structure #	Location	Zone	Chloride Content		
			Depth (in)	% Conc. Wt.	Chlorides (lbs/CY)
260007	L1	Atmospheric	0	0.162	6.189
			1	0.045	1.726
			2	0.010	0.400
			3	0.002	0.077
			4	0.002	0.072
			5	0.002	0.069
	L2	Atmospheric	0	0.095	3.608
			1	0.059	2.250
			2	0.004	0.163
			3	0.002	0.064
			4	0.002	0.076
			5	0.002	0.065

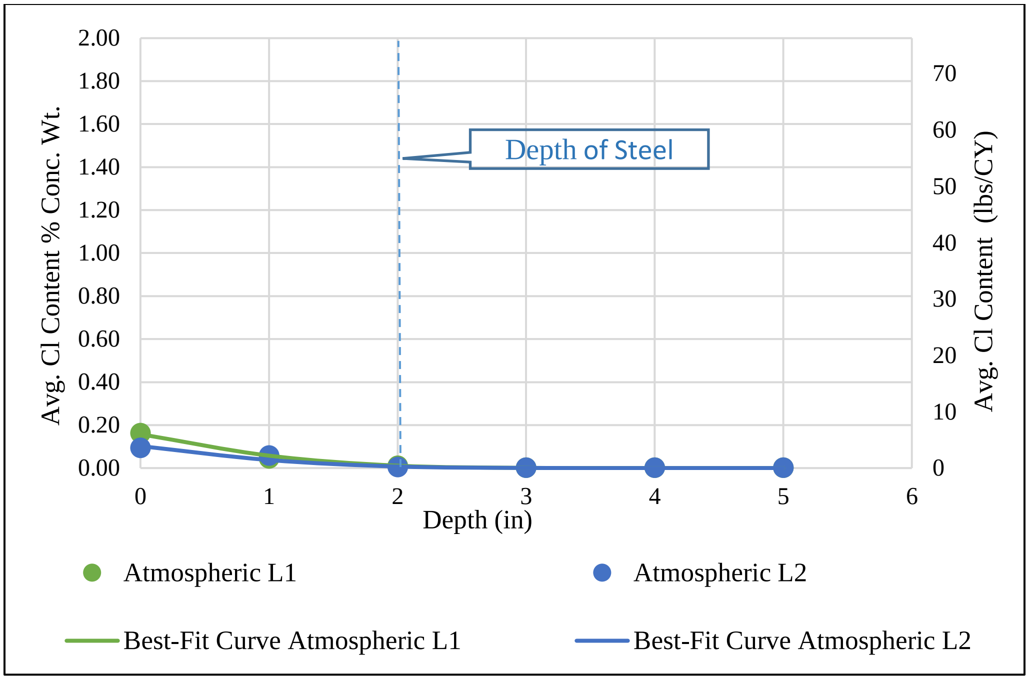


iCOR Test Results (Corrosion Rate & Surface Resistivity)

		Atmospheric Zone				
Structure #	**Location**	**Corrosion Rate (Y)**	**Avg. Corrosion Rate**	**Concrete Resist. (Y)**	**Avg. Concrete Resist.**	**R2**
260007	L1 & L2	19.0	22	125	149	0.99
		17.0		76		0.99
		9.2		88		1
		31.0		112		0.99
		40.0		95		0.98
		52.0		108		0.99
		46.0		67		0.99
		0.7		315		0.97
		18.0		170		0.95
		22.0		170		0.97
		4.6		210		0.98
		7.0		254		1

Iterative Non-linear Least-Squares Regression

Slag / Highly Corrosive	Structure #	Location	Zone	Chloride Content			Age (t)	Iterative Non-linear Least-Squares Regression				
				Depth (in) (x)	% Conc. Wt.	Chlorides (lbs./yd^3) (Cl^-_x)		Diffusion Coefficient (in*in/yr) (D_c)	Surface Concentration (lbs./yd^3) (C_o)	Best-Fit Curve $C_{(x,t)}$	Residual Sum Squares (RSS)	Sum of RSS
	260007	**L1**	**Atmospheric**	0	0.162	6.1892	13	**0.047**	**6.012**	**6.012**	0.032	1.053
				1	0.045	1.7263				**2.206**	0.230	
				2	0.010	0.4005				**0.428**	0.001	
				3	0.002	0.0767				**0.041**	0.001	
				4	0.002	0.0723				**0.002**	0.005	
				5	0.002	0.0686				**0.000**	0.005	
		L2	**Atmospheric**	0	0.095	3.6077	13	**0.047**	**3.900**	**3.900**	0.086	
				1	0.059	2.2495				**1.431**	0.670	
				2	0.004	0.1631				**0.277**	0.013	
				3	0.002	0.0637				**0.026**	0.001	
				4	0.002	0.0760				**0.001**	0.006	
				5	0.002	0.0654				**0.000**	0.004	



2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Avg. Cl Content % Conc. Wt.
70
60
50
40
30
20
10
0
Avg. Cl Content (lbs/CY)
Depth of Steel
0
1
2
3
4
5
6
Depth (in)
Atmospheric L1
Atmospheric L2
Best-Fit Curve Atmospheric L1
Best-Fit Curve Atmospheric L2

Corrosion Modeling Service Life Reports

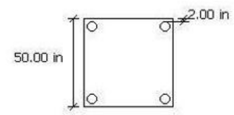
Life-365 v2.2 - Concrete Mixes and Service Lives

Project: 260007 L1

Description: Bent Cap\Highly Corrosive Zone

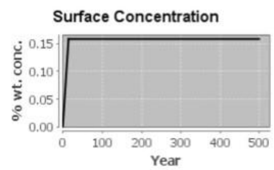
Analyst: Taiseer Al Salihi

Date: 07/30/2021



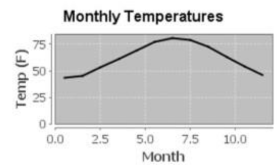
square column/beams (2-D)

Outer dim: 50in; clear cover: 2in



Max surface: 0.158 % wt. conc.

Years to buildup: 13



Loc: user-defined

Type: user-defined

Concrete Mixes

Alt name	User?	w/cm	SCMs	Inhib.	Barrier	Reinf.
Assumed Concret Properties		0.35	Slag (0.4%);	Ca Nitrite - 3 gal/cub. yd.		Black Steel
Measured Concrete Properties	yes	n/a	n/a	n/a		Black Steel

"n/a" indicates that, since the user is specifying the diffusion properties of this mix, this value is not specified.

Diffusion Properties and Service Lives

Alt name	D28	m	Ct	Init.	Prop.	Service life
Assumed Concret Properties	9.34E-9 in*in/sec	0.2	0.24 % wt. conc.	500+ yrs	6 yrs	**506+ yrs**
Measured Concrete Properties	-> 1.47E-8 in*in/sec	-> 0.45	-> 0.24 % wt. conc.	500+ yrs	-> 6 yrs	**506+ yrs**

"->" indicates that the user has directly specified this value; "+" indicates the service life exceeds the study period.

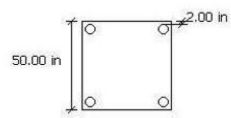
Life-365 v2.2 - Concrete Mixes and Service Lives

Project: 260007 L2

Description: Bent Cap\Highly Corrosive Zone

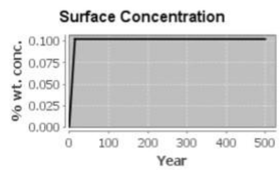
Analyst: Taiseer Al Salihi

Date: 07/30/2021



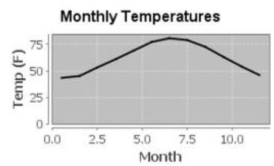
square column/beams (2-D)

Outer dim: 50in; clear cover: 2in



Max surface: 0.102 % wt. conc.

Years to buildup: 13



Loc: user-defined

Type: user-defined

Concrete Mixes

Alt name	User?	w/cm	SCMs	Inhib.	Barrier	Reinf.
Assumed Concret Properties		0.35	Slag (0.4%);	Ca Nitrite - 3 gal/cub. yd.		Black Steel
Measured Concrete Properties	yes	n/a	n/a	n/a		Black Steel

"n/a" indicates that, since the user is specifying the diffusion properties of this mix, this value is not specified.

Diffusion Properties and Service Lives

Alt name	D28	m	Ct	Init.	Prop.	Service life
Assumed Concret Properties	9.34E-9 in*in/sec	0.2	0.24 % wt. conc.	500+ yrs	6 yrs	**506+ yrs**
Measured Concrete Properties	-> 1.47E-8 in*in/sec	-> 0.45	-> 0.24 % wt. conc.	500+ yrs	-> 6 yrs	**506+ yrs**

"->" indicates that the user has directly specified this value; "+" indicates the service life exceeds the study period.

Materials and Tests Unit Statement of Concrete Mix Design

Form 312U
3-96

North Carolina Department of Transportation, Division of Highways, Materials and Tests Unit
Statement of Concrete Mix Design and Source of Materials

Project	**Date Expires** 12/31/2075
Mix Design Status Active	**Concrete Producer** COMMERCIAL READY MIX PRODUCTS
County	**Plant Location & DOT No.** MOYOCK, NC - 299
Resident Engr.	**Contractor**
Class of Concrete CLASS AA	**Date Assigned**
Mix Design No. 2992VGAACNI1E	**Contractor's Signature**
Note Mix Design Units (English or Metric) ENGLISH	

Mix Design Proportions Based on SSD Mass of Aggregates

Material	Producer	Source	Qty. per Cu. Yard
Cement	ROANOKE CEMENT COMPANY	TROUTVILLE, VA (TYPE I/II)	480 lbs.
Pozzolan	LAFARGE	LAFARGE - SLAG	205 lbs.
Fine Aggregate	VULCAN MATERIALS CO.	CURLES NECK Q -- HENRICO CO. VA.	1161 lbs.
Coarse Aggregate	VULCAN MATERIALS CO.	LAWRENCEVILLE Q. - FREEMAN, VA	1756 lbs.
Total Water		WELL	30.0 gals.
Air. Entr. Agent	SIKA CORPORATION	SIKA AEA-15	As recommended
Retarder	SIKA CORPORATION	PLASTIMENT	As recommended
Water Reducer	SIKA CORPORATION	*SIKEMENT NL	As recommended
Superplasticizer			
Corrosion Inhibitor	SIKA CORPORATION	SIKA-CNI	As recommended

Mix Properties and Specifications

Slump	3.50 in.	**Mortar Content**	16.54 cu. ft.
Max Water	35.0 gals.	**Air Content**	6.0 %

Material	Specific Gravity	% Absorption	Unit Mass	Fineness Modulus
Fine Aggregate	2.65	0.5	NA	2.79
Coarse Aggregate, #67	2.69	0.9	97.2	NA

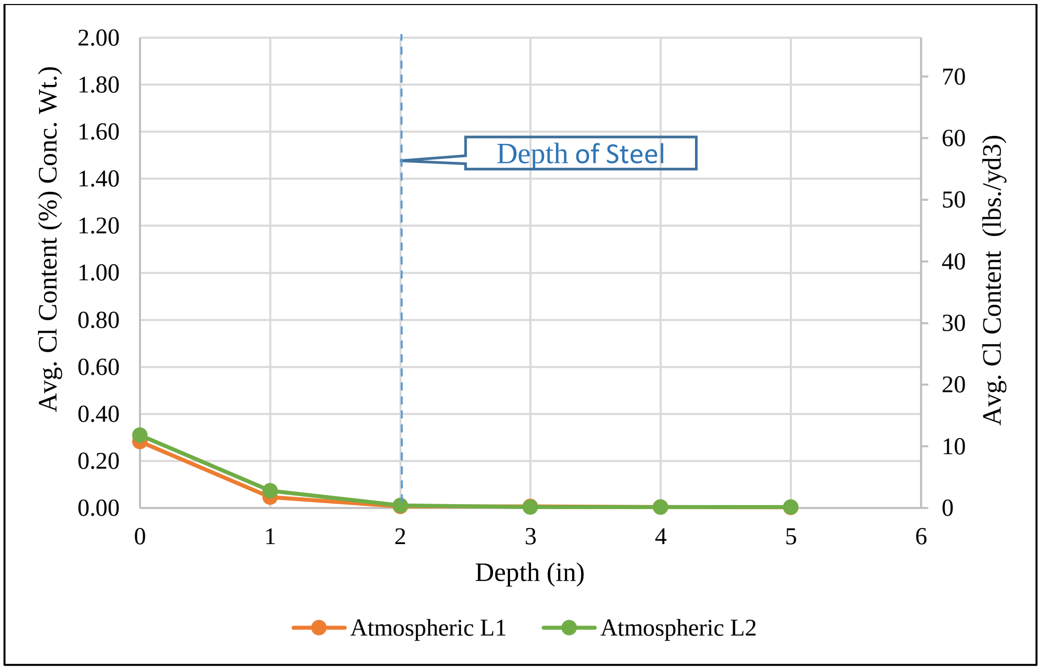
Comment Mix contains 3.0 gals. Sika CNI corrosion inhibitor.

Cast-in-place concrete shall conform to Section 1000, precast concrete to Section 1077, and prestressed concrete to Section 1078 of the applicable edition of the Standard Specifications for Roads and Structures plus all applicable Special Provisions.

Structure 150020 Results Summary

RCT Test Results (Chloride Content Profile)

Structure #	Location	Zone	Chloride Content		
			Depth (in)	% Conc. Wt.	Chlorides (lbs/CY)
150020	L1	Atmospheric	0	0.282	10.775
			1	0.046	1.767
			2	0.007	0.277
			3	0.006	0.237
			4	0.004	0.138
			5	0.003	0.119
	L2	Atmospheric	0	0.310	11.817
			1	0.073	2.781
			2	0.010	0.393
			3	0.004	0.165
			4	0.004	0.169
			5	0.004	0.150

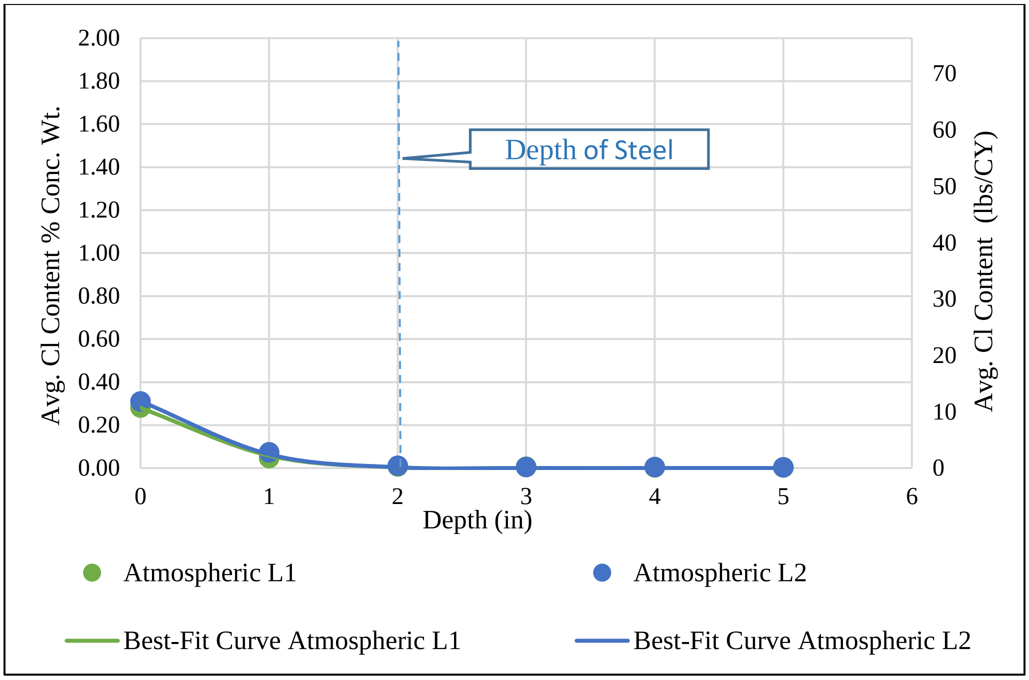


iCOR Test Results (Corrosion Rate & Surface Resistivity)

		Atmospheric Zone				
Structure #	**Location**	**Corrosion Rate (Y)**	**Avg. Corrosion Rate**	**Concrete Resist. (Y)**	**Avg. Concrete Resist.**	**R2**
150020	L1	0.45	4	477	267	0.94
		1.40		367		0.98
		1.40		332		0.87
		11.00		183		0.79
		6.40		108		0.89
		2.10		136		0.7
	L2	0.62	5	851	736	1
		4.00		681		0.94
		0.46		786		0.97
		11.00		498		0.97
		9.20		866		0.97
		9.40		739		0.93
		6.90		470		0.96
		3.50		549		1
		2.30		666		0.98
		1.40		407		0.9
		4.70		453		0.99
		2.10		565		0.91

Model 2: Iterative Non-linear Least-Squares Regression

	Structure #	Location	Zone	Chloride Content			Age (t)	Iterative Non-linear Least-Squares Regression				
				Depth (in) (x)	% Conc. Wt.	Chlorides (lbs./yd^3) (Cl^-_x)		Diffusion Coefficient (in*in/yr) (D_c)	Surface Concentration (lbs./yd^3) (C_o)	Best-Fit Curve $C_{(x,t)}$	Residual Sum Squares (RSS)	Sum of RSS
Fly Ash/ Corrosive	**150020**	**L1**	**Atmospheric**	0	0.282	10.775	12	**0.026**	**10.686**	**10.686**	0.008	0.568
				1	0.046	1.767				**2.209**	0.195	
				2	0.007	0.277				**0.124**	0.024	
				3	0.006	0.237				**0.002**	0.056	
				4	0.004	0.138				**0.000**	0.019	
				5	0.003	0.119				**0.000**	0.014	
		L2	**Atmospheric**	0	0.310	11.817	12	**0.026**	**11.887**	**11.887**	0.005	
				1	0.073	2.781				**2.457**	0.105	
				2	0.010	0.393				**0.137**	0.065	
				3	0.004	0.165				**0.002**	0.027	
				4	0.004	0.169				**0.000**	0.028	
				5	0.004	0.150				**0.000**	0.023	



Avg. Cl Content % Conc. Wt.
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Depth of Steel
70
60
50
40
30
20
10
0
Avg. Cl Content (lbs/CY)
0
1
2
3
4
5
6
Depth (in)
Atmospheric L1
Atmospheric L2
Best-Fit Curve Atmospheric L1
Best-Fit Curve Atmospheric L2

Corrosion Modeling Service Life Reports

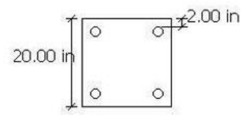
Life-365 v2.2 - Concrete Mixes and Service Lives

Project: 150020 L1

Description: Presressed Pile\ Corrosive Zone

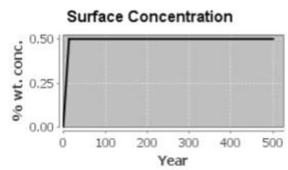
Analyst: Taiseer Al Salihi

Date: 07/30/2021



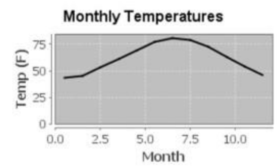
square column/beams (2-D)

Outer dim: 20in; clear cover: 2in



Max surface: 0.500 % wt. conc.

Years to buildup: 12



Loc: user-defined

Type: user-defined

Concrete Mixes

Alt name	User?	w/cm	SCMs	Inhib.	Barrier	Reinf.
Assumed Concret Properties		0.36	Class F Fly Ash (30%);	Ca Nitrite - 3 gal/cub. yd.		Black Steel
Measured Concrete Properties	yes	n/a	n/a	n/a		Black Steel

"n/a" indicates that, since the user is specifying the diffusion properties of this mix, this value is not specified.

Diffusion Properties and Service Lives

Alt name	D28	m	Ct	Init.	Prop.	Service life
Assumed Concret Properties	9.87E-9 in*in/sec	0.44	0.24 % wt. conc.	75.9 yrs	6 yrs	**81.9 yrs**
Measured Concrete Properties	-> 7.65E-9 in*in/sec	-> 0.44	-> 0.24 % wt. conc.	97.8 yrs	-> 6 yrs	**103.8 yrs**

"->" indicates that the user has directly specified this value; "+" indicates the service life exceeds the study period.

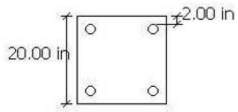
Life-365 v2.2 - Concrete Mixes and Service Lives

Project: 150020 L2

Description: Presressed Pile /Corrosive Zone

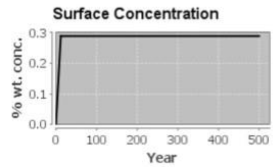
Analyst: Taiseer Al Salihi

Date: 07/30/2021



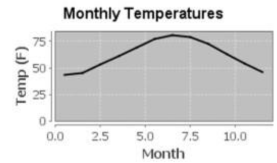
square column/beams (2-D)

Outer dim: 20in; clear cover: 2in



Max surface: 0.288 % wt. conc.

Years to buildup: 12



Loc: user-defined

Type: user-defined

Concrete Mixes

Alt name	User?	w/cm	SCMs	Inhib.	Barrier	Reinf.
Assumed Concret Properties		0.36	Class F Fly Ash (30%);	Ca Nitrite - 3 gal/cub. yd.		Black Steel
Measured Concrete Properties	yes	n/a	n/a	n/a		Black Steel

"n/a" indicates that, since the user is specifying the diffusion properties of this mix, this value is not specified.

Diffusion Properties and Service Lives

Alt name	D28	m	Ct	Init.	Prop.	Service life
Assumed Concret Properties	9.87E-9 in*in/sec	0.44	0.24 % wt. conc.	312.6 yrs	6 yrs	**318.6 yrs**
Measured Concrete Properties	-> 7.65E-9 in*in/sec	-> 0.44	-> 0.24 % wt. conc.	403 yrs	-> 6 yrs	**409 yrs**

"->" indicates that the user has directly specified this value; "+" indicates the service life exceeds the study period.

Materials and Tests Unit Statement of Concrete Mix Design

Form 312U
3-96

North Carolina Department of Transportation, Division of Highways, Materials and Tests Unit
Statement of Concrete Mix Design and Source of Materials

Project	**Date Expires** 12/31/2075
Mix Design Status Active	**Concrete Producer** ATLANTIC METROCAST, INC.
County	**Plant Location & DOT No.** PORTSMOUTH, VA - 7
Resident Engr.	**Contractor**
Class of Concrete PRESTRESS	**Date Assigned**
Mix Design No. 7PVF8106E	**Contractor's Signature**
Note Mix Design Units (English or Metric) ENGLISH	

Mix Design Proportions Based on SSD Mass of Aggregates

Material	Producer	Source	Qty. per Cu. Yard
Cement	LEHIGH	UNION BRIDGE, MD	638 lbs.
Pozzolan	BORAL MATERIAL TECHNOLOGIES	BORAL - CHESAPEAKE	212 lbs.
Fine Aggregate	Heard, Waverly, VA		1078 lbs.
Coarse Aggregate	VULCAN MATERIALS CO.	SKIPPERS Q. - SKIPPERS, VA	1598 lbs.
Total Water		WELL	36.0 gals.
Air. Entr. Agent	SIKA CORPORATION	SIKA AEA-14	As recommended
Retarder	SIKA CORPORATION	PLASTIMENT	As recommended
Water Reducer			
Superplasticizer	SIKA CORPORATION	SIKA VISCOCRETE-4100	As recommended
Corrosion Inhibitor			

Mix Properties and Specifications

Slump	9.00 **in.**	**Mortar Content**	17.37 **cu. ft.**
Max Water	45.9 **gals.**	**Air Content**	5.0 **%**

Material	Specific Gravity	% Absorption	Unit Mass	Fineness Modulus
Fine Aggregate	2.61	0.5	NA	2.94
Coarse Aggregate, #68 (VA Spec)	2.66	0.5	97.0	NA

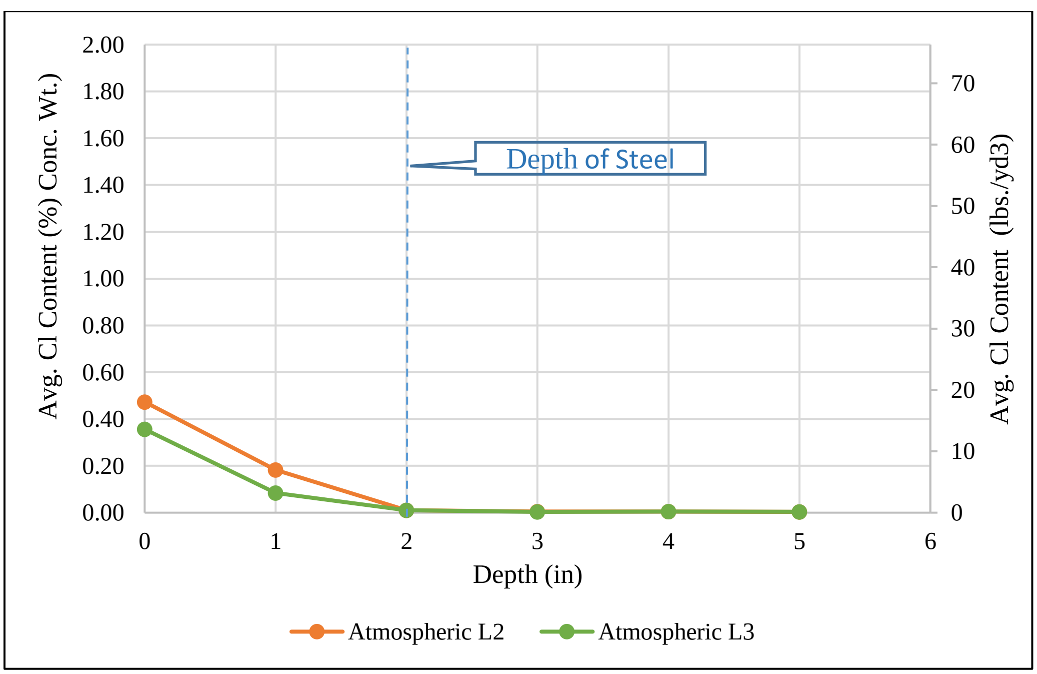
Comment Designed for 5500 psi. Cement is Type III.

Cast-in-place concrete shall conform to Section 1000, precast concrete to Section 1077, and prestressed concrete to Section 1078 of the applicable edition of the Standard Specifications for Roads and Structures plus all applicable Special Provisions.

Structure 150026 Results Summary

RCT Test Results (Chloride Content Profile)

Structure #	Location	Zone	Chloride Content		
			Depth (in)	% Conc. Wt.	Chlorides (lbs/CY)
150026	L2	Atmospheric	0	0.473	18.062
			1	0.183	6.976
			2	0.010	0.390
			3	0.005	0.181
			4	0.004	0.165
			5	0.004	0.142
	L3	Atmospheric	0	0.357	13.603
			1	0.085	3.241
			2	0.011	0.401
			3	0.004	0.153
			4	0.004	0.168
			5	0.004	0.151

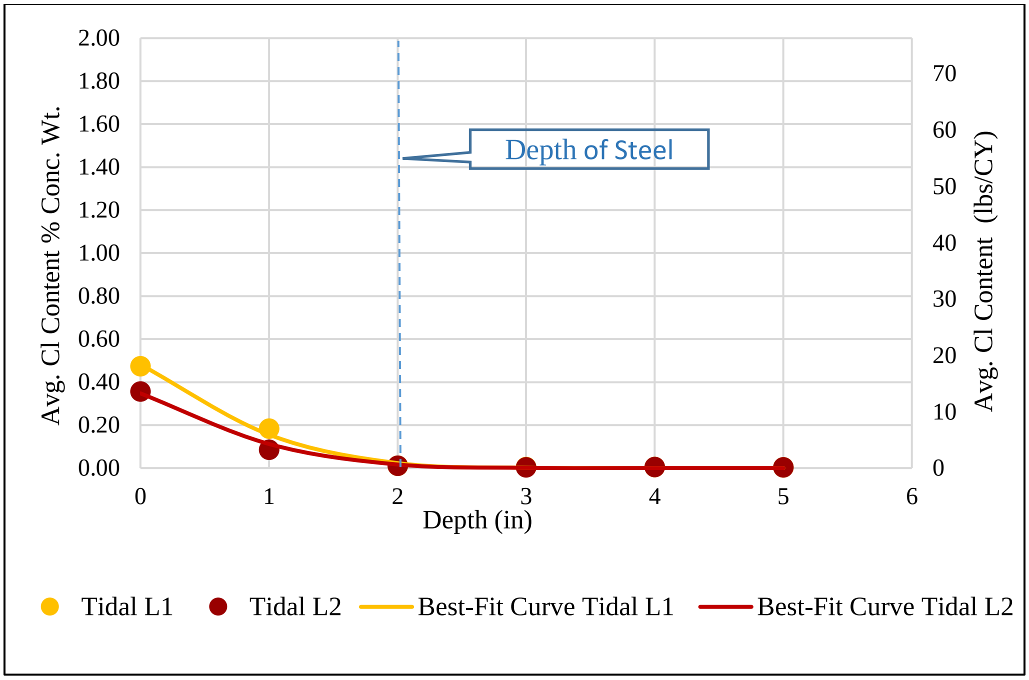


iCOR Test Results (Corrosion Rate & Surface Resistivity)

		Atmospheric Zone				
Structure #	**Location**	**Corrosion Rate (Y)**	**Avg. Corrosion Rate**	**Concrete Resist. (Y)**	**Avg. Concrete Resist.**	**R2**
150026	L2 & L3	1.2	6	745	433	0.99
		1.4		402		0.99
		1.0		400		0.99
		0.6		555		0.99
		0.6		775		1
		5.3		397		0.99
		2.6		379		0.99
		0.1		469		1
		2.5		309		1
		21.0		246		0.96
		28.0		199		0.94
		4.1		316		0.96

Iterative Non-linear Least-Squares Regression

Fly Ash / Highly Corrosive												
Structure #	Location	Zone	Chloride Content			Age (t)	Iterative Non-linear Least-Squares Regression				
			Depth (in) (x)	% Conc. Wt.	Chlorides (lbs./yd^3) (Cl^-_x)		Diffusion Coefficient (in*in/yr) (D_c)	Surface Concentration (lbs./yd^3) (C_o)	Best-Fit Curve $C_{(x,t)}$	Residual Sum Squares (RSS)	Sum of RSS
150026	L2	Tidal	0	0.473	18.0619	14	0.037	18.375	18.375	0.098	2.227
			1	0.183	6.9761				5.933	1.087	
			2	0.010	0.3903				0.883	0.243	
			3	0.005	0.1807				0.056	0.016	
			4	0.004	0.1648				0.001	0.027	
			5	0.004	0.1419				0.000	0.020	
	L3	Tidal	0	0.357	13.6030	14	0.037	13.257	13.257	0.120	
			1	0.085	3.2413				4.281	1.080	
			2	0.011	0.4011				0.637	0.056	
			3	0.004	0.1530				0.040	0.013	
			4	0.004	0.1683				0.001	0.028	
			5	0.004	0.1508				0.000	0.023	


2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Avg. Cl Content % Conc. Wt.
70
60
50
40
30
20
10
0
Avg. Cl Content (lbs/CY)
0
1
2
3
4
5
6
Depth (in)
Depth of Steel
Tidal L1
Tidal L2
Best-Fit Curve Tidal L1
Best-Fit Curve Tidal L2

Corrosion Modeling Service Life Reports

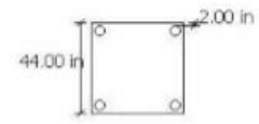
Life-365 v2.2 - Concrete Mixes and Service Lives

Project: 150026 L2

Description: Bent Cap\Highly Corrosive Zone

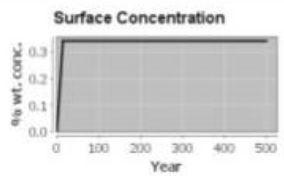
Analyst: Taiseer Al Salihi

Date: 07/30/2021



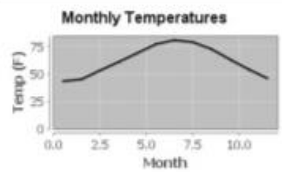
square column/beams (2-D)

Outer dim: 44in; clear cover: 2in



Max surface: 0.340 % wt. conc.

Years to buildup: 14



Loc: user-defined

Type: user-defined

Concrete Mixes

Alt name	User?	w/cm	SCMs	Inhib.	Barrier	Reinf.
Assumed Concret Properties		0.36	Class F Fly Ash (30%);	Ca Nitrite - 3 gal/cub. yd.		Black Steel
Measured Concrete Properties	yes	n/a	n/a	n/a		Black Steel

"n/a" indicates that, since the user is specifying the diffusion properties of this mix, this value is not specified.

Diffusion Properties and Service Lives

Alt name	D28	m	Ct	Init.	Prop.	Service life
Assumed Concret Properties	9.87E-9 in*in/sec	0.44	0.24 % wt. conc.	148 yrs	6 yrs	**154 yrs**
Measured Concrete Properties	-> 1.14E-8 in*in/sec	-> 0.44	-> 0.24 % wt. conc.	127.8 yrs	-> 6 yrs	**133.8 yrs**

"->" indicates that the user has directly specified this value; "+" indicates the service life exceeds the study period.

Materials and Tests Unit Statement of Concrete Mix Design

Form 312U
3-96

North Carolina Department of Transportation, Division of Highways, Materials and Tests Unit
Statement of Concrete Mix Design and Source of Materials

Project	**Date Expires** 12/31/2075
Mix Design Status Active	**Concrete Producer** S.T. WOOTEN CORP.
County	**Plant Location & DOT No.** NEWPORT, NC - 316
Resident Engr.	**Contractor**
Class of Concrete CLASS AA	**Date Assigned**
Mix Design No. 3162VFG5634CCIE	**Contractor's Signature**
Note Mix Design Units (English or Metric) ENGLISH	

Mix Design Proportions Based on SSD Mass of Aggregates

Material	Producer	Source	Qty. per Cu. Yard
Cement	CEMEX	KNOXVILLE, TN	560 lbs.
Pozzolan	SOUTHEASTERN FLY ASH	SEFA - WINYAH GENERATING STATION/GEORG	168 lbs.
Fine Aggregate	MARTIN MARIETTA	BELGRADE QUARRY - MAYSVILLE	1076 lbs.
Coarse Aggregate	MARTIN MARIETTA	CLARKS QUARRY - NEW BERN	1570 lbs.
Total Water		WELL	31.0 gals.
Air. Entr. Agent	W.R. GRACE & COMPANY	DAREX AEA	As recommended
Retarder	W.R. GRACE & COMPANY	DARATARD 17	As recommended
Water Reducer	W.R. GRACE & COMPANY	WRDA-35	As recommended
Superplasticizer			
Corrosion Inhibitor	W.R. GRACE & COMPANY	DCI S	As recommended

Mix Properties and Specifications

Slump	3.50 **in.**	**Mortar Content**	16.34 **cu. ft.**
Max Water	33.2 **gals.**	**Air Content**	6.0 **%**

Material	Specific Gravity	% Absorption	Unit Mass	Fineness Modulus
Fine Aggregate	2.62	0.4	NA	2.87
Coarse Aggregate, #67	2.36	5.3	79.0	NA

Comment Contains 3 gals DCI-S corrosion inhibitor. Maximum allowable water has been reduced to account for water (2.6 gals) in DCI-S.

Cast-in-place concrete shall conform to Section 1000, precast concrete to Section 1077, and prestressed concrete to Section 1078 of the applicable edition of the Standard Specifications for Roads and Structures plus all applicable Special Provisions.