IDEA

Innovations Deserving Exploratory Analysis Programs

*NCHRP IDEA Program*

# Determining Bridge Deck Chloride Quantities Using Ground Penetrating Radar

Final Report for
NCHRP IDEA Project 208

Prepared by:
Anthony J. Alongi
Penetradar Corporation

*June 2020*

TRB TRANSPORTATION RESEARCH BOARD
*The National Academies of*
SCIENCES · ENGINEERING · MEDICINE

## Innovations Deserving Exploratory Analysis (IDEA) Programs Managed by the Transportation Research Board

This IDEA project was funded by the NCHRP IDEA Program.

The TRB currently manages the following three IDEA programs:

- The NCHRP IDEA Program, which focuses on advances in the design, construction, and maintenance of highway systems, is funded by American Association of State Highway and Transportation Officials (AASHTO) as part of the National Cooperative Highway Research Program (NCHRP).
- The Safety IDEA Program currently focuses on innovative approaches for improving railroad safety or performance. The program is currently funded by the Federal Railroad Administration (FRA). The program was previously jointly funded by the Federal Motor Carrier Safety Administration (FMCSA) and the FRA.
- The Transit IDEA Program, which supports development and testing of innovative concepts and methods for advancing transit practice, is funded by the Federal Transit Administration (FTA) as part of the Transit Cooperative Research Program (TCRP).

Management of the three IDEA programs is coordinated to promote the development and testing of innovative concepts, methods, and technologies.

For information on the IDEA programs, check the IDEA website (www.trb.org/idea). For questions, contact the IDEA programs office by telephone at (202) 334-3310.

IDEA Programs
Transportation Research Board
500 Fifth Street, NW
Washington, DC 20001

# Determining Bridge Deck Chloride Quantities Using Ground Penetrating Radar

**IDEA Program Final Report**

**NCHRP IDEA Project 208**

Prepared for the IDEA Program

Transportation Research Board

The National Academies

Anthony J. Alongi

Penetradar Corporation

June 25, 2020

Penetradar

2509 Niagara Falls Blvd, Niagara Falls, NY 14304 USA (716)-731-4369

**Acknowledgements**

The research described herein was supported by the NCHRP IDEA Program. The author wishes to acknowledge the assistance of officials in the Virginia Department of Transportation, and the contributions of Penetradar staff including Bijan Pajoohi and other project participants.

Special thanks are also due Mr. Gary A. Runco, PE and Cecil Apple of the Virginia Department of Transportation (NOVA), Michael Sprinkel, PE and Soundar Balakumaran, PhD of the Virginia Transportation Research Council (VTRC) and Ali Akbar Sohanghpurwala, PE from Concorr, Inc.

## Table of Contents

1.0 Executive Summary ..... 1
1.1 Analytical Model Development ..... 2
1.2 Laboratory Experimentation ..... 2
1.3 Field Tests ..... 4
2.0 Discussion ..... 6
2.1 Idea Product ..... 6
2.2 Concept and Innovation ..... 7
2.3 Investigation ..... 7
2.3.1 Analytical Model ..... 8
2.3.1.1 Power Loss Derivation ..... 9
2.3.1.2 Modeling a PCC Slab ..... 12
2.3.2 Laboratory Experiments ..... 15
2.3.3 Field Testing and Data Collection ..... 22
2.3.3.1 Bridge Deck Chloride Measurements ..... 23
2.3.3.2 GPR Attenuation and Chloride Quantities ..... 25
2.3.3.3 Developing a Linear Regression Model ..... 27
2.3.3.4 Chloride Mapping ..... 30
2.3.3.5 Optimizing the Regression Model and Testing the Concept ..... 33
2.3.3.6 Comparison with Core Samples ..... 37
2.4 Plans for Implementation ..... 39
3.0 Conclusions and Recommendations ..... 40
4.0 References ..... 41

## List of Illustrations

FIGURE (1) GPR Attenuation - Chloride Relationship (Experimental) ........ 3
FIGURE (2) Chloride Mapping based on GPR Measurements based on (3) Cores ........ 5
FIGURE (3) Power Ray Diagram of Radar Wave in PCC ........ 8
FIGURE (4) Attenuation –vs- Conductivity ........ 11
FIGURE (5) Attenuation –vs- Conductivity with Reflective Loss ........ 12
FIGURE (6) Attenuation -vs- Chloride - Analytically Derived ........ 15
FIGURE (7) GPR Experiment to Measure Signal Attenuation ........ 17
FIGURE (8) Sand-Gravel Experimental Setup ........ 18
FIGURE (9) Attenuation -vs- Chloride at 1GHz - Experimental Results ........ 19
FIGURE (10) Attenuation -vs- Chloride at 2GHz - Experimental Results ........ 20
FIGURE (11) GPR Configuration used to Test the Sanger Avenue Bridge Deck ........ 23
FIGURE (12) Location of Core Samples on Sanger Bridge ........ 24
FIGURE (13) GPR Attenuation Mapping (in dB) from GPR Scan with Core Locations ........ 26
FIGURE (14) Linear Regression Model based on 7 cores (chloride) samples ........ 29
FIGURE (15) Linear Regression Model based on 6 cores (chloride) samples ........ 30
FIGURE (16) Chloride Mapping based on GPR Attenuation (R2=0.875 based on 6 chloride samples) ... 32
FIGURE (17) Optimized Linear Regression Model Based on 3 Core (chloride) Samples ........ 34
FIGURE (18) Chloride Mapping based on GPR Attenuation (R2=0.835 based on 3 chloride samples) ... 36
FIGURE (19) Comparison of Chloride Distribution Based on GPR and Core Samples ........ 38

## List of Tables

TABLE (1) Resistivity/Conductivity of Concrete ........ 10
TABLE (2) Corrosion-Conductivity in PCC ........ 10
TABLE (3) Estimation of Relative Dielectric of PCC Based on Moisture Content ........ 13
TABLE (4) Sand/Gravel with Water & Chloride Experiment ........ 16
TABLE (5) Dielectric constant as a measure of moisture content ........ 21
TABLE (6) Laboratory Chloride Measurements from Seven (7) Left Lane Core Samples ........ 25
TABLE (7) GPR Attenuation and Chloride Concentration ........ 27
TABLE (8) GPR Attenuation and Chloride Concentration ........ 33
TABLE (9) Comparison between Predicted and Measured Chloride Concentration ........ 35
TABLE (10) Laboratory Chloride Measurements from Fifteen (15) Left & Right Lane Cores ........ 37

## 1.0 EXECUTIVE SUMMARY

The focus of this project is the investigation of an entirely new method for determining chloride quantity in bridge decks using nondestructive GPR technology in combination with a limited number of cores for calibration. Chloride infiltration into concrete is the major cause of corrosion induced delamination in steel reinforced bridge decks and repairing delaminated concrete is a major cost factor in bridge deck rehabilitation. Knowledge of the quantity and location of chlorides in bridge deck concrete is an important factor in decisions relating to the type and extent of repairs. Traditionally, the measurement of chlorides involves core sampling and laboratory testing of concrete samples. While this gives an accurate measure of chloride at the location of the core, it cannot readily determine the distribution of chlorides throughout the deck or the maximum or minimum chloride amounts unless a great number of cores are taken. The GPR method developed here has the potential to provide that information and provide bridge owners with detailed information on the quantity and location of chlorides in their bridge decks, thereby improving the effectiveness of repairs, reducing the cost of maintenance and repairs, and potentially increasing the lifespan of the bridge deck.

GPR signal attenuation in bridge deck concrete occurs as a result of the conductive nature of the concrete when water and chlorides are introduced. Earlier research conducted by Alongi under SHRP C101 found that a relationship existed between radar signal attenuation, chloride levels in concrete and moisture content. The results of that research showed that the signal attenuation experienced by the radar wave in concrete is affected by the quantity of chloride and moisture. While that research centered on detecting delamination with GPR and defining the level of attenuation that would occur in delaminated bridge deck concrete, the current research approach focuses on the use of radar to determine the quantity of chloride in the concrete, and specifically to demonstrate the possibility of utilizing GPR along with limited coring (two or three core samples) and laboratory chloride measurements to produce an accurate and quantitative, spatial mapping of chlorides in bridge decks. The results of this research show that this is possible, based on in-situ field testing and is further confirmed by analytical modeling and laboratory experimentation. It should be noted, however, that these results are based on limited experimental data and further testing of the accuracy and reliability of the method is recommended.

Although not specifically within the scope of the present investigation, the results also suggest that with additional development, GPR may be able to predict chloride levels in bridge deck concrete independently and without the need of calibrating core samples.

A three-pronged approach was taken consisting of (1) the development of an analytical model, which describes through mathematical derivation the GPR losses or attenuation in chloride contaminated concrete, (2) laboratory experimentation with sand and gravel test specimens with varying concentrations of chloride and moisture, and (3) field testing on an asphalt overlaid, concrete bridge deck using laboratory chloride measurements to calibrate GPR attenuation. In each of these approaches the attenuation-chloride relationship for bridge deck concrete has been derived and quantified. Together, they define the fundamental theory for this technique and the methodology for putting it into practice.

## 1.1 ANALYTICAL MODEL DEVELOPMENT

An analytical model was developed which defines the signal loss experienced by a radar wave in concrete with varying levels of chloride and moisture. The model was developed based on conventional electromagnetic theory for plane waves in lossy media and shows the theoretical relationship, defined in mathematics, between GPR signal attenuation, chlorides and moisture in concrete, i.e. the attenuation-chloride relationship. It relates the level of radar signal attenuation (in dB per inch) that would occur based on a predefined chloride quantity ($lb/yd^3$) and moisture level (% by weight) in a material such as concrete. The model shows that GPR is responsive to chloride levels in concrete, and that there is a direct relationship between chloride quantity, when in the presence of moisture, and the conductivity and complex dielectric constant of the material. Greater levels of chloride, when in water solution, cause an increase in conductivity which results in greater signal loss or attenuation. The model also revealed that signal attenuation (as measured in dB) at 1GHz and 2GHz is almost linearly related to the quantity of chloride in the material at concentrations normally found in bridge deck concrete, for a given moisture content. This suggests that the chloride content can be adequately defined with a minimum of two or three calibrated GPR attenuation measurements. The analytical model also suggested that it may be possible to predict the chloride quantities in concrete, based on signal attenuation for a given moisture level independently and without the need of prior calibration.

## 1.2 LABORATORY EXPERIMENTATION

To support the project objectives and to confirm the analytical model, a series of experiments were conducted with parameters similar to those used in the analytical model. Several test boxes were constructed containing a mix of compacted sand and gravel to simulate PCC. A predefined amount of chloride and water were added to replicate the conditions that would be encountered in bridge deck concrete in-situ, with chloride ranging from 0-10 $lb/yd^3$ and moisture content ranging from 0% to 10% by weight. Radar testing was conducted using 1GHz and 2GHz (center frequency) air-coupled antennas to measure signal properties including relative dielectric constant and signal loss. The result of these experiments was the development of the attenuation-chloride relationship for different moisture concentrations. The attenuation-chloride relationship for a 1GHz antenna is shown in Figure (1). The experimental results confirmed the analytical modeling and while not identical were remarkably similar. The experiments also showed that the relative dielectric constant of the material is unaffected by the quantity of chloride introduced, at the frequencies tested, and that the presence of chlorides without moisture in the material had no measurable effect on signal attenuation relative to the case without chloride. It was only when moisture and chlorides were present together that the radar signal experienced attenuation. For chloride and moisture contents typically found in bridge deck concrete, the experiments determined that attenuation is directly, and in most cases linearly related to the quantity of chloride in the material for a given moisture content. This confirms what was found by the analytical model and also means that the attenuation-chloride relationship can be adequately defined with a minimum of two or three calibrated GPR attenuation measurements (cores). Once the relationship between attenuation and chloride content is known, subsequent measurements of signal attenuation in the bridge deck can then be used to determine chloride content, provided that the moisture content is relatively constant.

A chloride prediction will be less accurate when the moisture content is very low and may not work at all when moisture in the concrete is nonexistent. In cases when moisture is highly variable, i.e. where the moisture content varies greatly throughout the bridge deck, a chloride prediction based on calibrated attenuation measurements will also be less accurate since attenuation can vary based on chloride as well as moisture content. However, if the moisture content is known or can be estimated then it may be possible to compensate for variations in attenuation based on moisture. The experiments showed that moisture content could be estimated with a radar measurement of relative dielectric constant. With this information it may be possible to eliminate the effects of moisture and estimate chloride quantity regardless of variation in moisture content.

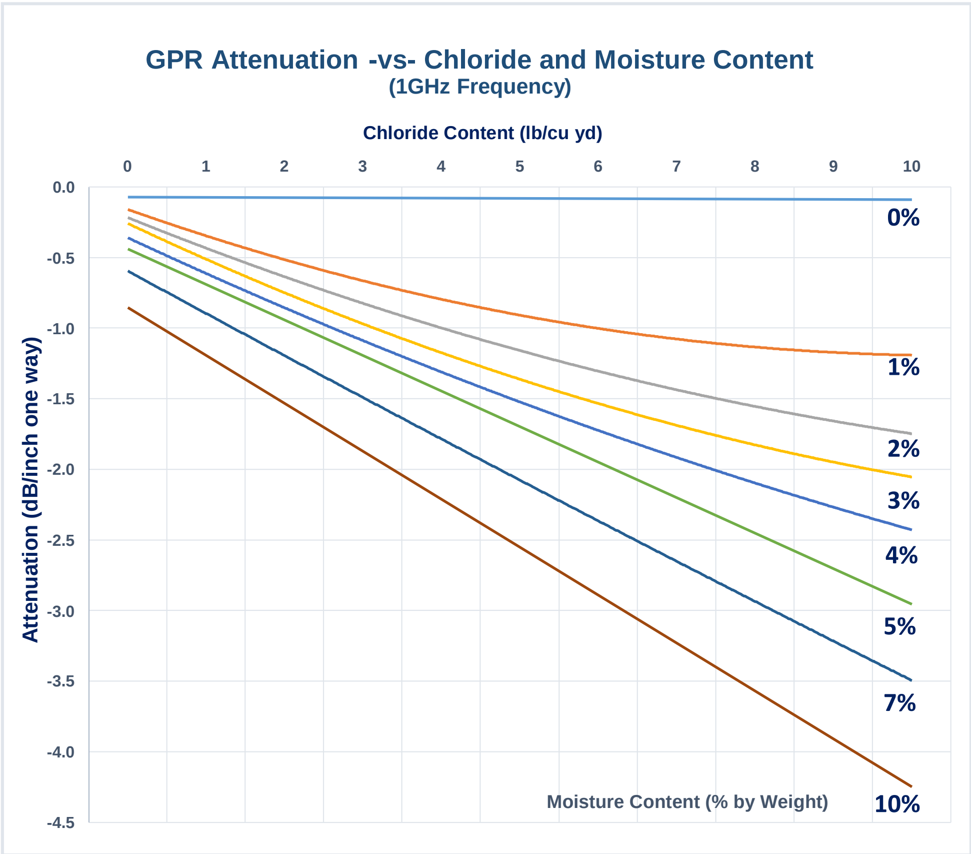



**FIGURE (1) GPR Attenuation - Chloride Relationship (Experimental)**

This shows the signal attenuation experienced by a radar wave traveling through material with varying amounts of moisture and chloride. The level of attenuation is based upon the combined amount of chloride and moisture. The attenuation-chloride relationship was determined both analytically and experimentally.

## 1.3 FIELD TESTS

The third approach involved field tests, which were carried out to determine the feasibility of the GPR method for predicting chlorides in-situ in bridge deck concrete. Good correlation was found between radar attenuation measurements and chloride levels in concrete, based on tests conducted on the Interstate 395 Southbound bridge over Sanger Avenue in Arlington, VA. Penetradar IRIS GPR equipment was used for data collection and bridge deck chloride information was provided by VDOT (NOVA District) from earlier in-depth coring that was performed. A comparison was made between the non-contacting, ground penetrating radar measurements of signal loss and laboratory measurements of chloride obtained from cores. A regression was performed between GPR signal attenuation and chloride quantity to determine the level of correlation that existed and the R-Squared value or quality of the relationship. R-Squared values can range from 0 for no correlation, to 1 for perfect correlation and generally the higher the R-Squared the better the ability of the independent variable, which in this case is GPR attenuation, to predict the dependent variable, chloride quantity. Based on the six laboratory chloride samples available, an R-squared value of (0.875) was determined to exist for this data set. For this bridge deck, the results suggest that GPR signal attenuation is likely to be a good predictor of chloride quantity in concrete.

From the GPR attenuation data it was possible to create a mapping of bridge deck chloride quantities, showing detailed levels of chloride throughout the deck. From the regression model and chloride mapping, the maximum and minimum chloride levels were extrapolated and found to vary between 0 $lb/yd^3$ and approximately 7.4 $lb/yd^3$ (at the 99$^{th}$ percentile), with an average chloride level for the entire bridge deck to be 2.0 $lb/yd^3$. This compared favorably with average laboratory chloride measurements of 2.6 $lb/yd^3$.

As detailed in this report, it was found that the attenuation-chloride relationship could be reasonably defined with only three chloride sample measurements, one corresponding to low, intermediate and high attenuation, with an R-squared of 0.835, as shown by the GPR chloride mapping in Figure (2). In a direct comparison between chloride quantities based on laboratory testing of cores and GPR predictions of chloride, 53% of the laboratory samples exceeded a level of 2 $lb/yd^3$ – which traditionally is in a range of chloride concentration that can cause corrosion of reinforcement in concrete, while 47.7% of the GPR measurements exceeded a 2 $lb/yd^3$ threshold.

It was found that the selection of core and chloride sample locations are important to overall accuracy, as is locational accuracy in GPR data collection and ensuring that the core samples are taken in the correct locations. Deviations in location can produce significant errors and adversely affect GPR's ability to predict chloride quantities.

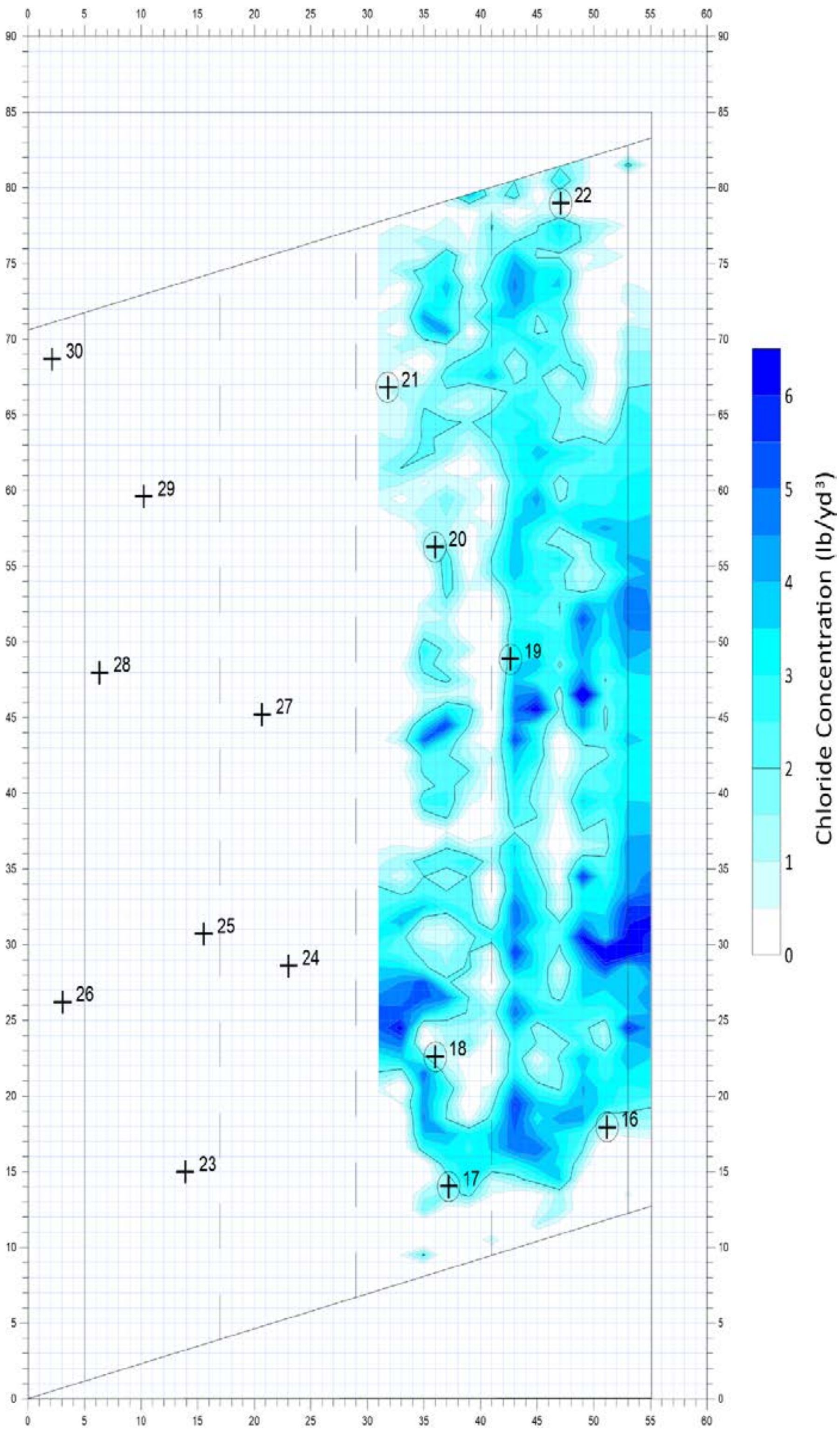



**FIGURE (2) Chloride Mapping based on GPR Measurements**
This shows a GPR mapping of chlorides based on measurement of signal attenuation and calibrated by (3) cores, 16, 19 & 22.

# 2.0 DISCUSSION

## 2.1 IDEA PRODUCT

Chlorides from deicing salts attack the steel reinforcement in bridge decks which can ultimately cause delamination and deterioration of the concrete. The repair cost from these defects are estimated to exceed $5B per year in USA and make up between 50% - 85% of bridge maintenance budgets. The removal and replacement of chloride contaminated concrete is the most long-lasting and cost-effective remediation, however, few methods exist to determine chloride content in bridge decks. The most widely used method requires closing traffic lanes, extraction of large numbers of core samples and laboratory testing for chloride. While providing quantitative information, this method is expensive and time consuming, it creates traffic slow-downs and can be a potential safety hazard, and because cores are discrete samples, they often produce inadequate information on the bridge deck condition and chloride quantities.

What is needed is a fast, accurate and low-cost method that provides quantitative information on chloride content over the entire bridge deck. Such a method would permit improved repair strategies by identifying chloride contaminated concrete and thereby improving the effectiveness of repairs.

To address this need, a high-speed, non-contacting, ground penetrating radar (GPR) technique was developed, that provides a deck-wide topographical mapping of chloride concentration at the rebar level. This method utilizes a GPR scan of the entire bridge deck along with a minimal number (3 or more) of core samples and laboratory chloride measurements to calibrate the GPR measurements.

This entirely new method for determining chloride quantity in bridge decks uses existing air-coupled GPR technology and the research establishes and quantifies the relationship between chlorides in concrete (which cause corrosion of reinforcing steel and delamination of concrete) and the effect on GPR signal propagation. The chloride mapping method that has been developed produces a complete and quantitative mapping of chlorides in bridge decks, the extent of which cannot be achieved in the same detail with any other method.

This development will provide bridge owners an unprecedented level of information on the condition of their bridge decks. It will improve effectiveness of repairs, decrease the overall cost of repairs and extend the life of the bridge deck, and when compared to traditional methods the GPR technique provides greater quantity and improved quality of information. It is less destructive and with less interference with traffic it is safer to highway workers and the public.

The benefit to highway departments and bridge owners include the potential to save millions of dollars in repair costs, allow better prioritization of repairs and to extend the life of bridges in their inventory. The traveling public will benefit from improved safety as well as the potential avoidance of thousands of hours of traffic “slow-downs” and lane closures.

## 2.2 CONCEPT AND INNOVATION

Ground Penetrating Radar has been utilized for several years on bridge decks. In the early days of the development of this technology the focus was on detection of delamination in concrete bridge decks. Research in this area took different approaches including investigation of waveform features and waveform signatures specific to bridge decks where delamination was present. SHRP C-101 research conducted by A. Alongi, found that a strong correlation existed between the level of signal loss or attenuation in a radar signal and the presence of delaminated concrete. It was found that the conditions in the concrete causing corrosion of reinforcing steel and subsequent delamination, i.e. chlorides and moisture, were the same conditions that caused signal loss or attenuation of the radar signal. This research showed that GPR measurement of attenuation could be used to identify areas of delaminated bridge deck concrete. This work was the basis for GPR detection of delamination in bridge decks that is in use today.

SHRP C-101 research not only showed that GPR was responsive to the chlorides and moisture content in concrete but also suggested that there was a deterministic relationship between GPR signal attenuation and the combined amount of moisture and chlorides in concrete. In other words, radar signal attenuation was a function of both the quantity of chloride and moisture content in concrete. This research set the stage for the present investigation. The present research builds upon that and shows that GPR can be used as an analytical tool to identify the quantity of chlorides in concrete based on measurement of signal loss. While radar signal attenuation in bridge deck concrete depends on several factors, many of these factors can be accounted for or are relatively constant, such as the composition or thickness of the concrete or the reflective nature of the reinforcement. The main variable factors associated with radar signal attenuation are believed to be related to the electrical impedance of the concrete, which is a function of moisture content and quantity of chlorides.

The current research shows that there is a deterministic relationship between radar signal attenuation and the amount of chloride and moisture in bridge deck concrete, and that when moisture content is known it is possible to estimate chloride quantity based on signal loss or attenuation measurements. It also demonstrates the practical application of this concept by utilizing GPR along with limited coring (three or more core samples) and laboratory chloride measurements to produce an accurate and quantitative, spatial mapping of chlorides in bridge decks

## 2.3 INVESTIGATION

Research was conducted with a three-pronged approach consisting of (1) the development of an analytical model, which describes through mathematical derivation the GPR losses or attenuation in chloride contaminated concrete, (2) laboratory experimentation with simulated concrete samples consisting of sand/gravel with varying concentrations of chloride and moisture, and (3) field testing on a bridge deck using laboratory chloride measurements to calibrate GPR signal attenuation. In each of these approaches the attenuation-chloride relationship for bridge deck concrete has been defined and quantified. The subsequent discussion details the work that was performed.

### 2.3.1 Analytical Model

Bridge deck pavement can be modeled as a lossy, multilayer dielectric material. In this model it is assumed that the radar utilizes a non-contacting antenna, that all materials are purely dielectric in nature and nonmagnetic, and that the radar radiates downward or normal to the pavement surface. The received radar signal power from a bridge deck is influenced by many factors, including the amount of power initially transmitted, the amount of beam spreading (waveform divergence), losses in the concrete – attenuation power loss and reflective power loss, as well as the gain of the transmitting antenna and effective aperture of the receiving antenna. While many of these factors relate to the radar design, only losses in the concrete are significant in the context of the bridge deck model.

Figure (3) shows a power ray diagram of radar wave propagation in PCC. The radio frequency energy generated by the radar first propagates from antenna to air. This emitted signal then encounters an air/concrete surface boundary where a portion of the signal power traverses the dielectric boundary and proceeds into the concrete material. Its complement is reflected from the boundary in accordance with the relationship shown in equation (1) between transmitted and reflected energy at a dielectric boundary. This relationship also describes the radio frequency (RF) power transmission and reflection at every subsequent material boundary that the radar waves encounter.

$$P_i = R + T \qquad (1)$$

Where $P_i$ = emitted power incident to boundary
R = power reflected from boundary
T = power transmitted through boundary

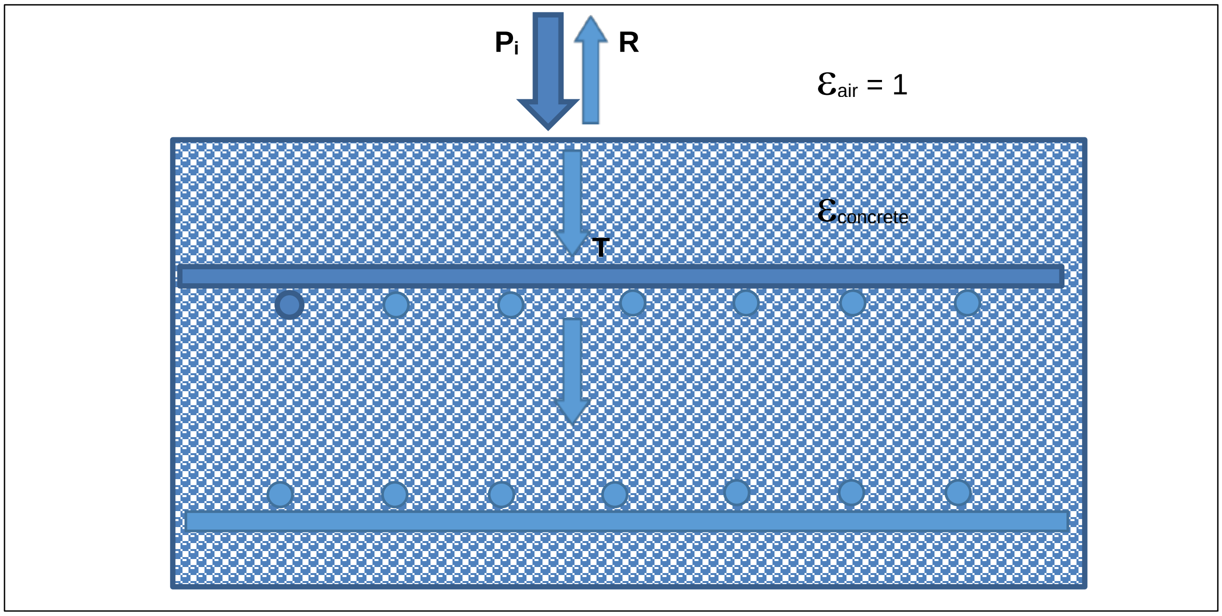



**FIGURE (3) Power Ray Diagram of Radar Wave in PCC**

If $P_i$ has unity value, then the power entering the concrete is reduced in the ratio *1-R*. The same factor occurs for the wave reentering the air. Consequently, the power reflected from a subsurface object is reduced by the factor $(1-R)^2$ relative to the incident power $P_i$.

The wave traveling in the concrete will encounter the embedded reinforcement. Metal objects are effectively a complete reflector of RF energy but due to the small cross-sectional area of the metal bar relative to the antenna radiation pattern and their cylindrical geometry, only a very small portion of the energy is actually reflected back to the radar antenna. Nevertheless, the magnitude of the reflection from the top layer of rebar can be measured. The reflection from the top reinforcing steel represents a convenient point of measure of signal attenuation since it is the concrete above the rebar that is exposed to chlorides and when those concentrations are sufficiently high, delamination is likely to occur. There are several factors that affect the magnitude of the reflection from the rebars in addition to their cross sectional area and geometry. This includes the depth of the bars, polarization of the radar wave relative to the bars and the dielectric properties of the concrete, which include the reflective and attenuative properties. Because the objective of this model is to predict the unit power loss in the radar wave based on chloride quantity in concrete, for the purpose of this model we can assume that the depth, polarization and geometry are not significant to its development.

### *2.3.1.1 Power Loss Derivation*

Attenuation power loss can be accounted for using conventional electromagnetic theory for plane waves in lossy media. The power loss factor or attenuation, $a$, for one-way propagation over a distance, D, is described by equation (2). The expression in equation (2) is exact but parameters such as dielectric constant and conductivity in concrete can have a wide range of values based on condition.

$$a = e^{-2D\left(\frac{2\pi f}{c}\right)\sqrt{\frac{\varepsilon rn(\sqrt{1+\tan(\delta_n)^2}-1)}{2}}} \qquad (2)$$

where

$f$ = frequency,
$D$ = one-way path length,
tan ($\delta$) = loss tangent
$c$ = velocity of light
$\varepsilon_r$ = relative dielectric constant

The loss tangent is defined as

$$\tan(\delta) = \sigma/(2\pi f \varepsilon_o \varepsilon_r) \qquad (3)$$

where

$\varepsilon_o$ = 8.854 x $10^{-12}$ fd/m
$\sigma$ = conductivity in the medium

From equation (2) it can be seen that attenuation in a material increases exponentially with frequency, distance and conductivity. If we assume that the frequencies generated by the radar are constant and attenuation is calculated on a unit distance basis (i.e. per cm, inch, etc.) then the variations in attenuation will be a function of the relative dielectric constant and conductivity.

Conductivity (and its inverse, Resistivity) can vary significantly in concrete based on the moisture content in the concrete and the quantity of chlorides. Moisture has a significant influence and can vary the conductivity of concrete by as much as six orders of magnitude. Dried concrete can have a conductivity of 1E-08 mho/m whereas wet concrete may have a conductivity of 0.01 mho/m. Table (1) shows the typical range of concrete resistivity and conductivity with respect to moisture or water content.

TABLE 1. Resistivity/Conductivity of Concrete

| **Resistivity** ohm-m | **Conductivity** mho/m | |
|---|---|---|
| 100 | 0.0100 | wet concrete |
| 10000 | 1.000E-04 | air-dried concrete |
| 1.00E+08 | 1.000E-08 | oven dried concrete |

Typical conductivities of concrete relative to reinforcement corrosion are shown in Table (2). Conductivity of 0.01 mho/m or greater are conditions where corrosion of rebar has been reported to occur.

TABLE 2. Corrosion-Conductivity in PCC[1,2]

| **Resistivity** ohm-m | **Conductivity** mho/m | |
|---|---|---|
| 1000 | 0.0010 | no corrosion |
| 500 | 0.0020 | no corrosion |
| 120 | 0.0083 | corrosion unlikely |
| 100 | 0.0100 | corrosion possible |
| 80 | 0.0125 | corrosion likely |
| 40 | 0.0250 | corrosion likely |

Figure (4) shows the signal loss of a radar wave based on the power loss formula shown in equation (2). It shows the attenuation experienced by a radar wave propagating in a dielectric material with conductivities ranging from 0 mho/m to 0.09 mho/m. While the range of conductivity shown here may be greater than what is experienced in typical bridge deck concrete, this illustrates that losses are inversely related to relative dielectric constant and directly related to conductivity. For the analysis shown in this example, a 1 GHz frequency is used along with relative dielectric constant ($\varepsilon_r$) of 1, 2, 4, 6.25, 9, 12 and 81. It is interesting to note that the level of attenuation where corrosion has been reported to occur (i.e. 0.01 mho/m) ranges from -0.09 dB/inch to -0.83 dB/inch depending on relative dielectric constant. This is not unreasonable considering that SHRP C101 research[3] determined radar signal attenuation for corrosion induced delamination to occur in reinforced concrete to be on the order of -0.5 dB/inch, based on empirical data from a large number of bridge decks. When taking into account reflective loss occurring at the air/concrete boundary, the signal attenuation ranges from -1.4 dB/inch to -1.7 dB/inch at a conductivity of 0.01 mho/m, as shown in Figure (5).

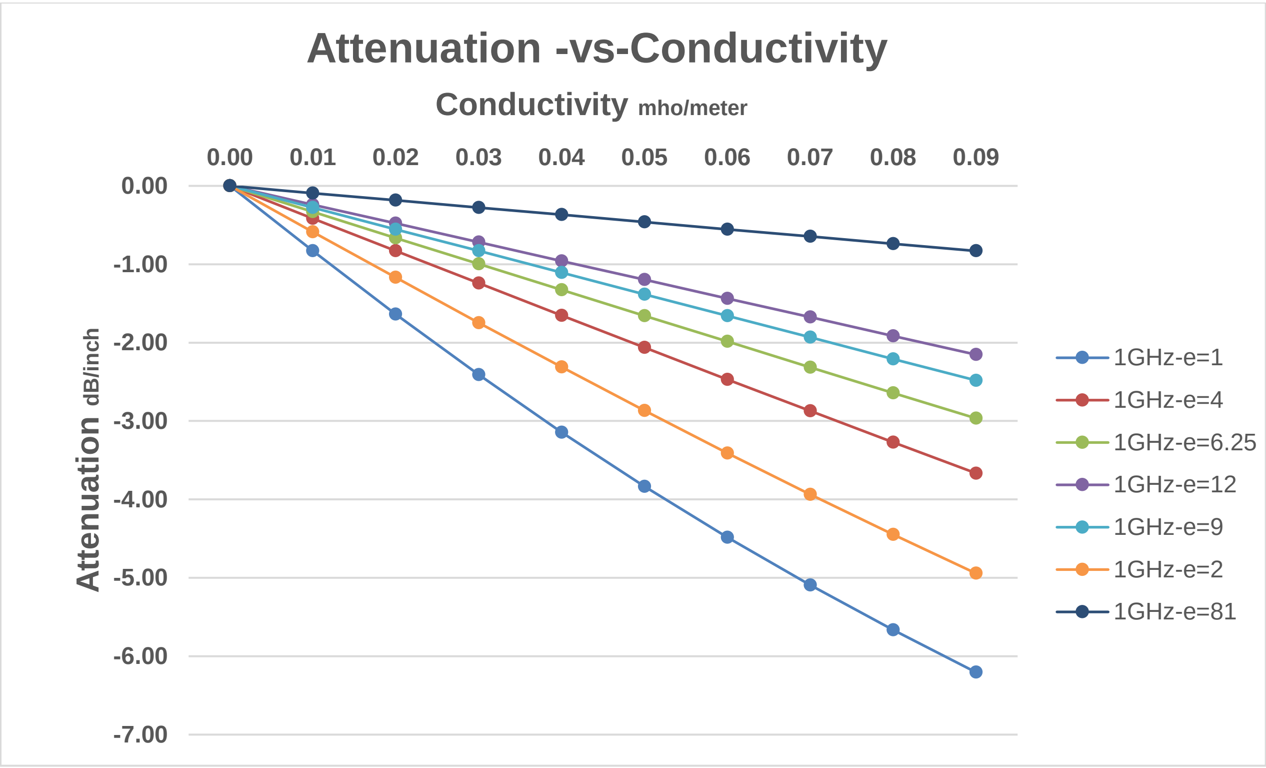



**FIGURE (4) Attenuation –vs- Conductivity**

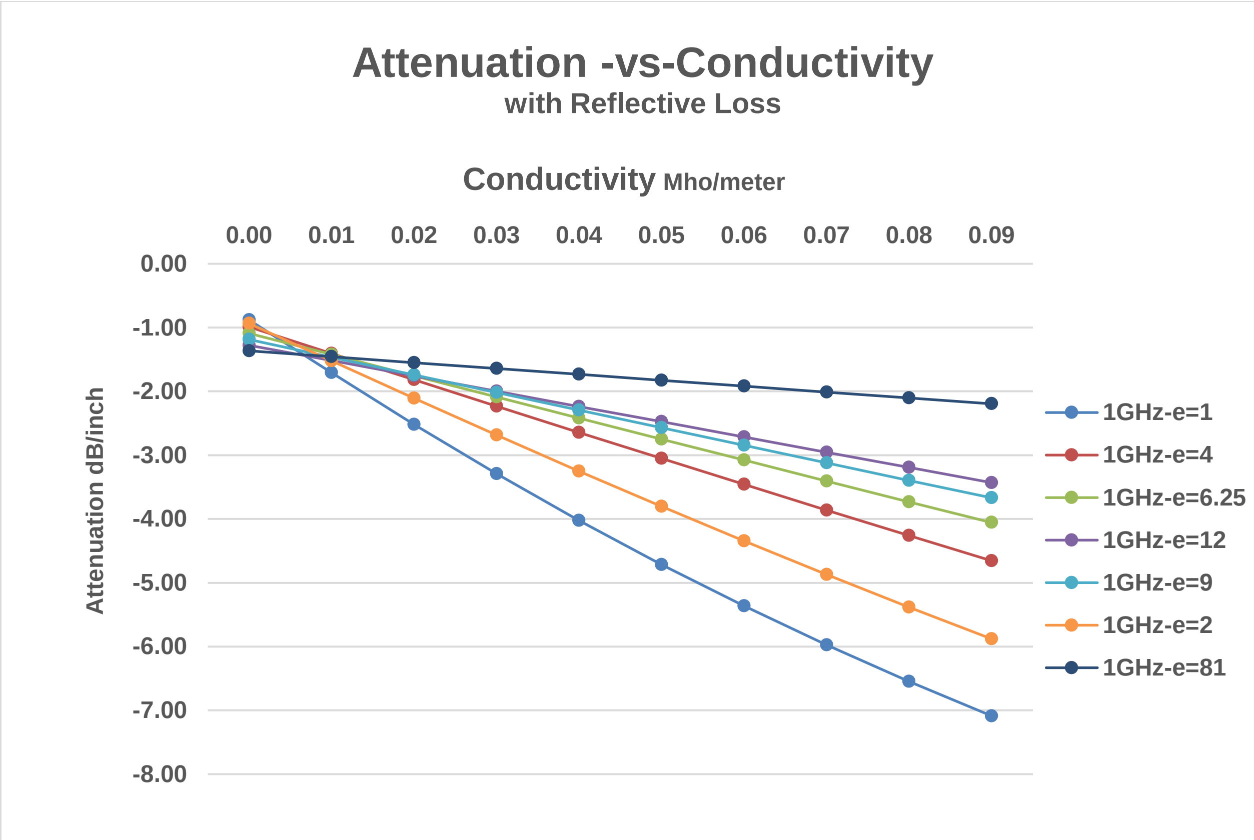



**FIGURE (5) Attenuation –vs- Conductivity with Reflective Loss**

***2.3.1.2 Modeling a PCC Slab***

While it is instructive to know the effect of conductivity on radar signal attenuation and how it may determine the threshold where delamination of reinforced concrete can occur, the objective of this analytical model is to define the levels of attenuation that may be experienced by a radar wave based on the concentration of chlorides in PCC. Chloride in a dry (solid) state is nonconductive due to the charge carriers or ions being fixed in their lattice, however, when in a water solution the conductivity increases significantly based on the concentration of chloride in solution. The water/chloride solution also affects the relative dielectric constant of the concrete in addition to its conductivity, therefore, the model must account for variation in relative dielectric constant based on moisture in the concrete and conductivity changes based on the water/chloride solution. Consequently, radar signal attenuation will be defined based on chloride concentration and moisture content.

To develop a suitable model that defines radar signal attenuation in PCC concrete it is necessary to know the conductivity of a salt-water solution, the conductivity of dry concrete, the weight of concrete and the weight of water. In addition, the relative dielectric constant of concrete with varying concentrations of water must be known or derived.

The conductivity of a water/chloride solution depends on the number of charge carriers (the concentrations of the ions), the mobility of the charge carriers and their charge. Theoretically, conductivity should increase in direct proportion to concentration. This implies that if the concentration of sodium chloride, for example, in a solution doubled, the conductivity should also double. In practice, for higher concentrations of chloride this does not hold true, as was shown in our laboratory experiments. The concentration and mobility of the ions are not independent properties since as the concentration of an ion increases, its mobility decreases. As a consequence, the conductivity increases linearly with respect to the square root of concentration instead of in direct proportion[4]. For our purpose, however, and for the chloride concentrations used for this model we will assume a linear relationship with the conductivity of a salt water solution approximated by the following relation[5]:

$$Md = 1.7641\sigma - 0.0098 \qquad (4)$$

where Md is the quantity of NaCl (in g/2.5l water) and $\sigma$ is conductivity

The conductivity of dry concrete is typically reported to be on the order of 1E-04 mho/m. By adding a proportionate amount of salt-water solution (percent by weight) to dry concrete, ranging between 0% to 10%, the conductivity of the salt-water saturated concrete was estimated using a first order, linear approximation. Similarly, the relative dielectric constant of the concrete with various quantities of salt-water can be estimated using a linear approximation, where dry concrete has a $\varepsilon_r$ = 6.25 and water has a $\varepsilon_r$ = 81. The linear approximation for the relative dielectric constant of concrete with varying quantities of salt-water is shown in Table (3).

| Relative Dielectric - Linear Approximation | | |
|---|---|---|
| % water | % PCC | Relative Dielectric |
| 0 | 100 | 6.25 |
| 0.5 | 99.5 | 6.62375 |
| 1 | 99 | 6.9975 |
| 2 | 98 | 7.745 |
| 3 | 97 | 8.4925 |
| 4 | 96 | 9.24 |
| 5 | 95 | 9.9875 |
| 6 | 94 | 10.735 |
| 7 | 93 | 11.4825 |
| 8 | 92 | 12.23 |
| 9 | 91 | 12.9775 |
| 10 | 90 | 13.725 |
| 20 | 80 | 21.2 |
| 30 | 70 | 28.675 |

TABLE (3). Estimation of Relative Dielectric of PCC Based on Moisture Content

An attenuation model was developed with values of conductivity and relative dielectric corresponding to typical concentrations of salt and water found in the concrete. The model predicts the signal attenuation as shown in Figure (6) and is based on a chloride content ranging between 0 and 10 lbs/yd$^3$ of PCC and moisture content ranging between 0% and 10% by weight.

In the context of this project scope, which is the estimation of bridge deck chlorides based on calibrated radar attenuation measurements, the model shows that a minimum of two attenuation measurements are needed to define the linear, attenuation-chloride relationship, provided that the moisture remains constant.

Further examination shows the analytical attenuation model can predict the level of attenuation that would be experienced by a radar wave based on the percentage of moisture (by weight) in concrete and the quantity of chloride (lb/yd$^3$). As an example, if the concrete is known to contain 3 lb chloride/yd$^3$ and 4% moisture, the radar signal will experience attenuation on the order of -0.85 dB/inch. It is also possible to work backward such that the chloride levels can be determined if signal attenuation and moisture quantity are known. For instance, if radar measurements are taken that result in attenuation of -0.85 dB per inch and there is 4% moisture (by weight) in the concrete, the model predicts that there should be 3 lb chloride per yd$^3$ of PCC. The attenuation levels predicted by the model are not unreasonable based on experience derived from actual GPR testing on bridge decks, which shows similar attenuation levels.

The model shows that it is possible to determine chloride levels in concrete with a radar measurement of attenuation along with knowledge of the moisture content. While radar does not measure the moisture content in concrete directly it can provide an estimate based on a measure of the dielectric constant of concrete, as shown in Table (3). This suggests in theory that it may be possible for radar to estimate chloride content independently by measurement of signal attenuation and relative dielectric constant, without the need for calibration cores and laboratory chloride measurements, however, additional work will be necessary to determine the practicability of this theory.

While the robustness of the model is not known at this time with respect to bridge decks in-situ, with further development it may be possible to utilize it as a standalone method to determine chloride quantity analytically based solely on GPR measurements of attenuation and relative dielectric constant.

In summary, the model shows that GPR is responsive to moisture and chloride levels in concrete based on signal attenuation and that the attenuation-chloride relationship can potentially be defined with two calibrated attenuation measurements, i.e. two attenuation measurements where chloride quantities are known, provided that moisture content is constant. From this, chloride quantities can be extrapolated for the remaining attenuation measurements. When moisture levels in the concrete are also known on an absolute basis, in theory radar can predict the amount of chloride contained in the concrete. The model also suggests that GPR may be able to estimate moisture content by measurement of relative dielectric constant of concrete. With moisture content and attenuation measurements, GPR may then be able to provide all the information needed to predict chloride quantities in concrete without the need for calibration cores and laboratory chloride measurements.

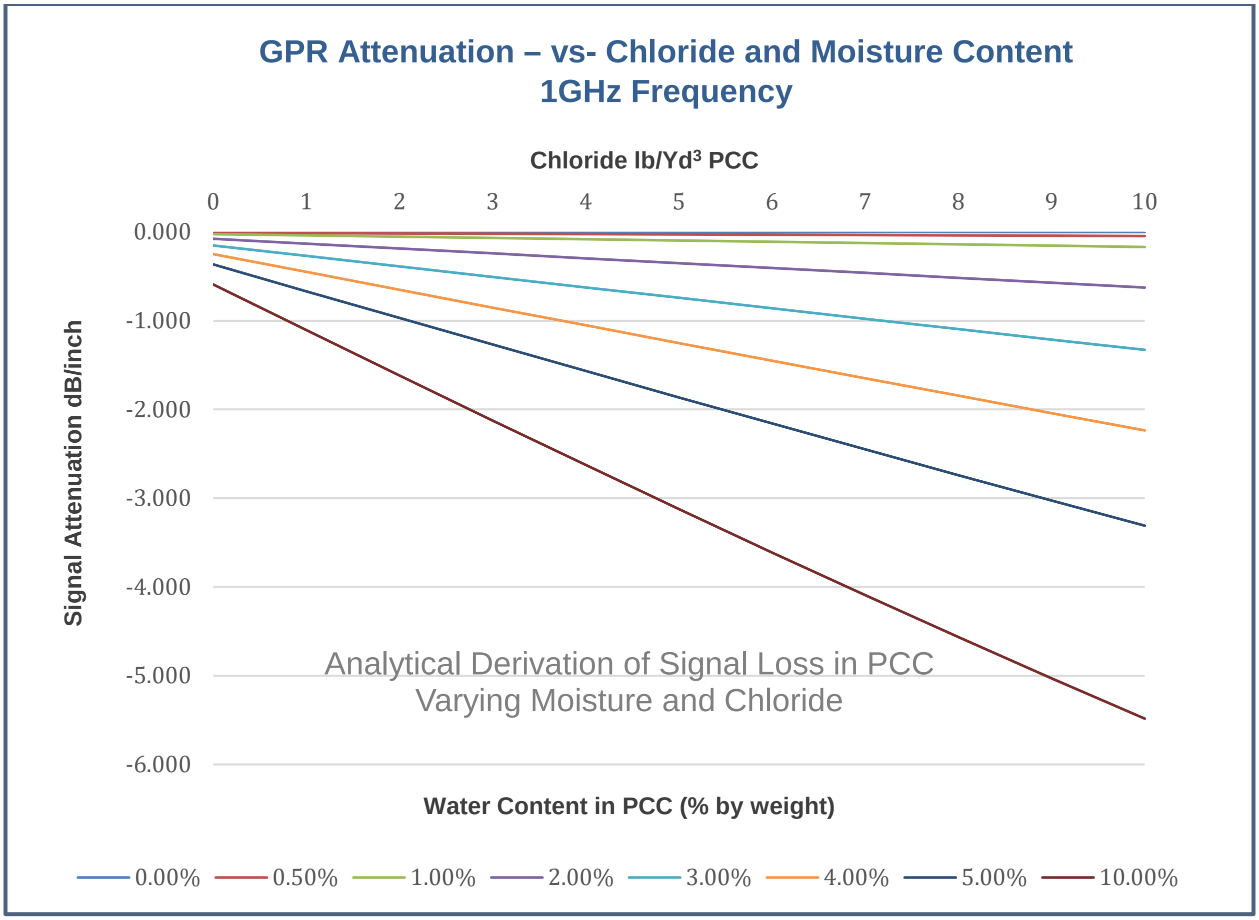



**FIGURE (6) Attenuation -vs- Chloride - Analytically Derived**

### 2.3.2 Laboratory Experiments

Chlorides and moisture can penetrate into the bridge deck concrete over time. This process may take many years, however, when the concentration of chloride is sufficiently high, corrosion of the reinforcing steel will take place and subsequent damage to the concrete will occur due to expansion of the corroded steel. From the standpoint of microwave and radio frequency (RF) propagation, bridge deck concrete is modeled as a lossy dielectric material and it was shown previously in analytical modeling of bridge deck concrete that radar waves traveling through lossy dielectric materials will experience signal loss in relation to the conductivity and relative dielectric constant of the material. The model suggested that the signal losses experienced by a radar wave in concrete were based on both the quantity of dissolved chlorides and the quantity of moisture together. To support the project objectives and validate the analytical model, an experiment was designed to show that dissolved chlorides and moisture introduced into a material will produce a signal loss by affecting the conductivity and relative dielectric constant of that material.

An experiment was designed to quantify radar signal attenuation in laboratory specimens made up of a gravel and sand mix to simulate concrete. The gravel and sand were air-dried to ensure that there was very low residual moisture in the specimen initially. Into this mix, calibrated amounts of moisture and chloride were introduced. The compacted sand/gravel mix was used instead of concrete specimens for several reasons. While being similar to dry concrete from a radar standpoint, it was possible to vary the moisture and chloride quantities in the sand/gravel mix in a precise and uniform manner throughout the sample. Uniform chloride and moisture distribution would be very difficult to achieve in concrete samples. This was important since the accuracy of the experiment depended on the ability to produce test samples with precisely known quantities of moisture and chloride, and distributed evenly throughout its volume. Also, by using the same sand/gravel/chloride sample and incrementing the moisture quantity for each test it was possible to eliminate variability in material properties based on differences in mix.

| CL- | | | | Water (% by weight) | | | | | | | Actual weight of sand/gravel box (LB) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| lb/cu yd | depth of mix | Volume/box | lb cl/box | 0 | 1 | 2 | 3 | 5 | 7 | 10 | |
| | (inch) | (cu yd) | | Fluid Ounce | | | | | | | |
| 0 | 6 | 0.0691 | 0.000 | 0 | 33.4 | 66.7 | 100.1 | 166.8 | 233.5 | 333.6 | 217.51 |
| 0.5 | 6 | 0.0691 | 0.035 | 0 | 33.4 | 66.7 | 100.1 | 166.8 | 233.5 | 333.6 | 217.51 |
| 1 | 6 | 0.0691 | 0.069 | 0 | 33.4 | 66.7 | 100.1 | 166.8 | 233.5 | 333.6 | 217.51 |
| 2 | 6 | 0.0691 | 0.138 | 0 | 33.4 | 66.7 | 100.1 | 166.8 | 233.5 | 333.6 | 217.51 |
| 3 | 6 | 0.0691 | 0.207 | 0 | 33.4 | 66.7 | 100.1 | 166.8 | 233.5 | 333.6 | 217.51 |
| 5 | 6 | 0.0691 | 0.345 | 0 | 33.4 | 66.7 | 100.1 | 166.8 | 233.5 | 333.6 | 217.51 |
| 7 | 6 | 0.0691 | 0.483 | 0 | 33.4 | 66.7 | 100.1 | 166.8 | 233.5 | 333.6 | 217.51 |
| 10 | 6 | 0.0691 | 0.691 | 0 | 33.4 | 66.7 | 100.1 | 166.8 | 233.5 | 333.6 | 217.51 |

Table (4) Sand/Gravel with Water & Chloride Experiment

For this experiment, 56 separate tests were conducted, with moisture contents ranging from 0% by weight to 10% by weight, while varying chloride contents from 0 $lb/yd^3$ to 10 $lb/yd^3$ as shown in the chart in Table (4). These variations represent what we believe to cover the range of conditions to be expected in-situ in the bridge deck environment. Radar measurements were then made to determine signal loss and relative dielectric constant. Radar measurements were made with two Penetradar air-coupled horn antennas having a center frequency of 1GHz and 2GHz.


**FIGURE (7) GPR Experiment to Measure Signal Attenuation**

Equal parts of dry sand and dry gravel were mixed together to fill a 24 inch x 23.375 inch x 6 inch plastic box along with water and table salt as a source of chloride, as shown in Figure (7). A metal plate was placed at the bottom of the box to reflect all impinging energy from the radar antenna. Tests were conducted with the antenna placed exactly 6 inches over the top of the sand-gravel box. To ensure complete mixing of sand, gravel, water and salt, a commercial concrete mixer was used. Measurements of the amplitude of the signal reflection from the metal plate under the box were made in each case to determine the losses resulting from varying amounts of chloride and water in the mix. The transit time between the surface and metal plate were also measured to determine the effect of water and chloride in varying amounts on the relative dielectric constant of the material.

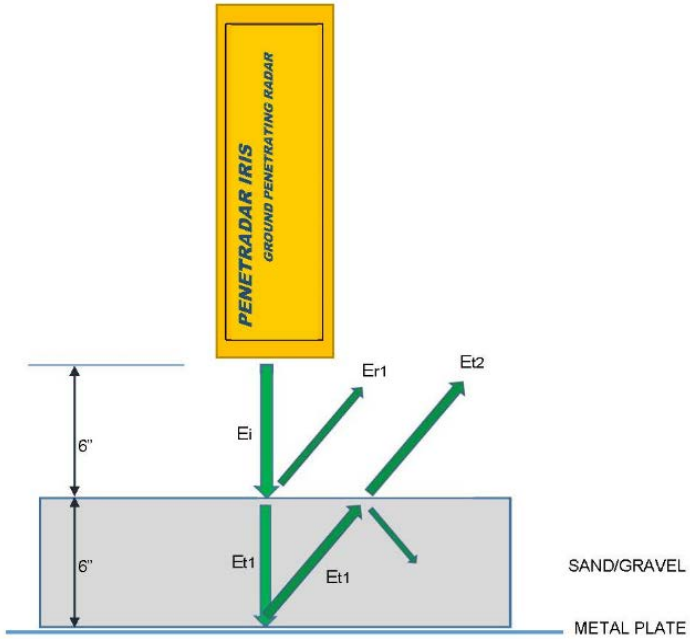



**FIGURE (8) Sand-Gravel Experimental Setup**

Figure (8) shows the experimental setup and a ray diagram showing the signal path. Loss measurements were determined by comparing the measured signal strength compared to the lossless case. Loss calculations (in dB) were made using the following equation:

$$L\ (\text{dB}) = 20 \log \frac{E_{t2}}{\sqrt{(E_i^2 - E_{r1}^2) \times (1-\rho^2)}} \quad (5)$$

Where $$\rho = \frac{1-\sqrt{\varepsilon}}{1+\sqrt{\varepsilon}} \quad (6)$$

Unit loss is defined as L divided by twice the depth of sand-gravel mix, which in this case is 12 inches.

The experiment produced a set of curves showing radar signal attenuation -vs chloride content (ranging from 0 to 10 lb/cubic yard of material), each at moisture levels of 0, 1, 2, 3, 4, 5, 7 and 10 percent by weight, as shown in Figure (9) for a 1 GHz center frequency radar signal and Figure (10) for a 2 GHz center frequency radar signal. Attenuation levels increase based upon frequency as is expected, and appear to vary linearly with the quantity of chloride in the mix and increase as the concentration of water increases for a given amount of chloride. However, at lower moisture levels with higher chloride content the curves become nonlinear with high chloride levels. The cause for nonlinearity is related to the reduction in mobility of chloride ions when in higher concentration and in these instances, greater quantities of chloride have less effect proportionately on conductivity as the water-chloride solution becomes saturated. This is not unreasonable since in the extreme case where there was no water added, there was no variation in signal attenuation in a dry mix regardless of the quantity of chloride added.

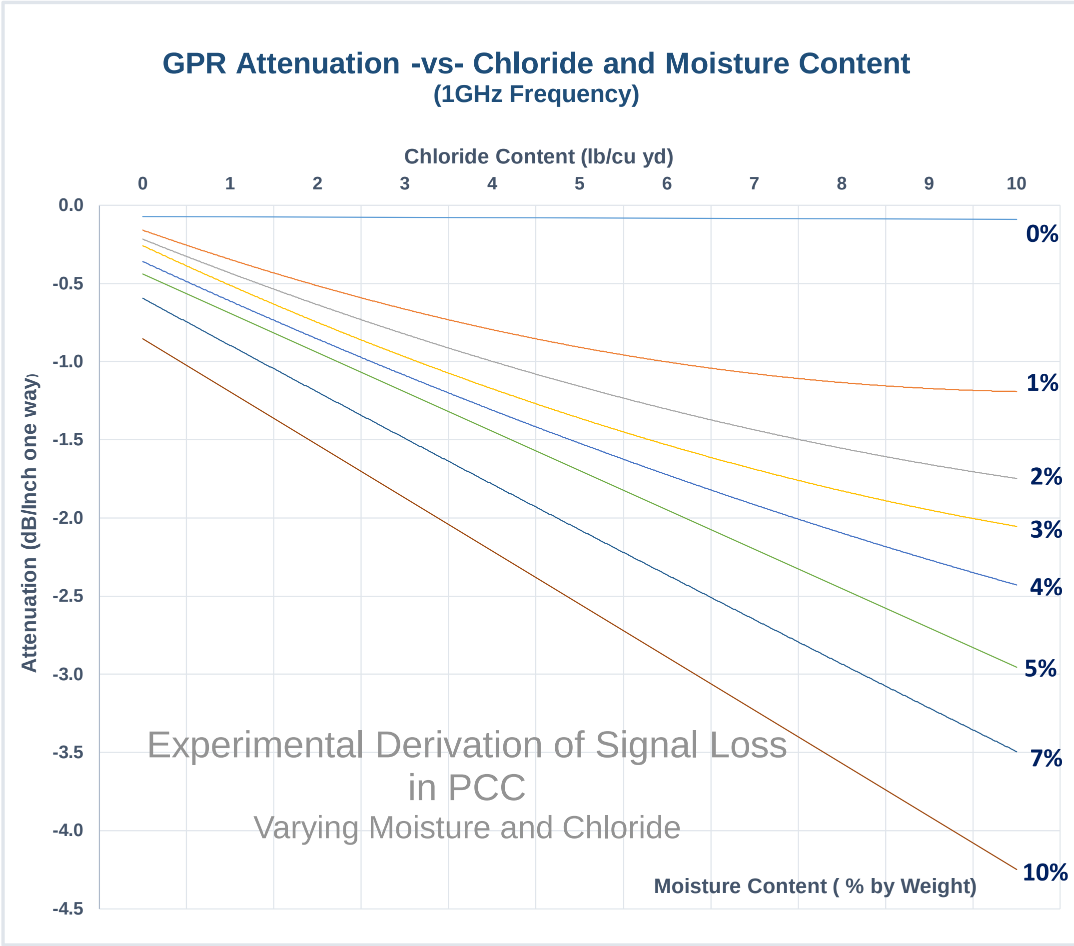



**FIGURE (9) Attenuation -vs- Chloride at 1GHz - Experimental Results**

Signal attenuation is affected both by the concentration of water and chlorides in a simulated concrete mix which confirms the modeling results. Both greater amounts of chloride and greater amounts of moisture cause increased attenuation. In this experiment, where no chloride and only moisture was present the signal attenuation ranged from approximately -0.04dB with 0% water to approximately -0.7dB per inch of material with 10% water at 1GHz. With 3-lb chloride/yd$^3$ of material, the attenuation ranged from -0.07dB with 0% water to -1.8dB per inch with 10% water at 1GHz. This is not unexpected since material with higher moisture content will have a greater conductivity and higher losses, and when chloride is introduced the losses are greater still. These measurements represent attenuation levels experienced one-way. Since radar measures two-way distance to a target and back, these levels will be multiplied by two.

The experiments demonstrated that there is little or no variation in attenuation without some moisture in the sand/gravel sample regardless of the quantity of chloride. However, small amounts of moisture, even on the order of 1-2% by weight are sufficient to produce a measurable variation in attenuation in the presence of chloride.

For chloride quantities less than 5 lb/yd$^3$ attenuation levels are linearly related to chloride quantity, for a given moisture level, however, as stated previously, signal attenuation tended to “level off” and reach an asymptotic limit with low moisture levels and high chloride levels. This was observed at low moisture

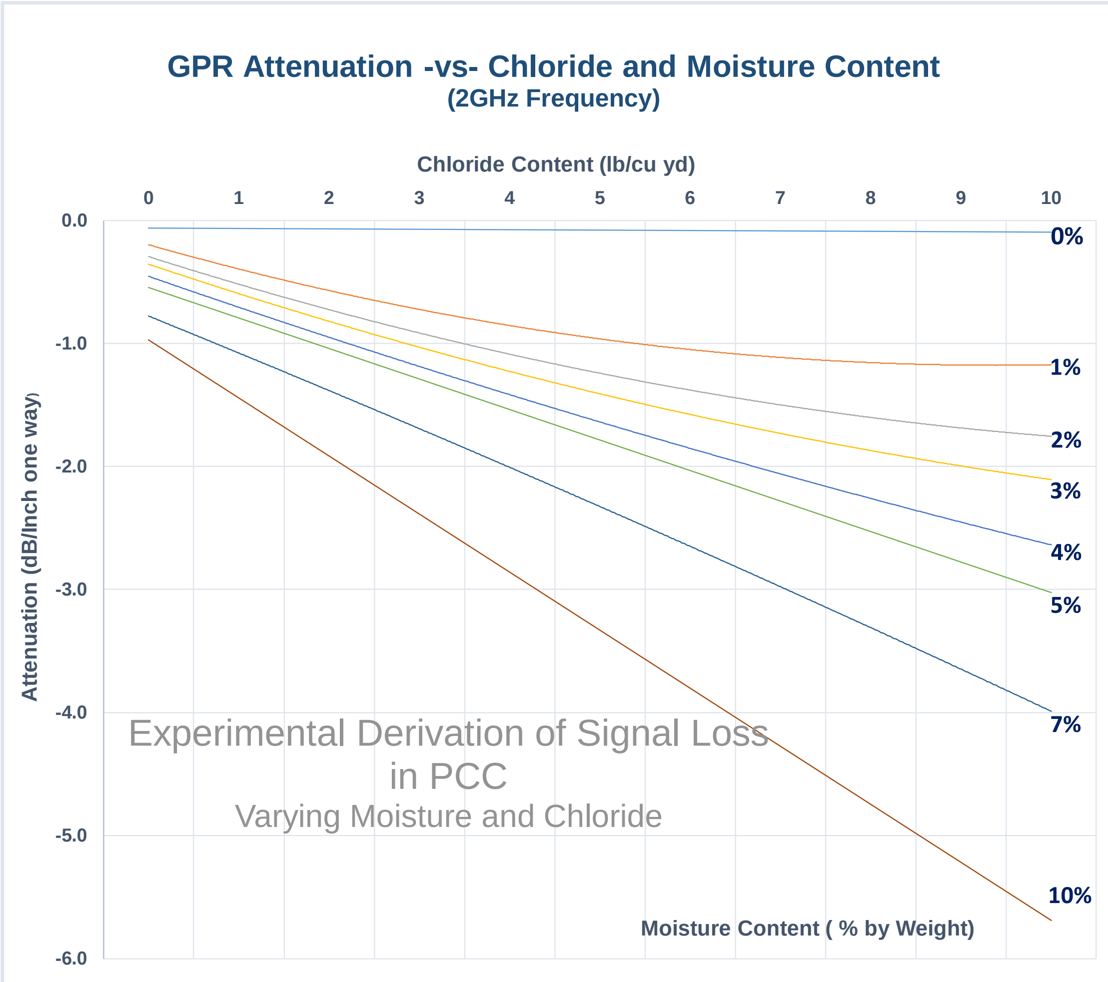



**FIGURE (10) Attenuation -vs- Chloride at 2GHz - Experimental Results**

levels of less than 2% and chloride levels in excess of 5 lb/yd$^3$. At higher moisture levels, i.e. 4% or more, this was not observed.

The experiments also support the proposition that a limited number of chloride samples can be utilized to calibrate radar measurements, provided that the moisture is constant throughout the concrete, and even though the quantity of moisture in the sample may be unknown. Because the attenuation –vs- chloride curves are approximately linear, in theory the chloride quantity can be predicted based on measurement of signal attenuation if the attenuation measurements are calibrated by as few as two or perhaps three chloride samples.

Chloride levels were not found to influence the relative dielectric constant of the sand/gravel mix at the frequencies propagated, only the attenuation was affected. There was no observable change in relative dielectric constant of the sand/gravel mix based on chloride level over a range of 0-10 lb/yd$^3$. However, moisture levels were found to significantly influence the relative dielectric constant. This suggests that the relative dielectric constant is independent of chloride content and is solely a function of moisture content for the frequencies tested.

A chloride prediction will be less accurate when the moisture content is very low and may not work at all when moisture in the concrete is nonexistent. This is shown by both the modeling and experiments and is illustrated by the 0% moisture curve in Figure 9 & 10. For the 0% moisture case, the attenuation does not vary for any level of chloride and it is not possible to determine chloride concentration. This suggests the method should not be used during hot summer months at times when the bridge deck is extremely dry or when the decks are frozen. This method will provide the best results in cases where moisture levels in concrete are greater than 1-2% and fairly uniform across the deck area. In cases where moisture is highly variable, i.e. where the moisture content varies greatly across the deck area, from location to location, a chloride prediction based on a few calibrated attenuation measurements will be less accurate, since attenuation can vary based on chloride as well as moisture content. Unless the moisture content can be determined, either by radar measurement or by other means, it is advisable that radar attenuation measurements be made when the deck is surface dry and when it can be reasonably assured that the deck moisture is relatively uniform.

Table (5) Dielectric Constant as a Measure of Moisture Content
(measured and estimated based on interpolation)

| Water Content % | Average Measured $\varepsilon$ | Interpolated $\varepsilon$ | Deviation |
|---|---|---|---|
| 0 | 4.53 | 4.53 | 0.00 |
| 1 | 5.10 | 5.29 | 0.04 |
| 2 | 5.83 | 6.06 | 0.04 |
| 3 | 6.77 | 6.82 | 0.01 |
| 4 | 7.60 | 7.59 | 0.00 |
| 5 | 8.62 | 8.35 | -0.03 |
| 7 | 10.45 | 9.88 | -0.05 |
| 10 | 14.07 | 12.18 | -0.13 |
| 15 | 19.79 | 16.00 | -0.19 |

The use of radar for measurement of moisture content was also investigated. The laboratory experiments showed that it may be possible to predict moisture concentration based on measurement of relative dielectric constant. Table (5) shows moisture content and measured dielectric constant from the experiment, along with estimated dielectric constant derived using a first order linear interpolation. The low deviation between measured and estimated (interpolated) relative dielectric constant (for moisture content of 0-7% by weight) says that moisture content can be reasonably approximated based on the dielectric constant, with a deviation of less than 5% for moisture levels between 0 to 7%.

With moisture content estimated by radar measurement of dielectric constant, as shown above, then it is possible for GPR to predict chloride quantity without the need of calibration information, i.e. without cores and chloride calibration. Using the attenuation-chloride relationship shown in Figure (9) and a radar measurement of attenuation and dielectric constant, the chloride content can be found.

### 2.3.3 Field Testing and Data Collection

The third research approach involved field testing. An in-situ test was designed to evaluate the GPR technique for measurement and mapping of chlorides in concrete. This field test involved GPR data collection on a bridge deck, the measurement of radar signal attenuation and comparison with laboratory measurements of chloride based on cores extracted from the deck. A regression model was developed between GPR signal attenuation and chloride quantity to illustrate how, in practice, GPR measurements of attenuation along with a limited number of cores can be used to predict chloride levels throughout the deck and produce a graphical mapping of chloride levels throughout the deck.

Field testing was conducted on the Sanger Avenue overpass bridge on I-395 in Alexandria, VA. At the time of testing the Sanger Avenue bridge had a 2-1/4 inch asphalt overlay, recently placed over the existing 8 inch concrete deck. The deck was 72 feet in length with four lanes and shoulders. Data collection on this bridge deck was conducted at night and only in the two left southbound lanes. Data were collected using 1GHz and 2GHz (center frequency) non-contacting horn antennas and 2GHz contacting antenna. Three polarizations were evaluated for the horn antennas – normal, perpendicular and 45 degrees relative to the direction of travel. For the contacting antenna, a perpendicular polarization was used. The GPR data was collected in a traditional manner as a series of parallel scans along the length of the deck. The continuous antenna scans were made with each antenna and polarization at a spacing of two feet along the length of the deck. After an initial review of the data, analysis efforts were concentrated on the data from a 1GHz horn antenna with parallel polarization (i.e. antenna polarization in the direction of travel).


**FIGURE (11) GPR Configuration used to Test the Sanger Avenue Bridge Deck**

### *2.3.3.1 Bridge Deck Chloride Measurements*

Detailed chloride information on the bridge deck was provided by NOVA District (VDOT). A total of (15) cores were taken with chloride sampling performed on the deck concrete. Seven of those cores and laboratory chloride measurements were taken in the two left lanes that were also tested with GPR. The core locations are shown in Figure (12). The chloride levels were measured at three depths for each core, including one inch below the concrete surface (Depth 1), at the top rebar (Depth 2) and at one half inch below the top layer of reinforcement (Depth 3) as shown in Table (6). Chloride measurements were performed by Concorr, Inc. of Sterling, VA, using an acid titration method for determining chloride levels [6].

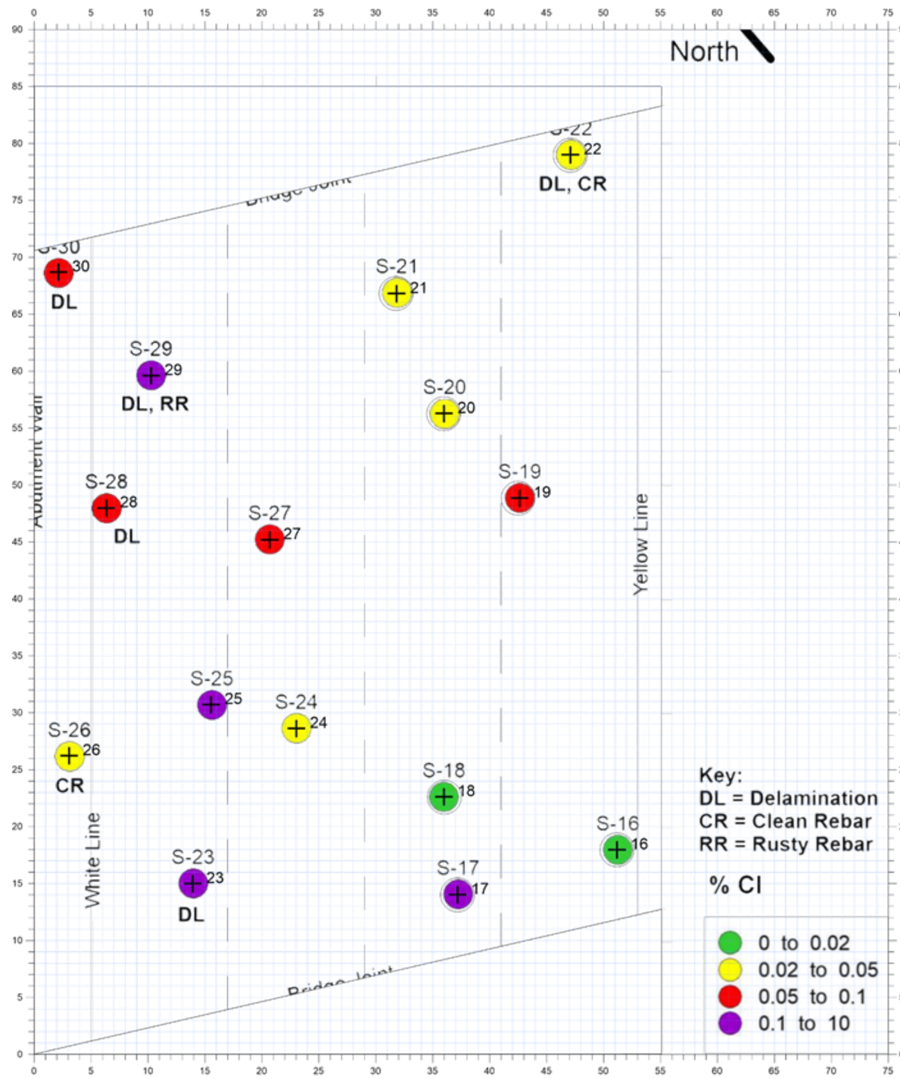



**FIGURE (12) Location of Core Samples on Sanger Bridge**

To develop a model relating chloride concentration and GPR attenuation at the rebar level, we used the chloride values at or above the rebar level to produce an average chloride concentration, since these would be most representative of what was experienced by the radar wave. The chloride measurements below the rebar level were not used. Because we are attempting to relate GPR signal attenuation to the overall chloride concentration in the concrete and not at a particular depth, we are measuring the total attenuation experienced by the radar wave as it travels through the top part of the concrete, i.e. between the surface and rebar. Since chloride penetration into concrete often follows a gradient, with higher concentration near the surface and lower concentration at depths, averaging chloride measurements from two depths is a reasonable measure and probably more accurate than only one chloride measurement at a single depth. The table below shows the chloride concentrations in parts per million (percentage) and in pounds per cubic yard of concrete.

| Core | Depth1 (in) | Depth2 (in) | Depth3 (in) | D1 % | D1 lb/yd$^3$ | D2 % | D2 lb/yd$^3$ | D3 % | D3 lb/yd$^3$ | Depth 1 & 2 lb/yd$^3$Avg |
|---|---|---|---|---|---|---|---|---|---|---|
| S-16 | 2.25 | 2.75 | 3.25 | 0.012 | 0.480 | 0.009 | 0.370 | 0.011 | 0.410 | 0.425 |
| S-17 | 2.25 | 2.75 | 3.25 | 0.150 | 5.880 | 0.112 | 4.380 | 0.080 | 3.150 | 5.130 |
| S-18 | 2.25 | 2.75 | 3.25 | 0.017 | 0.680 | 0.015 | 0.590 | 0.011 | 0.410 | 0.635 |
| S-19 | 2.25 | 2.75 | 3.25 | 0.079 | 3.100 | 0.043 | 1.700 | 0.032 | 1.250 | 2.400 |
| S-20 | 1.88 | 2.38 | 2.88 | 0.020 | 0.800 | 0.011 | 0.410 | 0.007 | 0.290 | 0.605 |
| S-21 | 1.75 | 2.25 | 2.75 | 0.031 | 1.200 | 0.020 | 0.770 | 0.012 | 0.480 | 0.985 |
| S-22 | 2.38 | 2.88 | 3.38 | 0.038 | 1.470 | 0.042 | 1.660 | 0.017 | 0.670 | 1.565 |

TABLE (6) Laboratory Chloride Measurements from Seven (7) Left Lane Core Samples

#### *2.3.3.2 GPR Attenuation and Chloride Quantities*

GPR signal attenuation is essentially a measurement of reflected power from the medium at or about the depth of the top reinforcement and is reported in decibels (dB) relative to the emitted power as measured at the surface of the material examined. A mapping of the GPR attenuation was generated which shows power levels in a colorized format along with the core locations superimposed. See Figure (13). Radar scans were made with a two-foot spacing starting at a transverse distance of 31 feet. To develop the attenuation-chloride relationship it is necessary to measure the GPR attenuation at the location of the core samples. For cores located on the GPR scan track, this measurement is straight forward, however, to derive an accurate measurement of attenuation for those cores that were taken in between the GPR scans it was necessary to interpolate the radar data from the two adjacent radar scans. We believe this to be a reasonable approach considering the nature of the elliptical antenna beam pattern or “footprint” on the pavement surface which extends beyond the dimensions of the actual antenna aperture. In normal practice, we anticipate that core sample selection and location would be made after GPR data were collected and not before as was the case here. In that way, not only would it be possible to sample a wider range of attenuation levels by coring, ranging from low to high attenuation, but the core samples could be located directly on a radar scan, thus eliminating the need to interpolate between GPR scans.

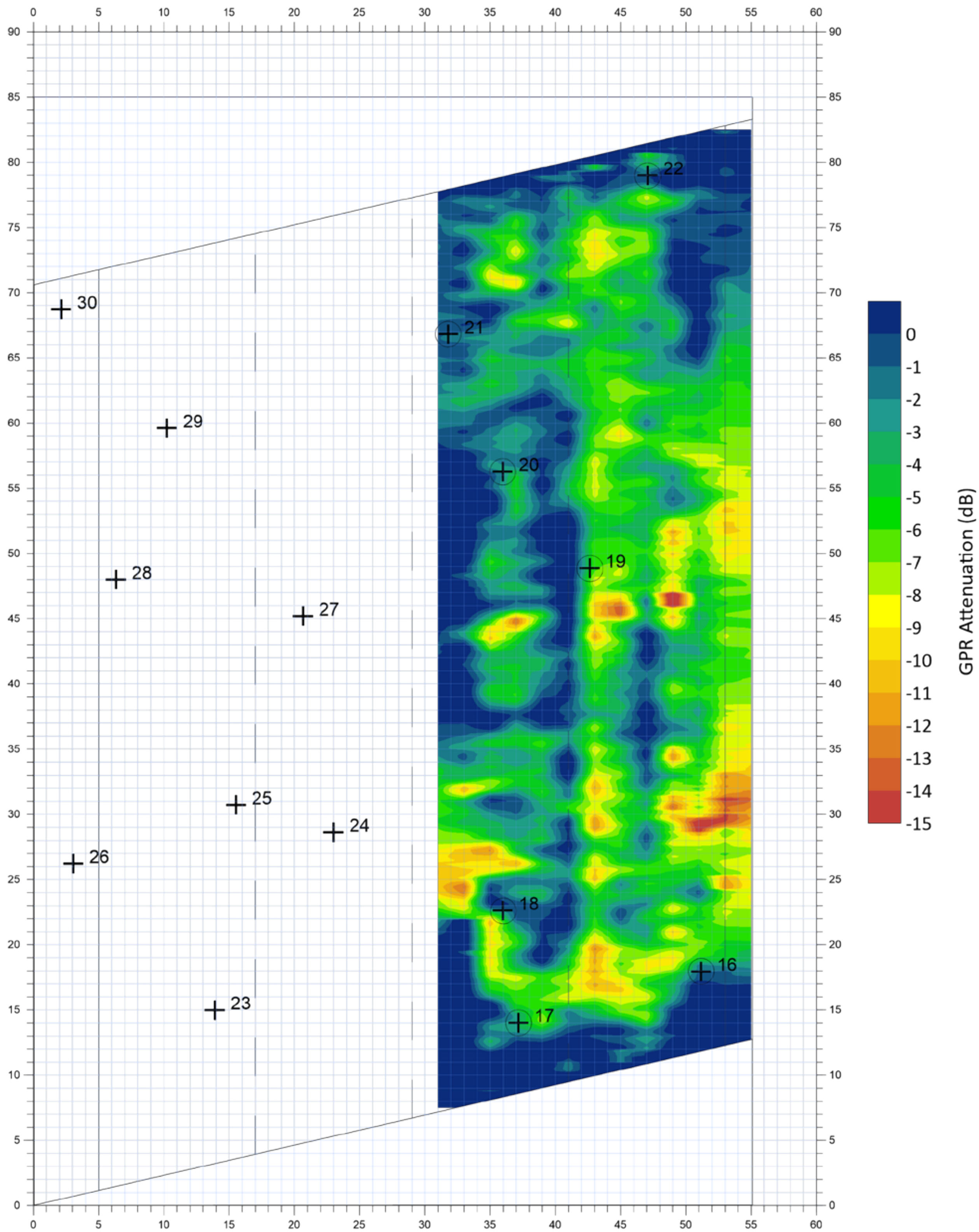



**FIGURE (13) GPR Attenuation Mapping (in dB) from GPR scan with core locations**

The table below shows GPR attenuation measurements and chloride concentrations (lb/yd$^3$) for each of seven core locations (S-16 through S-22) that were taken in the left, southbound lanes. It can be seen that GPR attenuation ranges from -2.758 dB to -6.379 dB while at the same time chloride concentrations also increase and range from 0.605 lb/yd$^3$ to 5.13 lb/yd$^3$. To determine the significance of the data and whether there is a correlation between GPR attenuation and chloride quantity it was necessary to develop a regression model.

| Core | GPR Attenuation (dB) | Chloride Concentration (lb/yd$^3$) |
|---|---|---|
| **S-16** | -2.991 | 0.425 |
| **S-17** | -5.389 | 5.130 |
| **S-18** | -2.758 | 0.635 |
| **S-19** | -6.379 | 2.400 |
| **S-20** | -3.036 | 0.605 |
| **S-21** | -3.398 | 0.985 |
| **S-22** | -3.680 | 1.565 |

TABLE (7) GPR Attenuation and Chloride Concentration

### *2.3.3.3 Developing a Linear Regression Model*

To develop a chloride-attenuation relationship we can utilize the seven core locations with known chloride concentrations and corresponding GPR attenuation in those locations to develop a model, and then apply that linear relationship to determine the chloride concentration for the rest of the bridge deck.

With these measurements, we can develop a linear regression model.

$$y = mx + b$$

where

x = GPR attenuation (dB) at the top reinforcement level
y = Chloride concentration (lb/yd$^3$)
m = slope/gradient, $\frac{\Delta y}{\Delta x}$
b = y-intercept (where the line intersects with the y-axis)

The slope (m) can be found using the equation:

$$m = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{n\sum x_i^2 - \sum x_i{}^2}$$

n = number of cores

$\sum x_i y_i$ = the summation of the products of each x-y pair

$\sum x_i \sum y_i$ = the sum of all x-values times the sum of all y-values

$\sum x_i^2$ = the sum of all squared x-values

$\sum x_i{}^2$ = the squared summation of all x-values

The y-intercept is calculated as:

$$b = \bar{Y} - m\bar{X}$$

where

$$\bar{X} = \frac{\sum x_i}{n}$$

$$\bar{Y} = \frac{\sum y_i}{n}$$

Using the values from all seven core locations yields a slope of

$$m = -0.9162$$

and a y-intercept of

$$b = -1.9388$$

So, the linear regression relationship is shown in equation (5) as follows:

$$y = -0.9162x - 1.9388 \qquad (5)$$

$R^2$ – Coefficient of Determination: Explained Variation / Total Variation

This value gives a proportion indicating how well a dependent variable (chloride concentration) can be predicted from the independent variable (GPR attenuation).

Where (R) is the correlation coefficient and can be calculated by the equation below

$$R = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{\sqrt{n\sum x_i^2 - \sum x_i{}^2}\sqrt{n\sum y_i^2 - \sum y_i{}^2}}$$

R = 0.760

$$R^2 = 0.578 = 57.8\% \qquad (6)$$

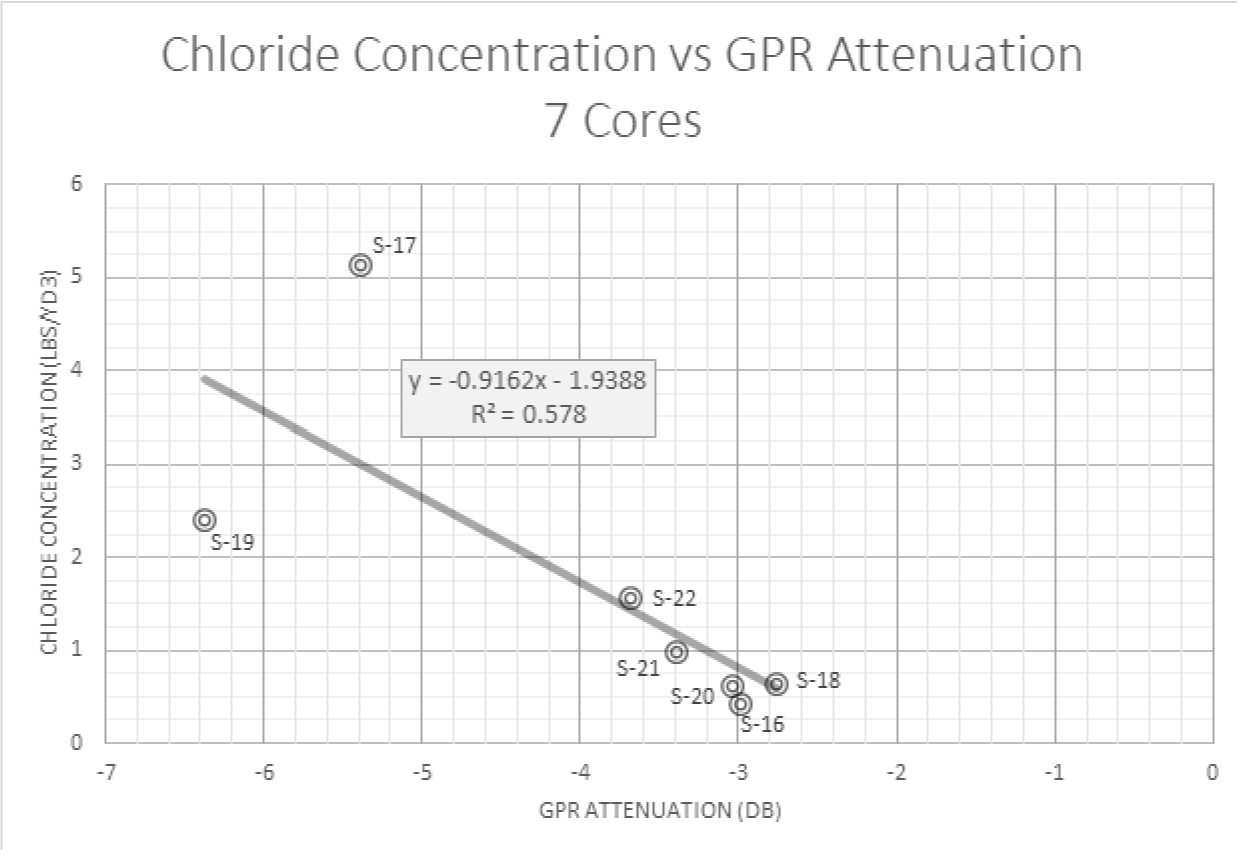



**FIGURE (14) Linear Regression Model Based on 7 Cores (Chloride) Samples**

An $R^2$ value of 57.8% indicates that this model accounts for roughly 58% of the variance. In this case the majority of the variance is from one sample, S-17, since six of seven chloride measurements seem to closely follow the linear regression relationship. The reason for the large variance in S-17 is unknown but could be due to an error in plotting the core location (there was a large nearby region of higher attenuation) or possibly due to a small, isolated area of very high chloride, not detected by the GPR. As stated previously, it is envisioned that chloride samples and core locations would be selected after analysis of the GPR data and based upon the GPR results, as well as located on the GPR scan and not in between scans. If the S-17 sample is eliminated the regression relationship changes significantly.

The linear regression relationship from equation (5) then becomes:

$$y = -0.5223x - 0.8338 \qquad (7)$$

The $R^2$ value increases significantly,

$$R = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{\sqrt{n\sum x_i^2 - \sum x_i{}^2}\sqrt{n\sum y_i^2 - \sum y_i{}^2}}$$

$$R = 0.936$$

$$R^2 = 0.875 = 87.5\% \qquad (8)$$

An $R^2$ value of approximately 87.5%, suggests that the relationship developed has a relatively high probability of predicting the expected chloride concentration based on a known GPR attenuation value.

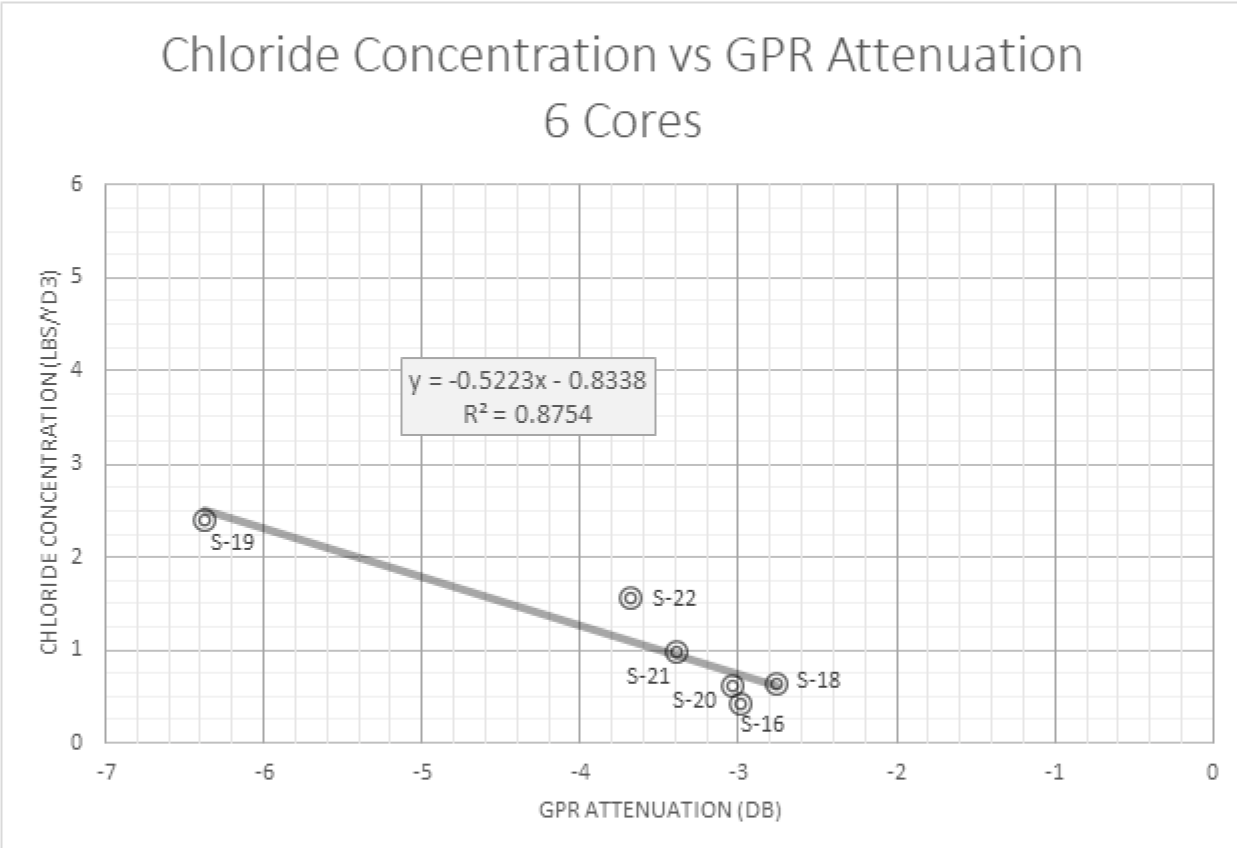



**FIGURE (15) Linear Regression Model Based on 6 Cores (Chloride) Samples**

### *2.3.3.4 Chloride Mapping*

To demonstrate how this method can be used, the attenuation-chloride relationship derived above along with the attenuation mapping shown in Figure (13) can now be used to produce a mapping of chlorides as shown in Figure (16). The mapping now provides an absolute measure of the average levels of chloride in the concrete at or above the rebar level. What is interesting to note is that by calibrating the GPR measurements it may now be possible to determine maximum and minimum chloride levels in the concrete as well as identify precise locations of high chloride or levels that exceed a predefined threshold.

While this mapping shows the chloride level based on GPR signal attenuation, we know that signal attenuation is based not only on chloride level but also moisture in the concrete, and it is in fact the combination of those two that causes GPR signal loss or attenuation in concrete. SHRP C101 research found that the same level of signal attenuation can be achieved with different combinations of moisture and chloride which was confirmed by the results of this project. It may be possible to account and compensate for variations in deck moisture but for the present we will assume that the moisture level is relatively consistent throughout the deck. In practice it may be necessary to conduct GPR measurements when deck moisture is most uniform, such as after a period of no precipitation and when the deck is surface dry.

Examining the regression relationship shown in equation (7) further,

$$y = -0.5223x - 0.8338$$

it is interesting to note that at a 0 lb/yd$^3$ chloride concentration, i.e. y = 0 lb/yd$^3$, the GPR attenuation is about -1.6 dB, meaning that in the absence of chloride there is still signal attenuation, which is to be expected. This is likely the result of the lossy properties of the concrete itself along with the moisture that is present. At a -16 dB level, which is the approximate maximum levels of signal attenuation based on the attenuation map in Figure (13), the maximum chloride concentration is estimated to be approximately 7.5 lb/yd$^3$.

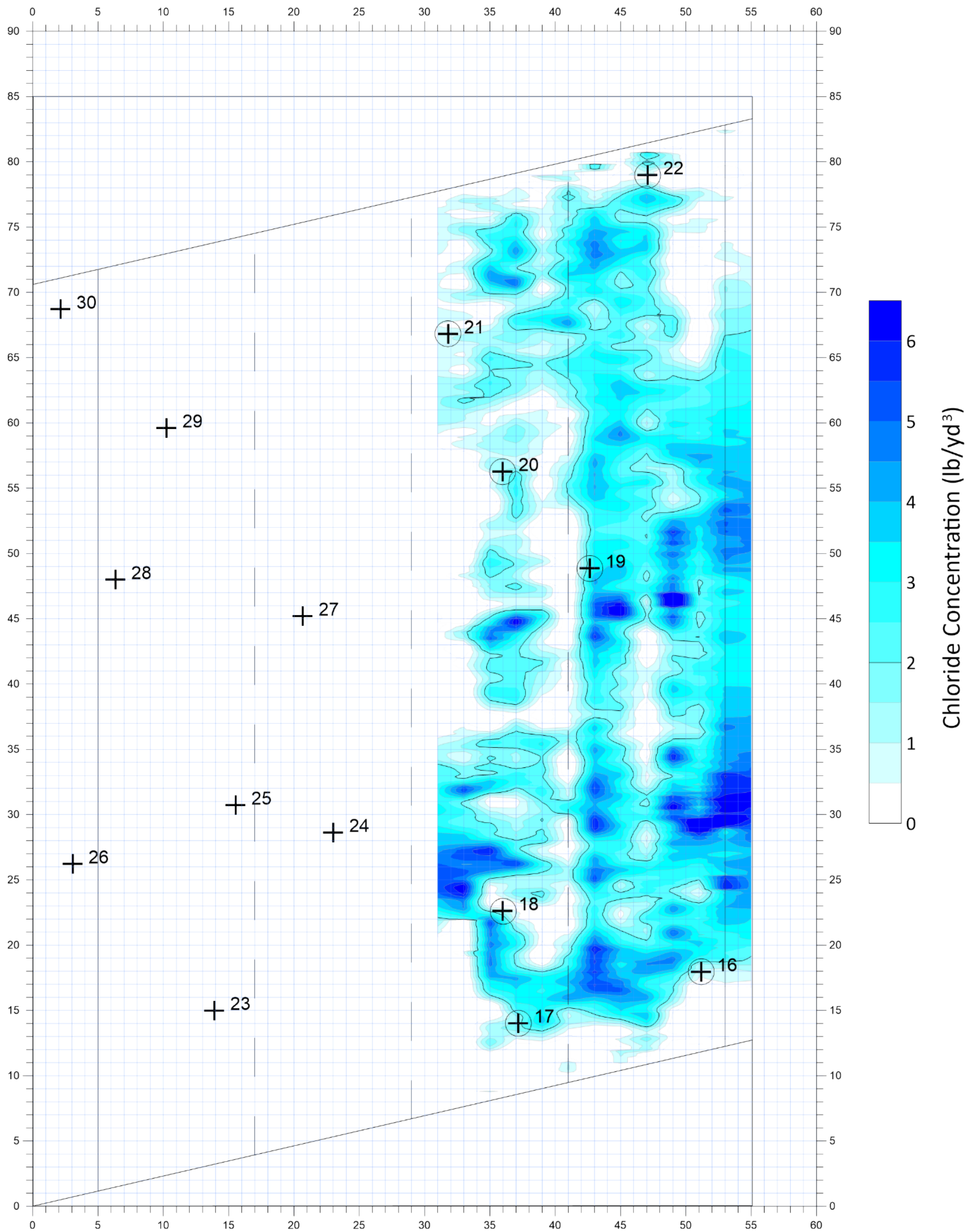



**FIGURE (16) Chloride Mapping Based on GPR Attenuation Measurements ($R^2$=0.875 based on 6 chloride samples, core 16, 18, 19, 20, 21 & 22)**

### *2.3.3.5 Optimizing the Regression Model and Testing the Concept*

To be a cost-effective method in practice, it is desirable to collect only the minimum number of chloride samples while at the same time maintaining an acceptable level of predictive accuracy. The advantages offered by the GPR technique would be diminished if large number of core samples were required. In practice, we anticipate that core locations would be selected to cover the greatest dynamic range of attenuation values and it is expected that only a few cores and chloride measurements for calibration may be needed. To optimize the regression model, we selected three cores (chloride samples), S-16, S-19 and S-22, from the six available samples that best span the range of GPR signal attenuation and in addition, were closest to the actual GPR scan path, i.e. where it was unnecessary to interpolate between scans. The three samples are highlighted in the chart below.

| Core | GPR Attenuation (dB) | Chloride Concentration (lb/yd$^3$) |
|---|---|---|
| **S-16** | -2.991 | 0.425 |
| **S-18** | -2.758 | 0.635 |
| **S-19** | -6.379 | 2.400 |
| **S-20** | -3.036 | 0.605 |
| **S-21** | -3.398 | 0.985 |
| **S-22** | -3.680 | 1.565 |

TABLE (8) GPR Attenuation and Chloride Concentration

By using these three chloride samples, we can develop the linear regression model using the equations discussed earlier.

$$y = mx + b$$

$$m = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{n\sum x_i^2 - \sum x_i{}^2}$$

$$b = \bar{Y} - m\bar{X}$$

Substituting x and y values yields the following:

$$m = \frac{-67.02 - -57.29}{189.56 - 170.32} = -0.5058$$

$$b = 4.39 - m * 6.60 = -0.7370$$

The linear regression relationship from using cores S-16, S-19 and S-22 is shown in equation (9) as follows:

$$y = -0.5058x - 0.7370 \qquad (9)$$

The linear regression model based on the three chloride samples from cores S-16, S-19 and S-22, is shown on the plot in Figure (17) and results in an $R^2$=0.835 = 83.5%. It can be seen that the optimized regression model using three samples is very similar to the regression model derived with six samples ($R^2$=0.875) as depicted in Figure (15). Therefore, it is not unreasonable to utilize the model that requires fewer cores, provided that the accuracy of the model is not significantly reduced.

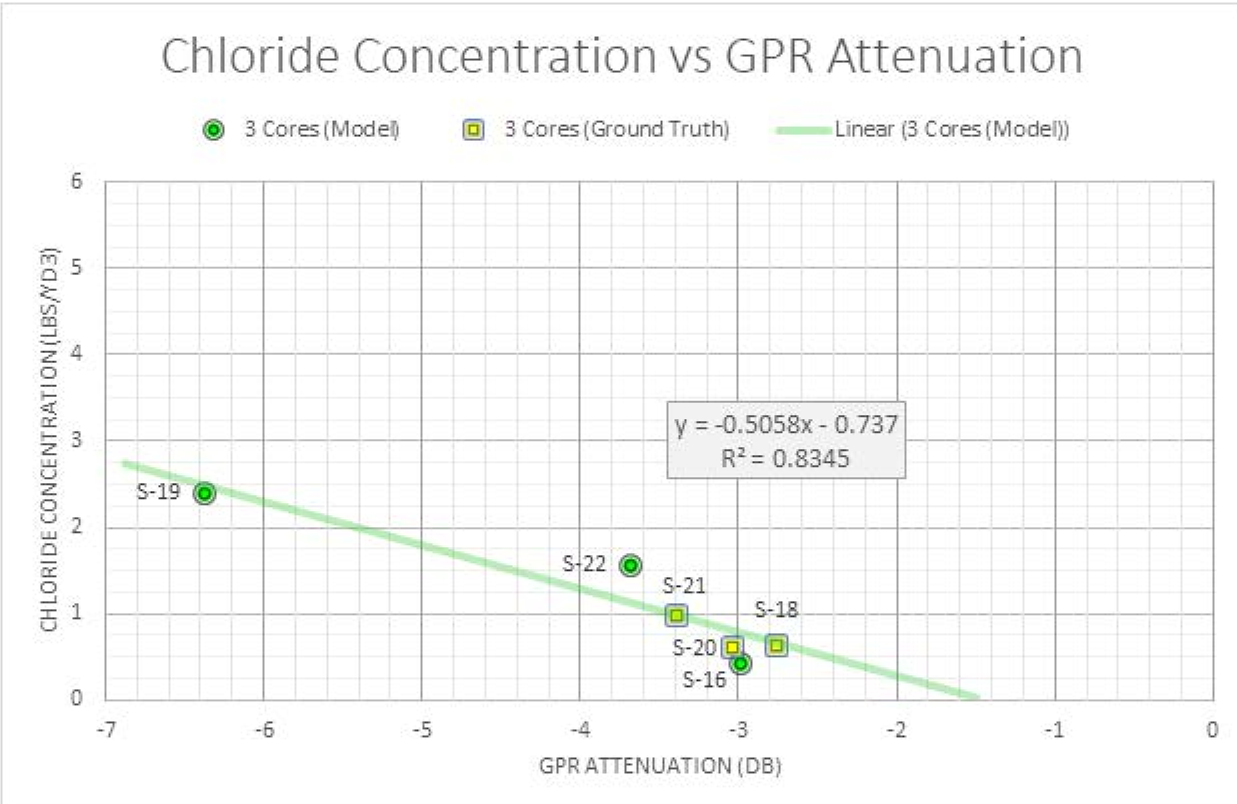



**FIGURE (17) Optimized Linear Regression Model Based on 3 Core (Chloride) Samples**

Now that an optimized (three-core sample) regression model has been developed it is possible to back test the regression model using the remaining three core samples. The cores highlighted in green were used to develop the linear regression relationship and the cores highlighted in yellow were used to determine the deviation between calculated chloride quantities, as given by the regression model and the actual chloride quantities as measured in the laboratory.

| Core | GPR Attenuation (dB) | Chloride Concentration (lb/yd$^3$) | Linear Regression Value (lb/yd$^3$) | Difference |
|---|---|---|---|---|
| **S-16** | -2.991 | 0.425 | - | - |
| **S-18** | -2.758 | 0.635 | 0.658 | 0.023 |
| **S-19** | -6.379 | 2.400 | - | - |
| **S-20** | -3.036 | 0.605 | 0.799 | 0.194 |
| **S-21** | -3.398 | 0.985 | 0.981 | 0.004 |
| **S-22** | -3.680 | 1.565 | - | - |

TABLE (9) Comparison between Predicted and Measured Chloride Concentration

Using the GPR attenuation values for cores S-18, S-20, and S-21 in the linear regression equation above yields the chloride concentration values shown in the 4$^{th}$ column. The difference or residual between these GPR predicted chloride levels and the actual amount measured in the laboratory are shown in the 5$^{th}$ column.

Averaging these differences results in a mean error of ± 0.073 lb/yd$^3$. For these three core samples and in this specific case the model predicted the chloride concentrations with very good accuracy, however, a larger sample of cores would be needed and several bridge decks tested before a good overall statistical measure could be determined for this technique.

Because each GPR measurement produces a chloride quantity, statistics are easily determined as shown in the following table. Average chloride levels as predicted by GPR were determined to be approximately 2 lb/yd$^3$ and levels at the 99th percentile, corresponding approximately to the maximum level, were 7.4 lb/yd$^3$.

| Sanger Avenue Bridge | Chloride Concentration (lb/yd$^3$) |
|---|---|
| **Average** | 1.965 |
| **Standard Deviation** | 1.952 |
| **90$^{th}$ Percentile** | 4.148 |
| **99$^{th}$ Percentile (Max)** | 7.406 |

The chloride map derived from the optimized regression is shown in Figure (18). The mapping is quite similar to that derived from the full data set which suggests that we are not losing information with the optimization.

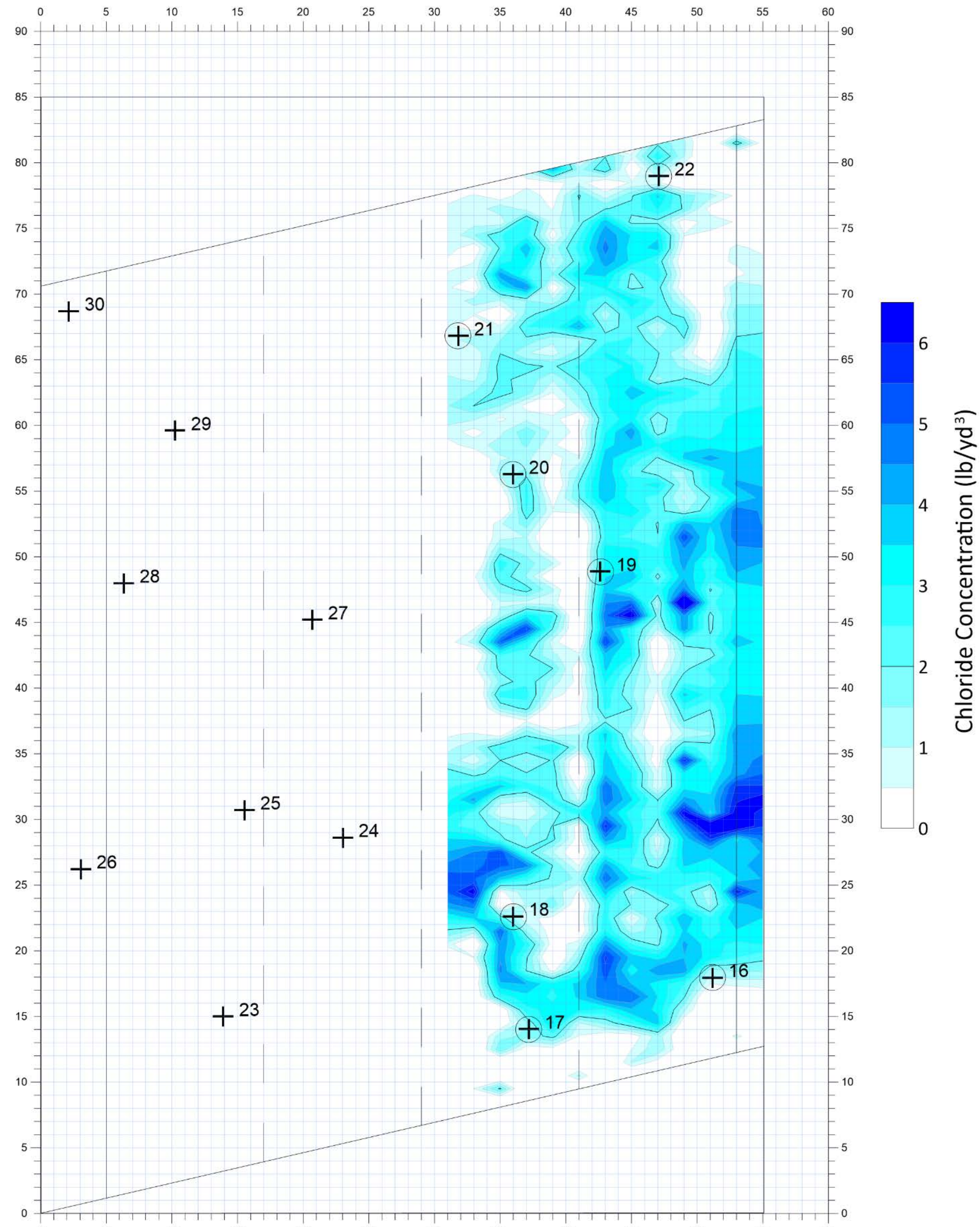



**FIGURE (18) Chloride Mapping Based on GPR Attenuation Measurements**
**($R^2$ = 0.835 based on 3-chloride samples, core 16, 19 & 22)**

### *2.3.3.6 Comparison with Core Samples*

Corrosion of the reinforcing steel and delamination begins when the chloride concentration surpasses a critical level. Typically, this level may range from 2 to 4 lbs/yd$^3$ [7][8]. At the low end of this range, at a threshold of 2 lb/yd$^3$, GPR measurements determined that 47.7% or 801 square feet of the tested 1680 square feet of bridge deck exceeded this value.

Chloride levels from the fifteen core samples taken from both the right and left lanes resulted in an average chloride level of 2.6 lb/yd$^3$ and 53% (8 of 15 samples) exceeding the 2 lb/yd$^3$ threshold level. The GPR determination of 47.7% exceeding the 2 lb/yd$^3$ threshold level compares favorably.

| **Core** | **Depth1 (in)** | **Depth2 (in)** | **Depth3 (in)** | **D1 %** | **D1 lb/yd$^3$** | **D2 %** | **D2 lb/yd$^3$** | **D3 %** | **D3 lb/yd$^3$** | **Depth 1 & 2 PCY Average** |
|---|---|---|---|---|---|---|---|---|---|---|
| S-16 | 2.25 | 2.75 | 3.25 | 0.012 | 0.480 | 0.009 | 0.370 | 0.011 | 0.410 | 0.425 |
| S-17 | 2.25 | 2.75 | 3.25 | 0.150 | 5.880 | 0.112 | 4.380 | 0.080 | 3.150 | 5.130 |
| S-18 | 2.25 | 2.75 | 3.25 | 0.017 | 0.680 | 0.015 | 0.590 | 0.011 | 0.410 | 0.635 |
| S-19 | 2.25 | 2.75 | 3.25 | 0.079 | 3.100 | 0.043 | 1.700 | 0.032 | 1.250 | 2.400 |
| S-20 | 1.88 | 2.38 | 2.88 | 0.020 | 0.800 | 0.011 | 0.410 | 0.007 | 0.290 | 0.605 |
| S-21 | 1.75 | 2.25 | 2.75 | 0.031 | 1.200 | 0.020 | 0.770 | 0.012 | 0.480 | 0.985 |
| S-22 | 2.38 | 2.88 | 3.38 | 0.038 | 1.470 | 0.042 | 1.660 | 0.017 | 0.670 | 1.565 |
| S-23 | 2.75 | 3.25 | 3.75 | 0.133 | 5.220 | 0.097 | 3.790 | 0.081 | 3.180 | 4.505 |
| S-24 | 2.38 | 2.88 | 3.38 | 0.028 | 1.100 | 0.028 | 1.110 | 0.020 | 0.790 | 1.105 |
| S-25 | 3.00 | 3.50 | 4.00 | 0.162 | 6.350 | 0.137 | 5.370 | 0.109 | 4.280 | 5.860 |
| S-26 | 2.50 | 3.00 | 3.50 | 0.020 | 0.790 | 0.010 | 0.410 | 0.006 | 0.250 | 0.600 |
| S-27 | 2.00 | 2.50 | 3.00 | 0.071 | 2.780 | 0.058 | 2.270 | 0.046 | 1.800 | 2.525 |
| S-28 | 2.75 | 3.25 | 3.75 | 0.051 | 2.000 | 0.078 | 3.060 | 0.079 | 3.110 | 2.530 |
| S-29 | 2.50 | 3.00 | 3.50 | 0.188 | 7.360 | 0.183 | 7.180 | 0.119 | 4.680 | 7.270 |
| S-30 | 1.88 | 2.38 | 2.88 | 0.064 | 2.500 | 0.089 | 3.480 | 0.069 | 2.680 | 2.990 |

TABLE (10) Laboratory Chloride Measurements from Fifteen (15) Left & Right Lane Cores

Using chloride values from the 15 cores, we can develop a simplistic model of chloride distribution on the bridge deck. By taking the percentile rank of each chloride concentration (in pounds per cubic yard of concrete), we can compare those results with the calculated area of the deck exceeding the same level based on GPR derived results. The chloride distributions are plotted below in Figure (19).

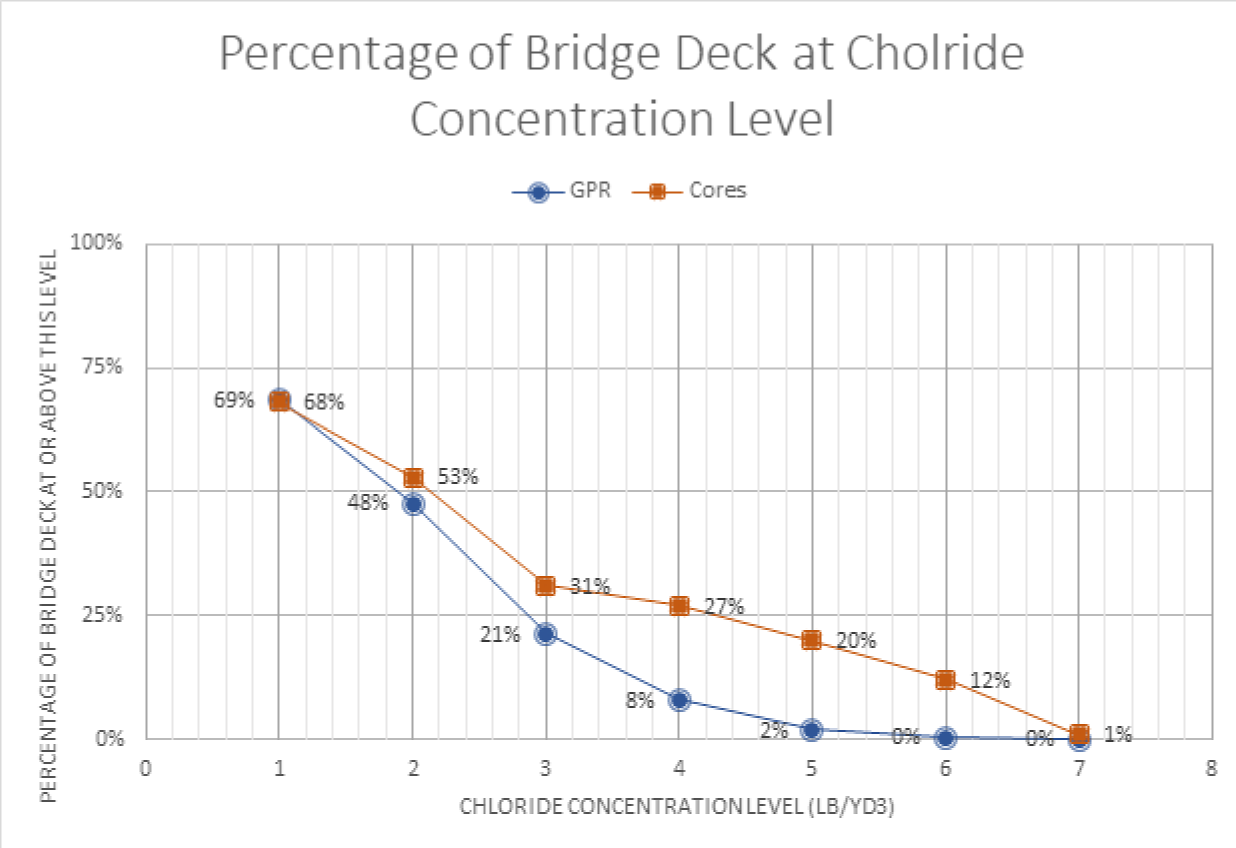



**FIGURE (19) Comparison of Chloride Distribution Based on GPR and Core Samples**

The distribution of chloride levels from cores and GPR follow a similar trend. Ideally, the distributions should be the same but tend to diverge at concentrations of 4 lb/yd$^3$ and greater, where GPR detected lower amounts. It is difficult to know the reason for this divergence, since there are many unknowns, including the rationale for the selection of each core location. For a proper comparison, cores would need to be taken in a random manner without regard to visual condition. In practice, however, core locations are often selected based on the condition and could skew toward the selection of more visually deteriorated areas. Also, it could be due to the simple fact that there were higher concentrations of chloride in the right lanes as compared to the left lanes where the GPR tests were conducted.

It should be emphasized that the GPR model is based on using the values from just three core samples which were selected from the attenuation values. With portions of the histogram similar at low chloride concentrations and diverging at higher concentrations may suggest that a greater number of samples are needed to develop a more precise model. However, if it is only necessary to locate areas of chloride above a specific chloride concentration, for example a 2 lb/yd$^3$ threshold, the GPR model appears to be quite accurate for that purpose.

## 2.4 PLANS FOR IMPLEMENTATION

The GPR technique for measurement of chlorides in concrete can be fielded in its present state of development. It is anticipated that this new chloride measurement technique can be used by all maintenance and design engineers to supplement existing methods of deck condition evaluation for the purpose of project estimation or in advance of actual remediation. In practice, the testing can be performed through contract with GPR service providers or conducted by DOT or engineering staff who operate GPR equipment. This research utilized air-coupled GPR, however, ground contacting GPR may be equally effective.

The GPR method for measurement of chlorides in bridge deck concrete could be implemented in two stages. In the first stage, GPR scanning and data collection of the bridge deck will be conducted in a traditional manner as described in ASTM D-6087. Core samples and laboratory measurements of chloride for calibration as outlined in the field test section of this report will be used to calibrate GPR signal attenuation measurements. GPR data will be collected on the deck in longitudinal scans, accurately positioned in both longitudinal and transverse location. Subsequent GPR measurement of signal attenuation will provide three or more locations on the deck for core samples and chloride calibration, which in theory should be sufficient, however, more samples could yield better reliability. The core locations should be selected to span the range of signal attenuation that was measured. Typically, this will sample as a minimum, an area of high signal attenuation, one midway and at a low signal attenuation measurement. Laboratory measurement of chloride will calibrate the attenuation measurements and from this the attenuation-chloride relationship for the deck will be determined. During this stage of implementation, the knowledge of absolute moisture content in the deck would be unnecessary, nevertheless efforts should be made to collect GPR data during times where it could be expected that the deck moisture was relatively uniform and not entirely dry. This would exclude times where there is visible moisture on the deck, within approximately 24 hours of precipitation or during dry periods, both when the deck is frozen or entirely dry. As pointed out earlier, this method may not be as effective in the absence of moisture in the concrete. Once the attenuation-chloride relationship is determined the measurement of signal attenuation can be mapped as chloride quantity. The mapping of chloride should be calibrated and show the spatial distribution of deck chlorides, along with information on the mean level of chloride, standard deviation, as well as maximum and minimum chloride levels for the deck. The intent of the measurement is to provide information on the spatial location of areas of high deck chloride as well as provide statistical information on the quantity of chloride in the concrete. This will assist bridge owners in decision making as to the best method of repair, and whether they are selective repairs or a deck replacement. Once put into practice and sufficient experience gained, the method can be standardized by ASTM and/or AASHTO.

The second stage of implementation will utilize GPR independently, without cores or chloride calibration. This will require additional development but in theory, it is possible to measure chlorides in concrete using GPR alone provided that it can supply the information necessary to develop the attenuation-chloride relationship and provide a measurement of deck moisture. As described in both the laboratory experimentation and theoretical modeling, each level of radar signal attenuation is defined by various levels of chloride and moisture in combination. The difficulty in measurement of chloride arises due to the fact that different levels of moisture and chloride can produce the same level of attenuation. The field tests avoided this problem by taking core samples with chloride calibration, which eliminated the effects of moisture, however, for independent GPR measurements without calibration cores, the moisture content must be known. It is believed that GPR may also be able to provide estimates of moisture, based on the relative dielectric constant of the material. The research conducted here suggests that GPR moisture estimates, using a simple linear interpolation method based on relative dielectric constant, can produce accurate results with errors of less than 1% for moisture contents of 4% or less. Prior to second stage implementation, the question of GPR moisture measurement and the attenuation-chloride relationship will need to be studied as well as other factors affecting accuracy investigated. The benefit of independent GPR measurement of chloride (without cores) would permit a high speed mapping of chloride, possibly at highway speed and without traffic slowdowns or lane closures. There are many obvious hurdles to overcome to achieve that level of operation, however, when successful the benefits are clear.

## 3.0 CONCLUSIONS AND RECOMMENDATIONS

Ground penetrating radar has been used in the past to measure material properties, however, radar measurement of chlorides in concrete has not been extensively studied in prior investigations. The method developed here represents an entirely new and novel approach to the measurement of chloride in concrete and the non-destructive evaluation of bridge decks.

The work performed in this project defines the relationship between GPR measurement of signal loss based on variations in conductivity resulting from intrusion of dissolved chlorides and moisture into concrete. This was demonstrated both analytically and experimentally, and will serve as the foundation for further research into this area.

The focus of the project was to investigate whether GPR technology is able to predict chloride quantities in bridge deck concrete using limited ground-truth information based on core samples and laboratory measurements of chloride. We have shown that this is possible using only three core samples for calibration, which resulted in an $R^2$ of 0.835. The high degree of correlation implies that a measurement of radar signal attenuation in bridge deck concrete will be a good predictor of chloride content. In developing the GPR attenuation-chloride relationship we were able to produce a chloride mapping that shows the chloride distribution throughout the bridge deck, and predict average, maximum and minimum chloride levels. Additionally, we showed that the attenuation-chloride relationship can be determined in three ways, (1) experimentally with laboratory measurements, (2) with actual GPR bridge deck data using core samples and (3) analytically using radio frequency (RF) and microwave theory.

We have developed a technique that can be fielded in its present state of development. However, we have also identified certain factors that can potentially affect the accuracy and reliability of the method, such as effects of variability of moisture from location to location throughout the deck concrete, the effects of very dry or frozen conditions, and when calibrating the attenuation measurements, the need for accuracy in data collection and the necessity for proper identification and location of calibration cores. These variables should be further investigated.

While in-situ test results were favorable and methods for data collection and analysis have been developed, the tests were conducted on one bridge deck only. It is recommended that future research should be conducted and include additional testing on bridge decks, with and without overlays and in different temperature and environmental conditions. This will help to better determine accuracy rates and the overall effectiveness of the technique.

The work also showed that the attenuation-chloride relationship, in theory can be developed without the need for chloride calibration information and with additional development it may be possible for radar to accurately predict chloride quantities in bridge deck concrete without the need for cores and laboratory measurement of chlorides for calibration. It is recommended that additional research be conducted to further develop the GPR method independent of calibration core samples.

We believe that this project has laid the ground work and first steps in the development of a nondestructive method that can provide much needed information to bridge owners on the condition of bridge decks, which will improve the effectiveness of bridge deck repairs, reduce repair costs and increase the longevity of bridge decks throughout the country.

## 4.0 REFERENCES


[1] W. J. McCarter, H. M. Taha, B. Suryanto, G. Starrs. Two-point concrete resistivity measurements: interfacial phenomena at the electrode-concrete contact zone, Heriot Watt University, Edinburgh, EH14 4AS

[2] Electrical resistivity measurement of concrete – Wikipedia

[3] A.J. Alongi, G.G. Clemena, P.D. Cady, Method for Evaluating the Condition of Asphalt-Covered Decks, SHRP C-101 1992

[4] Hamed Layssi, Pouria Ghods, Aali R. Alizadeh, and Mustafa Salehi, Electrical Resistivity of Concrete, www.concreteinternational.com, May 2015

[5] Liu, Zhuangzhuang & Sha, Aimin & He, Rui & Xing, Mingliang. (2016). Antifreeze asphalt mixtures design and antifreeze performances prediction based on the phase equilibrium of natural solution. Cold Regions Science and Technology. 129. 104–113.

[6] Virginia DOT Report – Bridge Deck Condition Assessment I-395 Crossing Sanger Ave, Braddock Rd, and Joyce St (NB) Chloride Testing and Depth of Concrete Cover, Fairfax and Arlington County, VA, Olson Engineering May 25, 2017

[7] Bridge Inspection and Rehabilitation, A Practical Guide, Parsons Brinckerhoff, Louis Silano, PE 1993 pp40

[8] ACI 318-14: Building Code Requirements for Structural Concrete

[9] John P. Broomfield, Corrosion of Steel in Concrete, Understanding, investigation and repair, 2nd edition, 1997, 2007

[10] R.J. Kessler, R.G. Powers, E. Vivas, M.A. Paredes, Y.P Virmani, Surface Resistivity as an Indicator of Concrete Chloride Penetration Resistance 2008 CBC

[11] F. Rajabinpour, J. Weiss, D. Abraham, Insitu Electrical Conductivity Measurements to Assess Moisture and Ionic Transport in Concrete, School of Civil Engineering, Purdue University, Indiana USA

[12] T. Madhavi, S. Annamalai, Electrical Conductivity of Concrete, ARPN Journal of Engineering and Applied Sciences, Vol 11, No. 9, May 2016
[13] L. Lepley, W. Adams, Reflectivity of Electromagnetic Waves at an Air-Water Interface for Pure and Sea Water, Technical Report No. 25, December 1968
[14] Moisture in Concrete and Moisture-sensitive Finishes and Coatings, www.concrete.net.au, April 2007

**Program Steering Committee: NCHRP IDEA Program Committee**

January 2020

**NCHRP Project 208**

Start Date: September 2018

Completion Date: January 2020


Principal Investigator: Anthony J. Alongi
anthony.alongi@penetradar.com


PENETRADAR CORPORATION

# Research Results

## Determining Bridge Deck Chloride Quantities Using Ground Penetrating Radar

### What was the need?

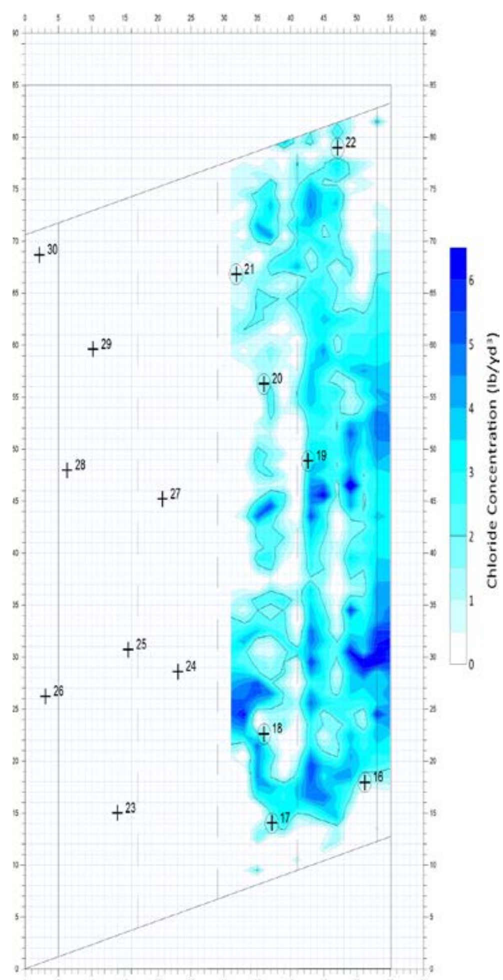
Chlorides from deicing salts attack the steel reinforcement in bridge decks which can ultimately cause delamination and deterioration of concrete. The repair cost from these defects are estimated to exceed $5B per year in USA and make up between 50% - 85% of bridge maintenance budgets. The removal and replacement of chloride contaminated concrete is the most long-lasting and cost-effective remediation, however, few methods exist to determine chloride content in bridge decks. The most widely used method requires closing traffic lanes, extraction of large numbers of core samples and laboratory testing for chloride. While providing quantitative information, this method is expensive and time consuming, it creates traffic slow-downs and can be a potential safety hazard. Because cores are discrete samples, they often produce inadequate information on the bridge deck condition and chloride quantities. What is needed is a fast, accurate and low-cost method that provides quantitative information on chloride content over the entire bridge deck. Such a method would permit improved repair strategies, by identifying chloride contaminated concrete and thereby improving the effectiveness of repairs.

### What was our goal?

The goal of this project was the development of an entirely new method for determining chloride quantity in bridge decks using nondestructive GPR technology.

### What did we do?

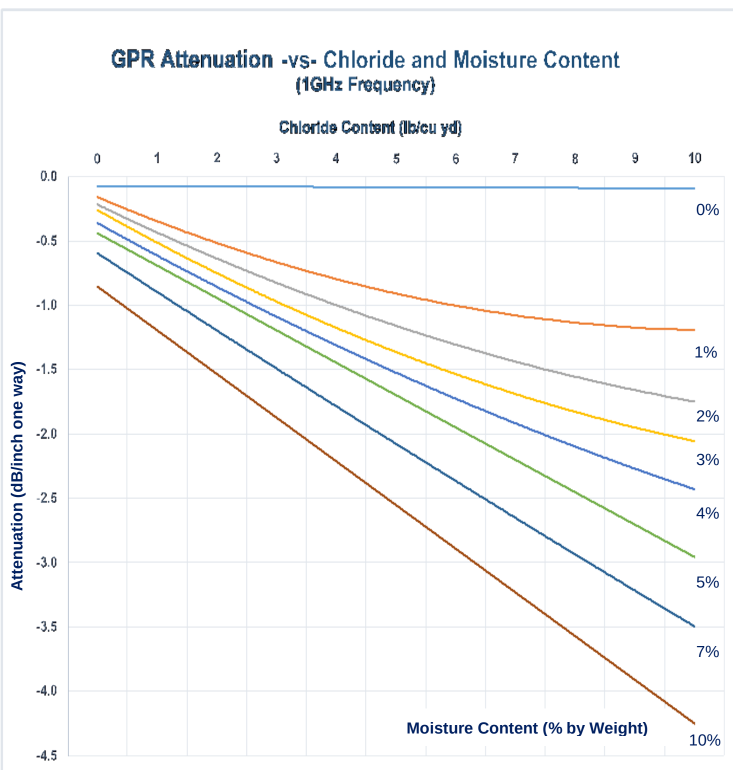
We investigated the use of non-contacting, ground penetrating radar (GPR) to measure chloride content in bridge deck concrete based on the level of signal attenuation (signal loss). We investigated and defined the relationship between chlorides in concrete (which cause corrosion of reinforcing steel and delamination of concrete) and their effect on GPR signal propagation. Our investigation was three-pronged and consisted of GPR field testing on a bridge deck with a comparison to core samples, analytical modeling of radar signal loss in concrete and laboratory measurement of signal loss to confirm field tests and analytical modeling.




**Chloride Mapping produced by GPR Scan of the Bridge Deck**

## What was the outcome?

The research results confirmed that non-contacting, ground penetrating radar (GPR) is able to predict chloride content in bridge deck concrete. A GPR technique was developed that measures signal loss or attenuation, and provides a deck-wide topographical mapping of chloride concentration in the concrete. This method utilizes a GPR scan of the entire bridge deck and measurement of signal attenuation, along with a minimal number of core samples and laboratory chloride measurements to calibrate the GPR measurements. It was found that the GPR attenuation-chloride relationship could be reasonably defined experimentally with only three chloride sample measurements with an R-squared of 0.835. This result was confirmed through analytical modeling and laboratory experiments. While initial results look promising additional in-situ tests are recommended to confirm the effectiveness of the method and to better define the accuracy on additional bridge decks and under a variety of environmental conditions.




**Attenuation-Chloride Relationship based on varying moisture content**

The attenuation-chloride relationship was derived both experimentally and analytically, and shows how chlorides and moisture in concrete affect the level of radar signal attenuation. It also shows that chloride can be predicted with a measurement of signal attenuation provided that the moisture in the concrete is known. With further development of this method, it may be possible to accurately predict chloride quantities in bridge deck concrete without the need for calibration cores using radar measurements alone.

## What was the benefit?

This development has the potential to provide bridge owners with an unprecedented level of information on the condition of their bridge decks. It will improve effectiveness of repairs, decrease the overall cost of repairs and extend the life of bridge decks, and when compared to traditional methods the GPR chloride measurement technique provides greater quantity and improved quality of information. It is less destructive and with less interference with traffic it is safer to highway workers and the public. The direct benefit to highway departments and bridge owners is the potential to save millions of dollars in repair costs. Engineering and maintenance personnel can prioritize repairs of bridges in their inventory and by focusing repairs where needed, extend the lifespan of bridge decks. The traveling public will benefit from improved safety as well as the potential avoidance of thousands of hours of lane closures and traffic "slow-downs".

## Learn more

To view the complete report:
http://www.trb.org/IDEAProgram/NCHRPHighwayIDEACompletedProjects.aspx

For more information:
anthony.alongi@penetradar.com