2014-03-20

Sensitivity of Electrochemical Impedance Spectroscopy Measurements to Concrete Bridge Deck Properties

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

Master of Science

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March 2014

ABSTRACT

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to Concrete Bridge Deck Properties

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Numerous methods have been developed to measure corrosion potential relating to chloride infiltration in concrete, including an emerging application of electrochemical impedance spectroscopy (EIS). EIS involves measurements of electrical impedance to evaluate the corrosion potential of steel reinforcement in concrete. With EIS, current is injected vertically into the concrete bridge deck between the surface and the embedded reinforcing steel, usually the top mat, to evaluate the degree to which the reinforcing steel is protected from chloride infiltration by the entire bridge deck system.

The objectives of this research were to 1) investigate the sensitivity of EIS measurements obtained at various frequencies to specific deck properties, 2) recommend a particular frequency or range in frequency at which impedance measurements can differentiate among various levels of corrosion protection for reinforcing steel in concrete bridge decks, and 3) compare impedance values measured at the recommended frequency(ies) to more traditional test measurements relating to corrosion of reinforcing steel in concrete bridge decks. This research involved impedance testing of 25 concrete slabs, divided into five sets. The effects of sealant presence, curing time, temperature, moisture content, cover depth, water-to-cementitious materials ratio, air content, chloride concentration, and epoxy coating condition on individual impedance measurements were evaluated.

For the controlled laboratory experiments, sealant presence, curing time, temperature, moisture content, cover depth, water-to-cementitious materials ratio, air content, and epoxy coating condition were shown to have a statistically significant effect on impedance measurements, with p-values less than 0.05. The statistical analyses indicated that impedance testing in the frequency range of approximately 100 Hz to 1 kHz would be expected to provide the best data about the degree to which the reinforcing steel is protected from chloride infiltration by a bridge deck system. In this frequency range, a high level of differentiation among levels of corrosion protection is expected, and a high speed of data collection is also possible.

For the uncontrolled laboratory experiments, a single frequency of 200 Hz was selected for impedance testing. Statistical analyses were performed to compare impedance with more traditional test measurements relating to corrosion of reinforcing steel in concrete bridge decks. Longitudinal and transverse cover, dry and wet resistivity, dry and wet half-cell potential, dry linear polarization, and chloride concentration were determined to be correlated with impedance, with p-values less than 0.15.

Key words: chloride concentration, corrosion, concrete bridge deck, cover depth, electrochemical impedance spectroscopy, half-cell potential, linear polarization, resistivity

ACKNOWLEDGEMENTS

I acknowledge the Utah Department of Transportation, Provo River Constructors, and Raba-Kistner Infrastructure for supporting this research. I also thank Eric Sumsion and Tenli Waters, who are members of the Brigham Young University Materials and Pavements Research Group, for their help with sampling and analysis of the decommissioned bridge decks. I especially thank Chloe Hanks for her incredible assistance in all things electrical and willingness to help me at all hours of the day, night, and weekend. I would like to thank my committee members, Dr. Mitsuru Saito and Dr. Brian Mazzeo, for their support and help in this process. Finally, I would like to thank Dr. W. Spencer Guthrie for his guidance and support through my graduate experience and for providing me with incredible learning opportunities I would not have had otherwise.

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1 INTRODUCTION

1.1 Problem Statement

In northern climates, condition assessment of concrete bridge decks centers primarily on damage caused by corrosion of the embedded reinforcing steel. A chief cause of corrosion is chloride infiltration resulting from applications of deicing salts during winter maintenance (Barrus 2012, Broomfield 2007, Morris et al. 2004). Numerous methods have been developed to measure corrosion potential relating to chloride infiltration in concrete (Andrade and Alonso 2004, Broomfield 2007, Scott et al. 2003), including an emerging application of electrochemical impedance spectroscopy (EIS). EIS involves measurements of electrical impedance to evaluate the corrosion potential of steel reinforcement in concrete (Guthrie and Tuttle 2006, Hema et al. 2004, Song and Saraswathy 2007).

Traditional electrical resistivity testing of concrete provides an indirect measure of the ability of concrete to resist chloride penetration (Barrus 2012, Guthrie and Tuttle 2006, Hema et al. 2004, Song and Saraswathy 2007), where increasing resistivity generally correlates to decreasing corrosion potential (Barrus 2012, Morris et al. 2002, Song and Saraswathy 2007). A typical method for measuring resistivity involves the use of either a two- or four-pronged resistivity instrument (Barrus 2012, Bartholomew et al. 2012, Hema et al. 2004, Song and Saraswathy 2007). The resistivity measurement in these cases is based on the resistance of the concrete to horizontal current flow between the prongs. This method of introducing current does not allow for control or knowledge of the depth of penetration of the current and is designed to interrogate only the concrete, requiring access to bare deck surfaces for testing (Barrus 2012). Furthermore, use of the two-pronged probe, in particular, is subject to operator error in a few respects (Barrus 2012, Bartholomew et al. 2012).

With EIS, however, current is injected vertically into the concrete bridge deck between the surface and the embedded reinforcing steel, usually the top mat, to evaluate the degree to which the reinforcing steel is protected from chloride infiltration by the entire bridge deck system (Bartholomew et al. 2012). That is, the vertical nature of EIS testing allows full penetration of the current through all layers from the deck surface down to the reinforcing steel, which, unlike typical resistivity testing, allows evaluation of the protection against chlorides provided by any deck surface treatments, the full depth of the concrete cover, and any rebar coatings (Bartholomew et al. 2012).

Existing research on EIS has been largely focused on development of equivalent circuits for modeling and interpretation of data collected in laboratory experimentation involving testing across a wide range of frequencies (Gamry Instruments 2007, Macdonald 2006, Sanchez et al. 2007, Song 2000). Although this method of analysis can provide specific information about the corrosion activity of reinforcing steel in concrete (Ismail and Ohtsu 2006, Lemoine et al. 1990, Macdonald and El-Tantawy 1994, Sanchez et al. 2007, Vedalakshmi and Palaniswamy 2010), the complexity of the process makes meaningful interpretation of the EIS measurements difficult in many cases, and the associated testing can also be very time-consuming. With the recent advent of EIS equipment suitable for field testing of bridge decks (Bartholomew et al. 2012), for which rapid data collection is required and for which the physical information necessary to develop an accurate circuit model(s) may not be attainable, a simpler approach is needed.

Specifically, as the use of individual impedance measurements for characterizing bridge deck condition has already been demonstrated (Bartholomew et al. 2012), investigations of the sensitivity of EIS measurements obtained at various frequencies to specific deck properties that influence corrosion of reinforcing steel are warranted. Such testing would be useful for identifying a particular frequency or range in frequency at which impedance measurements could differentiate among various levels of corrosion protection; while some research suggests that certain frequency ranges provide specific information regarding concrete bridge deck condition, conclusive evidence on the topic is not currently available (Andrade and Alonso 2004, Macdonald 2006).

1.2 Research Objectives and Scope

Considering the need for more information on these topics, the objectives of this research were to 1) investigate the sensitivity of EIS measurements obtained at various frequencies to specific deck properties, 2) recommend a particular frequency or range in frequency at which impedance measurements can differentiate among various levels of corrosion protection for reinforcing steel in concrete bridge decks, and 3) compare impedance values measured at the recommended frequency(ies) to more traditional test measurements relating to corrosion of reinforcing steel in concrete bridge decks. This research involved impedance testing of 25 concrete slabs, divided into five sets, at the Brigham Young University Highway Materials Laboratory. The effects of sealant presence, curing time, temperature, moisture content, cover depth, water-to-cementitious materials ratio, air content, chloride concentration, and epoxy coating condition on individual impedance measurements were evaluated. Twenty impedance values, spaced logarithmically between 100 mHz and 300 kHz, were measured for each test. The traditional testing techniques selected for comparison with impedance measurements included cover depth, rebound number, resistivity, half-cell potential, linear polarization, and chloride concentration measurements.

1.3 Outline of Report

This report contains five chapters. Chapter 1 presents the problem statement, objectives, and scope of the research. Chapter 2 discusses information from a literature review on corrosion and impedance theory. Chapter 3 presents the instrument design and experimental methodology used in this research for impedance testing. Chapter 4 provides the results of the impedance testing and statistical analyses performed on the data, and Chapter 5 offers conclusions and recommendations derived from the research.

2 BACKGROUND

2.1 Overview

The following sections present the findings of a literature review focused on corrosion and impedance theory. Both topics are presented in the context of concrete bridge deck performance and evaluation.

2.2 Corrosion Theory

The corrosion reaction is electrochemical in nature, involving anodic and cathodic reactions along the reinforcing steel in concrete (Bentur et al. 1997, Mindess et al. 2003, Pinkerton 2007). Although the iron oxide layer at the surface of the reinforcing steel is usually stable in the alkaline environment provided by concrete, it can become unstable in the presence of chloride concentrations typically exceeding 1.2 kg of chloride per cubic meter (2.0 lb of chloride per cubic yard) of concrete (Hema et al. 2004, Mindess et al. 2003). Under these conditions, the resulting dissociation of iron atoms produces ferrous ions that react with water and oxygen to form rust at anodic sites (Harit and Gupta 2001). The electrons released by the dissociation of iron then move along the rebar from anodic sites to cathodic sites, where they react with water and oxygen to produce hydroxyl ions (Bentur et al. 1997, Mindess et al. 2003). The movement of electrical charges from anodic sites, which have higher electrical potential, to cathodic sites, which have lower electrical potential, creates an electrical circuit that facilitates the corrosion reaction (Bentur et al. 1997). Because higher temperatures correspond to higher ion activity in the circuit, the rate of corrosion increases with increasing temperature (Barrus 2012, Song and Saraswathy 2007).

Although the cathodic reaction is generally beneficial to reinforcing steel in concrete, as higher concentrations of hydroxyl ions increase the stability of the iron oxide layer, the anodic reactions are highly detrimental. Not only does the formation of rust decrease the cross-sectional area of the reinforcing steel, which reduces the load-carrying capacity of the concrete structure (Song and Shayan 1998), it also causes tensile stress in the concrete (Bartholomew et al. 2012, Song and Shayan 1998), as rust is two to six times greater in volume than the parent steel. Because concrete is comparatively weak in tension, corrosion of the reinforcing steel leads to cracking, delamination, and spalling of the concrete surface (Bartholomew et al. 2012, Bentur et al. 1997, Mindess et al. 2003). Especially in cold regions, such damage permits increased chloride infiltration, which accelerates degradation of the concrete structure (Mindess et al. 2003, Morris et al. 2004, Pinkerton 2007, Schweitzer 2009, Song and Shayan 1998). For these reasons, increasing resistance to corrosion is primarily related to reducing the ability of chloride ions to accumulate in critical concentrations at the surface of the reinforcing steel.

Concrete material properties and bridge deck construction practices that increase resistance to chloride infiltration are therefore desirable for improving the durability of reinforced concrete structures. These may include application of protective sealants and/or overlays on the concrete surface (Bertolini et al. 2013, Birdsall 2007); use of longer concrete curing times (Bertolini et al. 2013, Hema et al. 2004); avoidance of stay-in-place metal forms, which have been shown to increase the long-term moisture content of concrete (Birdsall 2007, Birdsall and Guthrie 2008); specification of greater concrete cover thickness (Bertolini et al.

2013, Birdsall and Guthrie 2008, Teng 2000); specification of lower water-to-cementitious materials ratios (Bertolini et al. 2013, Hema et al. 2004, Teng 2000); and assurance of proper concrete consolidation to minimize the occurrence of entrapped air (Hema et al. 2004). The use of epoxy-coated rebar can also provide increased protection against chloride-induced corrosion (Teng 2000).

2.3 Impedance Theory

The impedance of a material reflects the difficulty with which current can flow through it when an electrical potential is applied and is therefore related to the material composition and structure (Encyclopedia Britannica undated, Gamry Instruments 2007). In some cases, such as metals, the primary current carriers are electrons (Nave undated). In other cases, such as certain kinds of liquids, the primary current carriers are ions (EPA 2012). For applications to reinforced concrete, EIS testing is performed by applying alternating potentials of varying frequencies between the embedded reinforcing steel, which behaves as the working electrode, and a metal testing probe, or counter electrode, that is placed on the concrete surface; the impedance of the system is then measured at each frequency (Bartholomew et al. 2012, Krauss et al. 1996). This approach allows interrogation of all materials between the two electrodes, providing impedance measurements that reflect both the impedance of the ions in the concrete pore water and the impedance of the electrochemical interfaces, where ions accumulate between the electrodes and the concrete (Ismail and Ohtsu 2006).

Resistance and capacitance can then be used to describe the various physical processes measured during EIS testing (Ismail and Ohtsu 2006, Pech-Canual and Castro 2002). The concrete can be represented as a basic resistor, while the electrochemical interface can be represented as a basic type of capacitor. The resistance of a material is given by Equation 3.1:

$$R = \frac{L}{A\sigma} \tag{3.1}$$

where:

R = resistance, ohms

L = length, m

A = area, m^2

σ = electrical conductivity, S/m

For a constant material dimension, the resistance of a material increases as the electrical conductivity decreases, or as the ability of the material to conduct electrical currents decreases. The capacitance of a material is given by Equation 3.2:

$$I(t) = \frac{dQ(t)}{dt} = CdE(t)/dt \tag{3.2}$$

where:

$I(t)$ = time-dependent current, amps

Q = charge, coulombs

C = capacitance, farads

$E(t)$ = time-dependent voltage, volts

t = time

In terms of a circuit model, the capacitive electrochemical interfaces are in series with the concrete resistor as illustrated in Figure 2-1. The figure also shows a parasitic circuit capacitance term that is inevitable due to the circuitry associated with EIS testing. While this circuit model is a simplification of the complicated, non-ideal circuit elements that are found in reality, it is sufficient to illustrate the basic impedance trends that are measured (Ismail and Ohtsu 2006). A simulation of the circuit depicted in Figure 2-1 is shown in Figure 2-2 over the range of frequencies from 0.1 Hz to 100 kHz. The values used in the simulation are 100 μF for each

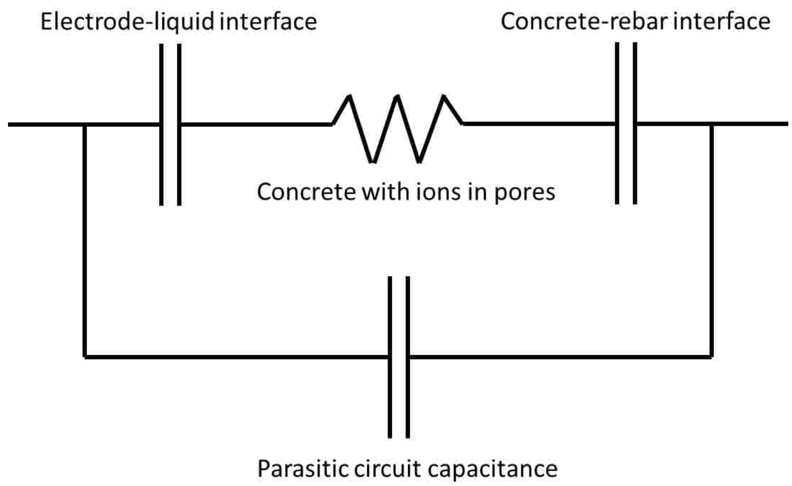

Figure 2-1. Basic circuit model for EIS testing.

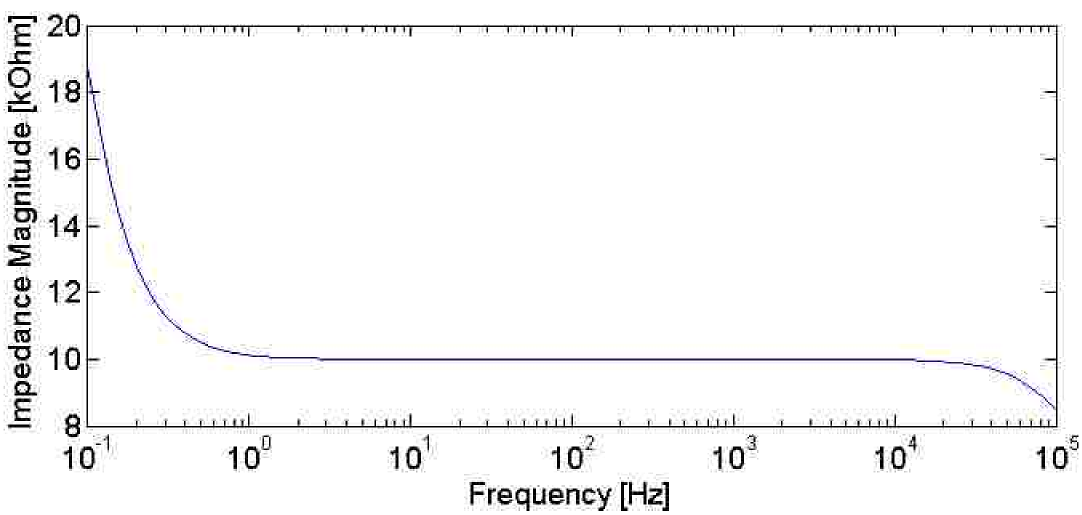

Figure 2-2. Simulation of basic circuit model.

interface capacitance, 10 kΩ for the concrete resistance, and 100 pF for the parasitic circuit capacitance, which represent the associated circuit components on an order-of-magnitude basis. The shape of the curve in Figure 2-2 indicates that EIS measurements are frequency-dependent. At low frequencies, the electrode-liquid interface dominates the impedance, and at high frequencies the parasitic properties of the circuit dominate the impedance, with impedance steadily decreasing with increasing frequency. At the intermediate frequencies, the resistance of the concrete dominates, suggesting that impedance testing between 10 Hz and 1 kHz may provide the best data about the degree to which the reinforcing steel is protected from chloride infiltration by a bridge deck system (Maierhofer et al. 2010).

Impedance measurements are appropriate for measuring the corrosion potential of reinforcing steel in concrete because the same factors that influence the corrosion rate also theoretically influence impedance. For example, studies have shown that the electrical resistivity of concrete is influenced by surface treatments, curing period, temperature, moisture content, cover depth, water-to-cementitious materials ratio, composition of the pore water solution, chloride concentration, and rebar coatings, which are all factors that affect the rate of the corrosion reaction (Bartholomew et al. 2012, Hope and Ip 1985, Mindess et al. 2003, Saleem et al. 1996).

Electrical impedance and the rate of corrosion have an inverse relationship. If electrical impedance is high, the movement of corrosive ions is more restricted, which decelerates the corrosion reaction. Conversely, if electrical impedance is low, the movement of corrosive ions is less restricted, which accelerates the reaction (Bentur et al. 1997). Therefore, high impedance measurements should theoretically signify high resistance to the movement and accumulation of corrosive ions in the vicinity of the reinforcing steel.

2.4 Summary

Resistance to corrosion is primarily related to reducing the ability of chloride ions to accumulate in critical concentrations at the surface of the reinforcing steel. Concrete material properties and bridge deck construction practices that increase resistance to chloride infiltration include application of protective sealants; use of longer concrete curing times; avoidance of stay-in-place metal forms, which have been shown to increase the long-term moisture content of concrete; specification of greater concrete cover thickness; specification of lower water-to-cementitious materials ratios; proper concrete consolidation to minimize the occurrence of entrapped air; and the use of epoxy-coated rebar.

The impedance of a material reflects the difficulty with which current can flow through it when an electrical potential is applied and is therefore related to the material composition and structure. For applications to reinforced concrete, EIS testing is performed by applying alternating potentials of varying frequencies between the embedded reinforcing steel, which behaves as the working electrode, and a metal testing probe, or counter electrode, that is placed on the concrete surface; the impedance of the system is then measured at each frequency. This approach allows interrogation of all materials between the two electrodes. Resistance and capacitance can be used to describe the various physical processes measured during EIS testing, with the concrete represented by a basic resistor and the electrochemical interface represented by a basic type of capacitor.

Impedance measurements are appropriate for measuring the corrosion potential of reinforcing steel in concrete because the same factors that influence the corrosion rate also theoretically influence impedance, including surface treatments, curing period, temperature, moisture content, cover depth, water-to-cementitious materials ratio, and rebar coatings. Electrical impedance and the rate of corrosion have an inverse relationship. Therefore, high impedance measurements should theoretically signify high resistance to the movement and accumulation of corrosive ions in the vicinity of the reinforcing steel.

3 EXPERIMENTAL METHODOLOGY

3.1 Overview

The sensitivity of EIS measurements obtained at various frequencies to specific deck properties was evaluated in this research. Details associated with the experimental design, data collection, and statistical analyses are provided in the following sections.

3.2 Experimental Design

An experiment was designed to evaluate the effects of sealant presence, curing time, temperature, moisture content, cover depth, water-to-cementitious materials ratio, air content, chloride concentration, and epoxy coating condition on individual impedance measurements. The following sections describe each set of slabs used in the research.

3.2.1 Set A

Set A, which was originally prepared for previous research (Pinkerton 2007), was comprised of nine concrete slabs, each measuring 55.8 x 45.7 x 13.9 cm (22 x 18 x 5.5 in.) and containing seven lengths of #16 (#5) reinforcing steel, as shown in Figure 3-1. The seven bars of reinforcing steel included three black bars and four epoxy-coated bars. The three black bars were situated at different cover depths of 5.1 cm (2.0 in.), 6.4 cm (2.5 in.), and 7.6 cm (3.0 in.). The four epoxy-coated bars, which were all situated at a cover depth of 6.4 cm (2.5 in.), each had

Figure 3-1. Typical slab from set A.

a different treatment to enable evaluation of different forms of damage to the epoxy coating. As a control, one bar was fully coated, including the end cut, while the other three bars had an unrepaired end cut, two pliers strikes spaced 30.5 cm (12 in.) apart, and a 30.5-cm (12-in.) rib scrape along one side of the bar. Pictures of these defects are given in Figures 3-2 to 3-4.

The cementitious materials used in the concrete mixture design consisted of 82 percent Type I/II portland cement and 18 percent Class F fly ash by weight, and the water-to-cementitious materials ratio was 0.44. To enable evaluation of different chloride concentration levels, different quantities of sodium chloride were added to each of three concrete batches used to create the nine slabs. Three of the nine slabs were cast from one batch that contained no sodium chloride. Three slabs were cast from another batch that contained 1.2 kg of chloride per cubic meter (2.0 lb of chloride per cubic yard) of concrete, the threshold at which corrosion is initiated (Hema et al. 2004, Mindess et al. 2003). The final three slabs were cast from a batch that contained 2.4 kg of chloride per cubic meter (4.0 lb of chloride per cubic yard) of concrete,

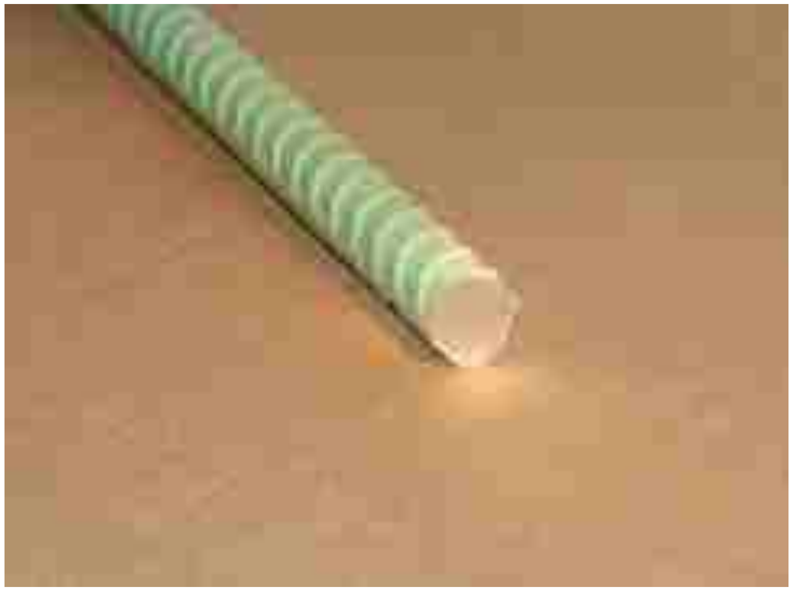

Figure 3-2. Epoxy coating damage from end cut.

Figure 3-3. Epoxy coating damage from pliers strike.

Figure 3-4. Epoxy coating damage from rib scrape.

which is representative of chloride concentrations in bare concrete bridge decks in cold regions, such as northern Utah, after a few winter seasons.

After being cast, the slabs were covered in plastic and kept moist for a period of 7 days before being exposed to the open air. The slabs were tested approximately 6.5 years after casting.

3.2.2 Set B

Set B was comprised of four concrete slabs, each measuring 45.7 x 91.4 x 8.9 cm (18 x 36 x 3.5 in.) and containing a single length of #13 (#4) uncoated reinforcing steel at a depth of 2.54 cm (1.0 in.), as shown in Figure 3-5. Each slab was cast from a separate concrete batch, with the water-to-cementitious materials ratio, entrained air dosage, and salt dosage specified as shown in Table 3-1. The cementitious materials in each batch included 80 percent Type I/II portland cement and 20 percent Class F fly ash by weight.

Figure 3-5. Typical slab from set B.

Table 3-1. Slab Specifications for Set B

Slab	Water-to-Cementitious Materials Ratio	Entrained Air Dosage (ml/100 kg of cement)	Chloride Dosage (kg Cl^-/m^3)
1	0.40	97.8	0.00
2	0.55	97.8	0.00
3	0.55	97.8	5.90
4	0.55	0.0	0.00

After being cast, the slabs were covered in plastic and kept moist for a period of 7 days before being exposed to the open air. The slabs were tested 28 days after casting.

3.2.3 Set C

Set C, which was originally prepared for previous research (Sumsion and Guthrie 2010 (unpublished manuscript)), was comprised of four concrete slabs, each measuring 30.5 x 30.5 x 14 cm (12 x 12 x 5.5 in.) and containing a single length of #16 (#5) uncoated reinforcing steel at a cover depth of 5.08 cm (2.0 in.), as shown in Figure 3-6. The cementitious materials used in the concrete mixture design consisted of 80 percent Type I/II portland cement and 20 percent

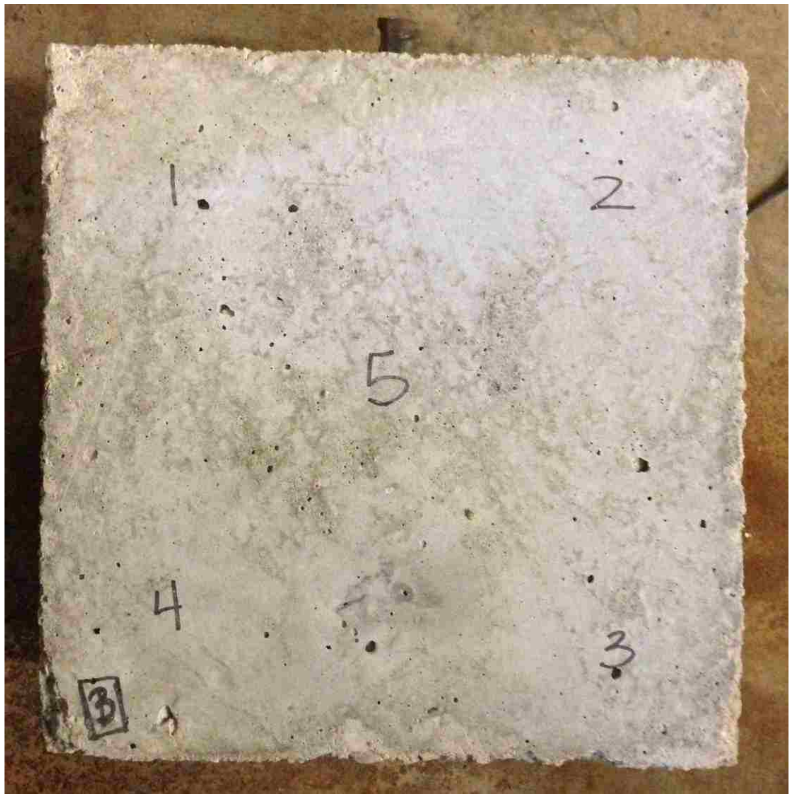

Figure 3-6. Typical slab from set C.

Class F fly ash by weight. Only two properties were varied in these slabs, the water-to-cementitious materials ratio and chloride concentration. Two of the four slabs were prepared with a water-to-cementitious materials ratio of 0.40, while the remaining two slabs were prepared with a water-to-cementitious materials ratio of 0.60. One slab from each water-to-cementitious materials ratio classification was treated with 5.9 kg of chloride per cubic meter (10.0 lb of chloride per cubic yard) of concrete, while the other had no chlorides added to the mixture.

After being cast, the slabs were covered in wet burlap and kept moist for a period of 7 days before being exposed to the open air. The slabs were tested approximately 3.5 years after casting.

3.2.4 Set D

Set D was comprised of four concrete slabs, each measuring 30.5 x 30.5 x 8.9 cm (12 x 12 x 3.5 in.) and containing a single length of uncoated reinforcing steel, as shown in Figure 3-7. The cementitious materials used in the concrete mixture design consisted of 80 percent Type II/V portland cement and 20 percent Class F fly ash by weight. Only two properties were varied in these slabs, including the cover depth of the reinforcing steel and the presence of a sealant. Two of the four slabs had a cover depth of 2.54 cm (1.0 in.), while the remaining two slabs had a cover depth of 6.35 cm (2.5 in.). After being cast, the slabs were covered in plastic and kept moist for a period of 7 days before being exposed to the open air. The slabs were tested at 7, 14, 21, 28, 35, 42, 49, and 56 days after casting.

Figure 3-7. Typical slab from set D.

After 56 days, a sealant was applied to the surface of one slab from each cover depth classification. One slab with a cover depth of 2.54 cm (1.0 in.) was sprayed with a single coat of lithium silicate sealant, while one slab with a cover depth of 6.35 cm (2.5 in.) was sprayed with a single coat of lithium silicate sealant followed by a single coat of silane. The remaining slabs were left untreated. According to the product manufacturers, the recommended coverage rates for the lithium silicate and silane treatments are 3.7 to 4.9 m^2/liter (150 to 200 ft^2/gal) and 6.1 to 7.4 m^2/liter (250 to 300 ft^2/gal), respectively (Convergent Concrete 2010). For a surface area of 30.5 x 30.5 cm (12 x 12 in.), the amount needed for the lithium silicate and silane sealants was calculated to be 27.2 g (0.06 lb) and 13.6 g (0.03 lb), respectively, for the upper end of each range. The pressure sprayer used to apply the sealants was weighed before and after spraying of each product to determine the actual amount of sealant that was applied. For the slab with a cover depth of 2.54 cm (1.0 in.), 42.2 g (0.09 lb) of lithium silicate was applied, while 39.2 g (0.09 lb) of lithium silicate and 17.0 g (0.04 lb) of silane were applied to the slab with a cover depth of 6.35 cm (2.5 in.). The slabs were tested again 10 weeks after the sealants were applied, which was 4 months after casting.

3.2.5 Set E

Set E, which was originally obtained for previous research (Sumsion 2013), was comprised of four decommissioned concrete bridge deck slabs obtained during reconstruction of Interstate 15 (I-15) in Provo, Utah, from 2010 to 2012. Two of the slabs were removed from bridges C-357 and C-358, both of which were built in 1964 to carry I-15 traffic over railroad tracks near 820 North. Both decks were overlaid with a protective membrane and asphalt overlay approximately 8 years after construction. The slab from bridge C-357 was 152.4 x 274.3

x 17.8 cm (60 x 108 x 7 in.) and contained uncoated #16 (#5) reinforcing steel that was spaced 45.7 cm (18 in.) on center in the longitudinal direction and 25.4 cm (10 in.) on center in the transverse direction. The slab from bridge C-358 measured 152.4 x 274.3 x 20.3 cm (60 x 108 x 8 in.) and contained uncoated #19 (#6) reinforcing steel that was spaced 17.8 cm (7 in.) on center in the longitudinal direction and 22.9 cm (9 in.) on center in the transverse direction. The third slab was removed from bridge C-363, which was built in 1985 to carry I-15 traffic over Center Street, and was overlaid with a membrane and asphalt overlay immediately after construction. The slab from bridge C-363 measured 152.4 x 274.3 x 16.5 cm (60 x 108 x 6.5 in.) and contained epoxy-coated #19 (#6) reinforcing steel that was spaced 30.5 cm (12 in.) on center in the longitudinal direction and 15.3 cm (6 in.) on center in the transverse direction. Finally, the fourth slab was removed from bridge D-413, which was built in 1937 to carry Center Street traffic over the railroad tracks just east of I-15. This deck was overlaid with asphalt in 1972 and 1984 and was overlaid with a protective membrane and new asphalt overlay in 2006. This slab measured 152.4 x 274.3 x 20.3 cm (60 x 108 x 8 in.) and contained uncoated #13 (#4) reinforcing steel spaced 30.5 cm (12 in.) on center in both directions. No specific information about the concrete mixture design was available for these bridge decks. As illustrated in Figure 3-8, the asphalt overlay and membrane were removed from each deck slab prior to testing.

Figure 3-8. Typical slab from set E.

3.3 Data Collection

The system used to collect impedance values utilized a probe connected to a computer. A signal source excited an alternating potential between the concrete surface and the reinforcing steel while the injected current was constantly monitored. An Agilent 33250A waveform generator produced the applied waveforms. Voltage followers drove the current for the measurement probe and provided impedance matching to the waveform generator. Current flowed through a known resistor of 100 ohms into the probe electrode. An Agilent 34410A digital multimeter recorded the voltage across the resistor so the current could be calculated, using Ohm's law. The waveform generator was configured to output a sinusoidal wave at a known frequency and amplitude. Twenty logarithmically spaced frequencies, between the frequencies of 100 mHz and 300 kHz, were measured in approximately 90 seconds. (The testing was performed in two series, the first ending at 200 Hz and the second beginning at 200 Hz.) A computer running LabVIEW controlled the instruments and logged data. After data acquisition, post-processing was performed in MATLAB to estimate the concrete impedance. The estimated impedance measurements over the entire frequency spectrum could then be plotted.

The circular probe shown in Figure 3-9 was used for testing. This probe, which had an overall diameter of 15.2 cm (6 in.), consisted of an inner circle and an outer ring. The inner circle was 10.2 cm (4 in.) in diameter and was separated from the outer guard ring by a gap having a width of 1.3 cm (0.5 in.). The outer guard ring was also 1.3 cm (0.5 in.) wide. Both the inner circle and the outer ring were constructed of three layers, including an aluminum foil electrode, an aluminum screen mesh, and an open-cell foam interface, which were all mounted to a square acrylic base plate. Immediately prior to a test, the foam pieces were soaked in a conductive solution prepared using a 1:200 ratio of generic dish soap to water by volume to facilitate good electrical coupling of the foam to the concrete surface; specifically, the probe was

Figure 3-9. EIS probe.

dipped in the solution for approximately 2 seconds and then allowed to drip for 5 seconds before being placed in position for testing. To apply the alternating potentials of various frequencies between the surface of the concrete slab and the reinforcing steel at a given location, the probe was approximately centered over a length of reinforcing steel of interest within the slab, and a grounding wire was connected to the exposed portion of the reinforcing steel.

For all of the slab sets A to E, a pressure sprayer was used to moisten the test area on each slab surface before impedance testing. The test area was evenly sprayed with water for approximately 3 seconds. For slabs with multiple lengths of reinforcing steel, the test areas were moistened and tested one at a time for consistency. Figure 3-10 shows the typical testing configuration of a slab. The following sections describe the controlled and uncontrolled laboratory experimentation performed using these slab sets.

Figure 3-10. EIS testing.

3.3.1 Controlled Laboratory Experiments

Controlled laboratory experiments were performed to investigate the sensitivity of EIS measurements obtained at various frequencies to specific concrete bridge deck properties. As described in the following sections, slab sets A through D were used to study the effects of sealant presence, curing time, temperature, moisture content, cover depth, water-to-cementitious materials ratio, air content, chloride concentration, and epoxy coating condition.

3.3.1.1 Sealant Presence

Set D was used to evaluate the sensitivity of impedance measurements to sealant presence. Two frequency sweeps were performed on each slab.

3.3.1.2 Curing Time

Set D was used to evaluate the sensitivity of impedance measurements to curing time. Two frequency sweeps were performed on each slab at each curing time.

3.3.1.3 Temperature

Set C was used to evaluate the sensitivity of impedance measurements to temperature. Two slabs from set C were used, including the slab with a water-to-cementitious materials ratio of 0.40 that contained no chlorides and the slab with a water-to-cementitious materials ratio of 0.60 that contained chlorides. The slabs were placed in a computer-controlled environmental chamber to equilibrate for 24 hours at a specified temperature before impedance testing. The slabs were tested at 5, 20, and 35°C (41, 68, and 95°F), which span the range in temperature in which impedance testing could be reasonably performed on a bridge deck in the field. Two frequency sweeps were performed on each slab at each temperature.

3.3.1.4 Moisture Content

Set C was used to evaluate the sensitivity of impedance measurements to moisture content. Two slabs from set C were used, including the slab with a water-to-cementitious materials ratio of 0.40 that contained no chlorides and the slab with a water-to-cementitious materials ratio of 0.60 that contained chlorides. To establish an initial dry condition, the slabs were placed in an oven at 40°C (104°F) for 96 hours, by which time daily weight and surface dielectric measurements indicated that the moisture content had stabilized. When the drying period was complete, the slabs were removed from the oven and allowed to equilibrate at room temperature. An initial frequency sweep was performed on the dry slabs, and then a wet towel was placed over the top surfaces of the slabs. Subsequent impedance testing was performed at soaking times of 0.25, 0.50, 1, 2, 4, 6, 12, 24, 36, and 72 hours. Plastic sheeting was placed over the wet towel to inhibit evaporation between readings, and the towel was rewetted every 24 hours. The plastic sheeting and towel were removed from the surface of each slab during impedance measurements. Weight and surface dielectric measurements were also recorded at each soaking time. One frequency sweep was performed on each slab at each soaking time; replicate measurements at a given soaking time were not possible due to the time required for each test.

3.3.1.5 Cover Depth

Sets A and D were used to evaluate the sensitivity of impedance measurements to cover depth. For set A, one frequency sweep was performed over each of the three lengths of black bar, which were positioned at three different cover depths in each slab. For set D, impedance measurements taken at a curing time of 28 days were specifically used for this analysis, in which two frequency sweeps were performed on each slab.

3.3.1.6 Water-to-Cementitious Materials Ratio

Set B was used to evaluate the sensitivity of impedance measurements to water-to-cementitious materials ratio. Two slabs from set B were used, including the slab with a water-to-cementitious materials ratio of 0.40 (slab 1 in Table 3-1) and the control slab with a water-to-cementitious materials ratio of 0.55 (slab 2 in Table 3-1). Two frequency sweeps were performed on each slab.

3.3.1.7 Air Content

Set B was used to evaluate the sensitivity of impedance measurements to air content. Two slabs from set B were used, including the slab with no entrained air dosage (slab 4 in Table 3-1) and the control slab with an entrained air dosage of 97.8 ml per 100 kg (1.5 fl oz per 100 lb) of cement (slab 2 in Table 3-1). Two frequency sweeps were performed on each slab.

3.3.1.8 Chloride Concentration

Sets A and B were used to evaluate the sensitivity of impedance measurements to chloride concentration. For set A, impedance measurements taken over the full epoxy-coated bar and the black bar positioned at a cover depth of 6.35 cm (2.5 in.) were specifically used for this analysis, and one frequency sweep was performed over each bar in each slab. For set B, two slabs were used, including the slab with 5.9 kg of chloride per cubic meter (10 lb of chloride per cubic yard) of concrete (slab 3 in Table 3-1) and the control slab with no chloride (slab 2 in Table 3-1); two frequency sweeps were performed on each slab.

3.3.1.9 Epoxy Coating Condition

Set A was used to evaluate the sensitivity of impedance measurements to epoxy coating condition. Impedance measurements from four lengths of epoxy-coated steel, each having a different epoxy coating condition, and one length of uncoated reinforcing steel at the same cover depth were compared. One frequency sweep was performed over each bar in each slab.

3.3.2 Uncontrolled Laboratory Experiments

Uncontrolled laboratory experiments were performed to compare impedance values measured at the recommended frequency(ies) to more traditional test measurements relating to bridge deck corrosion potential. Being representative of typical field conditions where individual deck properties cannot be controlled, slab set E was used for this experimentation.

For each slab in set E, one impedance test was performed at each of 32 test locations in a 1.5 x 2.4 m (4 x 8 ft) grid as shown in Figure 3-11. Three different grounding points were established on the long side of each slab by installing a screw into a hole drilled into the end of each of three lengths of reinforcing steel exposed along the side. As labeled in Figure 3-14, tests on rows 1 through 3 were performed using the first ground located at row 2, tests on rows 4 through 5 were performed using the second ground located between rows 4 and 5, and tests on rows 6 through 8 were performed using the third ground located at row 7. Placement of the probe on a slab in set E is illustrated in Figure 3-12; the probe was consistently placed over at least one length of reinforcing steel and between the chloride concentration test holes drilled into the slabs for previous research.

In addition to chloride concentration testing, which was performed at 1.3-cm (0.5-in.) depth intervals to a total depth of 10.2 cm (4 in.), set E had also been subjected to cover depth, rebound number, resistivity, half-cell potential, linear polarization, and chloride concentration

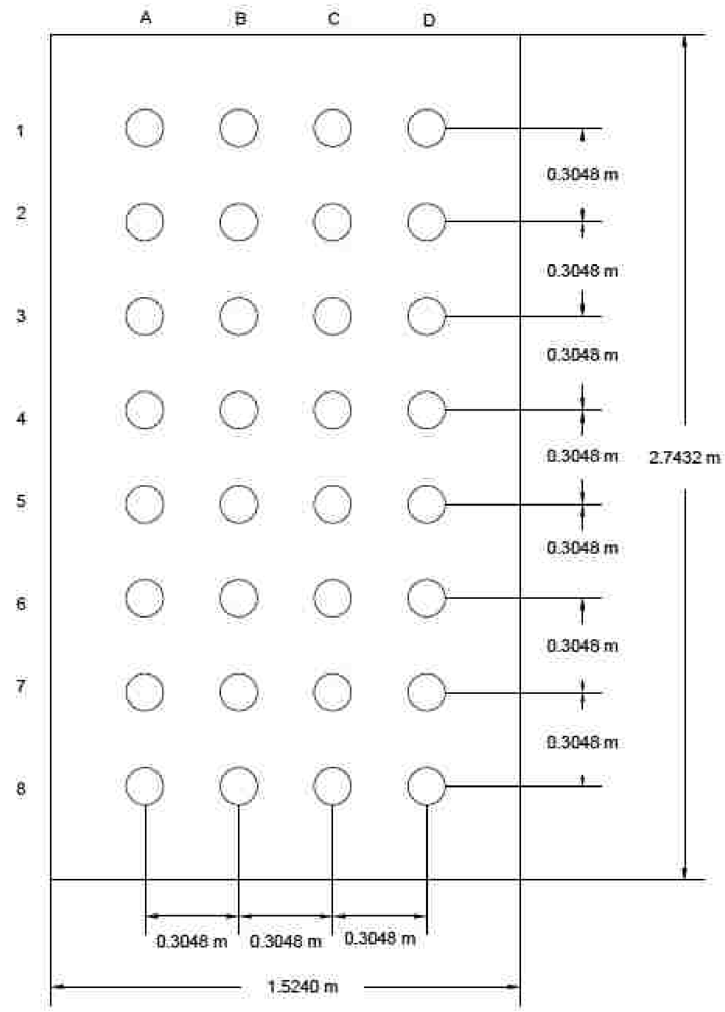

Figure 3-11. Testing locations for slabs in set E.

testing as part of previous research (Sumsion 2013). Half-cell potential, linear polarization, and resistivity testing were performed both before and after the deck slabs had been soaked with water for 72 hours. The results of these traditional testing techniques were compared with the impedance measurements collected in the current research.

Figure 3-12. Probe placement for slabs in set E.

3.4 Statistical Analysis

The following sections describe the statistical analyses applied to the controlled and uncontrolled laboratory experiments. In each case, only main effects were evaluated; any possible interactions were ignored. The statistical analyses were performed using JMP 10.0 software.

3.4.1 Controlled Laboratory Experiments

For the controlled laboratory experiments, statistical analyses were performed to determine if there was a statistically significant difference between impedance measurements obtained for each level of each deck property studied. For the properties of sealant presence, cover depth, water-to-cementitious materials ratio, air content, and chloride concentration, for which only two levels were present, a two-sided *t*-test was performed. The null hypothesis for the *t*-test was that the impedance values for the two levels were the same, while the alternative hypothesis was that the impedance values for the two levels were different. For these analyses, replicate impedance values collected on the same slab, or impedance values collected on replicate slabs when replicate slabs were available, were averaged by frequency, such that a single impedance value was computed for each frequency at each level. Each level was then represented in the *t*-test by a range of impedance values spanning the range in frequency. Each *t*-test produced a *p*-value that was used for evaluating the difference between the two levels; a *p*-value less than or equal to 0.05 indicated that the difference was statistically significant. The least squares mean (LSM) values were also computed for each property.

For curing time, temperature, moisture content, cover depth, chloride concentration, and epoxy coating condition, for which three or more levels were present, an analysis of variance (ANOVA) was performed. The null hypothesis for each ANOVA was that the impedance values for the levels were the same, while the alternative hypothesis was that the impedance values for at least two levels were different. Again, replicate impedance values collected on the same slab, or impedance values collected on replicate slabs when replicate slabs were available, were averaged by frequency, such that a single impedance value was computed for each frequency at each level. Each level was then represented in the ANOVA by a range of impedance values spanning the range in frequency. Each ANOVA produced a *p*-value that was used for evaluating differences between the levels; a *p*-value less than or equal to 0.05 indicated that the difference between at least two levels was statistically significant. The LSM values were computed for each deck property, and a Tukey-Kramer analysis was performed to identify the levels that differed from each other. In the Tukey-Kramer analysis, a *p*-value less than or equal to 0.05 indicated statistical significance.

To select a frequency(ies), individual deck properties were analyzed through a *t*-test (for two variable treatments) or an ANOVA (for three or more variable treatments). All deck properties were analyzed except for moisture content, for which the required replicate measurements were not available. The null hypothesis for each analysis was that the impedance values for the levels were the same, while the alternative hypothesis was that the impedance values for the levels, or for at least two of the levels, were different. In these analyses, replicate impedance values collected on the same slab, or impedance values collected on replicate slabs when replicate slabs were available, were analyzed individually for each frequency, such that each level was then represented in the given *t*-test or ANOVA by the impedance values measured at only the frequency of interest. (Measurements obtained at 200 Hz at the end of the first series were analyzed separately from the measurements obtained at 200 Hz at the beginning of the second series.) A *p*-value less than or equal to 0.05 indicated that the difference was statistically significant.

3.4.2 Uncontrolled Laboratory Experiments

For the uncontrolled laboratory experiments, pair-wise correlations were computed between impedance values and each of the other measurements performed on the slabs in set E, including longitudinal cover depth, transverse cover depth, rebound number, resistivity (dry and wet), half-cell potential (dry and wet), linear polarization (dry and wet), and chloride concentrations at depths of 1.27, 2.54, 3.81, 5.08, 6.35, 7.62, 8.89, and 10.16 cm (0.5, 1, 1.5, 2, 2.5, 3, 3.5, and 4 in.). As the traditional tests were performed at each of 45 test locations in a 1.5 x 2.7 m (5 x 9 ft) grid, those data were not precisely co-located with the impedance data, which were collected at each of 32 test locations in a 1.5 x 2.4 m (4 x 8 ft) grid as explained earlier; specifically, the impedance testing was performed between the locations of the traditional tests, as required to avoid the chloride concentration test holes drilled into the slabs for previous research. Therefore, to facilitate this correlation analysis, individual impedance values were paired with traditional test data collected above and to the left of the each impedance testing location shown in Figure 3-11. In the analyses, both the correlation coefficient R and the *p*-value were determined. As this was an exploratory experiment, correlations having *p*-values less than or equal to 0.15 were considered to be statistically significant.

3.5 Summary

An experiment was designed to evaluate the effects of sealant presence, curing time, temperature, moisture content, cover depth, water-to-cementitious materials ratio, air content, chloride concentration, and epoxy coating condition on individual impedance measurements. Five sets of slabs were used to conduct this research. Set A was comprised of nine concrete slabs, each containing seven lengths of reinforcing steel. The seven bars of reinforcing steel included three black bars, each situated at different cover depths, and four epoxy-coated bars, each with a different treatment to enable evaluation of different forms of damage to the epoxy coating. Three different quantities of sodium chloride were present across the nine concrete slabs. Set B was comprised of four concrete slabs, each containing a single length of uncoated reinforcing steel. Each slab varied in water-to-cementitious materials ratio, entrained air dosage, and chloride concentration. Set C was comprised of four concrete slabs, each containing a single length of uncoated reinforcing steel. Only two properties were varied in these slabs, the water-to-cementitious materials ratio and chloride concentration. Set D was comprised of four concrete slabs, each containing a single length of uncoated reinforcing steel. Only two properties were varied in these slabs, including the cover depth of the reinforcing steel and the presence of a sealant. Set E was comprised of four decommissioned concrete bridge deck slabs obtained during reconstruction of I-15 in Provo, Utah. Three of the slabs, from bridges C-357, C358, and D-413, contained uncoated reinforcing steel. One slab, from bridge C-363, contained epoxy-coated reinforcing steel.

The system used to collect impedance values utilized a probe connected to a computer. Twenty logarithmically spaced frequencies, between the frequencies of 100 mHz and 300 kHz, were measured. A full frequency sweep was used to evaluate slab sets A to D, and a single test was performed at the recommended frequency for set E. Set A was used to evaluate the sensitivity of impedance measurements to cover depth, chloride concentration, and epoxy coating condition; set B was used to evaluate the sensitivity of impedance measurements to water-to-cementitious materials ratio, air content, and chloride concentration; set C was used to evaluate the sensitivity of impedance measurements to temperature and moisture content; and set D was used to evaluate the sensitivity of impedance measurements to sealant presence, curing time, and cover depth. Set E was used to compare impedance values to more traditional test measurements relating to corrosion of reinforcing steel in concrete bridge decks.

For the controlled laboratory experiments, two-sided *t*-tests and ANOVAs were performed to determine if there was a statistically significant difference between impedance measurements obtained for each level of each deck property studied and to select a recommended frequency(ies). In these analyses, a *p*-value less than or equal to 0.05 indicated statistical significance. For the uncontrolled laboratory experiments, pair-wise correlations were computed between impedance values and each of the other measurements performed on the slabs in set E; as this was an exploratory experiment, correlations having *p*-values less than or equal to 0.15 were considered to be statistically significant.

4 RESULTS

4.1 Overview

Five sets of laboratory slabs were used to investigate the sensitivity of impedance measurements to specific concrete bridge deck properties. The following sections discuss the results for both the controlled laboratory experiments on slab sets A to D and the uncontrolled laboratory experiments on slab set E.

4.2 Controlled Laboratory Experiments

The following sections present the results of the statistical analyses performed to evaluate the effects of sealant presence, curing time, temperature, moisture content, cover depth, water-to-cementitious materials ratio (w/cm), air content, chloride concentration, and epoxy coating condition. All raw data are presented in Appendix A.

4.2.1 Sealant Presence

The results of the *t*-test used for analyzing the sensitivity of impedance to sealant presence are presented in Table 4-1. In both cases, sealant presence was determined to have a statistically significant effect, with *p*-values less than 0.05. Table 4-2 provides the LSM values for sealant presence, and Figures 4-1 and 4-2 graphically display the impedance values measured for each sealant treatment. Each point on the graph is the average of two measurements obtained on a single slab. The data show that application of either type of sealant increases impedance, which suggests increased protection of the embedded reinforcing steel.

Table 4-1. *P*-Values for Sealant Presence

Treatment	*p*-value
Lithium Silicate Treatment	0.0017
Silane and Lithium Silicate Treatment	<0.0001

Table 4-2. Least Squares Means for Sealant Presence

Treatment	Impedance (Ω-cm)
No Treatment	5350.6
Lithium Silicate Treatment	7264.1
No Treatment	5172.1
Silane and Lithium Silicate Treatment	7344.9

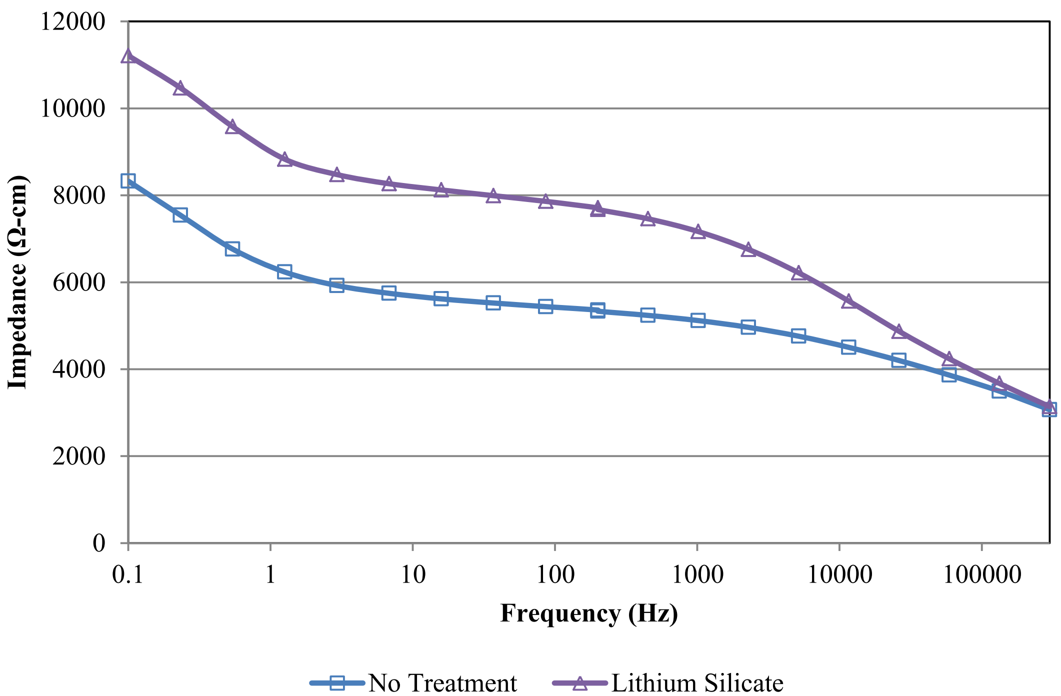

Figure 4-1. Impedance measurements for sealant presence using lithium silicate.

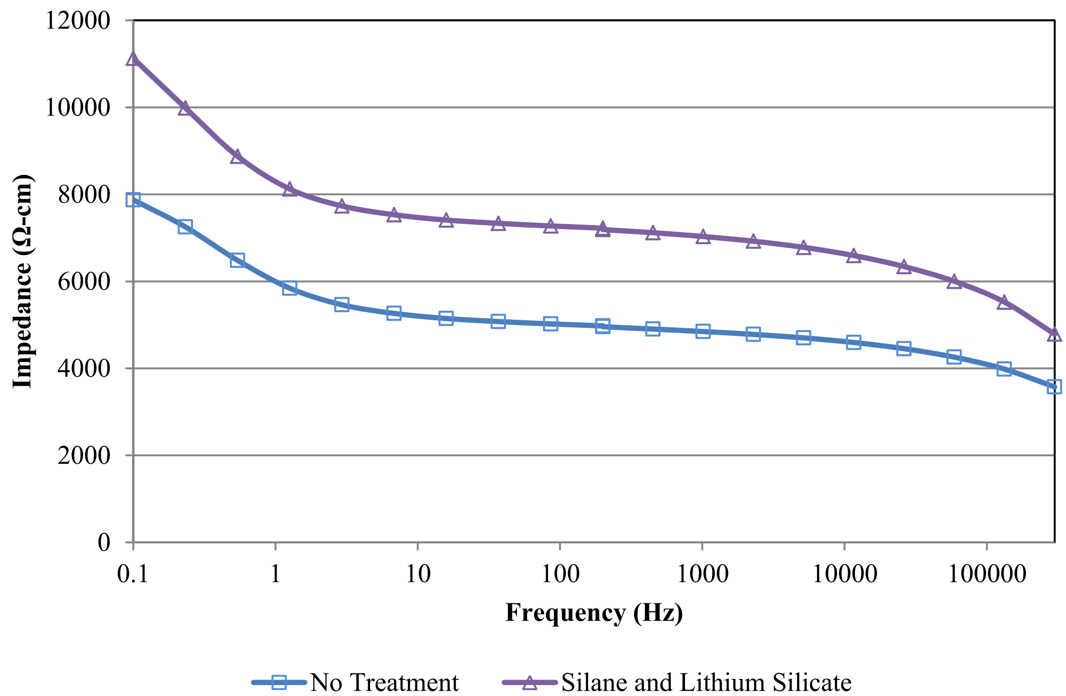

Figure 4-2. Impedance measurements for sealant presence using silane and lithium silicate.

4.2.2 Curing Time

The results of the ANOVA used for analyzing the sensitivity of impedance to concrete curing time are presented in Table 4-3. In all four cases, curing time was determined to have a statistically significant effect, with *p*-values all less than 0.05. Table 4-4 provides the LSM values for curing time, Tables 4-5 to 4-8 provide the results of the Tukey-Kramer analysis, and Figures 4-3 to 4-6 graphically display the impedance values measured for each curing time. (Data for the curing period of 21 days were excluded from the analysis of slab 3 because they were determined to be invalid.) Each point on the graph is the average of two measurements obtained on a single slab. The data show that longer curing periods increase impedance, which suggests increased protection of the embedded reinforcing steel. While the differences between curing periods differing by only a week were not statistically significant, larger differences of two or three weeks were statistically significant for all test slabs.

Table 4-3. *P*-Values for Curing Time

Treatment	*p*-value
6.3 cm Cover Slab 1	<0.0001
6.3 cm Cover Slab 2	<0.0001
2.5 cm Cover Slab 3	<0.0001
2.5 cm Cover Slab 4	<0.0001

Table 4-4. Least Squares Means for Curing Time

	Impedance (Ω-cm)			
Curing Time (days)	6.4 cm Cover Slab 1	6.4 cm Cover Slab 2	2.5 cm Cover Slab 3	2.5 cm Cover Slab 4
7	1150.6	1150.8	933.0	905.4
14	1368.4	1446.5	1075.0	1083.0
21	1292.4	1446.4	-	1305.1
28	1568.5	1628.8	1280.2	1311.0
35	1877.7	2370.3	1429.9	1489.5
42	2334.1	2416.7	2503.9	2011.4
49	2556.4	2155.8	2459.9	2198.4
56	2781.4	2726.6	2015.9	2044.5

Table 4-5. Tukey-Kramer Results for Curing Time for Slab 1 with 6.3 cm Cover

Curing Time (days)	14	21	28	35	42	49	56
7	0.7089	0.9591	0.0352	<0.0001	<0.0001	<0.0001	<0.0001
14	-	0.9991	0.7898	0.0036	<0.0001	<0.0001	<0.0001
21	-	-	0.4121	0.0004	<0.0001	<0.0001	<0.0001
28	-	-	-	0.2660	<0.0001	<0.0001	<0.0001
35	-	-	-	-	0.0142	<0.0001	<0.0001
42	-	-	-	-	-	0.6866	0.0177
49	-	-	-	-	-	-	0.6736

Table 4-6. Tukey-Kramer Results for Curing Time for Slab 2 with 6.3 cm Cover

Curing Time (days)	14	21	28	35	42	49	56
7	0.3178	0.3181	0.0079	<0.0001	<0.0001	<0.0001	<0.0001
14	-	1.0000	0.8564	<0.0001	<0.0001	<0.0001	<0.0001
21	-	-	0.8562	<0.0001	<0.0001	<0.0001	<0.0001
28	-	-	-	<0.0001	<0.0001	0.0021	<0.0001
35	-	-	-	-	1.0000	0.7214	0.1206
42	-	-	-	-	-	0.4842	0.2597
49	-	-	-	-	-	-	0.0006

Table 4-7. Tukey-Kramer Results for Curing Time for Slab 3 with 2.5 cm Cover

Curing Time (days)	14	21	28	35	42	49	56
7	0.9005	-	0.0699	0.0012	<0.0001	<0.0001	<0.0001
14	-	-	0.6140	0.0565	<0.0001	<0.0001	<0.0001
21	-	-	-	-	-	-	-
28	-	-	-	0.8755	<0.0001	<0.0001	<0.0001
35	-	-	-	-	<0.0001	<0.0001	<0.0001
42	-	-	-	-	-	0.9998	0.0016
49	-	-	-	-	-	-	0.0059

Table 4-8. Tukey-Kramer Results for Curing Time for Slab 4 with 2.5 cm Cover

Curing Time (days)	14	21	28	35	42	49	56
7	0.6873	0.0046	0.0038	<0.0001	<0.0001	<0.0001	<0.0001
14	-	0.4038	0.3693	0.0037	<0.0001	<0.0001	<0.0001
21	-	-	1.0000	0.6454	<0.0001	<0.0001	<0.0001
28	-	-	-	0.6821	<0.0001	<0.0001	<0.0001
35	-	-	-	-	<0.0001	<0.0001	<0.0001
42	-	-	-	-	-	0.6283	1.0000
49	-	-	-	-	-	-	0.8208

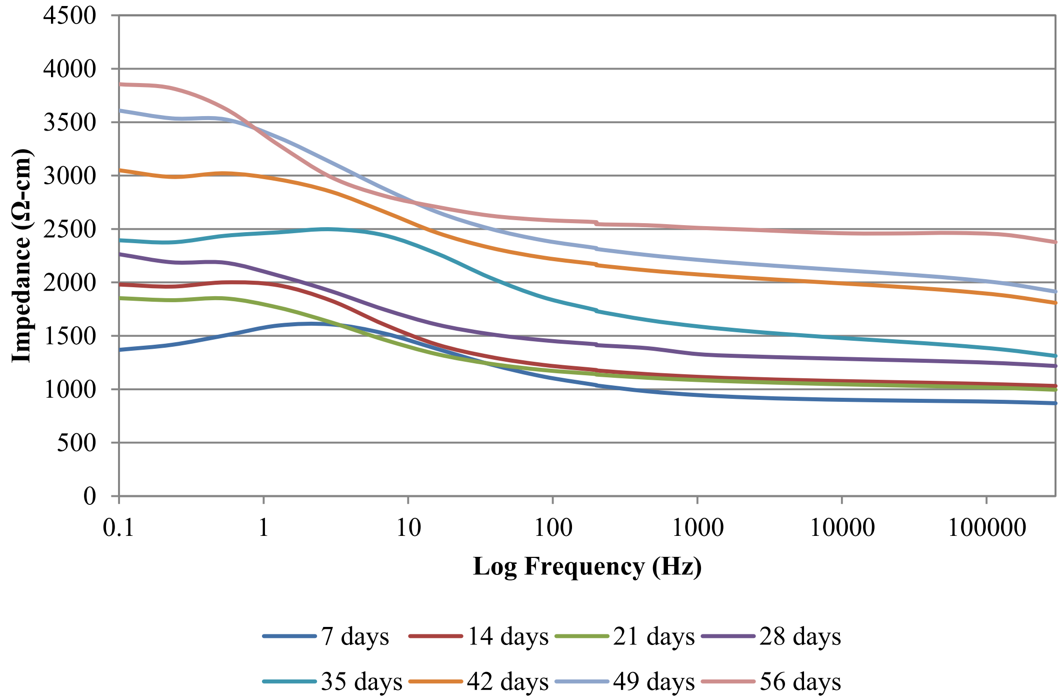

Figure 4-3. Impedance measurements for curing time for slab 1 with 6.3 cm cover

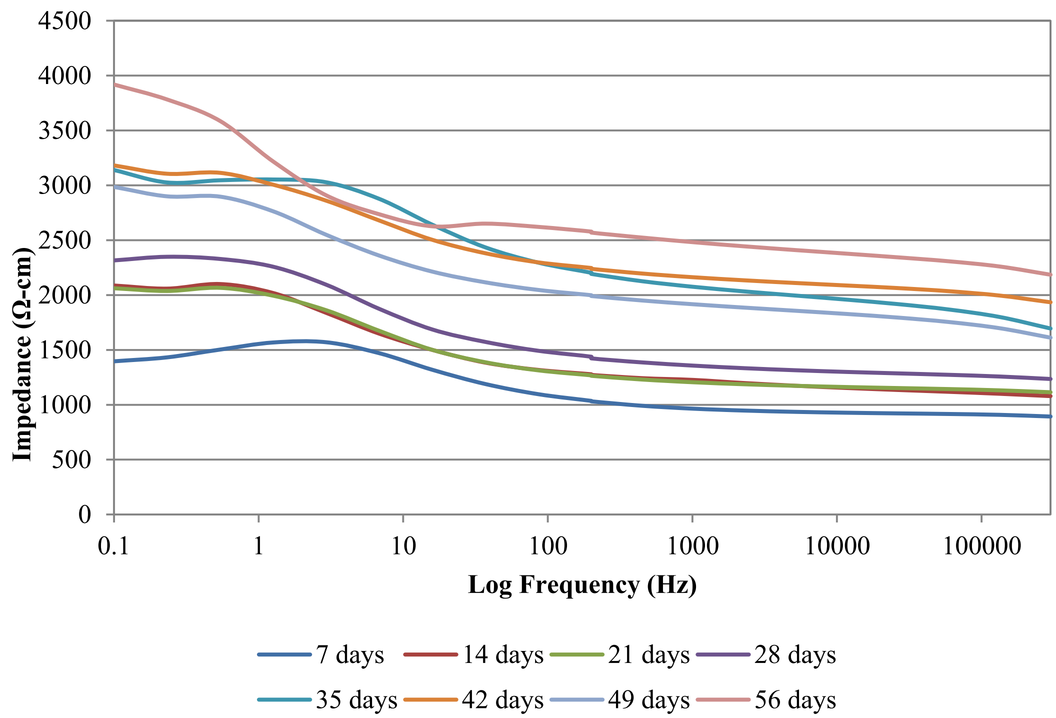

Figure 4-4. Impedance measurements for curing time for slab 2 with 6.3 cm cover.

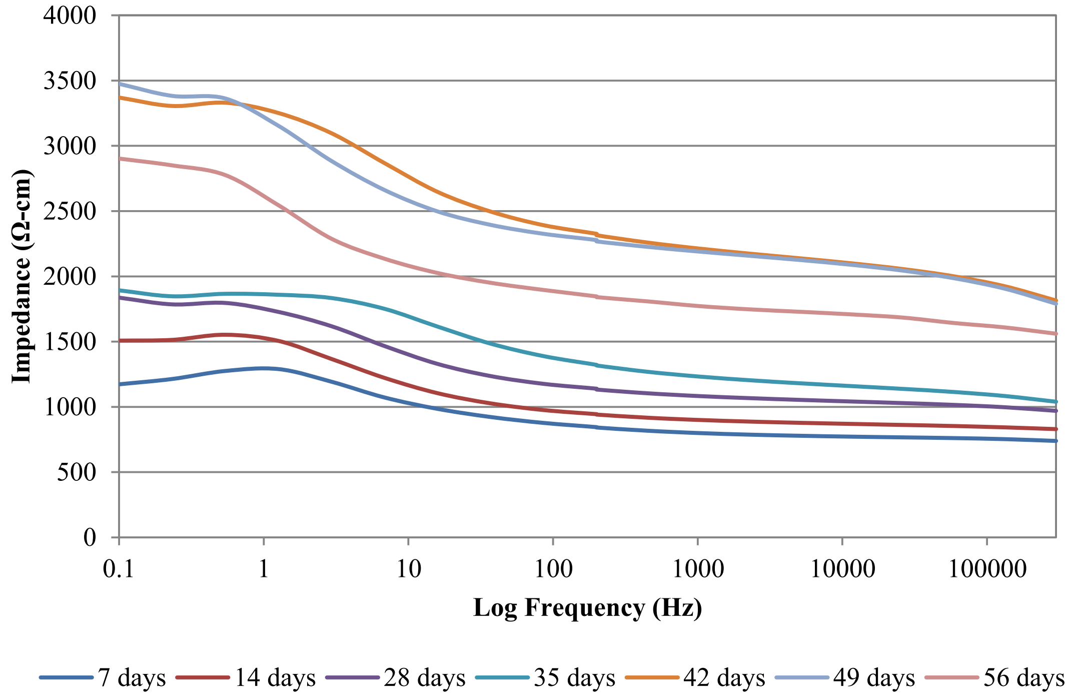

Figure 4-5. Impedance measurements for curing time for slab 3 with 2.5 cm cover.

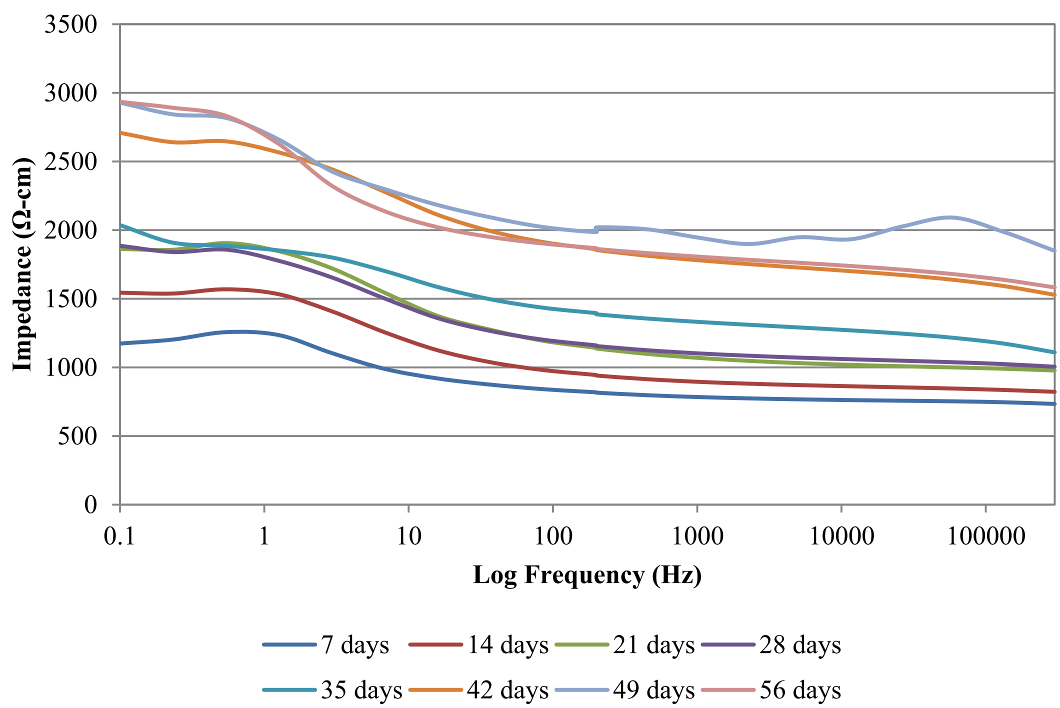

Figure 4-6. Impedance measurements for curing time for slab 4 with 2.5 cm cover.

4.2.3 Temperature

The results of the ANOVA used for analyzing the sensitivity of impedance to concrete temperature are given in Table 4-9. In both cases, temperature was determined to have a statistically significant effect, with *p*-values all less than 0.05. Table 4-10 provides the LSM values for temperature, Table 4-11 provides the results of the Tukey-Kramer, and Figures 4-7 to 4-8 graphically display the impedance values measured for each temperature. Each point on the graph is the average of two measurements obtained on a single slab. The data show that lower temperatures increase impedance, which suggests increased protection of the embedded reinforcing steel. (The unexpected trends in Figure 4-8, wherein the impedance values do not monotonically decrease with increasing frequency, may be the result of probe instability; these impedance values were the highest measurements recorded in all of the EIS testing performed in this research.)

Table 4-9. *P*-Values for Temperature

Treatment	*p*-value
0.40 w/cm 5.9 kg Cl^-/m^3	<0.0001
0.60 w/cm 0 kg Cl^-/m^5	<0.0001

Table 4-10. Least Squares Means for Temperature

Temperature (°C)	Impedance (Ω-cm) for Indicated Treatment: 0.40 w/cm 5.9 kg Cl^-/m^3	Impedance (Ω-cm) for Indicated Treatment: 0.60 w/cm 0 kg Cl^-/m^3
5	88801.4	266098.8
20	68224.0	154394.4
35	35866.4	48831.8

Table 4-11. Tukey-Kramer Results for Temperature

	Treatment			
	0.40 w/cm 5.9 kg Cl^-/m^3		0.60 w/cm 0 kg Cl^-/m^3	
Temperature (°C)	20	35	20	35
5	0.0278	<0.0001	0.0002	<0.0001
20	-	0.0003	-	0.0004

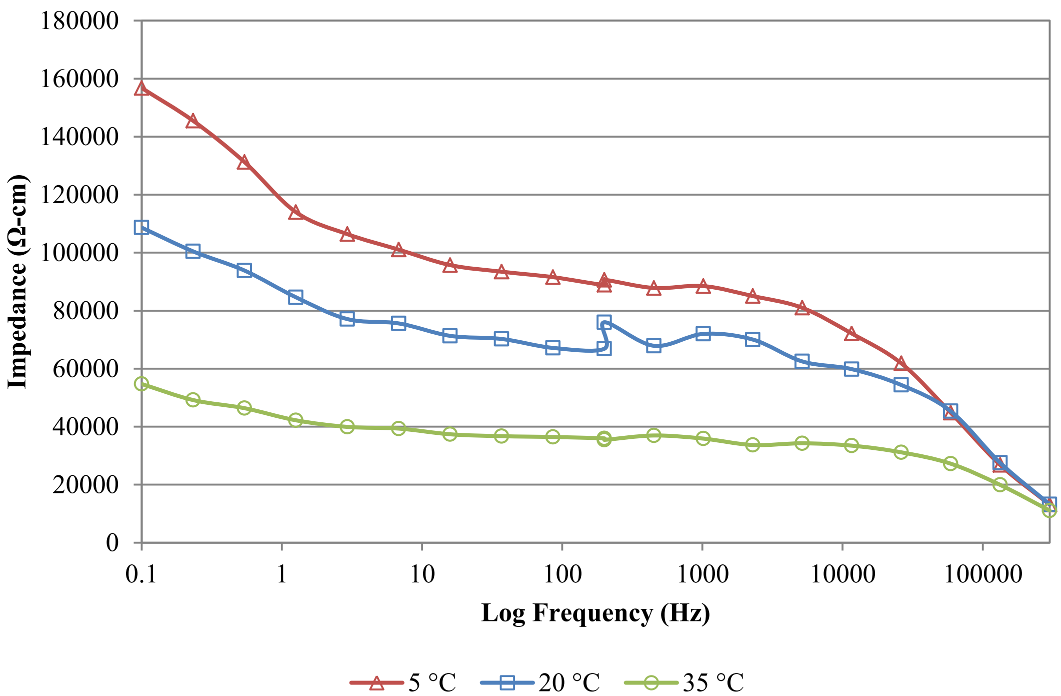

Figure 4-7. Impedance measurements for slab with 0.40 w/cm and 5.9 kg Cl^-/m^3.

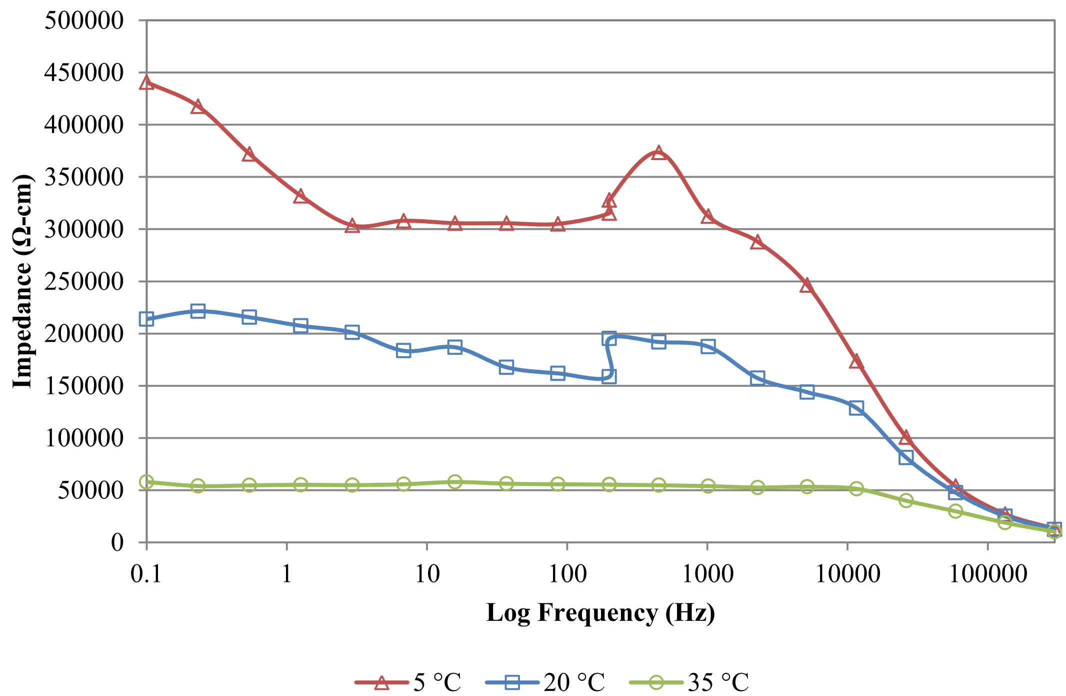

Figure 4-8. Impedance measurements for slab with 0.60 w/cm and 0 kg Cl^-/m^3.

4.2.4 Moisture Content

The results of the ANOVA used for analyzing the sensitivity of impedance to concrete moisture content are presented in Table 4-12. In both cases, moisture content was determined to have a statistically significant effect, with *p*-values all less than 0.05. Table 4-13 provides the LSM values for moisture content, Tables 4-14 and 4-15 provide the results of the Tukey-Kramer analysis, and Figures 4-9 and 4-10 graphically display the impedance values measured for each moisture content. Each point on the graph is a single measurement obtained on a single slab. The data show that lower moisture contents increase impedance, which suggests increased protection of the embedded reinforcing steel.

Table 4-12. *P*-Values for Moisture Content

Treatment	*p*-value
0.40 w/cm 5.9 kg Cl^-/m^3	<0.0001
0.60 w/cm 0 kg Cl^-/m^3	<0.0001

Table 4-13. Least Squares Means for Moisture Content

Soaking Time (hr)	Impedance (Ω-cm) for Indicated Treatment	
	0.40 w/cm 5.9 kg Cl^-/m^3	0.60 w/cm 0 kg Cl^-/m^3
0	16636.8	186723.6
0.25	8302.5	97703.7
0.5	8391.9	94428.3
1	9089.6	57989.0
2	8593.0	51039.9
4	8290.2	46164.4
6	8173.5	70816.1
8	8494.5	63982.4
12	13813.6	69283.5
24	8394.4	51597.1
36	8260.4	73828.8
48	7380.9	30986.8
96	7238.4	48438.7

Table 4-14. Tukey-Kramer Results for Moisture Content for Slab with 0.40 w/cm and 5.9 kg Cl^-/m^3

Soaking Time (hr)	0.25	0.5	1	2	4	6	8	12	24	36	48	96
0	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.2391	<0.0001	<0.0001	<0.0001	<0.0001
0.25	-	1.0000	0.9999	1.0000	1.0000	1.0000	1.0000	<0.0001	1.0000	1.0000	0.9996	0.9982
0.5	-	-	1.0000	1.0000	1.0000	1.0000	1.0000	<0.0001	1.0000	1.0000	0.9989	0.9962
1	-	-	-	1.0000	0.9999	0.9996	1.0000	0.0005	1.0000	0.9999	0.9093	0.8502
2	-	-	-	-	1.0000	1.0000	1.0000	<0.0001	1.0000	1.0000	0.9940	0.9842
4	-	-	-	-	-		1.0000	<0.0001	1.0000	1.0000	0.9996	0.9984
6	-	-	-	-	-	-	1.0000	<0.0001	1.0000	1.0000	0.9999	0.9995
8	-	-	-	-	-	-	-	<0.0001	1.0000	1.0000	0.9972	0.9917
12	-	-	-	-	-	-	-	-	<0.0001	<0.0001	<0.0001	<0.0001
24	-	-	-	-	-	-	-	-	-	1.0000	1.0000	1.0000
36	-	-	-	-	-	-	-	-	-	-	0.9997	0.9988
48	-	-	-	-	-	-	-	-	-	-	-	1.0000

Table 4-15. Tukey-Kramer Results for Moisture Content for Slab with 0.60 w/cm and 0 kg Cl⁻/m³

Soaking Time (hr)	0.25	0.5	1	2	4	6	8	12	24	36	48	96
0	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
0.25	-	1.0000	0.0522	0.0075	0.0015	0.5518	0.1960	0.4589	0.0089	0.7303	<0.0001	0.0033
0.5	-	-	0.1124	0.0197	0.0046	0.7446	0.3445	0.6575	0.0230	0.8815	<0.0001	0.0092
1	-	-	-		0.9988	0.9973	1.0000	0.9992	1.0000	0.9862	0.5448	0.9999
2	-	-	-	-		0.9088	0.9971	0.9479	1.0000	0.7872	0.9001	1.0000
4	-	-	-	-	-	0.6864	0.9562	0.7705	1.0000	0.5044	0.9879	1.0000
6	-	-	-	-	-	-			0.9248	1.0000	0.0507	0.8072
8	-	-	-	-	-	-	-		0.9981	0.9998	0.2244	0.9852
12	-	-	-	-	-	-	-	-	0.9586	1.0000	0.0737	0.8724
24	-	-	-	-	-	-	-	-	-	0.8140	0.8811	1.0000
36	-	-	-	-	-	-	-	-	-	-	0.0229	0.6429
48	-	-	-	-	-	-	-	-	-	-	-	0.9625

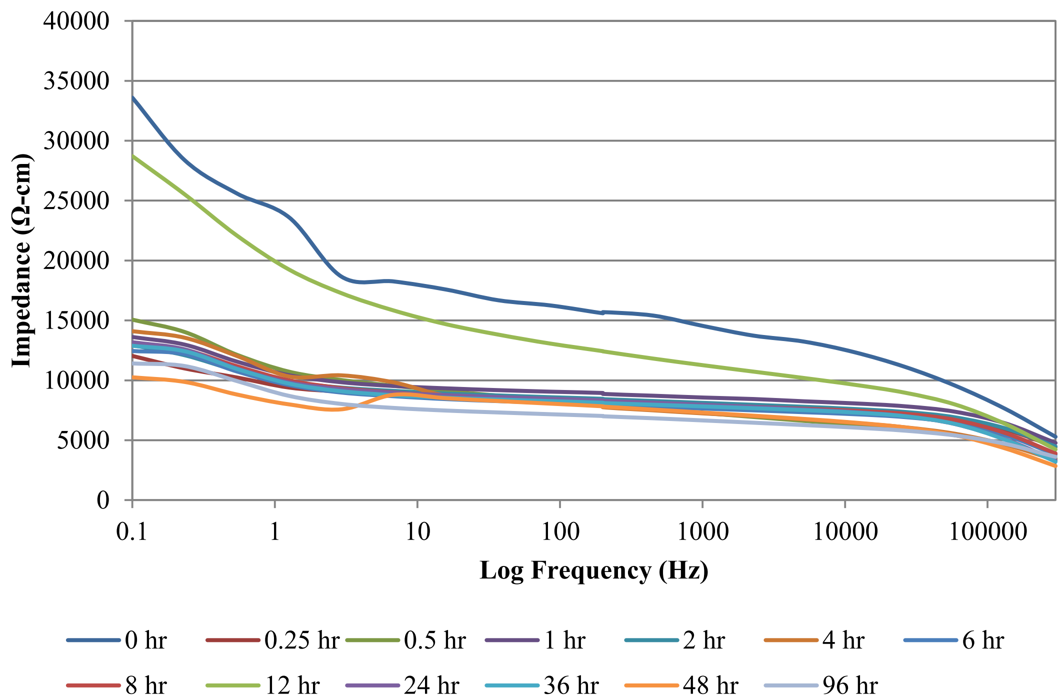

Figure 4-9. Impedance measurements for moisture content for slab with 0.40 w/cm and 5.9 kg Cl⁻/m³.

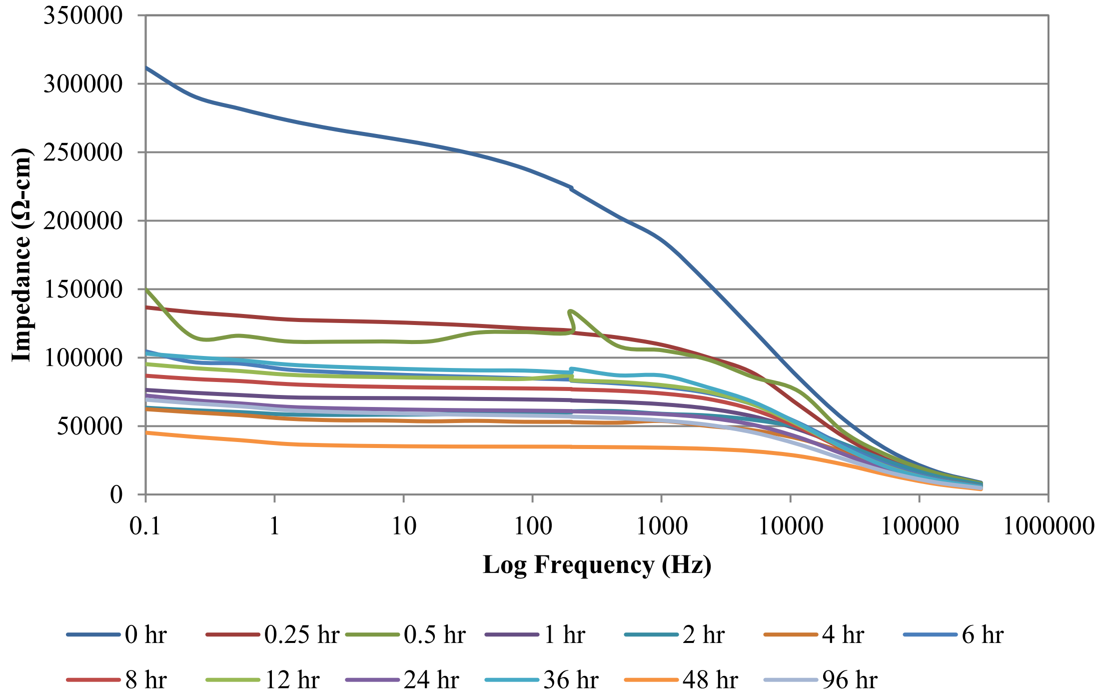

Figure 4-10. Impedance measurements for moisture content for slab with 0.60 w/cm and 0 kg Cl^-/m^3.

4.2.5 Cover Depth

For set A, the results of the ANOVA used for analyzing the sensitivity of impedance to concrete cover depth are presented in Table 4-16. For set D, the *t*-test used for analyzing the sensitivity of impedance to concrete cover depth yielded a *p*-value of 0.0093. In all four cases, cover depth was determined to have a statistically significant effect, with *p*-values all less than 0.05. For set A, Tables 4-17 and 4-18 provide the LSM values for cover depth, Table 4-19 provides the results of the Tukey-Kramer analysis, and Figures 4-11 to 4-14 graphically display the impedance values measured for each cover depth; each point on the graph is the average of three measurements obtained on three replicate slabs. For set D, each point on the graph is the average of two measurements obtained on a single slab. While the data for set A do not indicate a consistent effect of cover depth on impedance, the data for set D show that larger cover depths increase impedance, which suggests increased protection of the embedded reinforcing steel.

Table 4-16. *P*-Values for Cover Depth for Slabs in Set A

Treatment	*p*-value
0 kg Cl^-/m^3	<0.0001
1.2 kg Cl^-/m^3	0.0387
2.4 kg Cl^-/m^3	0.0138

Table 4-17. Least Squares Means for Cover Depth for Slabs in Set A

Cover Depth (cm)	Impedance (Ω-cm) for Indicated Treatment		
	0 kg Cl^-/m^3	1.2 kg Cl^-/m^3	2.4 kg Cl^-/m^3
5.1	28527.2	17357.8	18763.8
6.4	18872.3	17068.9	16049.0
7.6	18864.1	14564.8	15672.4

Table 4-18. Least Squares Means for Cover Depth for Slabs in Set D

Cover Depth (cm)	Impedance (Ω-cm)
2.5	1295.6
6.4	1598.6

Table 4-19. Tukey-Kramer Results for Cover Depth for Slabs in Set A

	Treatment					
	0 kg Cl^-/m^3		1.2 kg Cl^-/m^3		2.4 kg Cl^-/m^3	
Cover Depth (cm)	6.4	7.6	6.4	7.6	6.4	7.6
5.1	<0.0001	<0.0001	0.967	0.0909	0.0194	0.0454
6.4	-	1.0000	-	0.0524	-	0.9385

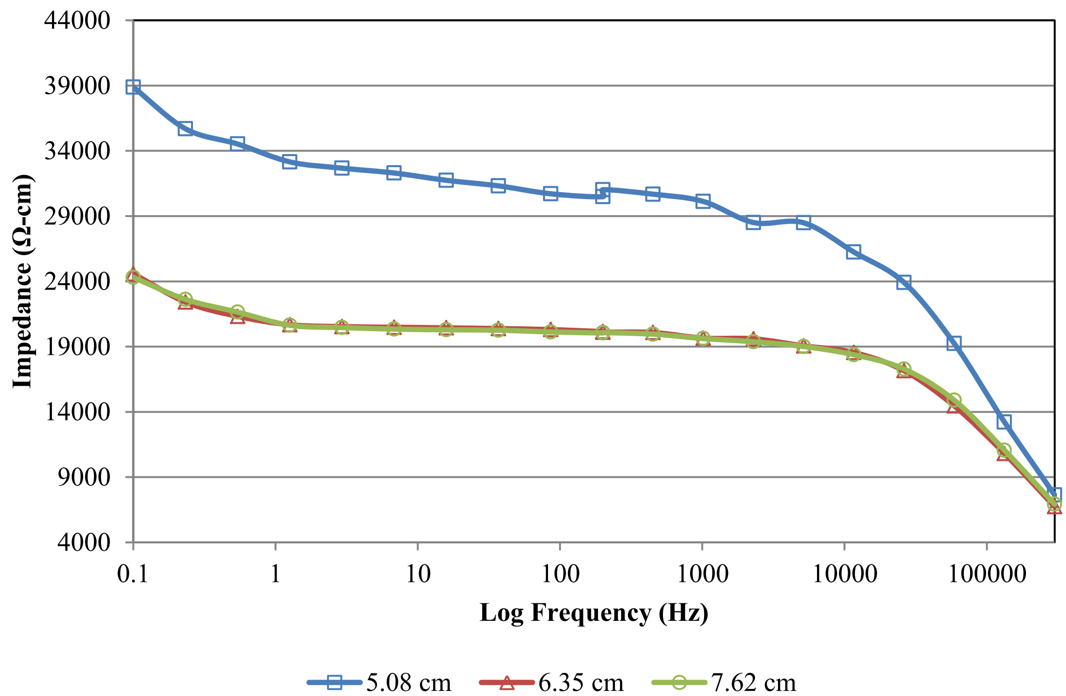

Figure 4-11. Impedance measurements for cover depth for slabs in set A with 0 kg Cl^-/m^3.

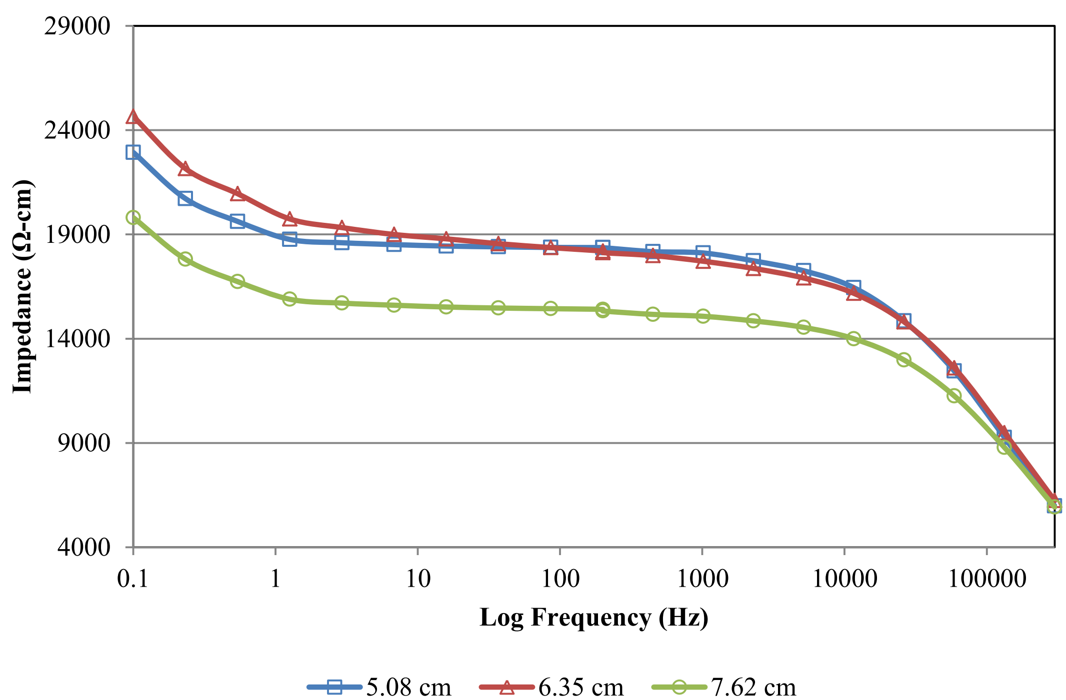

Figure 4-12. Impedance measurements for cover depth for slabs in set A with 1.2 kg Cl^-/m^3.

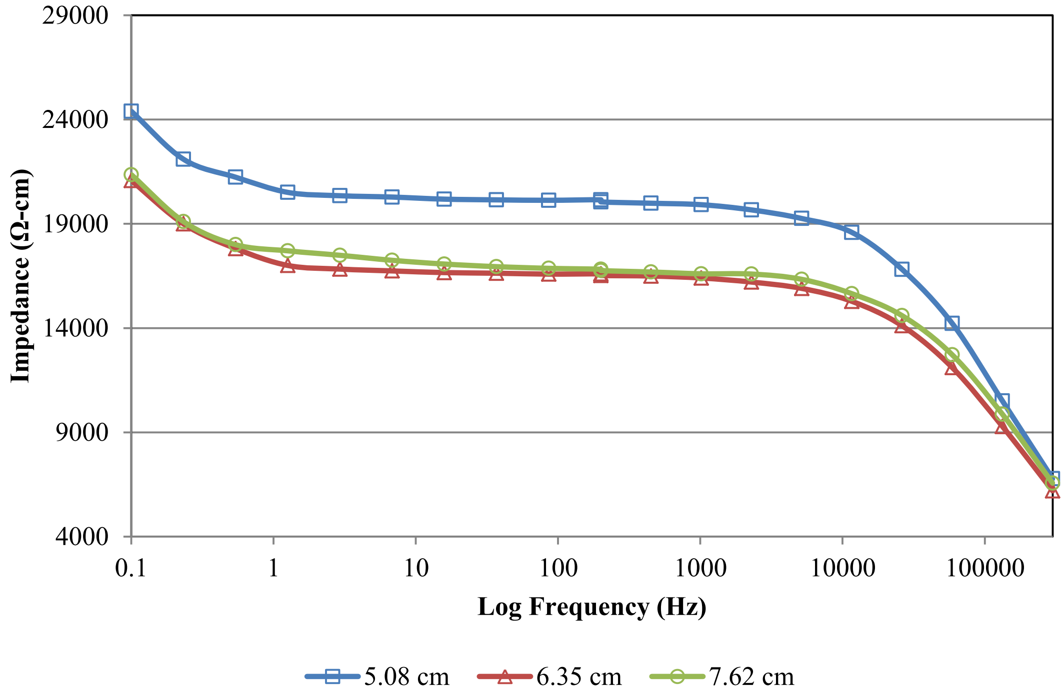

Figure 4-13. Impedance measurements for cover depth for slabs in set A with 2.4 kg Cl^-/m^3.

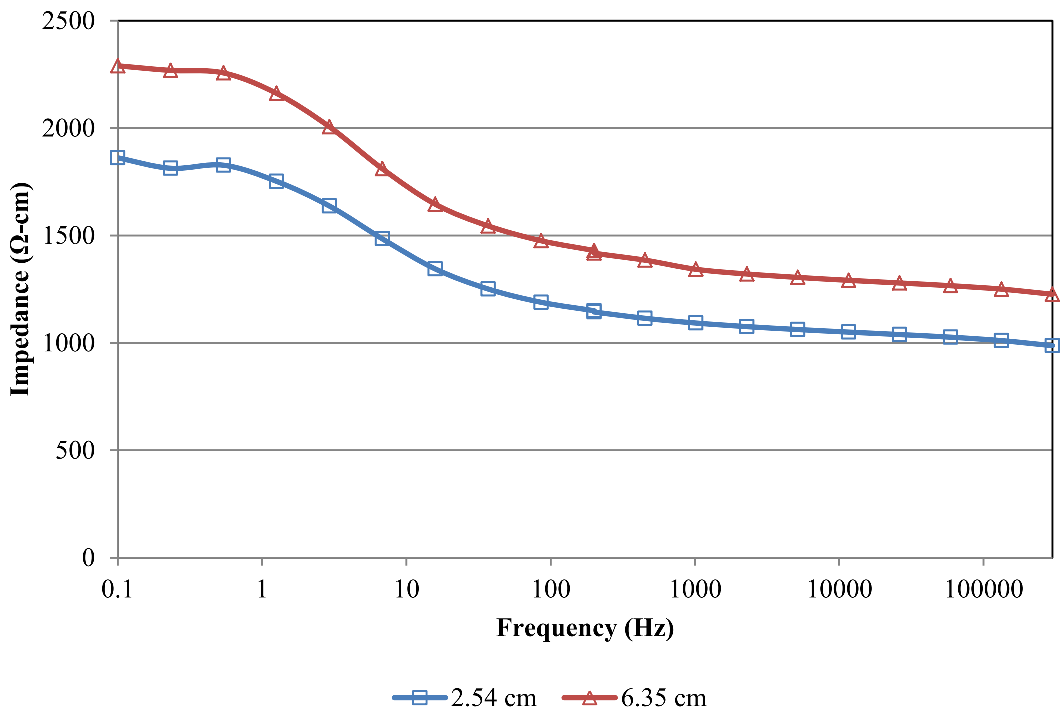

Figure 4-14. Impedance measurements for cover depth for slabs in set D.

4.2.6 Water-to-Cementitious Materials Ratio

The *t*-test used for analyzing the sensitivity of impedance to concrete water-to-cementitious materials ratio yielded a *p*-value of 0.0072. Water-to-cementitious materials ratio was determined to have a statistically significant effect, with a *p*-value less than 0.05. Figure 4-15 graphically displays the impedance values measured for each water-to-cementitious materials ratio. Each point on the graph is the average of two measurements obtained on a single slab. The data show that lower water-to-cementitious materials ratios increase impedance, which suggests increased protection of the embedded reinforcing steel.

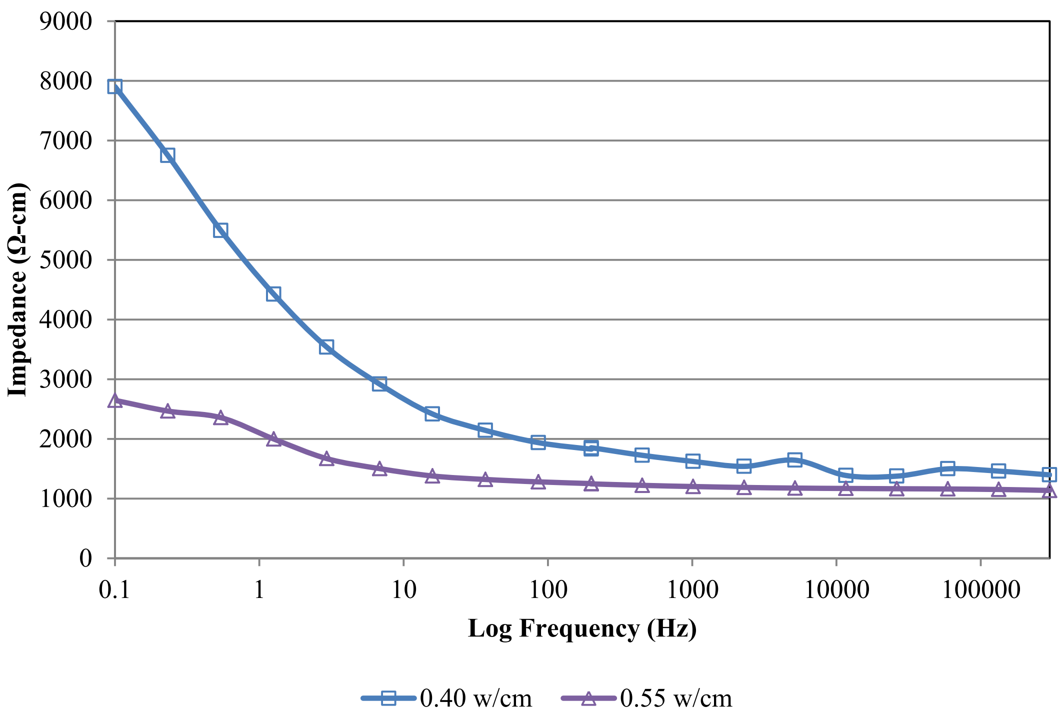

Figure 4-15. Impedance measurements for water-to-cementitious materials ratio.

4.2.7 Air Content

The *t*-test used for analyzing the sensitivity of impedance to concrete air content yielded a *p*-value of 0.0200. Air content was determined to have a statistically significant effect, with a *p*-value less than 0.05. Figure 4-16 graphically displays the impedance values measured for each air content. Each point on the graph is the average of two measurements obtained on a single slab. The data show that lower air contents increase impedance, which suggests increased protection of the embedded reinforcing steel.

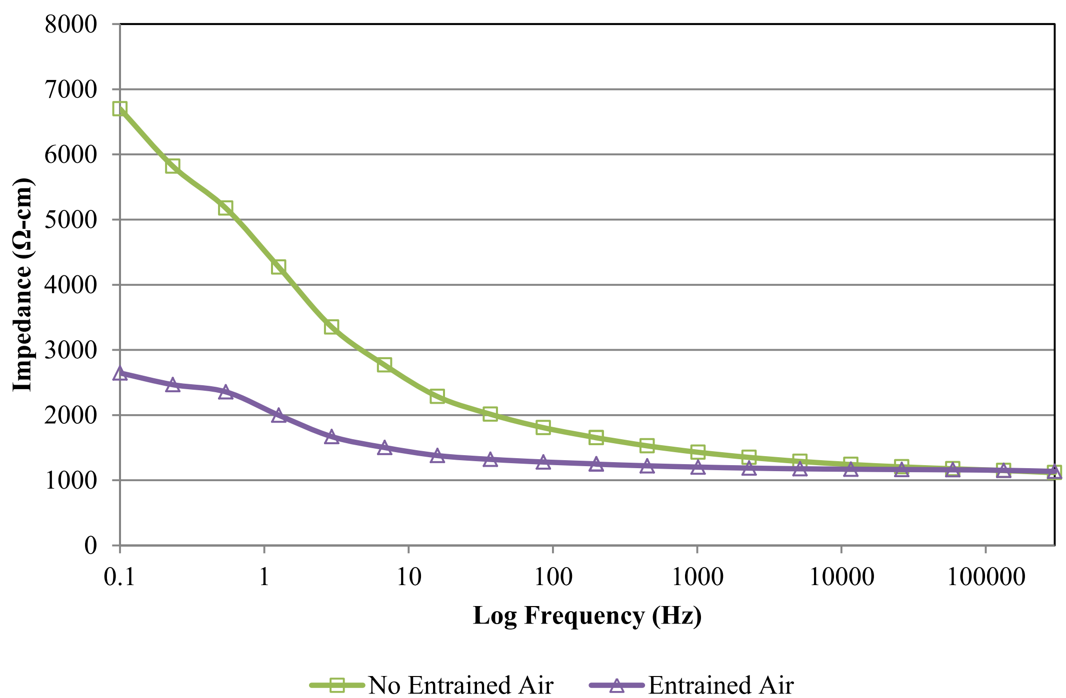

Figure 4-16. Impedance measurements for air content.

4.2.8 Chloride Concentration

For set A, the results of the ANOVA used for analyzing the sensitivity of impedance to concrete chloride concentration are presented in Table 4-20. For set B, the *t*-test used for analyzing the sensitivity of impedance to concrete chloride concentration yielded a *p*-value of

0.1592. For both analyses of black bar, chloride concentration was determined to have a statistically significant effect, with *p*-values all less than 0.05; however, for the analysis of epoxy-coated bar, the *p*-value was greater than 0.05, indicating that chloride concentration did not have a statistically significant effect in that case. For set A, Tables 4-21 and 4-22 provide the LSM values for chloride concentration, Table 4-23 provides the results of the Tukey-Kramer analysis, and Figures 4-17 to 4-19 graphically display the impedance values measured for each chloride concentration; each point on the graph is the average of three measurements obtained on three replicate slabs. For set B, each point on the graph is the average of two measurements obtained on a single slab. The data for black bar show that lower chloride concentrations increase impedance, which suggests increased protection of the embedded reinforcing steel. For epoxy-coated bar, chloride concentration within the range studied in this research was not shown to affect impedance.

Table 4-20. *P*-Values for Chloride Concentration for Slabs in Set A

Treatment	*p*-value
Black Bar	0.0365
Epoxy-Coated Bar	0.9702

Table 4-21. Least Squares Means for Chloride Concentration for Slabs in Set A

Chloride Concentration ($kg\ Cl^-/m^3$)	Impedance (Ω-cm) for Indicated Treatment	
	Black Bar	Epoxy-Coated Bar
0	18872.3	141870.9
1.2	17357.8	139108.7
2.4	15672.4	137152.4

Table 4-22. Least Squares Means for Chloride Concentration for Slabs in Set B

Chloride Concentration (kg Cl^-/m^3)	Impedance (Ω-cm)
0	1483.9
5.9	1260.3

Table 4-23. Tukey-Kramer Results for Chloride Concentration for Slabs in Set A

	Treatment			
	Black Bar		Epoxy-Coated Bar	
Chloride Concentration (kg Cl^-/m^3)	1.2	2.4	1.2	2.4
0	0.4272	0.0278	0.9675	0.9887
1.2	-	0.3504	-	0.9943

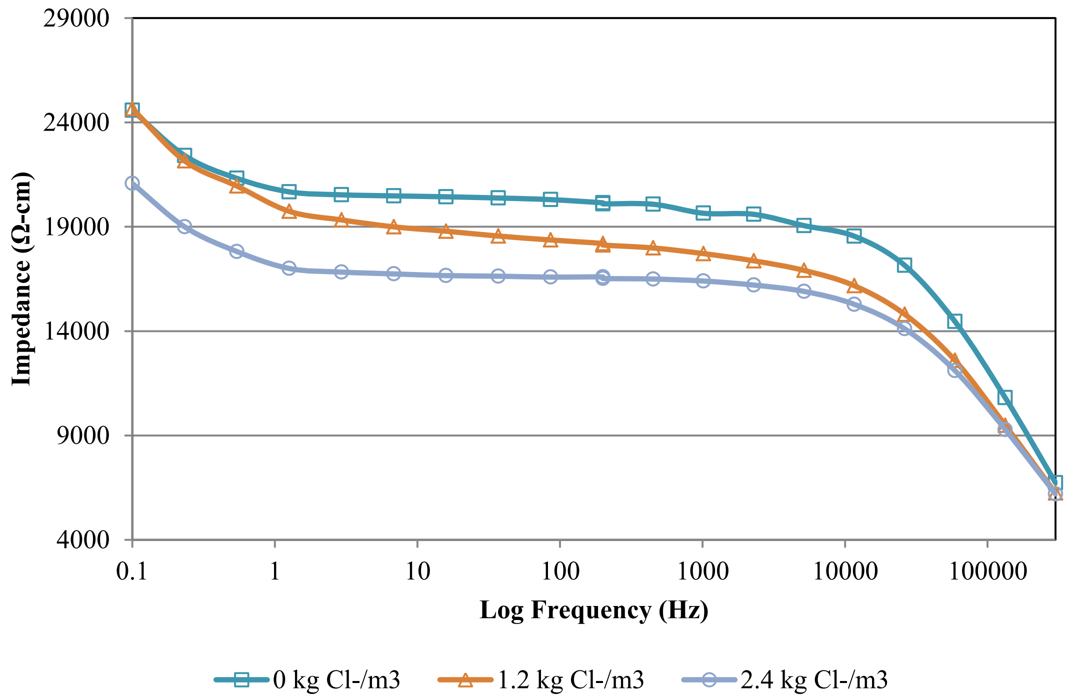

Figure 4-17. Impedance measurements for chloride concentration for slabs in set A with black bar.

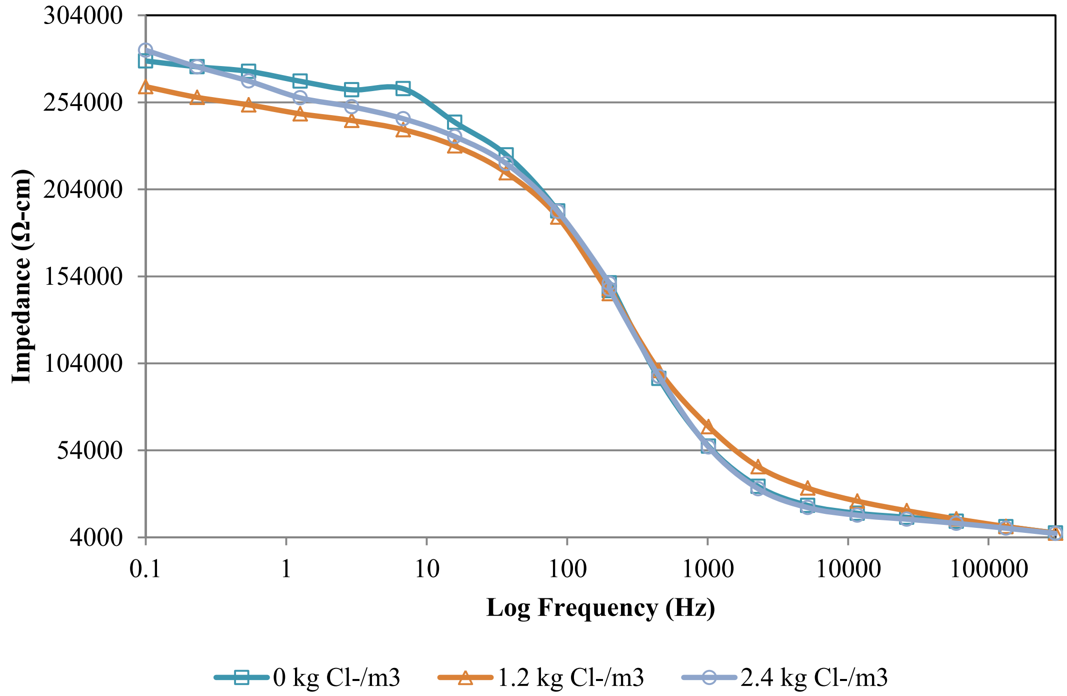

Figure 4-18. Impedance measurements for chloride concentration for slabs in set A with epoxy-coated bar.

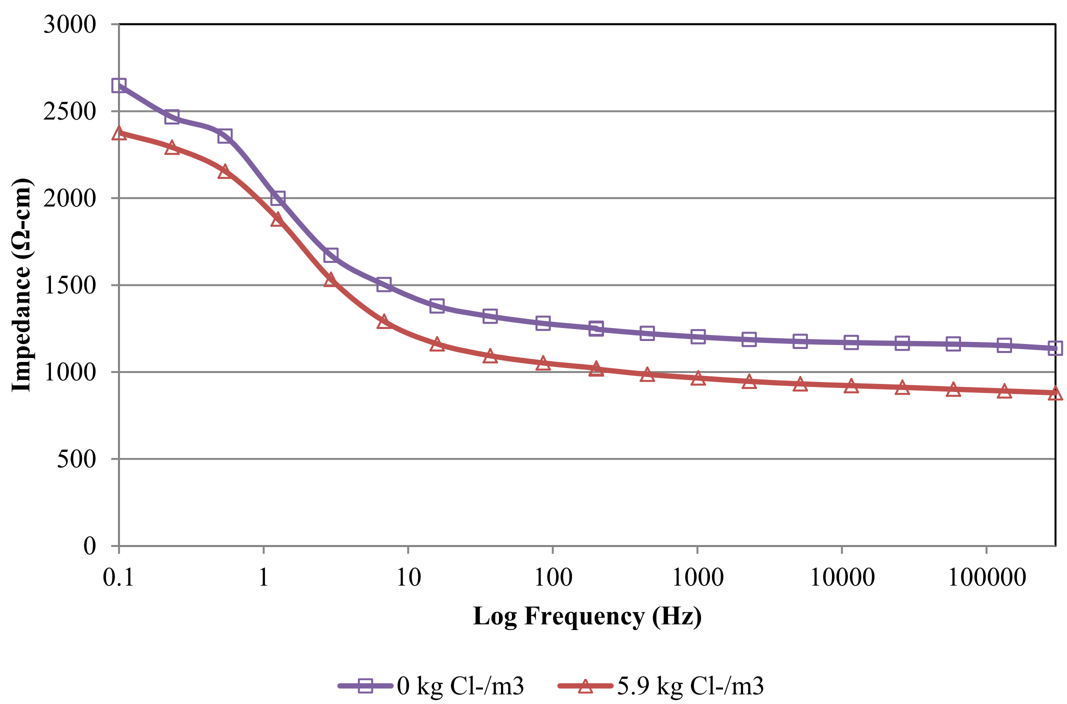

Figure 4-19. Impedance measurements for chloride concentration for slabs in set B.

4.2.9 Epoxy Coating Condition

The results of the ANOVA used for analyzing the sensitivity of impedance to reinforcing steel epoxy coating condition are presented in Table 4-24. In all three cases, epoxy coating condition was determined to have a statistically significant effect, with *p*-values all less than 0.05. Table 4-25 provides the LSM values for epoxy coating condition, Table 4-26 provides the results of the Tukey-Kramer analysis, and Figures 4-20 to 4-22 graphically display the impedance values measured for each epoxy coating condition. Each point on the graph is the average of three measurements obtained on three replicate slabs. The data show that improving the epoxy coating condition generally increases impedance, which suggests increased protection of the embedded reinforcing steel.

Table 4-24. *P*-Values for Epoxy Coating Condition

Treatment	*p*-value
0 kg Cl^-/m^3	<0.0001
1.2 kg Cl^-/m^3	<0.0001
2.4 kg Cl^-/m^3	<0.0001

Table 4-25. Least Squares Means for Epoxy Coating Condition

	Impedance (Ω-cm) for Indicated Treatment		
Epoxy Condition	0 kg Cl^-/m^3	1.2 kg Cl^-/m^3	2.4 kg Cl^-/m^3
Black Bar	18872.3	17357.8	15672.4
Full Epoxy	141870.9	137152.4	139108.7
End Cut	109367.2	129265.0	115784.7
Pliers Strike	142707.4	109715.7	72453.6
Rib Scrape	45910.1	48930.7	42396.0

Table 4-26. Tukey-Kramer Results for Epoxy Coating Condition

Treatment	Epoxy Condition	Full Epoxy	End Cut	Pliers Strike	Rib Scrape
0 kg Cl^{-}/m^{3}	Black Bar	<0.0001	0.0039	<0.0001	0.8121
	Full Epoxy	-	0.6867	1.0000	0.0019
	End Cut	-	-	0.6658	0.0874
	Pliers Strike	-	-	-	0.0017
1.2 kg Cl^{-}/m^{3}	Black Bar	<0.0001	<0.0001	0.0011	0.6455
	Full Epoxy	-	0.9970	0.7547	0.0020
	End Cut	-	-	0.9138	0.0063
	Pliers Strike	-	-	-	0.0702
2.4 kg Cl^{-}/m^{3}	Black Bar	<0.0001	<0.0001	0.0496	0.6854
	Full Epoxy	-	0.7829	0.0128	<0.0001
	End Cut	-	-	0.2183	0.0045
	Pliers Strike	-	-	-	0.5818

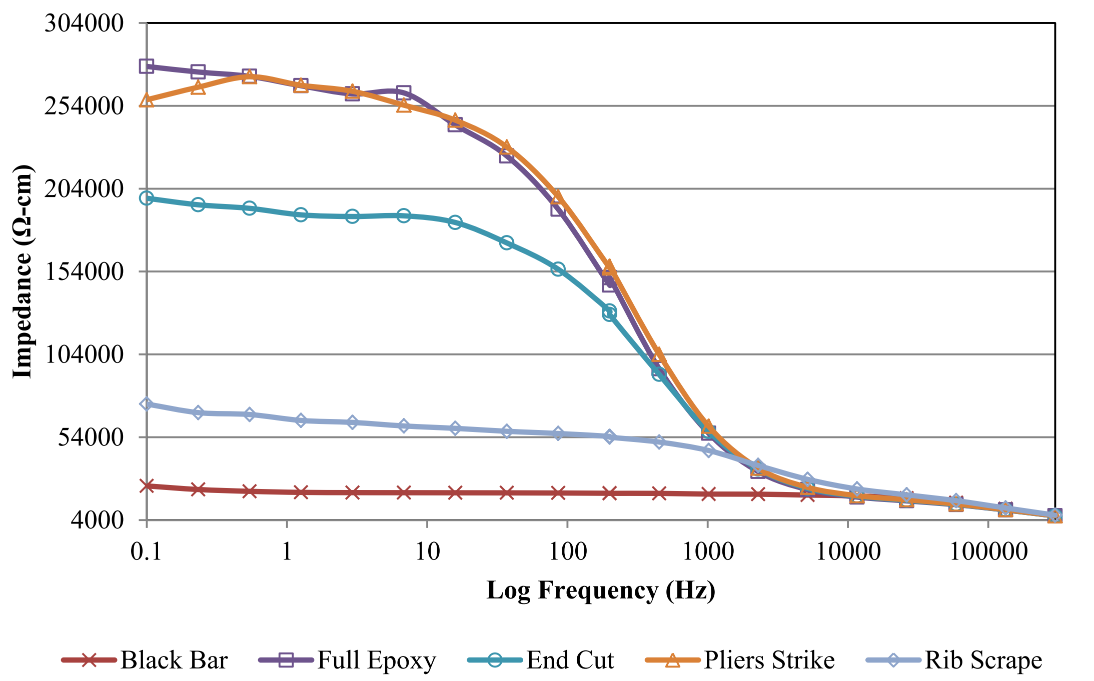

Figure 4-20. Impedance measurements for epoxy coating condition for slabs with 0 kg Cl-/m^{3}.

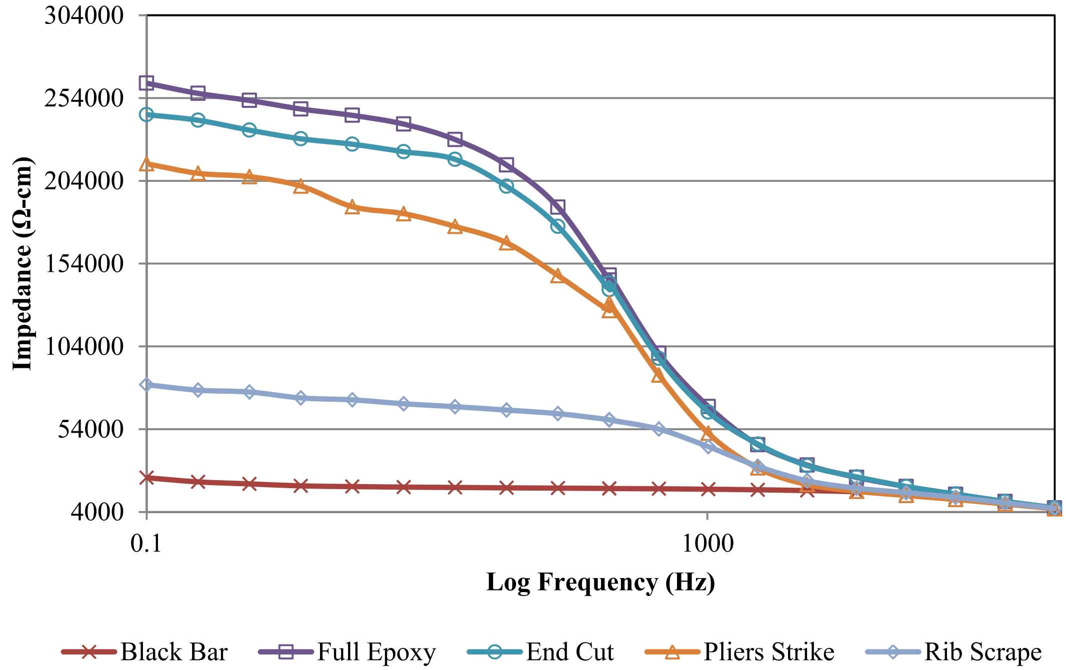

Figure 4-21. Impedance measurements for epoxy coating condition for slabs with 1.2 kg Cl^{-}/m^{3}.

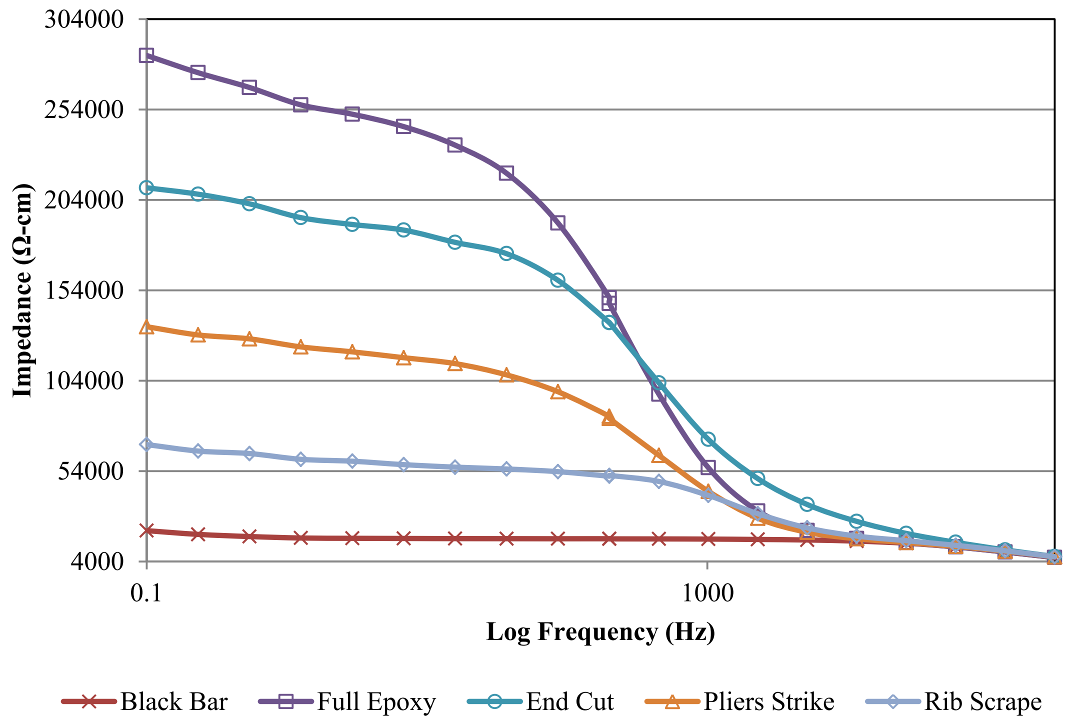

Figure 4-22. Impedance measurements for epoxy coating condition for slabs with 2.4 kg Cl^{-}/m^{3}.

4.2.10 Frequency Selection

The results of the *t*-tests and ANOVAs performed to determine a frequency or range in frequency at which impedance measurements can differentiate among various levels of corrosion protection for reinforcing steel in concrete bridge decks are presented in Figure 4-23, which shows a *p*-value for each deck property at each frequency of EIS testing. Given the objective of recommending a frequency or range in frequency for which the deck properties most commonly exhibit *p*-values less than or equal to 0.05, frequencies having the highest number of data points below the dashed line in Figure 4-23 are of greatest interest. Visual inspection of the figure indicates that impedance testing in the frequency range of approximately 100 Hz to 1 kHz would be expected to provide the best data about the degree to which the reinforcing steel is protected from chloride infiltration by a bridge deck system; in this frequency range, which is consistent with that initially identified from theoretical considerations in Figure 2-2, a high level of differentiation among levels of corrosion protection is expected, and a high speed of data collection is also possible.

In this research, a single frequency of 200 Hz was selected for impedance testing of the decommissioned bridge deck slabs contained in set E. In the United States, where the electric power grid operates on a frequency of 60 Hz, testing at 200 Hz is also ideal because 200 Hz is not an even multiple of 60 Hz; therefore, power grid noise harmonics would not be expected to couple in to the measurements. However, in other geographical locations where the frequency of the electric power grid is 50 Hz rather than 60 Hz, impedance testing should instead be performed at a frequency of 190 or 210 Hz, for example, to minimize interference from power grid harmonics.

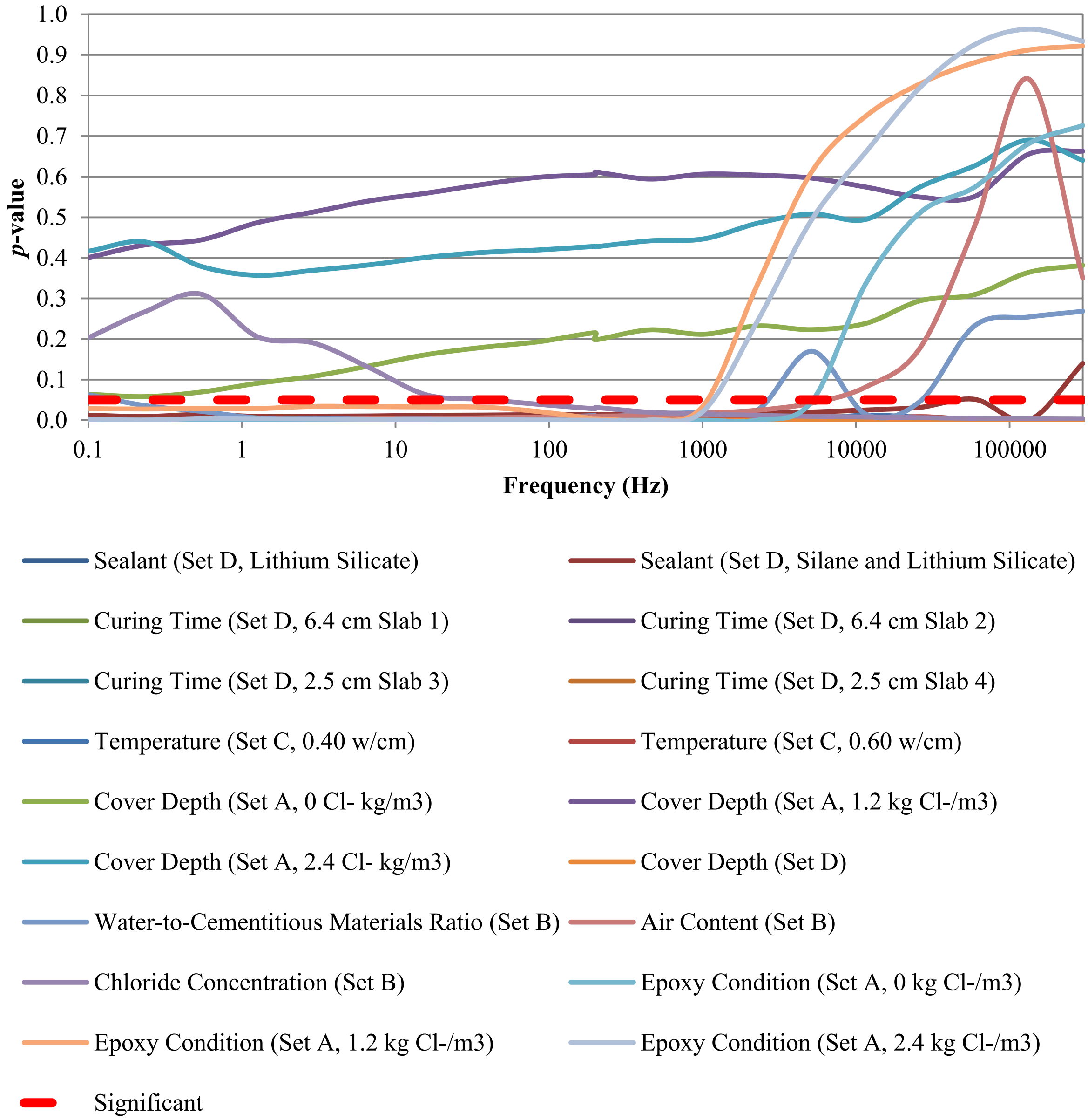

Figure 4-23. Summary of *p*-values for frequency selection.

4.3 Uncontrolled Laboratory Experiments

For each of the four decommissioned bridge deck slabs in set E, including those from bridges C-357, C-358, C-363, and D-413, the following sections present the results of the statistical analyses performed to compare impedance values measured at the selected frequency of 200 Hz to several traditional test measurements relating to corrosion of reinforcing steel in concrete bridge decks. For each deck slab, the results of the pair-wise correlations are presented, and contour plots of impedance, cover depth, resistivity, half-cell potential, and chloride concentration at a depth of 2.54 cm (1.0 in.) are provided. The contour plots were produced using Surfer 10 software. All raw data are presented in Appendix B.

4.3.1 Bridge C-357

Table 4-27 presents the results of the pair-wise correlations computed for the deck slab from bridge C-357. The data show that correlations between impedance and longitudinal cover, transverse cover, wet resistivity, wet half-cell potential, and chloride concentration at 3.18 cm (1.25 in.), 4.45 cm (1.75 in.), 6.98 cm (2.75 in.), 8.26 cm (3.25 in.), and 9.53 cm (3.75 in.) were statistically significant, with *p*-values less than 0.15. The correlations are in the expected direction for each of the tested variables; cover depth, resistivity, and half-cell potential were positively correlated with impedance, while chloride concentration was negatively correlated with impedance. For visual comparison of impedance values with selected traditional test measurements, Figures 4-24 to 4-28 provide contour plots of impedance, cover depth, resistivity, half-cell potential, and chloride concentration at 1.91 cm (0.75 in.), respectively, for this slab.

Table 4-27. Correlation Results for Slab from Bridge C-357

Variable	R Value	*p*-value
Longitudinal Cover	0.5175	0.0034
Transverse Cover	0.4067	0.0257
Rebound Number	0.1664	0.3794
Dry Resistivity	0.0347	0.8555
Dry Half-Cell Potential	0.2666	0.1543
Dry Linear Polarization	-0.1639	0.3869
Wet Resistivity	0.3212	0.0835
Wet Half-Cell Potential	0.6365	0.0002
Wet Linear Polarization	-0.3508	0.0574
Chloride Concentration at 0.63 cm	0.0210	0.9124
Chloride Concentration at 1.91 cm	-0.3394	0.0666
Chloride Concentration at 3.18 cm	-0.4540	0.0117
Chloride Concentration at 4.45 cm	-0.3286	0.0762
Chloride Concentration at 5.72 cm	-0.3052	0.1010
Chloride Concentration at 6.99 cm	-0.4642	0.0098
Chloride Concentration at 8.26 cm	-0.5096	0.0040
Chloride Concentration at 9.53 cm	-0.5937	0.0005

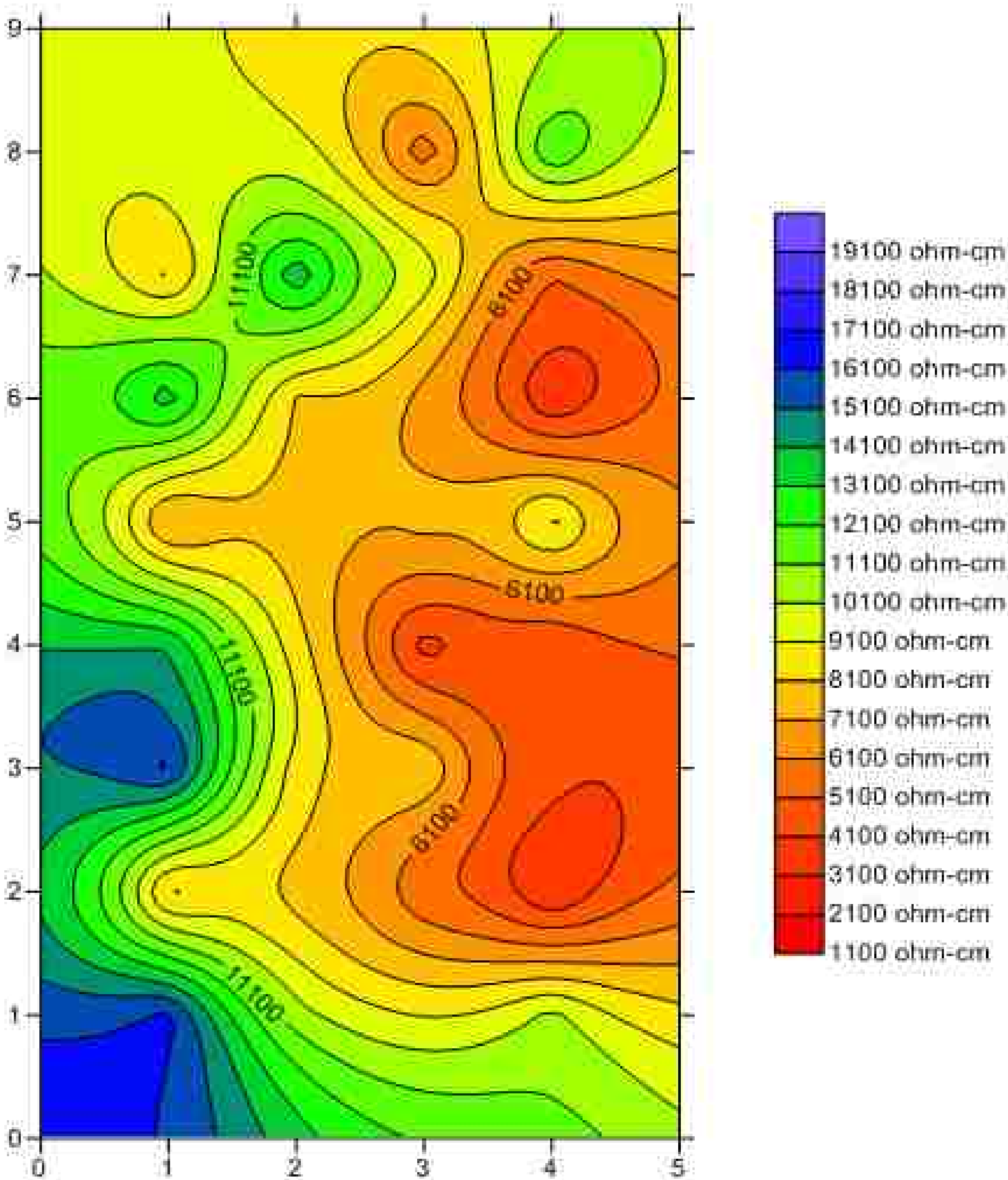

Figure 4-24. Contour plot of impedance for slab from bridge C-357.

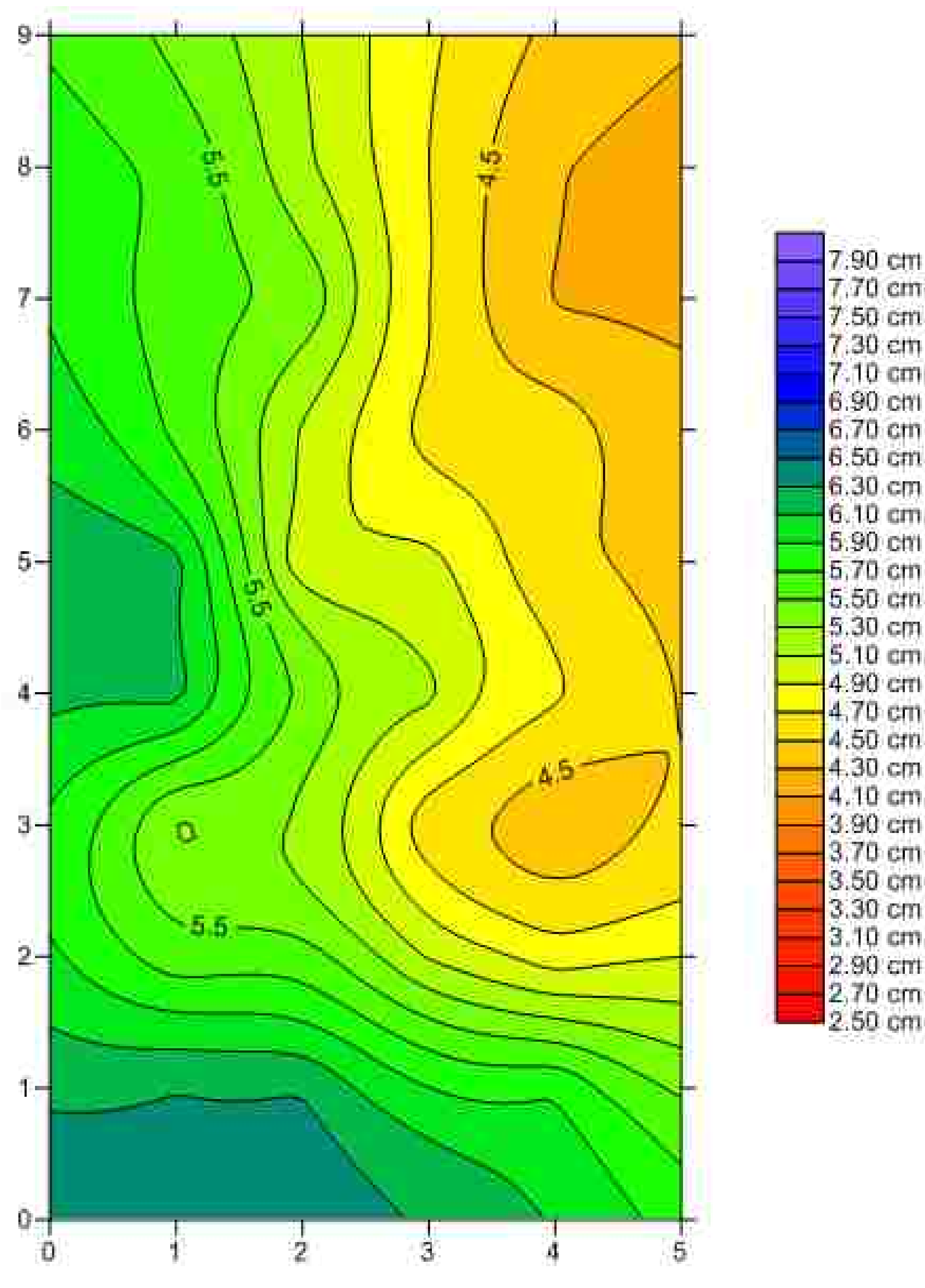

Figure 4-25. Contour plot of longitudinal cover depth for slab from bridge C-357.

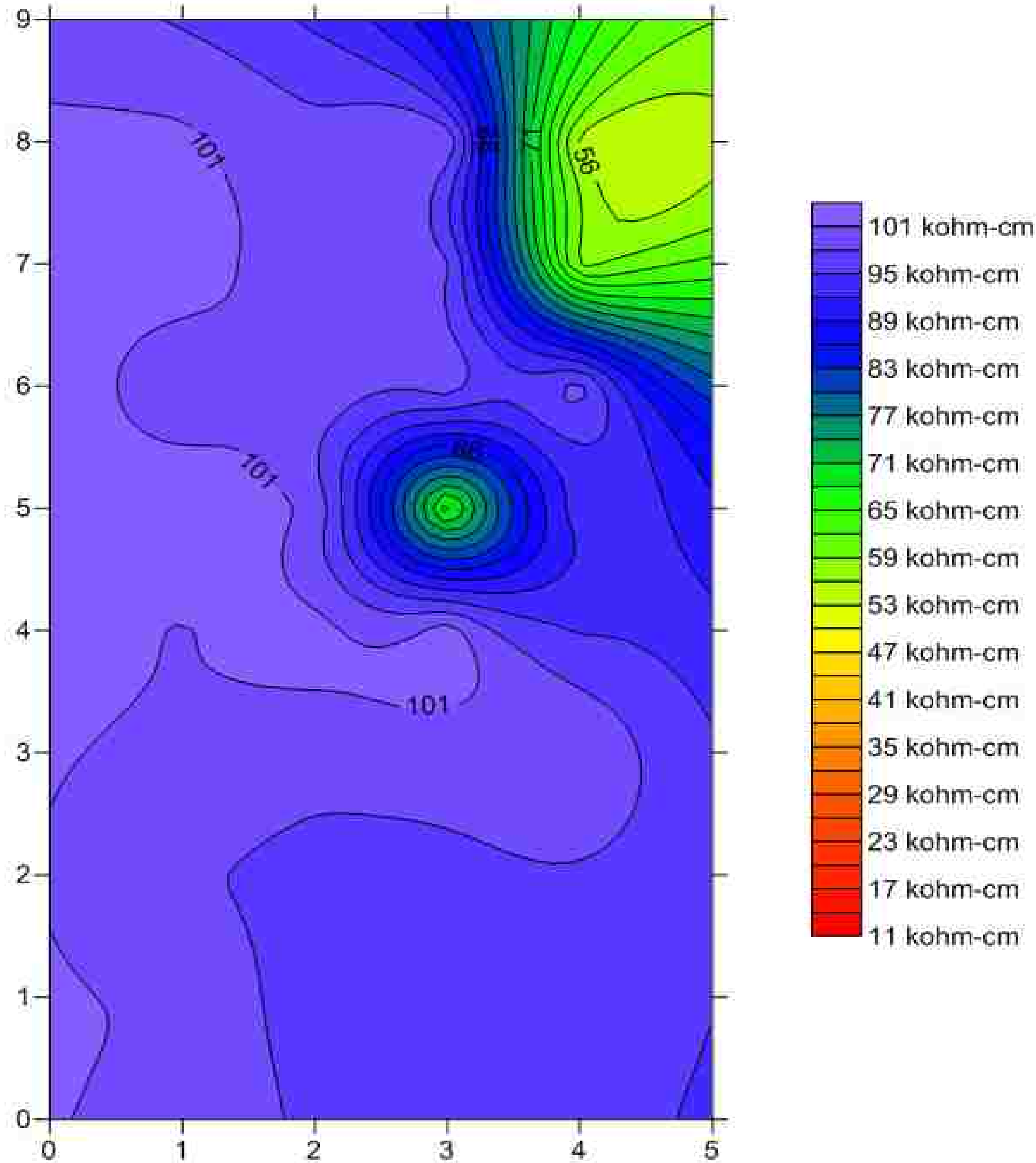

Figure 4-26. Contour plot of dry resistivity for slab from bridge C-357.

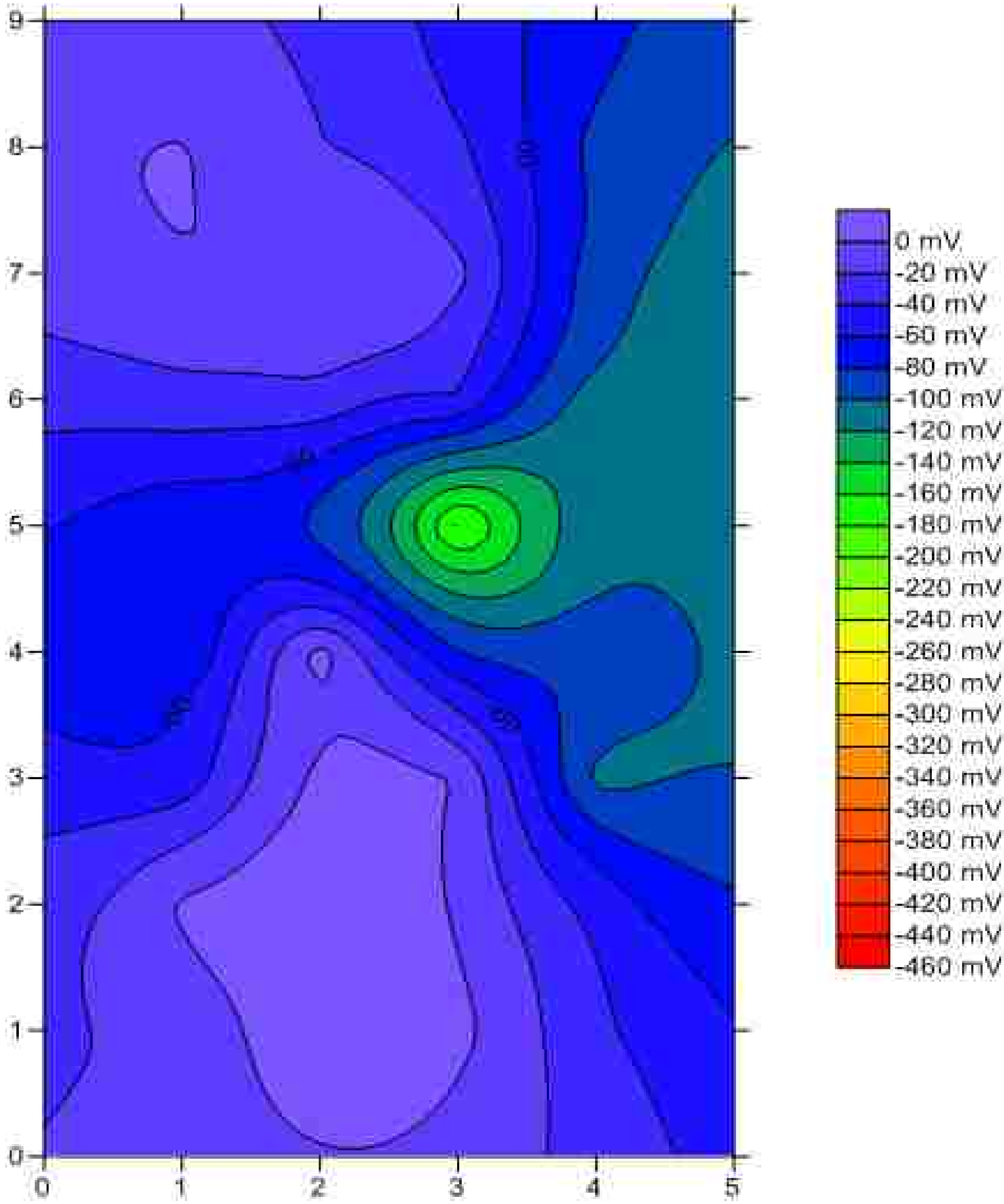

Figure 4-27. Contour plot of dry half-cell potential for slab from bridge C-357.

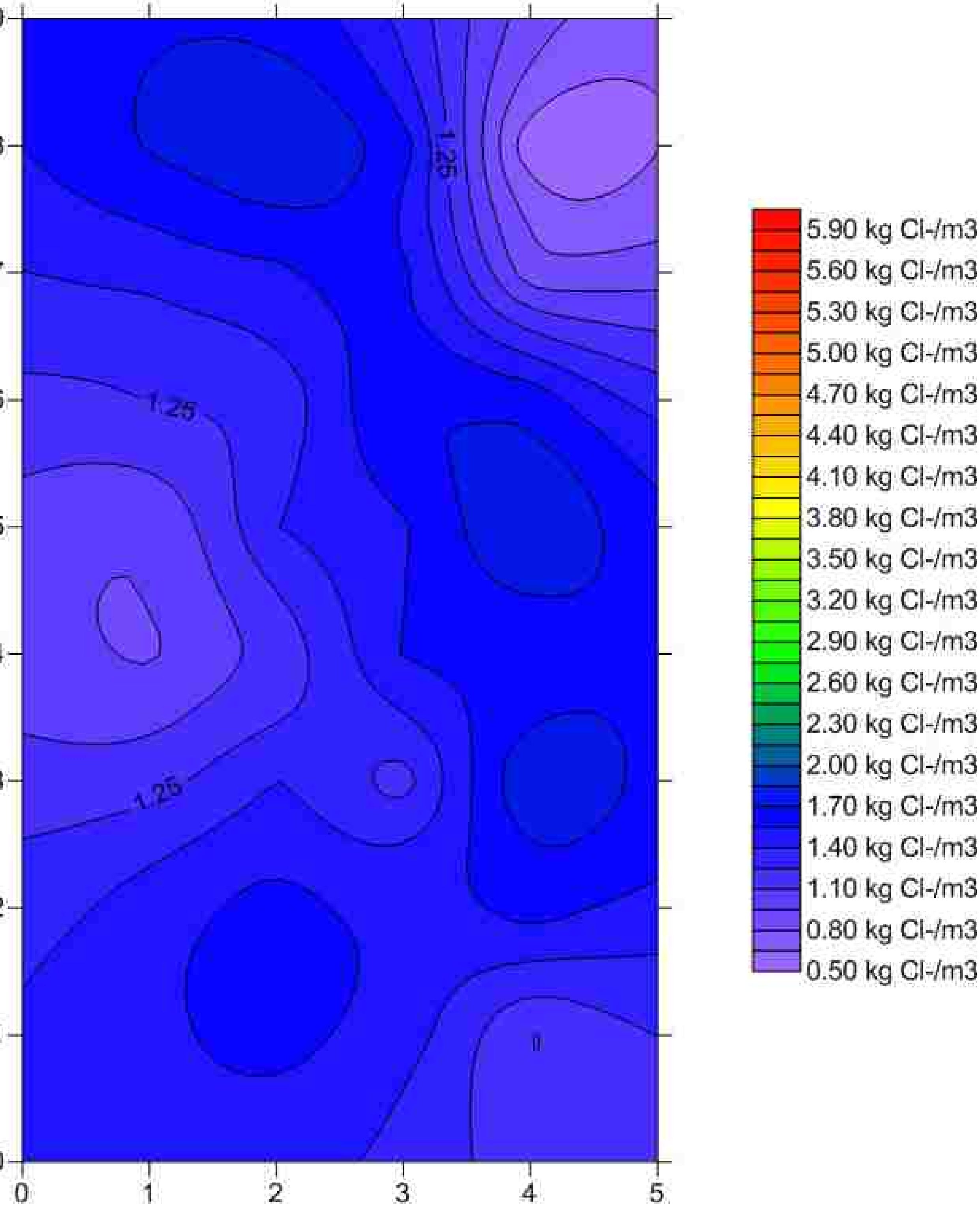

Figure 4-28. Contour plot of chloride concentration at 1.91 cm for slab from bridge C-357.

4.3.2 Bridge C-358

Table 4-28 presents the results of the pair-wise correlations computed for the deck slab from bridge C-358. The data showed that correlations between impedance and transverse cover, dry half-cell potential, dry linear polarization, wet linear polarization, wet half-cell potential, dry resistivity, and chloride concentration at depths between 0.635 and 8.26 cm (0.25 and 3.25 in.) were statistically significant, with *p*-values less than 0.15. The correlations are in the expected direction for transverse cover, half-cell potential, and all chloride concentrations; transverse cover depth and half-cell potential were positively correlated with impedance, while chloride concentration was negatively correlated with impedance. For visual comparison of impedance values with selected traditional test measurements, Figures 4-29 to 4-33 provide contour plots for impedance, cover depth, resistivity, half-cell potential, and chloride concentration at 1.91 cm (0.75 in.), respectively, for this slab.

Table 4-28. Correlation Results for Slab from Bridge C-358

Variable	R Value	*p*-value
Longitudinal Cover	-0.0664	0.7179
Transverse Cover	0.3254	0.0691
Rebound Number	0.1328	0.4688
Dry Resistivity	-0.3154	0.0787
Dry Half-Cell Potential	0.6111	0.0002
Dry Linear Polarization	-0.3669	0.0389
Wet Resistivity	-0.1110	0.5454
Wet Half-Cell Potential	0.5882	0.0004
Wet Linear Polarization	-0.2932	0.1034
Chloride Concentration at 0.63 cm	-0.6068	0.0002
Chloride Concentration at 1.91 cm	-0.6756	<0.0001
Chloride Concentration at 3.18 cm	-0.6716	<0.0001
Chloride Concentration at 4.45 cm	-0.6348	<0.0001
Chloride Concentration at 5.72 cm	-0.6035	0.0003
Chloride Concentration at 6.99 cm	-0.4869	0.0047
Chloride Concentration at 8.26 cm	-0.3677	0.0384
Chloride Concentration at 9.53 cm	-0.2290	0.2075

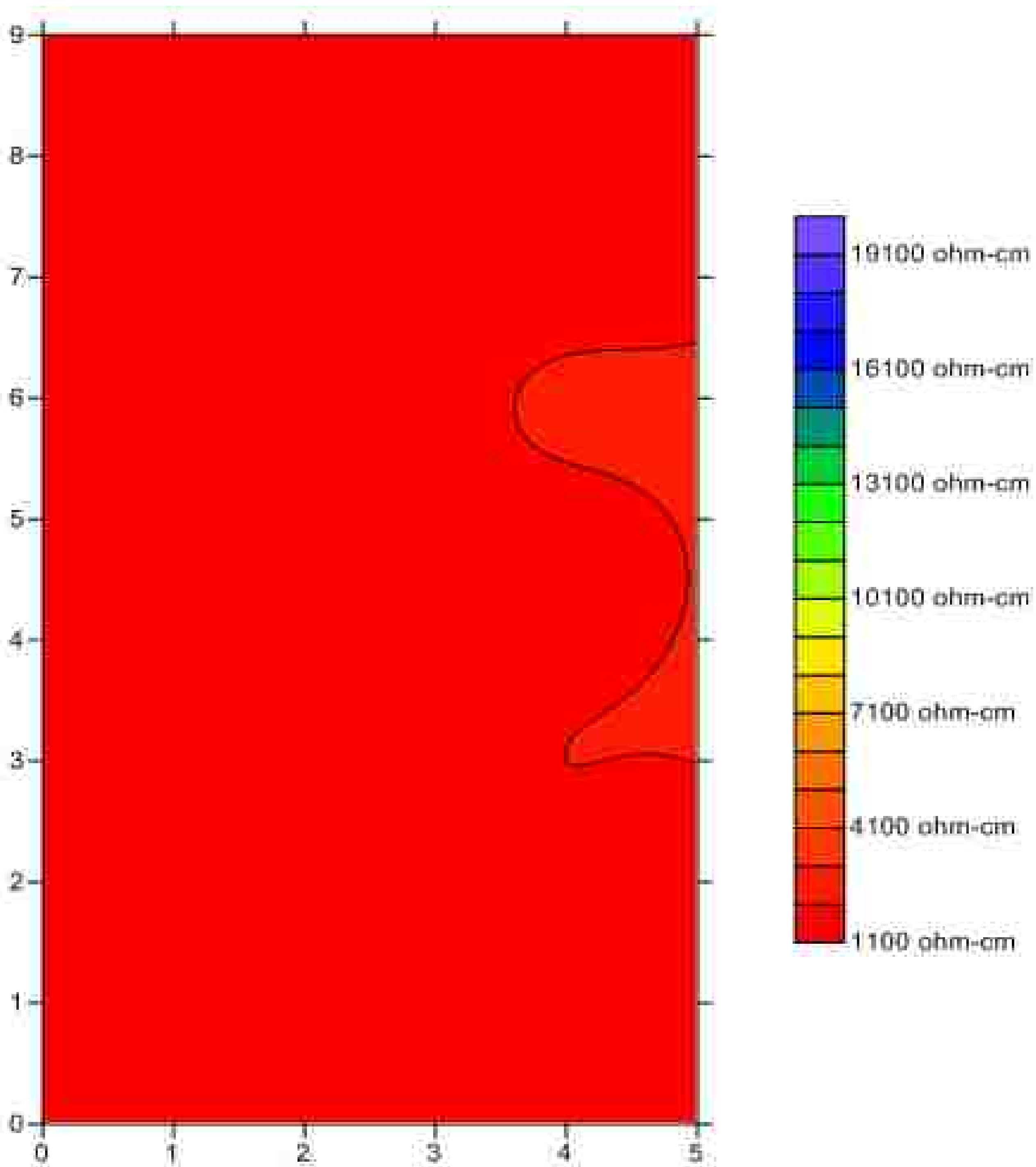

Figure 4-29. Contour plot of impedance for slab from bridge C-358.

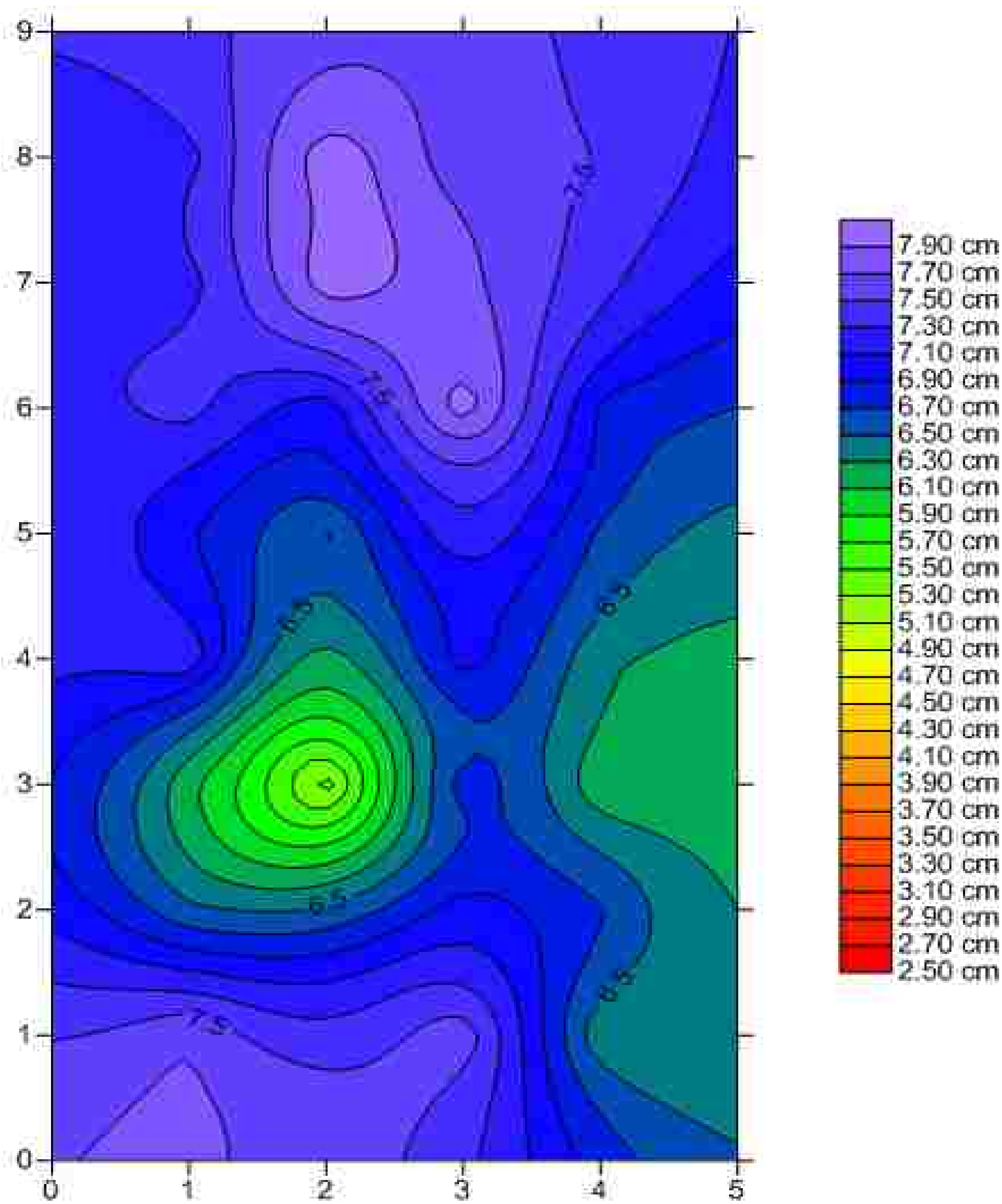

Figure 4-30. Contour plot of longitudinal cover depth for slab from bridge C-358.

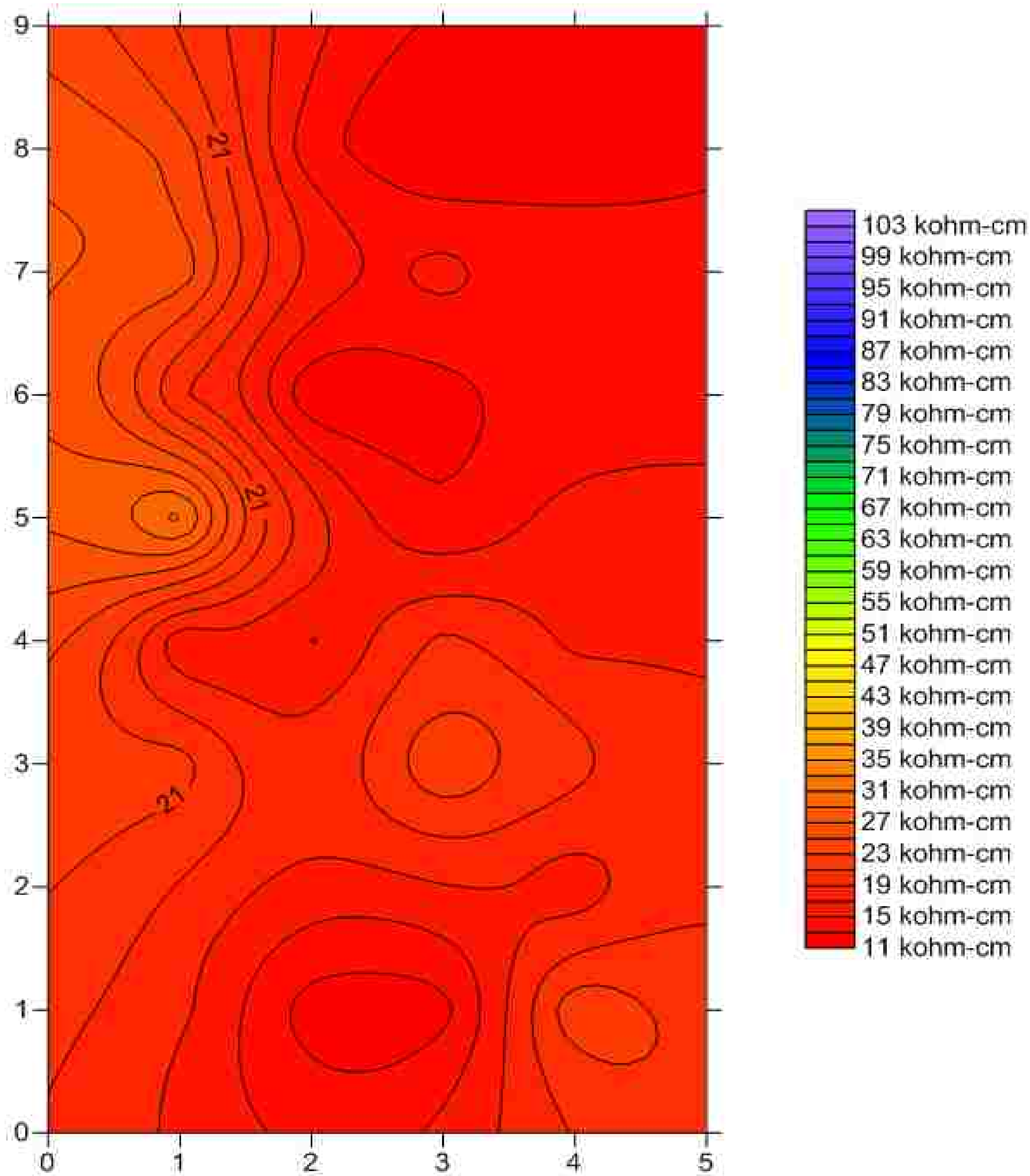

Figure 4-31. Contour plot of dry resistivity for slab from bridge C-358.

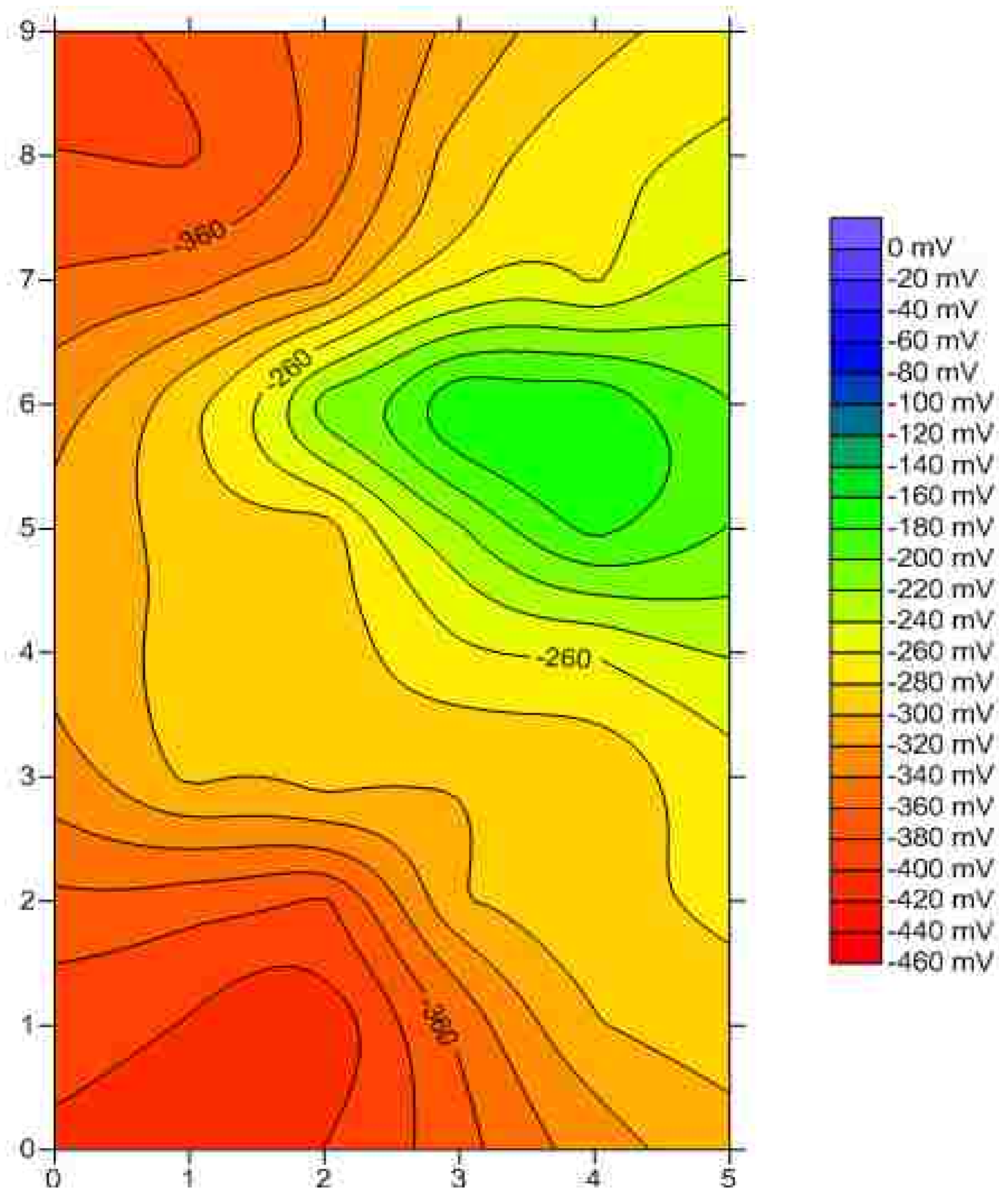

Figure 4-32. Contour plot of dry half-cell potential for slab from bridge C-358.

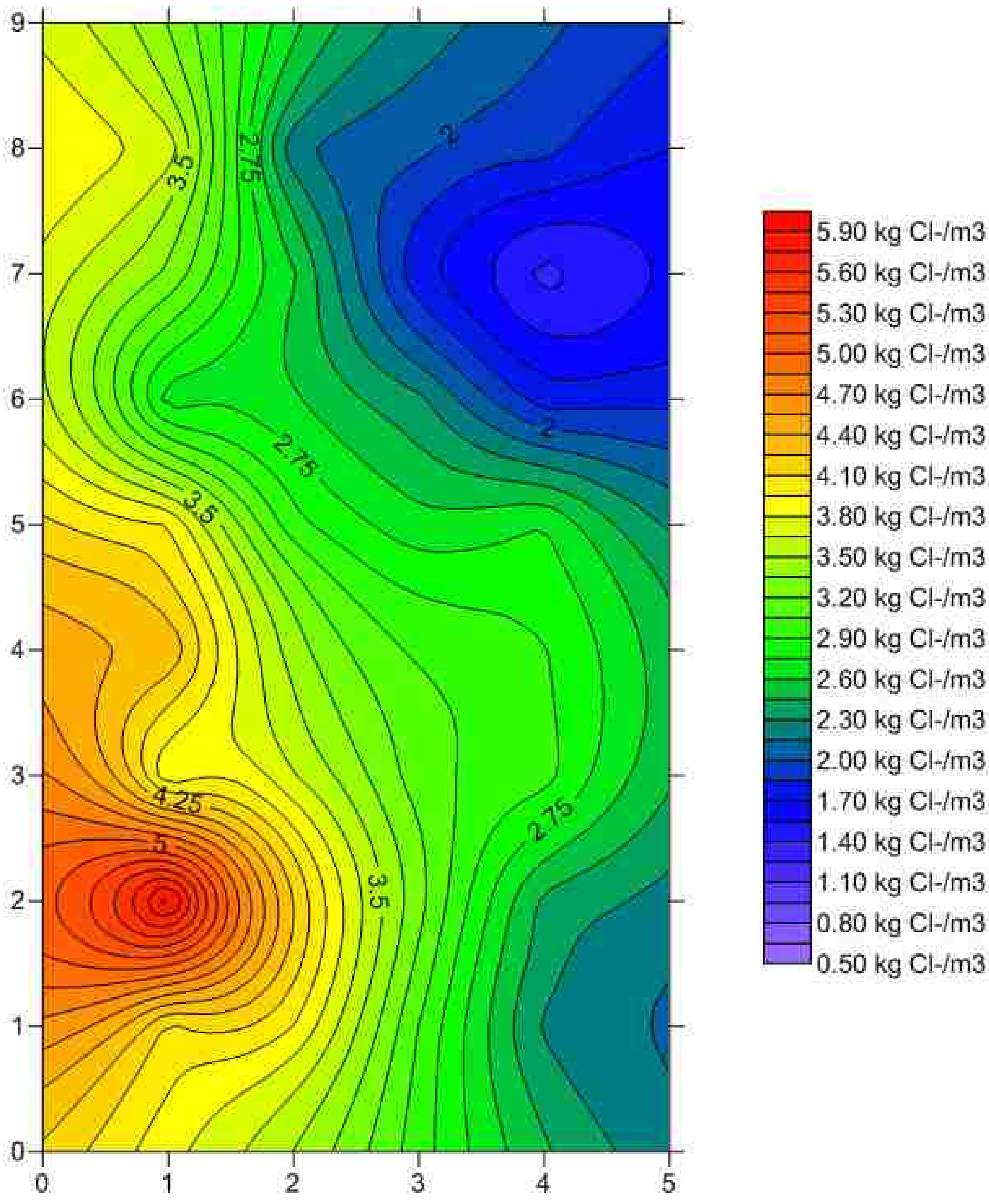

Figure 4-33. Contour plot of chloride concentration at 1.91 cm for slab from bridge C-358.

4.3.3 Bridge C-363

Table 4-29 presents the results of the pair-wise correlations computed for the deck slab from bridge C-363. (Chloride concentration measurements were discontinued at a depth of 4.45 cm (1.75 in.) on this slab because the values were so low at this depth that further testing was determined to be unnecessary.) The data show that correlations between impedance and longitudinal cover and chloride concentration at a depth of 0.635 cm (0.25 in.) and 1.91 cm (0.75 in.) were statistically significant, with *p*-values less than 0.15. The correlation is in the expected direction for longitudinal cover; cover depth was positively correlated with impedance. For visual comparison of impedance values with selected traditional test measurements, Figures 4-34 to 4-37 provide contour plots for impedance, cover depth, resistivity, and chloride concentration at 1.91 cm (0.75 in.), respectively, for this slab. (As a result of the comparatively higher impedance values caused by the epoxy coating on the reinforcing steel within this slab, the contour plot for impedance for this slab is given on a different scale than that used in the contour plots for impedance for the other slabs.)

Table 4-29. Correlation Results for Slab from Bridge C-363

Variable	R Value	*p*-value
Longitudinal Cover	0.3353	0.0652
Transverse Cover	0.1431	0.4426
Rebound Number	-0.0642	0.7317
Dry Resistivity	-0.2226	0.2288
Wet Resistivity	-0.0681	0.7159
Chloride Concentration at 0.63 cm	0.7468	<0.0001
Chloride Concentration at 1.91 cm	0.4305	0.0156
Chloride Concentration at 3.18 cm	0.1041	0.5774
Chloride Concentration at 4.45 cm	0.0125	0.9468

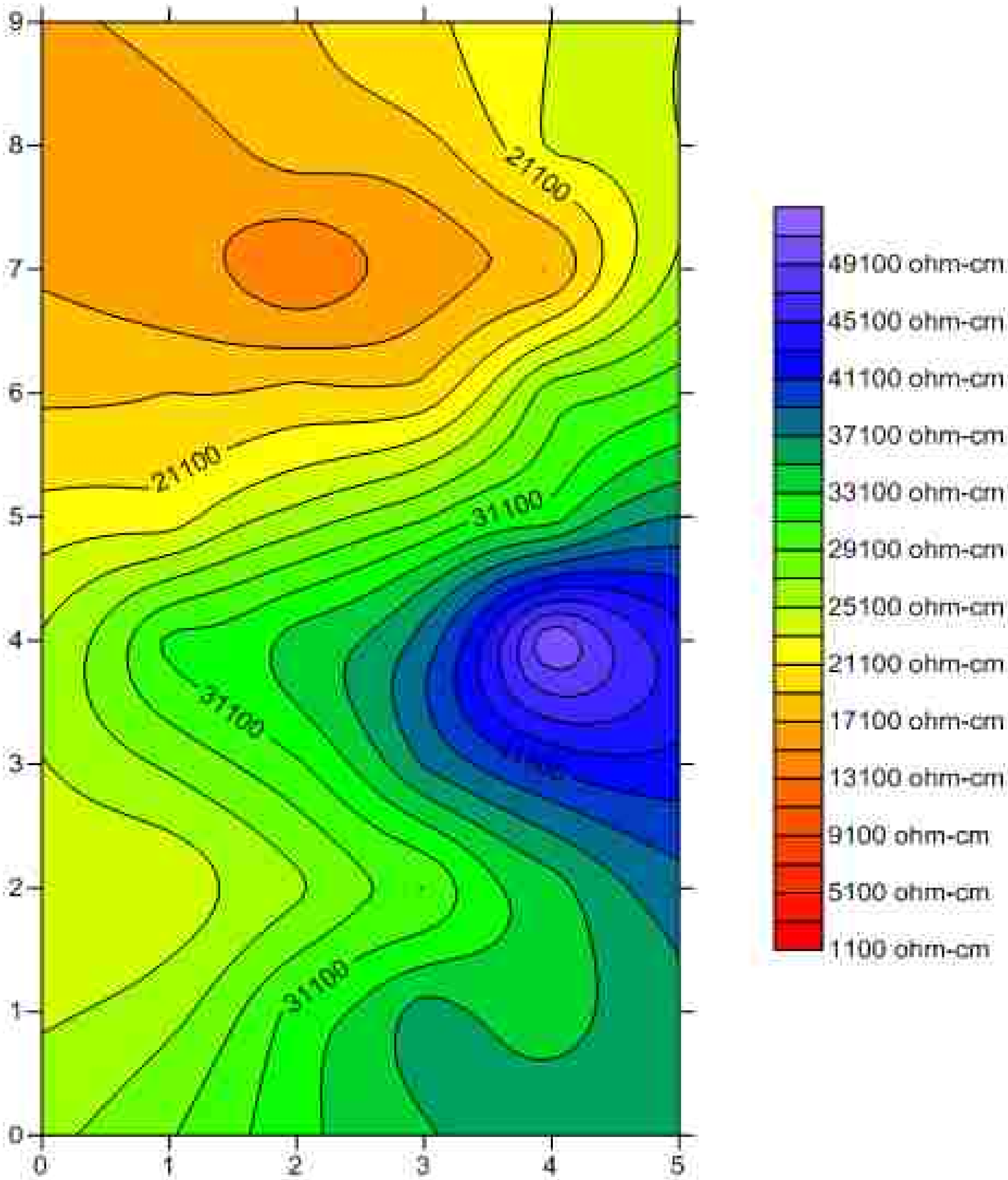

Figure 4-34. Contour plot of impedance for slab from bridge C-363.

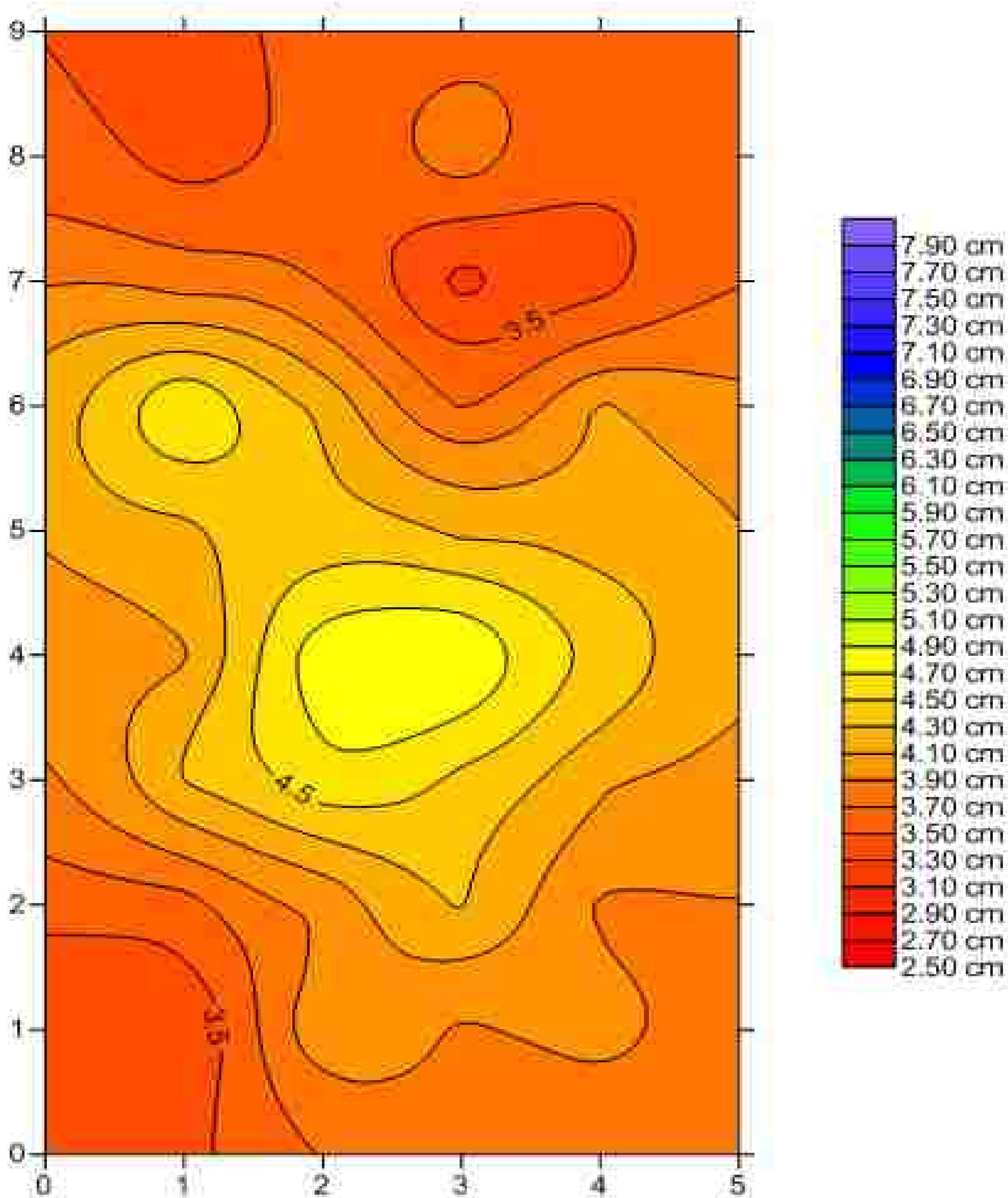

Figure 4-35. Contour plot of longitudinal cover depth for slab from bridge C-363.

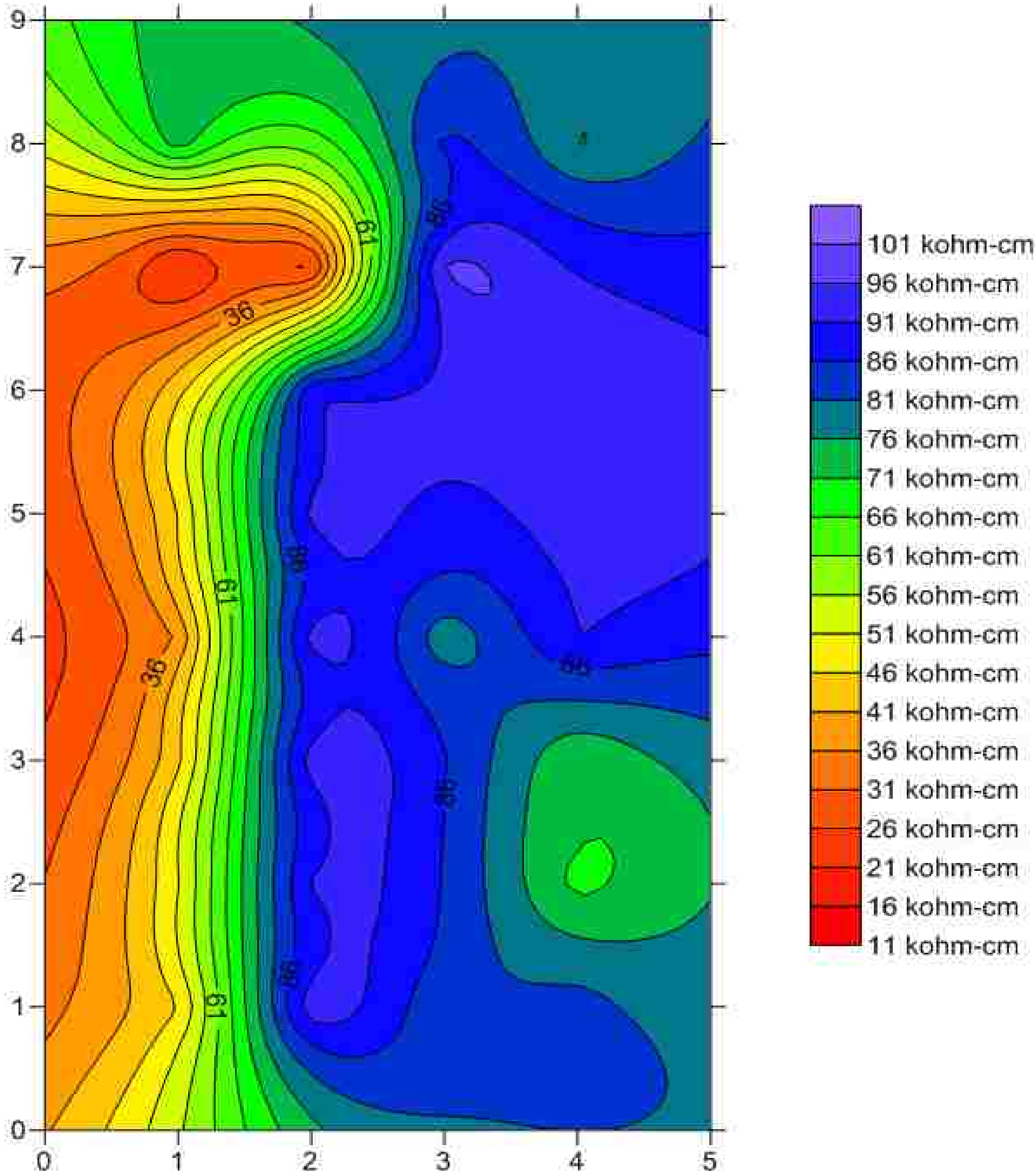

Figure 4-36. Contour plot of dry resistivity for slab from bridge C-363.

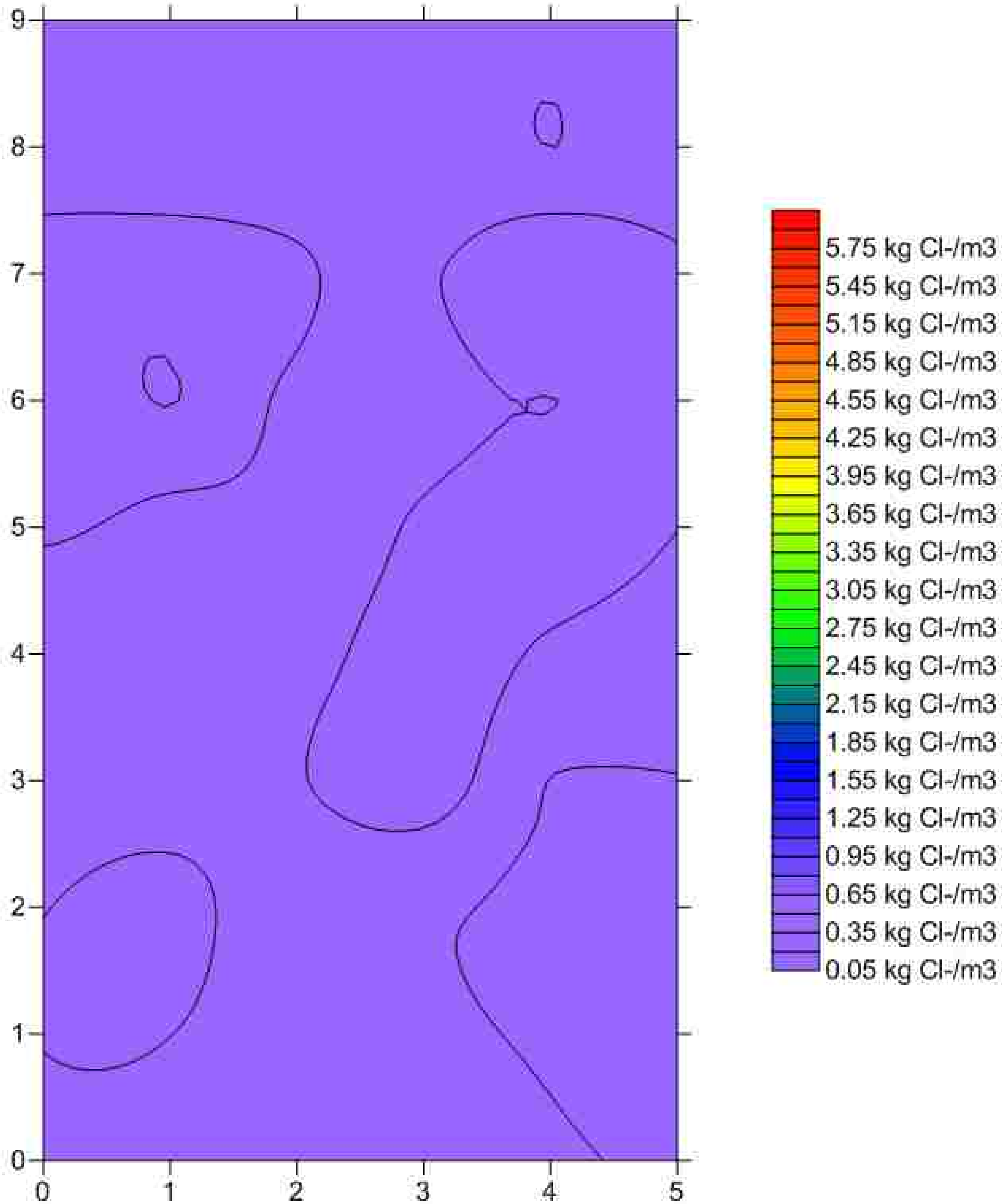

Figure 4-37. Contour plot of chloride concentration at 1.91 cm for slab from bridge C-363.

4.3.4 Bridge D-413

Table 4-30 presents the results of the pair-wise correlations computed for the deck slab from bridge D-413. The data show that correlations between impedance and dry resistivity, dry half-cell potential, wet half-cell potential, and chloride concentrations at depths between 3.18 and 9.53 cm (1.25 and 3.75 in.) were statistically significant, with *p*-values less than 0.15. The correlations are in the expected direction for each of the tested variables; resistivity and half-cell potential were positively correlated with impedance, while chloride concentration was negatively correlated with impedance. For visual comparison of impedance values with selected traditional test measurements, Figures 4-38 to 4-42 provide contour plots for impedance, cover depth, resistivity, half-cell potential, and chloride concentration at 1.91 cm (0.75 in.), respectively, for this slab.

Table 4-30. Correlation Results for Slab from Bridge D-413

Variable	R Value	*p*-value
Longitudinal Cover	0.1595	0.3833
Transverse Cover	0.2166	0.2339
Rebound Number	0.1127	0.5391
Dry Resistivity	0.4941	0.0040
Dry Half-Cell Potential	0.6152	0.0002
Dry Linear Polarization	0.1124	0.5401
Wet Resistivity	0.1266	0.4899
Wet Half-Cell Potential	0.5568	0.0009
Wet Linear Polarization	0.0647	0.7251
Chloride Concentration at 0.63 cm	0.0542	0.7684
Chloride Concentration at 1.91 cm	-0.2975	0.0982
Chloride Concentration at 3.18 cm	-0.4682	0.0069
Chloride Concentration at 4.45 cm	-0.4107	0.0196
Chloride Concentration at 5.72 cm	-0.4071	0.0208
Chloride Concentration at 6.99 cm	-0.4453	0.0106
Chloride Concentration at 8.26 cm	-0.3996	0.0235
Chloride Concentration at 9.53 cm	-0.5101	0.0029

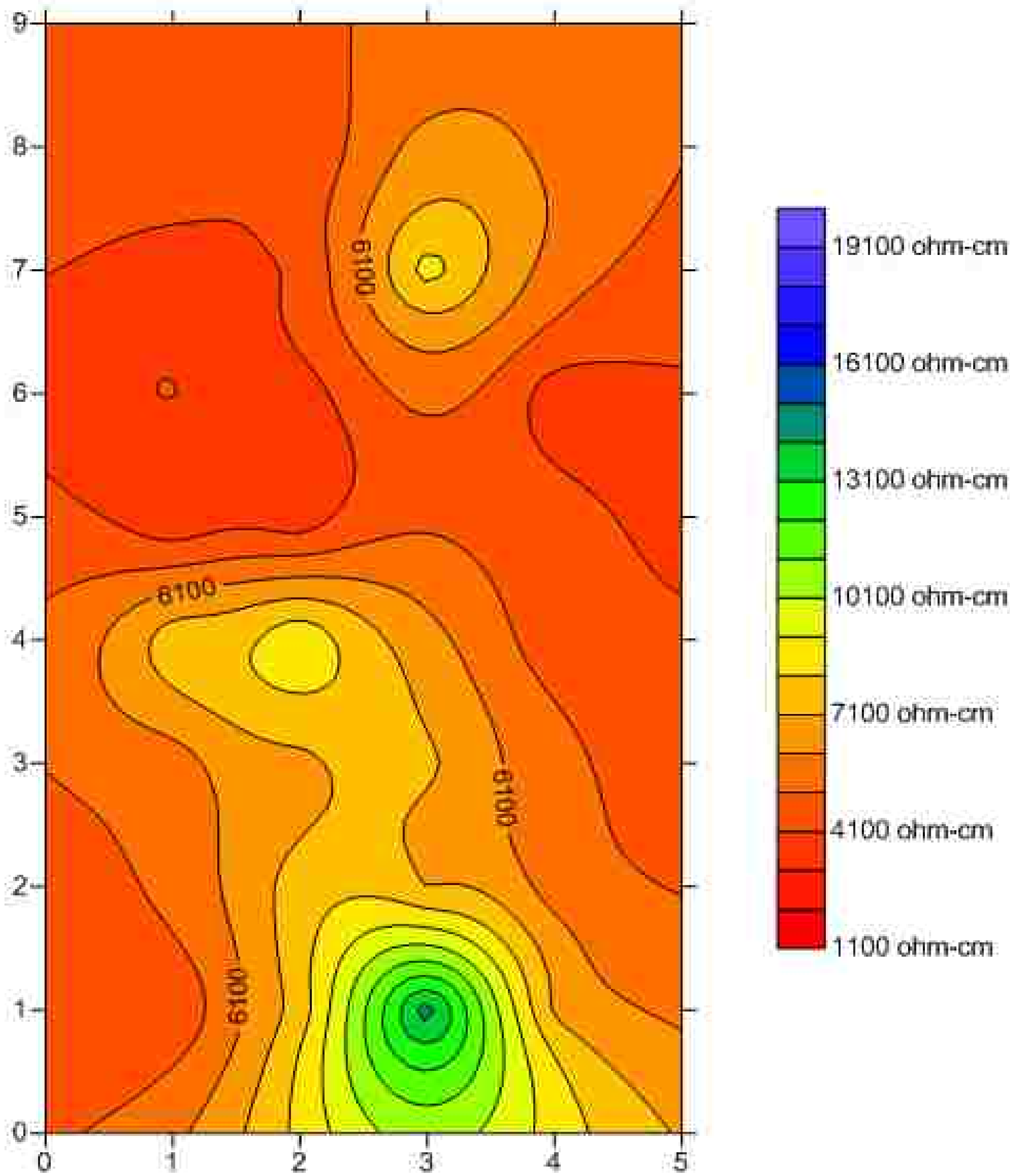

Figure 4-38. Contour plot of impedance for slab from bridge D-413.

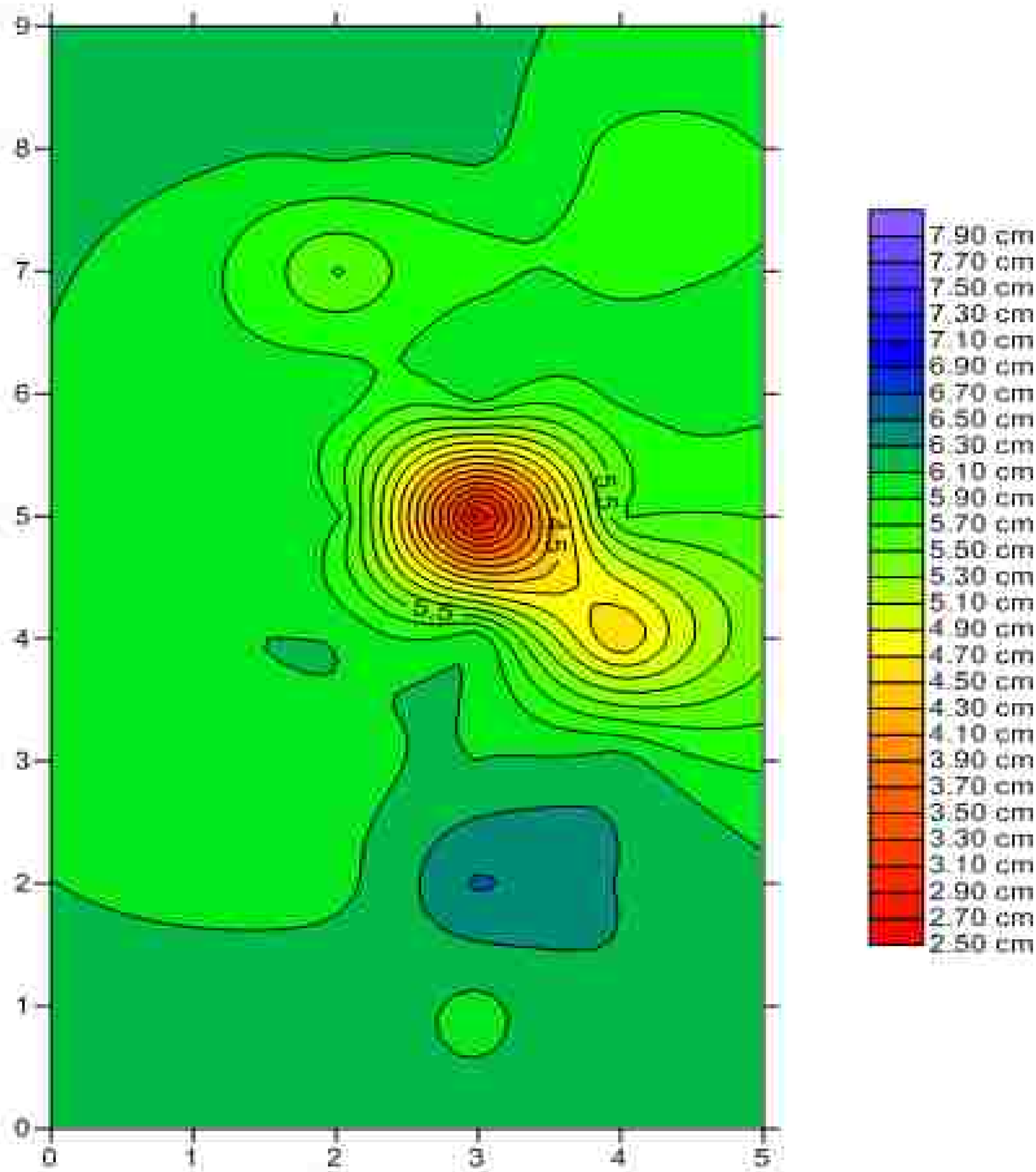

Figure 4-39. Contour plot of longitudinal cover depth for slab from bridge D-413.

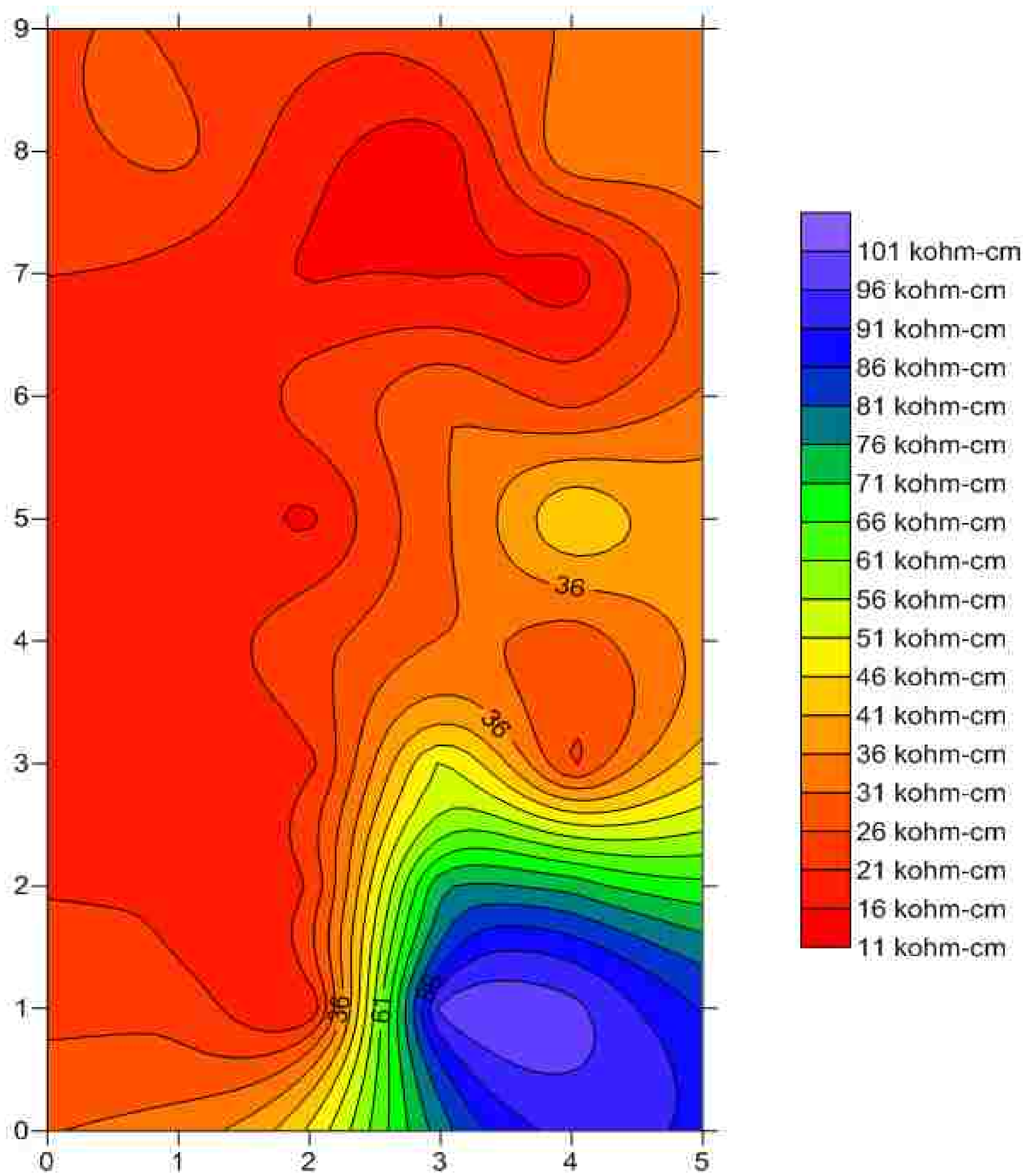

Figure 4-40. Contour plot of dry resistivity for slab from bridge D-413.

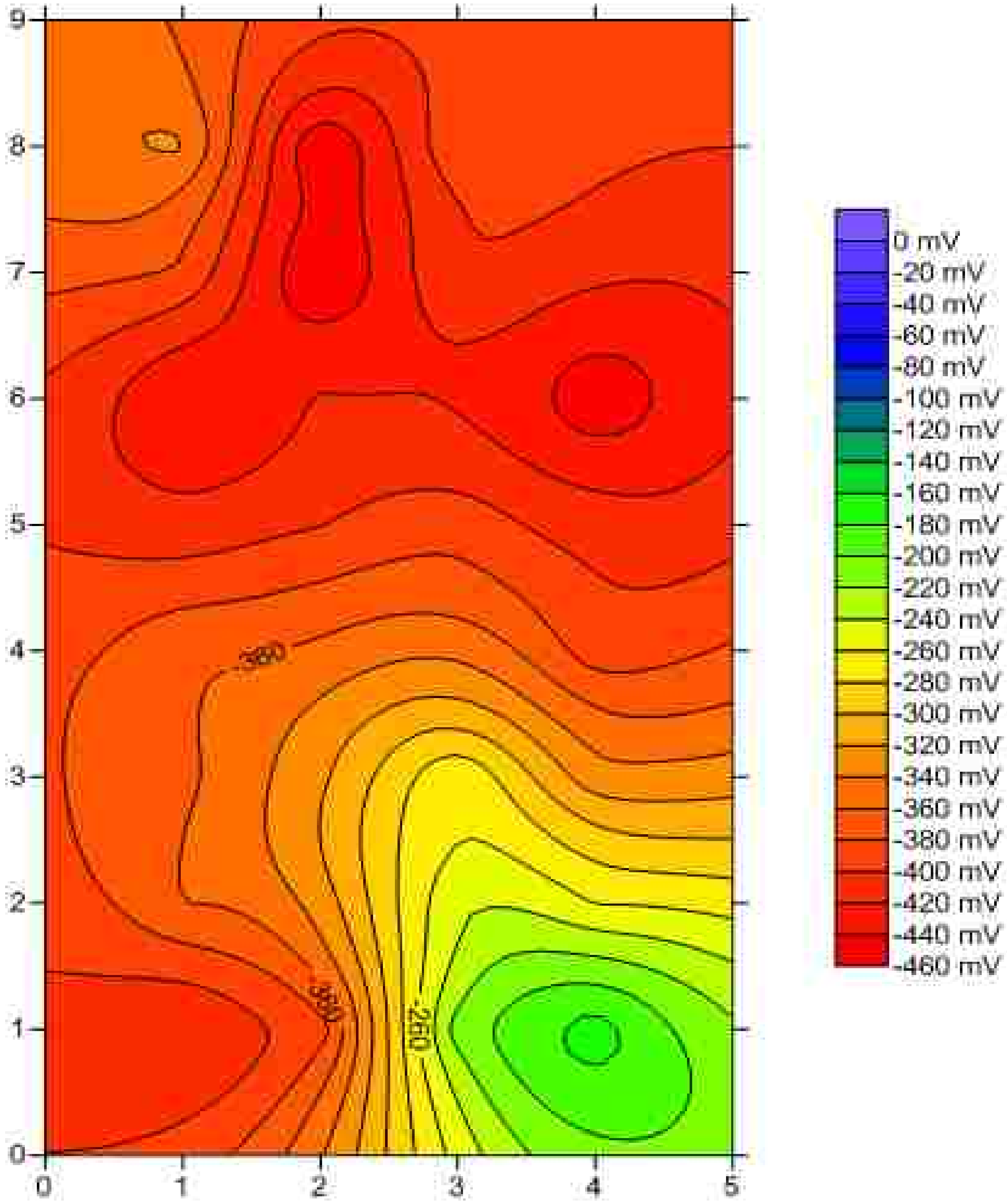

Figure 4-41. Contour plot of dry half-cell potential for slab from bridge D-413.

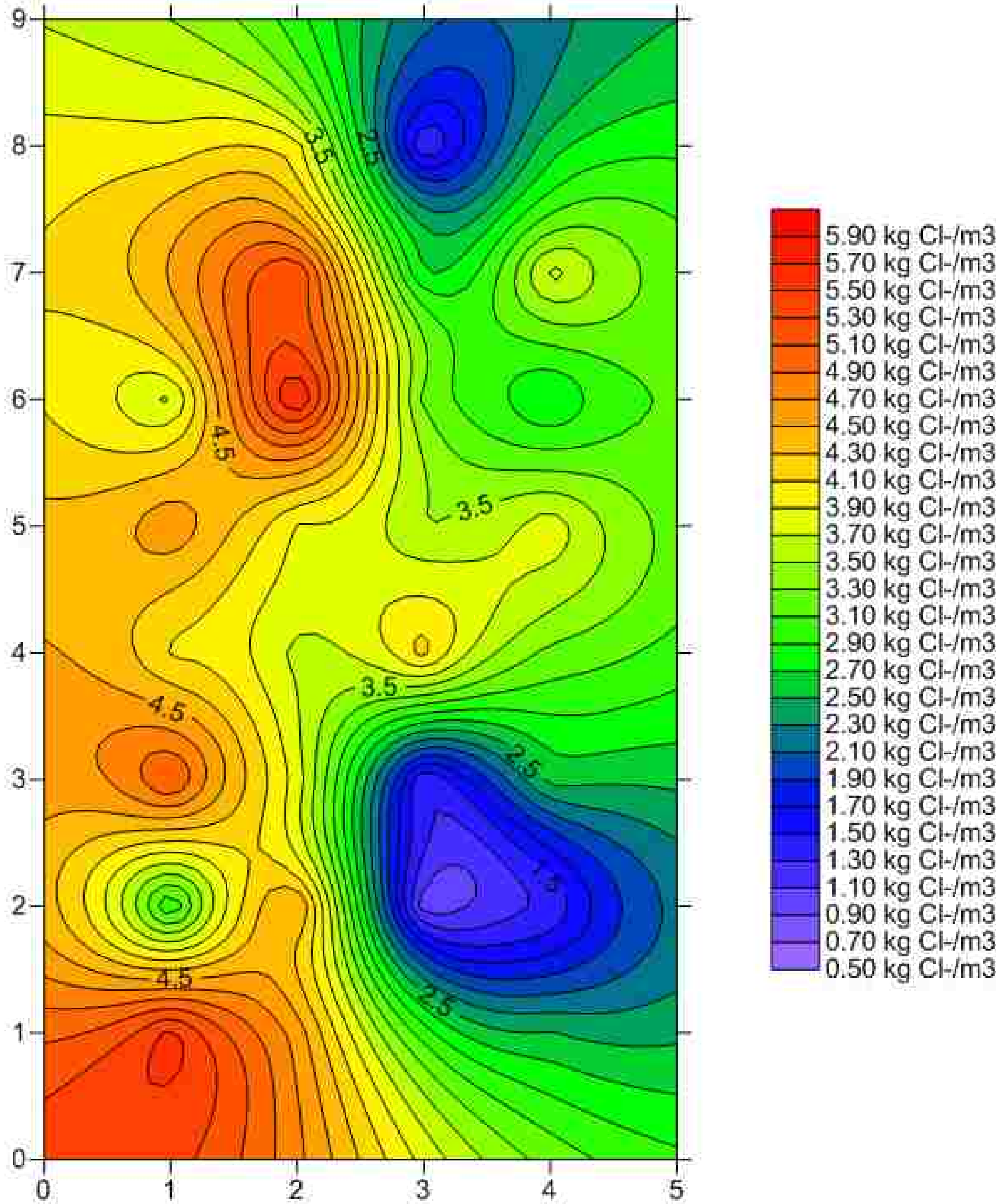

Figure 4-42. Contour plot of chloride concentration at 1.91 cm for slab from bridge D-413.

4.4 Summary

For the controlled laboratory experiments on slab sets A to D, sealant presence, curing time, temperature, moisture content, cover depth, water-to-cementitious materials ratio, air content, and epoxy coating condition were shown to have a statistically significant effect on impedance measurements, with *p*-values less than 0.05. Sealant presence, longer curing times, lower temperatures, lower moisture contents, larger cover depths, lower water-to-cementitious materials ratios, lower air contents, lower chloride concentrations, and improved epoxy coating condition produced higher impedance values in the testing.

The statistical analyses indicated that impedance testing in the frequency range of approximately 100 Hz to 1 kHz would be expected to provide the best data about the degree to which the reinforcing steel is protected from chloride infiltration by a bridge deck system. In this frequency range, a high level of differentiation among levels of corrosion protection is expected, and a high speed of data collection is also possible. Therefore, for the uncontrolled laboratory experiments on slab set E, a single frequency of 200 Hz was selected for impedance testing. Through statistical analyses performed to compare impedance with more traditional test measurements relating to corrosion of reinforcing steel in concrete bridge decks, several bridge deck properties were determined to be correlated with impedance, with *p*-values less than 0.15. Specifically, longitudinal and transverse cover, dry and wet resistivity, dry and wet half-cell potential, and dry linear polarization were positively correlated with impedance, while chloride concentration was negatively correlated with impedance.

5 CONCLUSION

5.1 Summary

The objectives of this research were to 1) investigate the sensitivity of EIS measurements obtained at various frequencies to specific deck properties, 2) recommend a particular frequency or range in frequency at which impedance measurements can differentiate among various levels of corrosion protection for reinforcing steel in concrete bridge decks, and 3) compare impedance values measured at the recommended frequency(ies) to more traditional test measurements relating to corrosion of reinforcing steel in concrete bridge decks.

Resistance to corrosion is primarily related to reducing the ability of chloride ions to accumulate in critical concentrations at the surface of the reinforcing steel. The impedance of a material reflects the difficulty with which current can flow through it when an electrical potential is applied and is therefore related to the material composition and structure. For applications to reinforced concrete, EIS testing is performed by applying alternating potentials of varying frequencies between the embedded reinforcing steel and a metal testing probe that is placed on the concrete surface; the impedance of the system is then measured at each frequency.

Impedance measurements are appropriate for measuring the corrosion potential of reinforcing steel in concrete because the same factors that influence the corrosion rate also theoretically influence impedance. High impedance measurements should theoretically signify high resistance to the movement and accumulation of corrosive ions in the vicinity of the reinforcing steel.

An experiment was designed to evaluate the effects of sealant presence, curing time, temperature, moisture content, cover depth, water-to-cementitious materials ratio, air content, chloride concentration, and epoxy coating condition on individual impedance measurements. Five sets of slabs were used to conduct this research. The system used to collect impedance values utilized a probe connected to a computer. Twenty logarithmically spaced frequencies, between the frequencies of 100 mHz and 300 kHz, were measured.

5.2 Findings

For the controlled laboratory experiments on slab sets A to D, sealant presence, curing time, temperature, moisture content, cover depth, water-to-cementitious materials ratio, air content, and epoxy coating condition were shown to have a statistically significant effect on impedance measurements, with p-values less than 0.05. Sealant presence, longer curing times, lower temperatures, lower moisture contents, larger cover depths, lower water-to-cementitious materials ratios, lower air contents, lower chloride concentrations, and improved epoxy coating condition produced higher impedance values in the testing.

The statistical analyses indicated that impedance testing in the frequency range of approximately 100 Hz to 1 kHz would be expected to provide the best data about the degree to which the reinforcing steel is protected from chloride infiltration by a bridge deck system. In this frequency range, a high level of differentiation among levels of corrosion protection is expected, and a high speed of data collection is also possible. Therefore, for the uncontrolled laboratory experiments on slab set E, a single frequency of 200 Hz was selected for impedance testing. Through statistical analyses performed to compare impedance with more traditional test measurements relating to corrosion of reinforcing steel in concrete bridge decks, several bridge deck properties were determined to be correlated with impedance, with *p*-values less than 0.15. Specifically, longitudinal and transverse cover, dry and wet resistivity, dry and wet half-cell potential, and dry linear polarization were positively correlated with impedance, while chloride concentration was negatively correlated with impedance.

5.3 Recommendations

Impedance testing is recommended as a valuable tool for non-destructive bridge deck condition assessment, as measurements can effectively differentiate among various levels of corrosion protection for reinforcing steel in concrete bridge decks. In the United States, where the electric power grid operates on a frequency of 60 Hz, testing at 200 Hz is ideal because 200 Hz is not an even multiple of 60 Hz; therefore, power grid noise harmonics would not be expected to couple in to the measurements. However, in other geographical locations where the frequency of the electric power grid is 50 Hz rather than 60 Hz, impedance testing should instead be performed at a frequency of 190 or 210 Hz, for example, to minimize interference from power grid harmonics. With respect to using impedance testing to evaluate in-service bridge deck condition, additional research is recommended to develop standardized methods of testing and to investigate possible implementation of threshold impedance values.

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APPENDIX A CONTROLLED LABORATORY DATA

Table A-1. Impedance Values for Sealant Presence for Slabs in Set D with 6.4 cm Cover

Frequency (Hz)	Impedance (Ω-cm) for Indicated Treatment			
	6.4 cm Cover (Slab 1)		6.4 cm Cover (Slab 2)	
	Test 1	Test 2	Test 1	Test 2
0.10	7931.6	7815.0	11211.1	11040.0
0.23	7275.0	7225.9	10089.1	9880.5
0.54	6494.2	6467.6	8978.8	8767.1
1.26	5862.5	5821.0	8225.5	8018.6
2.93	5484.8	5437.1	7829.1	7636.0
6.82	5287.4	5238.5	7626.0	7438.1
15.87	5170.9	5121.7	7500.1	7317.6
36.94	5100.5	5052.4	7422.1	7245.3
85.95	5044.8	4998.7	7362.1	7184.4
200.00	4998.9	4952.6	7305.2	7135.7
200.00	4981.1	4935.9	7277.5	7107.7
450.74	4926.0	4881.2	7201.6	7035.5
1015.85	4868.4	4823.9	7111.3	6950.2
2289.43	4802.9	4759.1	6999.4	6846.1
5159.72	4721.7	4679.6	6853.3	6710.6
11628.54	4614.5	4575.3	6657.2	6528.9
26207.41	4469.5	4435.0	6394.9	6285.6
59064.05	4271.7	4243.7	6044.3	5958.8
133113.50	3993.0	3972.0	5552.9	5493.6
300000.00	3580.5	3566.0	4803.9	4770.7

Table A-2. Impedance Values for Sealant Presence for Slabs in Set D with 2.5 cm Cover

Frequency (Hz)	Impedance (Ω-cm) for Indicated Treatment			
	2.5 cm Cover (Slab 3)		2.5 cm Cover (Slab 4)	
	Test 1	Test 2	Test 1	Test 2
0.10	8567.1	8083.6	11426.2	10998.9
0.23	7767.8	7315.0	10301.8	10638.2
0.54	6966.0	6559.5	9308.0	9851.8
1.26	6427.3	6040.8	8667.9	8993.2
2.93	6102.3	5745.4	8293.1	8660.5
6.82	5916.5	5574.7	8070.4	8462.0
15.87	5782.8	5451.7	7900.7	8346.0
36.94	5683.6	5361.1	7762.6	8220.6
85.95	5596.5	5280.9	7622.1	8099.9
200.00	5513.6	5207.9	7477.8	7943.3
200.00	5484.3	5183.7	7437.1	7910.0
450.74	5381.8	5093.6	7228.9	7690.4
1015.85	5254.0	4982.7	6945.1	7387.3
2289.43	5086.8	4838.7	6552.5	6958.8
5159.72	4867.1	4650.6	6035.8	6396.8
11628.54	4590.6	4413.6	5418.5	5713.9
26207.41	4266.3	4132.9	4768.7	4974.7
59064.05	3908.8	3819.0	4162.7	4315.6
133113.50	3520.9	3468.8	3625.7	3718.5
300000.00	3079.9	3056.2	3111.6	3165.9

Table A-3. Impedance Values for Curing Time for Slab 1 with 6.4 cm Cover

Frequency (Hz)	Impedance (Ω-cm) for Indicated Treatment						
	7 days		14 days		21 days	28 days	
	Test 1	Test 2	Test 1	Test 2	Test 1	Test 1	Test 2
0.10	1373.5	1364.5	2046.0	1915.1	1852.9	2305.0	2223.1
0.23	1435.0	1397.6	2028.1	1894.5	1833.8	2230.0	2146.7
0.54	1530.6	1477.8	2065.8	1935.6	1850.4	2224.6	2144.5
1.26	1613.7	1579.2	2011.7	1934.8	1765.0	2096.9	2033.6
2.93	1606.6	1607.5	1836.9	1822.0	1626.2	1940.1	1895.3
6.82	1514.2	1531.1	1601.7	1610.5	1464.2	1765.8	1727.7
15.87	1370.6	1384.2	1414.0	1421.6	1328.0	1622.8	1586.8
36.94	1228.0	1239.2	1299.7	1304.7	1238.8	1532.9	1498.2
85.95	1115.2	1122.7	1226.0	1229.3	1180.0	1475.7	1441.9
200.00	1036.9	1041.2	1178.5	1181.7	1141.9	1436.7	1404.9
200.00	1033.3	1037.5	1175.3	1176.7	1137.4	1426.1	1399.8
450.74	979.4	982.3	1140.4	1141.8	1107.8	1397.2	1371.6
1015.85	944.1	946.6	1115.6	1116.8	1085.9	1375.9	1281.2
2289.43	922.1	924.3	1098.0	1099.0	1069.1	1359.4	1256.8
5159.72	908.3	910.3	1085.0	1085.8	1055.8	1345.7	1244.1
11628.54	899.3	901.0	1074.5	1075.3	1044.6	1333.1	1232.8
26207.41	893.0	894.6	1065.2	1066.0	1034.5	1320.8	1222.1
59064.05	888.0	889.5	1055.8	1056.6	1024.6	1307.7	1211.0
133113.50	881.4	882.9	1044.5	1045.5	1012.4	1289.8	1196.0
300000.00	868.4	870.1	1030.0	1031.5	995.5	1262.6	1173.0

Table A-3. Continued

Frequency (Hz)	Impedance (Ω-cm) for Indicated Treatment							
	35 days		42 days		49 days		56 days	
	Test 1	Test 2	Test 1	Test 2	Test 1	Test 2	Test 1	Test 2
0.10	2507.4	2281.1	3074.8	3025.3	3567.9	3649.7	3881.5	3829.0
0.23	2491.6	2258.9	3011.8	2963.0	3488.8	3582.5	3814.1	3820.0
0.54	2564.0	2309.4	3041.9	3001.1	3472.5	3579.7	3641.1	3612.1
1.26	2594.6	2342.7	2985.5	2943.9	3322.9	3391.3	3287.6	3292.8
2.93	2607.2	2388.1	2864.8	2833.1	3108.3	3137.3	2969.6	3000.1
6.82	2527.2	2354.8	2672.7	2651.0	2871.5	2883.7	2781.8	2840.1
15.87	2349.5	2188.8	2473.3	2455.1	2654.6	2662.7	2669.3	2743.0
36.94	2116.5	1971.2	2332.9	2316.4	2496.3	2507.9	2594.5	2655.1
85.95	1924.4	1796.2	2239.8	2224.1	2386.8	2400.7	2541.0	2628.3
200.00	1797.4	1683.3	2176.2	2164.9	2314.7	2328.2	2520.5	2607.8
200.00	1787.0	1675.1	2167.0	2155.5	2306.1	2320.4	2523.9	2567.1
450.74	1699.8	1596.4	2117.9	2107.6	2249.2	2263.5	2504.2	2566.2
1015.85	1636.5	1539.5	2078.8	2069.9	2204.2	2218.2	2472.3	2549.4
2289.43	1588.1	1497.0	2046.2	2038.3	2166.6	2180.2	2456.7	2531.0
5159.72	1548.4	1463.0	2017.0	2010.1	2133.6	2146.8	2434.5	2511.3
11628.54	1514.2	1433.7	1988.6	1983.0	2102.6	2115.2	2425.2	2492.7
26207.41	1481.3	1406.2	1958.8	1954.8	2071.0	2082.5	2435.8	2482.1
59064.05	1445.9	1377.0	1924.0	1922.1	2034.7	2045.2	2453.0	2473.8
133113.50	1401.1	1339.8	1877.0	1878.1	1986.8	1994.5	2440.2	2452.9
300000.00	1338.3	1286.4	1807.5	1809.6	1915.0	1913.4	2361.2	2393.7

Table A-4. Impedance Values for Curing Time for Slab 2 with 6.4 cm Cover

Frequency (Hz)	Impedance (Ω-cm) for Indicated Treatment						
	7 days		14 days		21 days	28 days	
	Test 1	Test 2	Test 1	Test 2	Test 1	Test 1	Test 2
0.10	1393.7	1398.8	2112.7	2061.2	2062.0	2330.7	2301.1
0.23	1446.7	1417.7	2107.2	2010.3	2037.2	2456.3	2241.3
0.54	1524.3	1481.9	2154.3	2046.4	2066.1	2410.8	2247.3
1.26	1592.0	1543.5	2067.8	1969.6	1994.4	2348.5	2167.8
2.93	1578.6	1561.4	1869.9	1805.6	1861.7	2147.6	2041.0
6.82	1470.7	1470.0	1657.9	1638.7	1674.2	1906.1	1842.4
15.87	1315.2	1323.1	1501.4	1498.9	1501.0	1710.9	1661.8
36.94	1187.9	1191.0	1377.3	1391.0	1387.6	1600.2	1545.9
85.95	1097.4	1095.4	1313.4	1321.7	1313.7	1512.7	1471.4
200.00	1036.6	1034.4	1281.6	1274.4	1268.3	1453.7	1422.4
200.00	1031.8	1030.7	1270.6	1273.3	1264.0	1429.7	1416.2
450.74	991.6	990.0	1243.3	1241.6	1230.0	1392.3	1379.6
1015.85	965.2	963.6	1236.3	1216.8	1205.2	1362.6	1351.2
2289.43	948.1	946.3	1203.9	1191.9	1186.9	1338.2	1328.6
5159.72	936.7	934.7	1178.9	1168.4	1172.9	1319.1	1310.5
11628.54	928.8	926.5	1157.5	1148.7	1161.8	1303.6	1295.5
26207.41	923.1	920.2	1138.8	1131.5	1152.3	1290.1	1282.4
59064.05	917.8	914.6	1121.3	1115.6	1143.2	1276.5	1269.7
133113.50	910.0	906.6	1102.5	1098.3	1131.5	1261.7	1253.6
300000.00	895.0	891.4	1080.2	1077.9	1114.2	1239.2	1230.9

Table A-4. Continued

Frequency (Hz)	Impedance (Ω-cm) for Indicated Treatment							
	35 days		42 days		49 days		56 days	
	Test 1	Test 2	Test 1	Test 2	Test 1	Test 2	Test 1	Test 2
0.10	3258.9	3019.9	3176.4	3186.4	3004.6	2966.2	3946.9	3890.6
0.23	3131.0	2921.4	3105.6	3105.8	2923.6	2876.1	3812.6	3752.3
0.54	3145.5	2946.8	3119.9	3108.1	2922.6	2871.2	3619.5	3553.3
1.26	3140.2	2966.5	3013.9	2998.1	2781.4	2745.1	3215.3	3219.5
2.93	3109.5	2946.4	2864.2	2856.1	2558.6	2540.1	2887.4	2930.2
6.82	2947.2	2806.5	2681.0	2678.3	2368.0	2351.5	2712.9	2760.1
15.87	2705.4	2577.5	2504.5	2502.7	2222.4	2205.2	2604.3	2648.9
36.94	2491.1	2378.6	2380.4	2381.9	2125.6	2106.6	2541.7	2760.3
85.95	2350.3	2240.3	2295.6	2300.0	2056.5	2036.3	2499.9	2742.7
200.00	2254.9	2150.7	2243.8	2249.5	2010.2	1986.8	2475.8	2681.1
200.00	2243.7	2141.4	2235.3	2242.1	2002.5	1979.8	2466.4	2671.7
450.74	2175.3	2076.4	2192.0	2200.0	1962.2	1938.5	2440.8	2606.2
1015.85	2122.8	2027.2	2157.8	2166.6	1928.2	1903.7	2417.3	2546.1
2289.43	2079.3	1987.1	2129.7	2138.9	1897.8	1873.1	2396.8	2491.6
5159.72	2039.8	1951.4	2105.3	2114.6	1869.2	1844.6	2377.7	2442.3
11628.54	1999.9	1916.7	2082.5	2091.9	1839.7	1815.7	2358.7	2396.1
26207.41	1955.9	1879.5	2059.0	2068.4	1806.4	1783.6	2334.6	2353.4
59064.05	1902.4	1835.1	2031.0	2040.1	1765.2	1744.2	2305.3	2311.0
133113.50	1828.1	1772.8	1991.2	1999.9	1707.1	1689.1	2262.3	2258.5
300000.00	1715.2	1675.0	1930.1	1938.3	1618.5	1605.2	2189.3	2181.3

Table A-5. Impedance Values for Curing Time on Slab 3 with 2.5 cm Cover

Frequency (Hz)	Impedance (Ω-cm) for Indicated Treatment						
	7 days		14 days		21 days	28 days	
	Test 1	Test 2	Test 1	Test 2	Test 1	Test 1	Test 2
0.10	1168.1	1177.7	1514.8	1500.4	-	1880.1	1793.8
0.23	1219.6	1207.4	1541.7	1484.9	-	1828.0	1742.5
0.54	1285.9	1264.1	1585.7	1519.7	-	1839.3	1753.5
1.26	1299.6	1279.6	1529.2	1482.5	-	1770.6	1685.1
2.93	1188.4	1197.4	1372.9	1362.0	-	1648.5	1588.2
6.82	1061.9	1082.1	1222.1	1222.7	-	1488.5	1444.3
15.87	974.7	994.8	1105.3	1104.8	-	1349.7	1308.7
36.94	914.3	930.6	1028.6	1025.3	-	1254.5	1217.7
85.95	871.2	882.6	978.5	972.7	-	1194.4	1158.6
200.00	840.8	848.7	947.1	940.6	-	1157.5	1120.7
200.00	837.6	846.0	944.0	937.4	-	1149.3	1116.0
450.74	813.4	820.7	920.3	913.4	-	1120.0	1087.9
1015.85	796.0	802.9	903.1	896.5	-	1098.4	1067.3
2289.43	783.7	790.5	890.4	884.1	-	1081.8	1051.6
5159.72	775.0	781.8	880.5	874.7	-	1068.0	1038.6
11628.54	768.3	775.2	871.9	866.8	-	1055.3	1026.8
26207.41	762.8	769.8	863.8	859.3	-	1042.6	1015.1
59064.05	757.1	764.4	855.1	851.3	-	1028.2	1002.3
133113.50	748.8	756.6	844.4	841.2	-	1008.7	985.2
300000.00	734.7	743.2	830.8	828.3	-	979.4	959.6

Table A-5. Continued

Frequency (Hz)	Impedance (Ω-cm) for Indicated Treatment							
	35 days		42 days		49 days		56 days	
	Test 1	Test 2	Test 1	Test 2	Test 1	Test 2	Test 1	Test 2
0.10	1913.7	1871.8	3390.4	3349.8	3493.1	3457.0	2848.3	2956.9
0.23	1867.4	1827.1	3326.8	3284.2	3406.3	3359.6	2820.9	2879.8
0.54	1887.7	1844.7	3350.3	3310.6	3384.7	3341.4	2751.0	2801.3
1.26	1879.8	1838.6	3266.6	3237.5	3162.3	3146.2	2528.3	2563.5
2.93	1853.8	1814.3	3105.4	3089.1	2883.1	2886.4	2264.5	2313.0
6.82	1767.7	1735.2	2871.1	2865.3	2661.0	2662.8	2113.5	2157.2
15.87	1627.6	1603.0	2649.3	2645.7	2500.8	2494.8	2007.2	2044.7
36.94	1495.9	1473.6	2498.7	2494.8	2400.1	2389.3	1933.8	1967.8
85.95	1399.0	1378.6	2392.9	2391.2	2332.5	2319.3	1887.1	1904.2
200.00	1332.0	1311.7	2328.2	2323.1	2287.4	2268.7	1834.1	1858.5
200.00	1327.1	1306.9	2316.6	2313.7	2275.8	2259.9	1833.4	1848.2
450.74	1278.4	1258.9	2260.5	2257.2	2234.2	2217.7	1802.5	1813.7
1015.85	1241.7	1223.2	2215.0	2211.5	2198.4	2182.0	1773.9	1770.9
2289.43	1212.7	1195.4	2175.7	2172.5	2165.3	2149.6	1747.3	1746.9
5159.72	1188.4	1172.3	2138.8	2136.3	2131.7	2117.6	1730.0	1726.4
11628.54	1166.3	1151.6	2100.3	2098.9	2094.0	2082.4	1710.0	1706.7
26207.41	1144.4	1131.1	2055.6	2056.0	2048.1	2039.8	1685.3	1683.0
59064.05	1119.8	1108.2	1998.8	2001.6	1987.5	1984.1	1628.8	1656.5
133113.50	1087.7	1078.3	1920.9	1926.7	1903.8	1906.5	1595.1	1621.9
300000.00	1042.6	1036.1	1810.5	1819.4	1785.5	1795.3	1547.2	1573.9

Table A-6. Impedance Values for Curing Time on Slab 4 with 2.5 cm Cover

Frequency (Hz)	Impedance (Ω-cm) for Indicated Treatment						
	7 days		14 days		21 days	28 days	
	Test 1	Test 2	Test 1	Test 2	Test 1	Test 1	Test 2
0.10	1159.0	1188.5	1576.7	1511.7	1863.3	1901.3	1871.1
0.23	1206.8	1198.8	1584.7	1491.7	1857.0	1851.0	1830.2
0.54	1266.7	1247.2	1616.3	1522.0	1905.6	1875.8	1840.0
1.26	1233.7	1237.0	1563.0	1503.4	1846.6	1791.9	1761.4
2.93	1088.4	1120.9	1418.1	1400.2	1722.2	1670.5	1641.1
6.82	972.6	1006.0	1256.6	1255.3	1544.3	1517.1	1487.5
15.87	904.7	934.5	1125.0	1125.1	1375.2	1366.5	1351.8
36.94	862.1	886.6	1038.3	1037.1	1274.0	1270.5	1260.2
85.95	831.2	851.5	981.4	979.8	1193.5	1203.1	1200.0
200.00	810.2	826.7	944.8	944.4	1142.2	1161.0	1159.3
200.00	807.6	824.1	941.6	939.7	1137.3	1155.8	1155.5
450.74	790.0	805.0	915.0	913.2	1098.4	1124.8	1125.1
1015.85	777.0	791.1	895.9	894.2	1069.3	1101.7	1102.5
2289.43	767.6	781.0	882.2	880.5	1047.6	1084.6	1085.2
5159.72	760.8	773.6	872.0	870.1	1031.2	1070.6	1071.5
11628.54	755.6	767.9	863.5	861.5	1018.5	1058.7	1059.9
26207.41	751.4	763.2	855.5	853.5	1008.5	1047.7	1049.7
59064.05	747.2	758.5	847.1	845.1	1000.0	1036.1	1039.6
133113.50	740.8	751.5	836.6	834.7	990.3	1021.0	1027.2
300000.00	729.0	739.0	823.0	821.3	977.4	999.7	1010.1

Table A-6. Continued

Frequency (Hz)	Impedance (Ω-cm) for Indicated Treatment							
	35 days		42 days		49 days		56 days	
	Test 1	Test 2	Test 1	Test 2	Test 1	Test 2	Test 1	Test 2
0.10	2036.4	1666.9	2721.0	2697.0	2963.2	2894.8	2887.4	2982.4
0.23	1908.8	1608.1	2653.4	2627.7	2869.6	2817.6	2879.7	2903.3
0.54	1885.8	1600.7	2660.1	2634.1	2821.1	2814.7	2825.2	2840.5
1.26	1852.3	1575.4	2575.2	2557.8	2655.4	2664.7	2613.1	2642.1
2.93	1801.0	1538.0	2449.6	2437.9	2423.0	2433.3	2299.9	2347.9
6.82	1702.7	1461.9	2279.9	2278.8	2265.8	2331.6	2116.0	2160.0
15.87	1586.0	1363.5	2110.5	2113.8	2139.8	2226.9	2001.8	2041.0
36.94	1496.2	1281.3	1990.8	1995.3	2053.4	2132.9	1931.2	1969.0
85.95	1434.5	1222.3	1910.1	1915.3	1997.3	2047.2	1884.1	1920.6
200.00	1395.0	1184.2	1858.1	1863.4	1958.8	2013.7	1851.1	1885.5
200.00	1386.9	1179.4	1852.5	1857.9	2003.7	2036.6	1846.4	1879.4
450.74	1356.0	1150.3	1810.8	1816.7	1999.4	2012.8	1817.2	1848.3
1015.85	1331.6	1128.0	1777.5	1783.8	1915.1	1976.0	1791.9	1821.8
2289.43	1310.5	1109.8	1749.2	1755.8	1893.9	1903.8	1769.0	1798.2
5159.72	1290.6	1093.8	1723.4	1730.3	1865.1	2031.8	1747.1	1776.5
11628.54	1269.8	1078.2	1697.7	1704.9	1874.1	1993.0	1723.7	1753.6
26207.41	1246.1	1061.6	1669.3	1676.7	1881.2	2170.8	1697.1	1727.3
59064.05	1216.0	1041.8	1634.7	1642.4	2023.4	2159.3	1664.4	1695.1
133113.50	1173.6	1014.0	1588.4	1596.7	1946.2	2027.3	1622.4	1653.5
300000.00	1109.7	971.4	1524.1	1533.8	1815.4	1883.0	1567.4	1598.5

Table A-7. Impedance Values for Temperature for Slabs in Set C at 5 °C

Frequency (Hz)	Impedance (Ω-cm) for Indicated Treatment			
	0.40 w/cm Ratio		0.60 w/cm Ratio	
	Test 1	Test 2	Test 1	Test 2
0.10	155350.8	158195.4	421507.3	459947.8
0.23	150169.7	140775.9	428124.5	407197.8
0.54	132802.9	129657.1	377243.7	366800.8
1.26	116925.5	110996.0	334219.5	329526.3
2.93	109122.5	103650.9	305314.1	301998.6
6.82	103291.8	98785.1	319162.0	296914.6
15.87	96609.3	94819.1	317694.8	293744.9
36.94	95044.5	91823.1	317806.7	293448.6
85.95	91829.3	91272.9	296607.9	313456.2
200.00	88879.6	88869.7	296270.8	334446.0
200.00	86541.6	94698.2	355723.9	299964.3
450.74	91497.7	84130.7	347371.1	399653.5
1015.85	87995.5	88947.5	335687.2	289013.8
2289.43	84375.9	85688.3	306733.4	268951.8
5159.72	80245.7	81717.7	220466.7	272477.6
11628.54	74175.5	70058.1	167787.3	179653.4
26207.41	63363.8	60333.8	98158.6	103280.1
59064.05	45631.8	43974.5	52444.2	54874.6
133113.50	26709.1	26888.2	26533.4	27508.1
300000.00	13061.7	13147.8	12976.5	13258.9

Table A-8. Impedance Values for Temperature for Slabs in Set C at 20 °C

Frequency (Hz)	Impedance (Ω-cm) for Indicated Treatment			
	0.40 w/cm Ratio		0.60 w/cm Ratio	
	Test 1	Test 2	Test 1	Test 2
0.10	107693.7	109581.8	220046.5	207657.9
0.23	99811.0	101065.5	230235.9	212418.3
0.54	95593.5	92067.5	224475.5	206690.3
1.26	85242.4	83989.9	214507.2	200325.8
2.93	77625.2	76575.2	208567.8	193564.7
6.82	76065.6	75123.6	179523.8	187526.8
15.87	70487.2	72132.8	193648.8	180037.2
36.94	70840.8	69632.7	163736.5	171674.2
85.95	69090.6	65219.3	157856.4	165836.6
200.00	67302.4	66468.6	154536.8	162702.1
200.00	76585.8	75401.9	203953.0	186616.4
450.74	62401.1	73374.7	200166.5	183618.6
1015.85	72590.0	71382.3	195426.6	179374.4
2289.43	70693.2	69366.5	142651.3	171759.4
5159.72	57950.2	67032.5	131824.3	155890.5
11628.54	64828.7	54821.3	131798.7	125164.0
26207.41	58441.2	50302.2	86444.6	75874.7
59064.05	45593.4	45082.9	48969.3	46021.8
133113.50	27612.2	27452.1	24998.5	25028.9
300000.00	13246.0	13194.1	12310.1	12316.5

Table A-9. Impedance Values for Temperature for Slabs in Set C at 35 °C

Frequency (Hz)	Impedance (Ω-cm) for Indicated Treatment			
	0.40 w/cm Ratio		0.60 w/cm Ratio	
	Test 1	Test 2	Test 1	Test 2
0.10	59688.0	49733.0	60184.8	55562.8
0.23	54242.2	44121.5	54132.1	53828.3
0.54	51646.6	41099.4	55865.2	53283.9
1.26	46440.1	37962.3	57196.8	53076.9
2.93	43489.8	36365.4	56122.6	53521.0
6.82	43154.4	35537.2	57079.9	54234.5
15.87	39992.1	34753.5	60912.7	54667.5
36.94	39228.6	34225.2	57518.6	54871.7
85.95	38574.5	34304.9	56488.0	54785.7
200.00	38761.5	33153.4	56170.5	54559.0
200.00	37963.2	32945.6	56330.8	54217.6
450.74	41506.8	32420.7	55767.8	53657.1
1015.85	36700.6	35068.6	54859.6	52834.4
2289.43	35975.2	31389.7	53481.7	51596.8
5159.72	35136.1	33393.8	51201.1	55252.8
11628.54	37274.6	29639.4	51847.2	50760.2
26207.41	32019.0	30293.4	40376.3	39338.8
59064.05	27814.9	26655.7	30105.9	29405.4
133113.50	20003.7	19848.2	18960.3	18803.2
300000.00	11285.6	10849.2	10326.6	10084.5

Table A-10. Impedance Values for Moisture Content for Slabs in Set C with 0.40 w/cm

Frequency (Hz)	Impedance (Ω-cm) for Indicated Treatment					
	0 hr	0.25 hr	0.5 hr	1 hr	2 hr	4 hr
0.10	33595.0	12036.7	15063.5	13616.3	12935.6	14100.3
0.23	28376.2	10995.9	14036.2	12981.9	12096.8	13557.8
0.54	25596.6	10236.7	12132.5	11562.6	10816.0	12032.6
1.26	23595.8	9396.9	10719.0	10430.6	9879.9	10322.9
2.93	18655.8	9057.6	10026.9	9840.3	9393.4	10415.6
6.82	18255.2	8845.3	9545.6	9525.8	9118.8	9828.3
15.87	17578.8	8664.3	9116.9	9331.5	8900.6	8714.8
36.94	16683.2	8518.9	8713.1	9181.5	8740.0	8426.2
85.95	16250.4	8401.0	8339.4	9055.1	8592.0	8160.0
200.00	15599.5	8276.3	7992.2	8944.1	8460.0	7945.5
200.00	15694.3	8268.9	7964.3	8867.2	8428.0	7759.1
450.74	15407.1	8108.0	7617.2	8717.0	8275.8	7497.2
1015.85	14532.9	7965.2	7275.8	8564.4	8118.4	7240.6
2289.43	13729.3	7814.8	6942.7	8439.2	7958.0	7007.8
5159.72	13232.8	7653.7	6617.1	8250.7	7791.1	6744.3
11628.54	12349.5	7467.6	6286.1	8076.4	7608.1	6444.7
26207.41	11132.0	7213.6	5917.0	7837.3	7361.7	6082.8
59064.05	9563.9	6774.6	5421.3	7382.7	6913.0	5541.4
133113.50	7620.1	5906.9	4639.2	6411.6	5993.8	4639.6
300000.00	5287.4	4446.7	3472.1	4776.7	4479.5	3342.5

Table A-10. Continued

Frequency (Hz)	Impedance (Ω-cm) for Indicated Treatment						
	6 hr	8 hr	12 hr	24 hr	36 hr	48 hr	96 hr
0.10	12448.6	13158.3	28713.7	13180.0	12884.6	10254.2	11414.3
0.23	12188.5	12560.8	25525.5	12586.8	12431.0	9869.4	11193.6
0.54	10739.9	11179.8	22081.4	10993.3	10953.0	8816.0	9942.1
1.26	9604.5	9993.9	19238.4	9830.7	9729.0	7991.8	8699.5
2.93	8980.1	9353.2	17273.5	9272.2	9092.7	7583.2	8031.0
6.82	8672.4	8994.6	15829.4	8965.8	8755.9	8795.2	7697.2
15.87	8434.3	8754.1	14685.3	8762.1	8548.9	8505.5	7479.0
36.94	8266.8	8581.1	13816.9	8608.0	8399.8	8272.5	7320.2
85.95	8122.8	8423.1	13064.6	8463.5	8263.3	8054.3	7170.5
200.00	7982.8	8283.9	12436.2	8329.6	8133.1	7834.9	7026.6
200.00	7949.4	8254.7	12418.8	8294.0	8102.2	7806.1	7001.2
450.74	7798.6	8098.4	11815.8	8132.7	7967.0	7561.5	6833.9
1015.85	7645.6	7942.1	11258.1	7961.6	7823.0	7307.7	6652.9
2289.43	7493.7	7788.1	10724.7	7781.0	7673.0	7048.1	6462.5
5159.72	7341.2	7634.9	10192.7	7586.9	7512.0	6777.2	6267.2
11628.54	7173.6	7466.3	9633.2	7357.4	7316.4	6473.5	6057.7
26207.41	6933.8	7217.9	8972.8	7016.0	7008.2	6074.9	5801.4
59064.05	6451.3	6702.5	7988.4	6354.1	6360.5	5424.3	5404.7
133113.50	5426.4	5601.3	6365.3	5081.4	5043.8	4317.5	4698.3
300000.00	3815.1	3900.0	4237.8	3331.3	3211.6	2849.6	3613.7

Table A-11. Impedance Values for Moisture Content for Slabs in Set C with 0.60 w/cm

Frequency (Hz)	Impedance (Ω-cm) for Indicated Treatment					
	0 hr	0.25 hr	0.5 hr	1 hr	2 hr	4 hr
0.10	311685.7	136687.5	149765.1	76395.8	63404.2	62368.2
0.23	291135.3	133129.0	115269.8	74357.1	61607.6	60046.6
0.54	281675.1	130573.8	115946.5	72667.9	60229.8	58029.7
1.26	273414.1	127853.4	111817.1	71032.7	58488.6	55390.0
2.93	266732.4	126857.2	111608.9	70599.6	58168.8	54257.3
6.82	261212.3	126067.2	111816.6	70440.0	58306.7	54094.3
15.87	255327.5	124878.4	111852.2	70265.1	58523.7	53473.7
36.94	248016.4	123313.1	118215.0	69854.0	59311.1	53842.8
85.95	238151.1	121404.8	118695.0	69508.6	59197.8	53116.2
200.00	224213.0	119772.8	118609.2	68940.1	60081.2	53101.8
200.00	222800.0	118313.4	133933.4	68731.6	60839.8	52852.3
450.74	203469.0	114778.3	108812.4	67663.2	60966.2	52448.8
1015.85	185339.1	109268.3	105348.1	65937.4	58974.5	53709.6
2289.43	154203.1	100207.6	98536.7	62811.1	57713.5	50091.2
5159.72	119942.3	88626.6	85741.4	57036.1	54528.3	46932.0
11628.54	85211.8	65296.4	75335.5	47441.6	48822.4	40761.9
26207.41	54538.9	41996.7	45321.5	34867.0	36774.3	31061.8
59064.05	31716.0	24683.1	27868.5	21916.0	23906.3	20220.8
133113.50	17018.3	13514.1	15871.4	12670.8	13546.3	11526.7
300000.00	8669.5	6851.5	8201.7	6644.7	7405.9	5961.7

Table A-11. Continued

Frequency (Hz)	Impedance (Ω-cm) for Indicated Treatment						
	6 hr	8 hr	12 hr	24 hr	36 hr	48 hr	96 hr
0.10	104586.8	86776.7	95256.0	72315.2	102953.3	45179.3	69263.4
0.23	96790.3	84453.4	92391.7	68911.6	100239.4	42172.7	66628.2
0.54	95610.7	82885.3	90224.6	66570.9	98079.0	39709.4	64449.4
1.26	91270.3	80666.9	87547.9	64054.1	94961.0	36907.0	61635.7
2.93	89409.7	79413.4	86394.4	62987.9	93290.9	35892.9	60289.9
6.82	88000.0	78692.9	85804.1	62369.0	92202.2	35418.8	59462.4
15.87	86805.1	78161.3	85241.6	61843.1	91278.4	35139.1	58779.3
36.94	85908.2	77851.9	84875.8	61543.1	90698.7	35026.5	58215.8
85.95	84883.6	77522.7	84440.5	61320.2	90543.7	35000.2	57744.0
200.00	83950.2	77062.6	86865.7	60965.5	89224.5	34914.1	57103.8
200.00	83144.9	76829.7	83566.3	60752.8	91920.8	34801.5	56879.6
450.74	81216.7	75822.6	82322.5	60010.9	87132.6	34591.7	55806.7
1015.85	78677.2	73816.4	79884.2	58702.0	86908.8	34185.0	54070.6
2289.43	74114.1	69844.9	75049.8	56083.6	78247.2	33368.9	50940.3
5159.72	65780.8	61968.6	65691.8	50900.5	67562.8	31649.2	45361.3
11628.54	52179.6	48917.1	50787.7	41727.3	51628.4	28086.1	36581.1
26207.41	35529.8	33118.2	33706.7	29270.3	34041.2	21837.0	25826.0
59064.05	21108.1	19642.1	19673.7	17514.4	19418.2	14128.7	15996.5
133113.50	11488.6	10716.9	10581.5	9392.8	10716.4	7819.0	8989.0
300000.00	5867.2	5485.0	5362.8	4705.7	5527.6	3909.1	4750.0

Table A-12. Moisture Data for Slabs in Set C with 0.40 w/cm

Time (hr)	Test	Weight (lb)	Temperature (°C)	Relative Humidity	Dielectric Values				
					1	2	3	4	5
0	1	66.25	22.2	0.22	6.5	7.4	7.9	6.9	7.5
0.25	2	66.25	22.1	0.23	7.9	9.1	8.9	8.7	9.0
0.5	3	66.30	22.0	0.25	-	-	-	-	-
1	4	66.30	21.2	0.29	-	-	-	-	-
2	5	66.35	19.9	0.33	-	-	-	-	-
4	6	66.35	19.3	0.37	9.7	11.0	10.7	10.9	11.7
6	7	66.35	18.7	0.39	9.5	10.8	10.9	11.3	11
8	8	66.35	18.0	0.41	9.8	10.5	10.6	10.6	11.3
12	9	66.40	17.7	0.44	10.2	11.7	11.0	11.5	11.5
24	10	66.40	17.3	0.49	9.9	11.3	11.1	10.1	10.4
36	11	66.45	17.9	0.51	10.6	11.8	11.4	11.2	12.1
48	12	66.45	17.4	0.53	10.3	11.3	11.1	10.9	11.4
96	13	66.45	20.5	0.57	9.7	10.5	9.1	8.9	10.5

Table A-13. Moisture Data for Slabs in Set C with 0.40 w/cm

Time (hr)	Test	Weight (lb)	Temperature (°C)	Relative Humidity	Dielectric Values 1	2	3	4	5
0	1	61.30	22.4	0.21	5.0	5.0	5.1	5.0	5.4
0.25	2	61.35	22.3	0.22	6.7	6.2	5.7	5.8	7.2
0.5	3	61.40	22.2	0.22	-	-	-	-	-
1	4	61.40	21.6	0.26	-	-	-	-	-
2	5	61.45	20.4	0.31	-	-	-	-	-
4	6	61.45	18.9	0.33	10.3	8.2	8.4	10.3	12.3
6	7	61.50	18.5	0.38	8.2	8.0	7.9	7.8	9.9
8	8	61.55	17.3	0.36	9.0	8.1	8.4	8.0	10.4
12	9	61.55	17.5	0.35	8.5	7.2	6.2	6.8	9.3
24	10	61.65	16.8	0.44	8.4	8.6	7.9	8.3	10.3
36	11	61.70	17.6	0.41	8.6	8.8	9.2	8.8	9.9
48	12	61.80	17.6	0.48	9.2	8.8	9.4	9.0	11.0
96	13	61.80	20.7	0.61	7.7	7.5	8.1	8.4	10.0

Table A-14. Impedance Values for Cover Depth for Slabs in Set A with 0 kg Cl^-/m^3

Frequency (Hz)	Impedance (Ω-cm) for Indicated Treatment: 6.1 cm Cover			6.4 cm Cover			7.6 cm Cover		
	Slab 1	Slab 2	Slab 3	Slab 1	Slab 2	Slab 3	Slab 1	Slab 2	Slab 3
0.10	50896.5	32576.3	33172.2	29501.4	21004.9	23230.3	27867.9	23856.7	21181.2
0.23	45635.1	31401.7	30029.0	27357.0	19018.1	20870.6	26874.7	21989.0	18990.9
0.54	45085.6	30038.9	28438.6	26141.8	18035.4	19781.1	25902.8	21108.3	17907.9
1.26	44401.6	28300.7	26760.6	25603.3	17429.6	18988.2	24370.3	20500.2	17033.8
2.93	44339.1	27523.6	26161.7	25505.8	17279.7	18810.5	24148.8	20457.3	16776.6
6.82	44613.8	26790.1	25500.5	25441.8	17264.6	18736.3	24224.5	20378.8	16426.5
15.87	44422.1	25876.8	24933.7	25362.0	17235.0	18713.8	24174.9	20365.0	16331.4
36.94	44114.3	25261.6	24571.4	25253.8	17233.0	18654.7	24089.0	20372.3	16312.1
85.95	43285.0	24774.4	24073.4	25113.1	17219.9	18573.1	23823.9	20366.1	16188.2
200.00	43160.3	24555.5	23748.3	24733.6	17269.7	18439.3	23664.1	20364.6	16102.2
200.00	45112.8	24321.1	23628.9	24612.1	17336.1	18348.5	23567.6	20604.8	16043.1
450.74	44357.8	24387.5	23295.0	25024.3	17037.1	18179.5	23785.9	20188.8	15895.4
1015.85	43462.7	23981.1	22928.0	24079.0	16898.8	17970.5	23079.5	20052.2	15723.5
2289.43	40006.3	23024.3	22491.0	24386.5	16698.3	17704.8	22749.8	19855.5	15513.1
5159.72	40692.0	22884.2	21880.8	23219.0	16619.3	17328.7	22286.5	19507.2	15240.4
11628.54	36044.6	21822.0	20869.2	23040.8	15781.4	16818.6	21514.6	18808.1	14815.0
26207.41	33251.3	19456.2	19028.0	21318.7	14643.8	15493.8	20442.9	17403.9	14001.9
59064.05	25641.2	16243.9	15830.8	17435.2	12638.2	13307.2	17399.5	14877.9	12395.1
133113.50	16599.4	11759.0	11302.3	12652.4	9752.7	10015.3	12450.2	11101.6	9628.4
300000.00	8805.8	7138.3	6940.9	7446.4	6347.1	6404.4	7509.2	6899.8	6356.1

Table A-15. Impedance Values for Cover Depth for Slabs in Set A with 1.2 kg Cl^-/m^3

Frequency (Hz)	Impedance (Ω-cm) for Indicated Treatment								
	6.1 cm Cover			6.4 cm Cover			7.6 cm Cover		
	Slab 4	Slab 5	Slab 6	Slab 4	Slab 5	Slab 6	Slab 4	Slab 5	Slab 6
0.10	29010.6	23007.4	16774.3	25686.6	21802.7	26478.3	21990.6	20616.0	16813.9
0.23	26444.3	20578.2	15126.0	23686.7	19144.4	23637.2	20074.4	18365.0	14984.6
0.54	25395.9	19295.1	14178.1	22582.1	17916.8	22355.3	19012.2	17181.3	14013.5
1.26	24676.2	18303.9	13301.3	21662.8	17049.2	20513.2	18138.8	16247.5	13290.1
2.93	24588.4	18124.3	13093.1	21421.4	16894.3	19669.5	17926.0	16043.1	13150.7
6.82	24559.2	17983.8	12995.8	21319.1	16789.2	18884.7	17795.1	15929.4	13090.0
15.87	24503.7	17893.3	12932.1	21538.8	16740.2	18086.9	17679.6	15836.6	13042.4
36.94	24467.8	17838.1	12911.6	21528.7	16708.6	17431.1	17610.5	15778.3	13024.3
85.95	24434.2	17792.9	12905.3	21508.2	16682.3	16916.8	17563.5	15738.0	13017.1
200.00	24441.2	17761.7	12911.3	21471.3	16673.1	16449.4	17517.1	15683.7	13011.8
200.00	24495.9	17692.3	12912.7	21391.8	16603.1	16385.1	17397.8	15625.6	12971.3
450.74	24099.9	17593.3	12831.3	21359.4	16611.5	15984.6	17047.9	15520.2	12927.7
1015.85	24023.0	17540.2	12770.6	21125.8	16386.7	15631.1	16938.1	15420.8	12866.5
2289.43	23290.9	17242.6	12670.3	20628.2	16180.8	15301.1	16633.4	15155.7	12769.1
5159.72	22375.9	16901.1	12495.7	19925.3	15868.3	14938.5	16198.2	14830.6	12600.3
11628.54	20923.1	16270.0	12148.5	18671.8	15333.9	14521.4	15408.0	14321.6	12259.0
26207.41	18112.6	15034.4	11401.7	16597.1	14328.0	13497.7	14090.0	13274.1	11571.1
59064.05	14605.9	12813.1	9932.7	13614.5	12444.5	11737.4	12015.0	11586.6	10167.0
133113.50	10470.5	9611.1	7714.1	9918.1	9456.8	9086.8	9249.1	9030.3	8077.1
300000.00	6509.7	6192.2	5231.6	6392.1	6229.9	6089.7	6165.8	6053.9	5553.0

Table A-16. Impedance Values for Cover Depth for Set A with 2.4 kg Cl^-/m^3

Frequency (Hz)	Impedance (Ω-cm) for Indicated Treatment								
	6.1 cm Cover			6.4 cm Cover			7.6 cm Cover		
	Slab 7	Slab 8	Slab 9	Slab 7	Slab 8	Slab 9	Slab 7	Slab 8	Slab 9
0.10	26545.0	21106.4	25536.5	23667.8	17161.6	22392.7	22126.4	17924.5	24020.2
0.23	24078.4	18876.0	23336.9	21470.9	15154.8	20369.3	19783.7	15641.6	21892.3
0.54	23026.3	17971.7	22708.3	19999.8	14072.5	19366.2	18553.4	14519.3	20926.3
1.26	22245.0	17314.4	21964.9	19119.1	13182.9	18707.4	17731.5	15138.2	20244.4
2.93	22054.1	17127.1	21862.4	18919.5	12940.5	18630.8	17538.3	14733.5	20198.8
6.82	21897.9	16996.4	21957.4	18789.1	12794.2	18641.8	17448.9	14092.5	20209.0
15.87	21812.6	16908.7	21829.2	18678.5	12645.8	18659.3	17406.9	13579.9	20225.6
36.94	21745.2	16863.8	21841.4	18642.2	12549.5	18704.1	17402.3	13191.0	20245.3
85.95	21674.4	16847.9	21864.9	18557.2	12471.0	18736.9	17420.0	12901.0	20276.7
200.00	21686.8	16858.5	21909.7	18554.7	12402.2	18835.6	17456.1	12682.7	20322.5
200.00	21548.3	16795.2	21812.2	18457.6	12359.2	18757.4	17397.6	12642.0	20235.1
450.74	21433.4	16758.1	21771.3	18445.4	12257.1	18785.6	17380.6	12444.4	20241.7
1015.85	21386.0	16686.8	21680.3	18285.2	12123.8	18795.6	17319.2	12256.6	20234.4
2289.43	20925.6	16559.0	21518.3	17908.8	11939.6	18773.2	17153.4	12046.8	20574.6
5159.72	20312.9	16290.5	21167.4	17385.7	11682.2	18643.5	16777.5	11792.6	20445.7
11628.54	19138.1	15707.7	20921.4	16439.5	11207.1	18202.0	16033.2	11345.0	19571.6
26207.41	17217.3	14508.2	18728.5	14857.3	10439.4	17039.4	14767.5	10650.0	18370.9
59064.05	14222.6	12399.9	16045.1	12503.2	9163.8	14651.7	12819.9	9485.0	15847.2
133113.50	10523.6	9503.3	11482.7	9500.0	7353.2	10988.4	10036.6	7736.5	11825.7
300000.00	6790.9	6381.6	7166.1	6331.7	5310.3	6939.4	6699.2	5599.6	7380.1

Table A-17. Impedance Values for Cover Depth for Slabs in Set D

Frequency (Hz)	Impedance (Ω-cm) for Indicated Treatment							
	Slab 1 with 6.4 cm Cover		Slab 2 with 6.4 cm Cover		Slab 3 with 2.5 cm Cover		Slab 4 with 2.5 cm Cover	
	Test 1	Test 2	Test 1	Test 2	Test 1	Test 2	Test 1	Test 2
0.10	2305.0	2223.1	2330.7	2301.1	1880.1	1793.8	1901.3	1871.1
0.23	2230.0	2146.7	2456.3	2241.3	1828.0	1742.5	1851.0	1830.2
0.54	2224.6	2144.5	2410.8	2247.3	1839.3	1753.5	1875.8	1840.0
1.26	2096.9	2033.6	2348.5	2167.8	1770.6	1685.1	1791.9	1761.4
2.93	1940.1	1895.3	2147.6	2041.0	1648.5	1588.2	1670.5	1641.1
6.82	1765.8	1727.7	1906.1	1842.4	1488.5	1444.3	1517.1	1487.5
15.87	1622.8	1586.8	1710.9	1661.8	1349.7	1308.7	1366.5	1351.8
36.94	1532.9	1498.2	1600.2	1545.9	1254.5	1217.7	1270.5	1260.2
85.95	1475.7	1441.9	1512.7	1471.4	1194.4	1158.6	1203.1	1200.0
200.00	1436.7	1404.9	1453.7	1422.4	1157.5	1120.7	1161.0	1159.3
200.00	1426.1	1399.8	1429.7	1416.2	1149.3	1116.0	1155.8	1155.5
450.74	1397.2	1371.6	1392.3	1379.6	1120.0	1087.9	1124.8	1125.1
1015.85	1375.9	1281.2	1362.6	1351.2	1098.4	1067.3	1101.7	1102.5
2289.43	1359.4	1256.8	1338.2	1328.6	1081.8	1051.6	1084.6	1085.2
5159.72	1345.7	1244.1	1319.1	1310.5	1068.0	1038.6	1070.6	1071.5
11628.54	1333.1	1232.8	1303.6	1295.5	1055.3	1026.8	1058.7	1059.9
26207.41	1320.8	1222.1	1290.1	1282.4	1042.6	1015.1	1047.7	1049.7
59064.05	1307.7	1211.0	1276.5	1269.7	1028.2	1002.3	1036.1	1039.6
133113.50	1289.8	1196.0	1261.7	1253.6	1008.7	985.2	1021.0	1027.2
300000.00	1262.6	1173.0	1239.2	1230.9	979.4	959.6	999.7	1010.1

Table A-18. Impedance Values for Water-to-Cementitious Materials Ratio for Slabs in Set B

Frequency (Hz)	Impedance (Ω-cm) for Indicated Treatment			
	0.40 w/cm Ratio		0.55 w/cm Ratio	
	Test 1	Test 2	Test 1	Test 2
0.10	9281.7	6525.9	2786.0	2506.3
0.23	7579.0	5919.1	2573.3	2358.7
0.54	5941.4	5043.0	2502.5	2209.8
1.26	4594.6	4255.8	2060.3	1935.6
2.93	3632.7	3444.1	1740.4	1599.2
6.82	2965.4	2868.1	1585.1	1418.2
15.87	2464.1	2369.8	1434.6	1322.3
36.94	2173.6	2110.6	1372.6	1267.4
85.95	1959.6	1914.1	1325.0	1233.9
200.00	1803.3	1853.4	1291.4	1210.8
200.00	1799.6	1903.0	1284.6	1207.6
450.74	1672.1	1777.2	1254.3	1187.8
1015.85	1570.4	1673.2	1231.4	1171.6
2289.43	1487.7	1591.1	1212.5	1159.9
5159.72	1422.5	1864.0	1199.4	1151.3
11628.54	1372.0	1402.1	1191.1	1147.2
26207.41	1332.5	1418.5	1184.1	1144.4
59064.05	1299.5	1696.3	1178.2	1142.3
133113.50	1266.2	1653.5	1169.3	1135.0
300000.00	1225.4	1568.0	1151.3	1119.7

Table A-19. Impedance Values for Air Content for Slabs in Set B

Frequency (Hz)	Impedance (Ω-cm) for Indicated Treatment			
	Air		No Air	
	Test 1	Test 2	Test 1	Test 2
0.10	2786.0	2506.3	6660.3	6739.4
0.23	2573.3	2358.7	5893.0	5742.9
0.54	2502.5	2209.8	5216.5	5134.3
1.26	2060.3	1935.6	4292.9	4247.0
2.93	1740.4	1599.2	3360.8	3341.0
6.82	1585.1	1418.2	2773.6	2760.6
15.87	1434.6	1322.3	2286.8	2281.1
36.94	1372.6	1267.4	2013.8	2011.8
85.95	1325.0	1233.9	1806.9	1806.3
200.00	1291.4	1210.8	1652.0	1652.8
200.00	1284.6	1207.6	1651.1	1651.9
450.74	1254.3	1187.8	1527.1	1528.3
1015.85	1231.4	1171.6	1428.2	1429.6
2289.43	1212.5	1159.9	1349.8	1350.9
5159.72	1199.4	1151.3	1288.5	1288.9
11628.54	1191.1	1147.2	1241.2	1240.8
26207.41	1184.1	1144.4	1205.2	1204.2
59064.05	1178.2	1142.3	1176.6	1175.1
133113.50	1169.3	1135.0	1149.3	1147.1
300000.00	1151.3	1119.7	1117.6	1115.0

Table A-20. Impedance Values for Chloride Concentration for Slabs in Set A with Full Epoxy

Frequency	Impedance (Ω-cm)								
	0 kg Cl⁻/m³			1.2 kg Cl⁻/m³			2.4 kg Cl⁻/m³		
(Hz)	Slab 1	Slab 2	Slab 3	Slab 4	Slab 5	Slab 6	Slab 7	Slab 8	Slab 9
0.10	246969.0	238470.4	347931.3	165741.5	216412.3	406870.1	369761.9	321912.9	160135.2
0.23	246344.6	231072.4	345868.0	159916.5	212648.6	397949.7	359555.8	314431.7	149183.1
0.54	240066.6	227958.6	347410.8	153794.4	210024.2	393852.8	354255.4	309687.9	134741.0
1.26	235105.1	223752.8	339514.3	150450.8	205224.5	386517.1	338330.1	300350.2	131069.1
2.93	230671.6	220985.9	331998.4	147440.2	201237.0	382061.6	330316.6	293221.3	130795.5
6.82	234255.8	229049.5	322110.8	144202.6	196108.0	374525.8	318583.5	283712.2	131423.4
15.87	215221.5	209424.6	302888.7	139342.8	187739.6	359760.5	302779.1	268930.3	131218.0
36.94	198990.8	197637.9	274619.1	132251.4	175658.9	332717.0	278730.0	247350.9	130172.3
85.95	172407.1	175973.5	226368.5	120835.7	165090.9	278312.1	236838.8	210339.9	126524.7
200.00	135495.5	140681.6	161067.6	101984.9	138557.9	191675.2	175604.4	153727.7	120453.8
200.00	146643.5	139976.2	163969.2	101298.3	148873.1	190813.3	171312.3	153130.3	115546.4
450.74	93698.7	95809.3	96376.6	75007.9	115751.1	108665.6	103736.5	93512.7	92341.7
1015.85	58907.8	57633.4	52556.5	48211.3	98556.7	56158.9	56317.4	50392.6	60920.2
2289.43	36697.7	34199.4	28903.9	29952.6	74307.8	29528.7	31624.0	26837.7	37304.7
5159.72	25581.8	23174.2	18296.4	21001.1	58242.4	17738.7	21218.8	16265.5	25798.1
11628.54	20771.0	18710.1	14077.0	17072.1	44357.9	13051.1	16885.4	12147.7	21110.1
26207.41	18130.5	16331.8	12180.8	14528.5	32410.6	10995.1	14339.5	10398.6	18556.9
59064.05	15313.6	13797.9	10589.8	11854.8	22522.7	9368.9	12007.4	9016.0	15175.3
133113.50	11363.1	10391.1	8408.7	8868.4	14395.7	7456.6	9316.6	7312.3	11165.5
300000.00	7052.4	6602.8	5795.8	5871.6	8117.9	5261.0	6347.7	5336.2	7011.3

Table A-21. Impedance Values for Chloride Concentration for Slabs in Set A with Black Bar

Frequency	Impedance (Ω-cm)								
	0 kg Cl⁻/m³			1.2 kg Cl⁻/m³			2.4 kg Cl⁻/m³		
(Hz)	Slab 1	Slab 2	Slab 3	Slab 4	Slab 5	Slab 6	Slab 7	Slab 8	Slab 9
0.10	29501.4	21004.9	23230.3	25686.6	21802.7	26478.3	23667.8	17161.6	22392.7
0.23	27357.0	19018.1	20870.6	23686.7	19144.4	23637.2	21470.9	15154.8	20369.3
0.54	26141.8	18035.4	19781.1	22582.1	17916.8	22355.3	19999.8	14072.5	19366.2
1.26	25603.3	17429.6	18988.2	21662.8	17049.2	20513.2	19119.1	13182.9	18707.4
2.93	25505.8	17279.7	18810.5	21421.4	16894.3	19669.5	18919.5	12940.5	18630.8
6.82	25441.8	17264.6	18736.3	21319.1	16789.2	18884.7	18789.1	12794.2	18641.8
15.87	25362.0	17235.0	18713.8	21538.8	16740.2	18086.9	18678.5	12645.8	18659.3
36.94	25253.8	17233.0	18654.7	21528.7	16708.6	17431.1	18642.2	12549.5	18704.1
85.95	25113.1	17219.9	18573.1	21508.2	16682.3	16916.8	18557.2	12471.0	18736.9
200.00	24733.6	17269.7	18439.3	21471.3	16673.1	16449.4	18554.7	12402.2	18835.6
200.00	24612.1	17336.1	18348.5	21391.8	16603.1	16385.1	18457.6	12359.2	18757.4
450.74	25024.3	17037.1	18179.5	21359.4	16611.5	15984.6	18445.4	12257.1	18785.6
1015.85	24079.0	16898.8	17970.5	21125.8	16386.7	15631.1	18285.2	12123.8	18795.6
2289.43	24386.5	16698.3	17704.8	20628.2	16180.8	15301.1	17908.8	11939.6	18773.2
5159.72	23219.0	16619.3	17328.7	19925.3	15868.3	14938.5	17385.7	11682.2	18643.5
11628.54	23040.8	15781.4	16818.6	18671.8	15333.9	14521.4	16439.5	11207.1	18202.0
26207.41	21318.7	14643.8	15493.8	16597.1	14328.0	13497.7	14857.3	10439.4	17039.4
59064.05	17435.2	12638.2	13307.2	13614.5	12444.5	11737.4	12503.2	9163.8	14651.7
133113.50	12652.4	9752.7	10015.3	9918.1	9456.8	9086.8	9500.0	7353.2	10988.4
300000.00	7446.4	6347.1	6404.4	6392.1	6229.9	6089.7	6331.7	5310.3	6939.4

Table A-22. Impedance Values for Chloride Concentration for Slabs in Set B

Frequency (Hz)	Impedance (Ω-cm) for Indicated Treatment			
	0 kg Cl^-/m^3		5.9 kg Cl^-/m^3	
	Test 1	Test 2	Test 1	Test 2
0.10	2786.0	2506.3	2413.5	2338.8
0.23	2573.3	2358.7	2331.0	2253.1
0.54	2502.5	2209.8	2186.8	2122.1
1.26	2060.3	1935.6	1894.7	1863.4
2.93	1740.4	1599.2	1531.3	1532.4
6.82	1585.1	1418.2	1283.6	1298.8
15.87	1434.6	1322.3	1151.9	1171.1
36.94	1372.6	1267.4	1084.7	1102.6
85.95	1325.0	1233.9	1043.3	1060.5
200.00	1291.4	1210.8	1012.0	1032.3
200.00	1284.6	1207.6	1008.7	1025.5
450.74	1254.3	1187.8	984.0	989.1
1015.85	1231.4	1171.6	962.5	967.9
2289.43	1212.5	1159.9	945.9	946.4
5159.72	1199.4	1151.3	932.1	931.5
11628.54	1191.1	1147.2	920.0	923.0
26207.41	1184.1	1144.4	910.9	913.0
59064.05	1178.2	1142.3	899.0	903.0
133113.50	1169.3	1135.0	888.2	894.0
300000.00	1151.3	1119.7	877.8	882.6

Table A-23. Impedance Values for Epoxy Coating Condition for Slabs in Set A with 0 kg Cl^-/m^3

Frequency (Hz)	Impedance (Ω-cm) for Indicated Treatment					
	Black Bar			Full Epoxy		
	Slab 1	Slab 2	Slab 3	Slab 1	Slab 2	Slab 3
0.10	29501.4	21004.9	23230.3	246969.0	238470.4	347931.3
0.23	27357.0	19018.1	20870.6	246344.6	231072.4	345868.0
0.54	26141.8	18035.4	19781.1	240066.6	227958.6	347410.8
1.26	25603.3	17429.6	18988.2	235105.1	223752.8	339514.3
2.93	25505.8	17279.7	18810.5	230671.6	220985.9	331998.4
6.82	25441.8	17264.6	18736.3	234255.8	229049.5	322110.8
15.87	25362.0	17235.0	18713.8	215221.5	209424.6	302888.7
36.94	25253.8	17233.0	18654.7	198990.8	197637.9	274619.1
85.95	25113.1	17219.9	18573.1	172407.1	175973.5	226368.5
200.00	24733.6	17269.7	18439.3	135495.5	140681.6	161067.6
200.00	24612.1	17336.1	18348.5	146643.5	139976.2	163969.2
450.74	25024.3	17037.1	18179.5	93698.7	95809.3	96376.6
1015.85	24079.0	16898.8	17970.5	58907.8	57633.4	52556.5
2289.43	24386.5	16698.3	17704.8	36697.7	34199.4	28903.9
5159.72	23219.0	16619.3	17328.7	25581.8	23174.2	18296.4
11628.54	23040.8	15781.4	16818.6	20771.0	18710.1	14077.0
26207.41	21318.7	14643.8	15493.8	18130.5	16331.8	12180.8
59064.05	17435.2	12638.2	13307.2	15313.6	13797.9	10589.8
133113.50	12652.4	9752.7	10015.3	11363.1	10391.1	8408.7
300000.00	7446.4	6347.1	6404.4	7052.4	6602.8	5795.8

Table A-23. Continued

Frequency (Hz)	Impedance (Ω-cm) for Indicated Treatment					
	End Cut			Pliers Strike		
	Slab 1	Slab 2	Slab 3	Slab 1	Slab 2	Slab 3
0.10	172489.4	207808.4	214367.5	192084.4	234526.5	346405.7
0.23	169926.9	204804.7	208140.8	186486.5	276395.6	332998.0
0.54	169425.8	201588.5	205414.0	184816.1	300953.8	329002.3
1.26	163534.1	199541.8	201515.5	180376.3	304374.4	314559.2
2.93	163132.6	198285.9	200165.1	177989.6	303277.0	307148.5
6.82	160616.9	203884.7	198361.7	172850.5	297062.2	293338.5
15.87	156128.4	190308.0	204346.0	165832.6	290473.6	279746.4
36.94	148279.3	179292.0	186242.0	154387.8	274269.0	258822.8
85.95	135347.5	159666.6	171004.9	137380.8	232234.0	227808.2
200.00	114481.4	133906.9	141999.3	113088.4	183718.0	171648.5
200.00	113959.5	128322.8	141690.3	112475.2	182967.2	176208.8
450.74	85996.7	90297.1	99370.4	83405.0	119653.2	108851.2
1015.85	57177.7	55916.4	59090.9	55963.8	67057.6	58643.0
2289.43	36357.6	34292.8	33511.8	36548.7	37277.3	32107.3
5159.72	25273.9	22865.7	21206.5	26407.6	24338.5	20416.7
11628.54	20303.3	18556.1	16197.7	21188.1	19011.2	15849.5
26207.41	17670.3	16123.8	13893.0	18569.1	16429.6	13695.4
59064.05	14744.3	13586.7	11947.0	15374.8	13785.0	11779.9
133113.50	10825.8	10168.2	9308.4	11291.8	10263.1	9180.9
300000.00	6744.4	6471.1	6153.4	7023.4	6472.2	6155.8

Table A-23. Continued

Frequency (Hz)	Impedance (Ω-cm) for Indicated Treatment		
	Rib Scrape		
	Slab 1	Slab 2	Slab 3
0.10	68183.2	70464.1	83352.9
0.23	63312.1	67597.9	75581.8
0.54	61979.5	67053.6	74033.0
1.26	59557.2	65036.2	67742.2
2.93	59329.4	64003.6	65394.5
6.82	57698.6	62758.6	61879.7
15.87	56019.3	61764.3	60195.7
36.94	54897.6	60818.9	56931.9
85.95	54391.4	59646.1	54628.6
200.00	52761.2	58205.3	52470.1
200.00	51810.1	58055.4	52148.7
450.74	49325.6	54740.8	49138.0
1015.85	45249.1	48691.7	43889.2
2289.43	38721.0	36913.1	35168.9
5159.72	31857.7	27360.7	26420.2
11628.54	25654.5	21762.0	20733.5
26207.41	21648.8	18531.6	17432.7
59064.05	17346.7	15162.7	14544.0
133113.50	12158.8	10953.2	10703.5
300000.00	7275.9	6760.6	6758.0

Table A-24. Impedance Values for Epoxy Coating Condition for Slabs in Set A with 1.2 kg Cl^-/m^3

Frequency	Impedance (Ω-cm) for Indicated Treatment					
	Black Bar			Full Epoxy		
	Slab 4	Slab 5	Slab 6	Slab 4	Slab 5	Slab 6
0.10	25686.6	21802.7	26478.3	165741.5	216412.3	406870.1
0.23	23686.7	19144.4	23637.2	159916.5	212648.6	397949.7
0.54	22582.1	17916.8	22355.3	153794.4	210024.2	393852.8
1.26	21662.8	17049.2	20513.2	150450.8	205224.5	386517.1
2.93	21421.4	16894.3	19669.5	147440.2	201237.0	382061.6
6.82	21319.1	16789.2	18884.7	144202.6	196108.0	374525.8
15.87	21538.8	16740.2	18086.9	139342.8	187739.6	359760.5
36.94	21528.7	16708.6	17431.1	132251.4	175658.9	332717.0
85.95	21508.2	16682.3	16916.8	120835.7	165090.9	278312.1
200.00	21471.3	16673.1	16449.4	101984.9	138557.9	191675.2
200.00	21391.8	16603.1	16385.1	101298.3	148873.1	190813.3
450.74	21359.4	16611.5	15984.6	75007.9	115751.1	108665.6
1015.85	21125.8	16386.7	15631.1	48211.3	98556.7	56158.9
2289.43	20628.2	16180.8	15301.1	29952.6	74307.8	29528.7
5159.72	19925.3	15868.3	14938.5	21001.1	58242.4	17738.7
11628.54	18671.8	15333.9	14521.4	17072.1	44357.9	13051.1
26207.41	16597.1	14328.0	13497.7	14528.5	32410.6	10995.1
59064.05	13614.5	12444.5	11737.4	11854.8	22522.7	9368.9
133113.50	9918.1	9456.8	9086.8	8868.4	14395.7	7456.6
300000.00	6392.1	6229.9	6089.7	5871.6	8117.9	5261.0

Table A-24. Continued

Frequency (Hz)	Impedance (Ω-cm) for Indicated Treatment					
	End Cut			Pliers Strike		
	Slab 4	Slab 5	Slab 6	Slab 4	Slab 5	Slab 6
0.10	147056.0	217080.7	367898.6	128295.4	186332.8	328329.7
0.23	143928.6	215007.9	362950.7	124553.6	181507.0	319625.2
0.54	141143.1	210078.8	352697.5	122413.5	179152.1	318028.1
1.26	137636.5	206556.7	344044.5	118940.5	172445.6	311159.3
2.93	134912.2	203831.4	339729.4	116763.5	141336.2	307085.9
6.82	131849.8	199676.1	333255.9	114085.7	140638.8	297787.0
15.87	127123.9	201785.5	322046.7	110484.6	132435.7	286535.1
36.94	120167.9	180554.3	301368.7	105539.2	127541.6	266570.5
85.95	109048.4	163576.4	256828.3	97510.8	112426.8	230396.0
200.00	91130.5	142443.9	181314.3	84524.8	123306.5	168982.8
200.00	90685.4	155447.9	180691.7	84125.2	139609.5	167089.8
450.74	66704.8	118767.9	104728.7	64814.6	95529.0	99815.2
1015.85	43120.8	94717.5	54958.2	43625.7	57658.2	53148.8
2289.43	27072.5	78259.5	29597.0	27745.5	34712.2	29116.7
5159.72	19168.3	58033.1	18568.1	19593.3	22972.7	18920.8
11628.54	15607.6	45585.2	14269.1	15824.4	18590.6	15047.0
26207.41	13284.5	32537.3	12301.1	13292.7	15496.1	12985.8
59064.05	10922.0	22869.9	10577.5	10823.6	12734.2	10986.5
133113.50	8347.6	14311.6	8377.0	8223.8	9534.4	8551.2
300000.00	5707.3	8206.4	5750.3	5633.5	6201.9	5803.5

Table A-24. Continued

Frequency (Hz)	Impedance (Ω-cm) for Indicated Treatment		
	Rib Scrape		
	Slab 4	Slab 5	Slab 6
0.10	88852.9	78226.3	75474.1
0.23	85890.1	74211.4	72552.5
0.54	84864.0	72629.3	71837.6
1.26	81180.7	69206.0	68228.2
2.93	79919.4	68544.5	66682.8
6.82	77196.9	66880.0	63926.8
15.87	75013.0	65802.3	61912.5
36.94	72153.6	64568.6	59862.2
85.95	68661.6	63652.8	57739.5
200.00	63723.2	60494.2	55004.6
200.00	63438.4	60342.3	54825.4
450.74	55353.2	56815.7	49848.7
1015.85	43402.0	46217.4	40659.7
2289.43	31122.3	34828.3	28688.8
5159.72	23193.8	25391.7	19850.6
11628.54	18986.6	20634.4	15397.4
26207.41	15960.9	17743.6	13164.3
59064.05	12731.4	14421.9	11157.2
133113.50	9253.0	10422.9	8642.0
300000.00	6023.1	6602.3	5833.4

Table A-25. Impedance Values for Epoxy Coating Condition for Slabs in Set A with 2.4 kg Cl^-/m^3

Frequency (Hz)	Impedance (Ω-cm) for Indicated Treatment					
	Black Bar			Full Epoxy		
	Slab 7	Slab 8	Slab 9	Slab 7	Slab 8	Slab 9
0.10	23667.8	17161.6	22392.7	369761.9	321912.9	160135.2
0.23	21470.9	15154.8	20369.3	359555.8	314431.7	149183.1
0.54	19999.8	14072.5	19366.2	354255.4	309687.9	134741.0
1.26	19119.1	13182.9	18707.4	338330.1	300350.2	131069.1
2.93	18919.5	12940.5	18630.8	330316.6	293221.3	130795.5
6.82	18789.1	12794.2	18641.8	318583.5	283712.2	131423.4
15.87	18678.5	12645.8	18659.3	302779.1	268930.3	131218.0
36.94	18642.2	12549.5	18704.1	278730.0	247350.9	130172.3
85.95	18557.2	12471.0	18736.9	236838.8	210339.9	126524.7
200.00	18554.7	12402.2	18835.6	175604.4	153727.7	120453.8
200.00	18457.6	12359.2	18757.4	171312.3	153130.3	115546.4
450.74	18445.4	12257.1	18785.6	103736.5	93512.7	92341.7
1015.85	18285.2	12123.8	18795.6	56317.4	50392.6	60920.2
2289.43	17908.8	11939.6	18773.2	31624.0	26837.7	37304.7
5159.72	17385.7	11682.2	18643.5	21218.8	16265.5	25798.1
11628.54	16439.5	11207.1	18202.0	16885.4	12147.7	21110.1
26207.41	14857.3	10439.4	17039.4	14339.5	10398.6	18556.9
59064.05	12503.2	9163.8	14651.7	12007.4	9016.0	15175.3
133113.50	9500.0	7353.2	10988.4	9316.6	7312.3	11165.5
300000.00	6331.7	5310.3	6939.4	6347.7	5336.2	7011.3

Table A-25. Continued

Frequency (Hz)	Impedance (Ω-cm) for Indicated Treatment					
	End Cut			Pliers Strike		
	Slab 7	Slab 8	Slab 9	Slab 7	Slab 8	Slab 9
0.10	214696.0	259763.0	157754.8	179488.4	65737.9	156423.0
0.23	209072.1	256706.0	155771.7	173073.0	60656.8	154248.9
0.54	205600.0	247893.7	152075.7	169591.1	57914.7	153972.7
1.26	201658.8	230946.5	150077.0	162964.4	54898.7	150292.5
2.93	197398.8	224250.2	149653.4	156735.6	53591.1	149604.7
6.82	193951.8	214071.0	153954.7	149587.1	52770.6	147851.6
15.87	189247.2	203946.0	148439.5	144063.6	51001.7	145362.4
36.94	181498.8	190148.2	151196.3	131024.4	50142.6	140521.3
85.95	166602.9	170638.8	141389.2	115216.0	47807.6	130690.6
200.00	137081.7	136915.2	134312.0	93312.4	45167.3	114381.5
200.00	136656.4	137808.8	134021.2	92913.0	45940.4	110560.8
450.74	93070.6	91898.9	123562.7	67283.1	40500.0	80420.4
1015.85	53667.3	51952.5	109036.0	43783.9	33212.4	51501.6
2289.43	30904.4	28148.7	90492.8	28183.8	24036.2	31563.5
5159.72	20897.7	16955.7	68699.0	20448.9	16794.6	23176.4
11628.54	16775.8	12444.6	49377.6	16944.5	13125.9	19666.5
26207.41	14361.8	10478.6	33775.0	14730.6	11413.3	17258.5
59064.05	12060.1	9023.1	22792.8	12506.3	10027.0	14540.1
133113.50	9377.7	7340.0	14525.3	9774.9	8215.4	11032.2
300000.00	6381.2	5378.2	8506.5	6602.7	5894.3	7069.8

Table A-25. Continued

Frequency (Hz)	Impedance (Ω-cm) for Indicated Treatment		
	Rib Scrape		
	Slab 7	Slab 8	Slab 9
0.10	85845.8	44041.6	76186.7
0.23	82332.4	40031.0	72948.2
0.54	81030.6	38090.3	72053.0
1.26	76340.8	35626.2	69626.1
2.93	75103.2	34704.7	68654.5
6.82	72288.3	33632.1	66820.9
15.87	70585.8	32728.8	65264.4
36.94	70383.5	31823.7	63310.1
85.95	68821.9	30885.0	61378.6
200.00	64787.1	29789.0	59044.5
200.00	66225.8	29676.8	58856.1
450.74	60787.9	28030.9	56044.7
1015.85	50028.8	25350.0	46297.8
2289.43	35263.3	21414.5	34640.1
5159.72	25236.2	16631.7	25891.4
11628.54	19694.8	13564.5	20918.1
26207.41	16540.6	11887.7	18091.3
59064.05	13456.8	10359.0	15051.8
133113.50	10149.3	8400.1	11213.8
300000.00	6782.8	5998.2	7118.4

Table A-26. Summary of *P*-Values for Frequency Selection

Frequency (Hz)	*P* -Values for Indicated Properties				
	Sealant (Set D, Lithium Silicate)	Sealant (Set D, Silane and Lithium Silicate)	Curing Time (Set D, 6.35 cm, Slab 1)	Curing Time (Set D, 6.35 cm, Slab 2)	Curing Time (Set D, 2.54 cm, Slab 3)
0.10	0.0010	0.0123	<0.0001	<0.0001	<0.0001
0.23	0.0015	0.0091	<0.0001	<0.0001	<0.0001
0.54	0.0020	0.0142	<0.0001	<0.0001	<0.0001
1.26	0.0021	0.0093	<0.0001	<0.0001	<0.0001
2.93	0.0019	0.0099	<0.0001	<0.0001	<0.0001
6.82	0.0018	0.0105	<0.0001	<0.0001	<0.0001
15.87	0.0017	0.0120	<0.0001	<0.0001	<0.0001
36.94	0.0016	0.0126	<0.0001	<0.0001	<0.0001
85.95	0.0017	0.0137	<0.0001	<0.0001	<0.0001
200.00	0.0015	0.0138	<0.0001	<0.0001	<0.0001
200.00	0.0015	0.0140	<0.0001	<0.0001	<0.0001
450.74	0.0015	0.0147	<0.0001	<0.0001	<0.0001
1015.85	0.0015	0.0157	<0.0001	<0.0001	<0.0001
2289.43	0.0014	0.0172	<0.0001	<0.0001	<0.0001
5159.72	0.0013	0.0202	<0.0001	<0.0001	<0.0001
11628.54	0.0011	0.0252	<0.0001	<0.0001	<0.0001
26207.41	0.0009	0.0318	<0.0001	<0.0001	<0.0001
59064.05	0.0007	0.0516	<0.0001	<0.0001	<0.0001
133113.50	0.0004	<0.0001	<0.0001	<0.0001	<0.0001
300000.00	0.0002	0.1398	<0.0001	<0.0001	<0.0001

Table A-26. Continued

Frequency (Hz)	*P*-Values for Indicated Properties		
	Curing Time (Set D, 2.54 cm Slab 4)	Temperature (Set C, 0.40 w/cm)	Temperature (Set C, 0.60 w/cm)
0.10	<0.0001	0.0004	0.0004
0.23	<0.0001	0.0010	0.0002
0.54	<0.0001	0.0009	<0.0001
1.26	<0.0001	0.0010	<0.0001
2.93	<0.0001	0.0009	0.0024
6.82	<0.0001	0.0010	0.0005
15.87	<0.0001	0.0003	0.0006
36.94	<0.0001	0.0004	0.0005
85.95	<0.0001	0.0004	<0.0001
200.00	<0.0001	0.0004	0.0012
200.00	<0.0001	0.0017	0.0034
450.74	<0.0001	0.0101	0.0028
1015.85	<0.0001	<0.0001	0.0024
2289.43	<0.0001	0.0003	0.0007
5159.72	<0.0001	0.0027	0.0004
11628.54	<0.0001	0.0123	0.0017
26207.41	<0.0001	0.0071	0.0087
59064.05	<0.0001	0.0004	0.0013
133113.50	<0.0001	<0.0001	0.0003
300000.00	<0.0001	0.0022	0.0001

Table A-26. Continued

Frequency (Hz)	*P*-Values for Indicated Properties				
	Cover Depth (Set A, 0 kg/m^3 Chlorides)	Cover Depth (Set A, 1.2 kg/m^3 Chlorides)	Cover Depth (Set A, 2.4 kg/m^3 Chlorides)	Cover Depth (Set D)	Water-to-Cementitious Material Ratios (Set B)
0.10	0.0640	0.4009	0.4163	<0.0001	0.0629
0.23	0.0581	0.4317	0.4393	0.0006	0.0361
0.54	0.0694	0.4441	0.3790	0.0004	0.0219
1.26	0.0910	0.4867	0.3569	0.0013	0.0055
2.93	0.1085	0.5130	0.3693	0.0008	0.0040
6.82	0.1342	0.5406	0.3829	0.0003	0.0046
15.87	0.1615	0.5593	0.4010	<0.0001	0.0049
36.94	0.1794	0.5808	0.4133	<0.0001	0.0055
85.95	0.1934	0.5985	0.4195	<0.0001	0.0059
200.00	0.2154	0.6051	0.4282	<0.0001	0.0112
200.00	0.1983	0.6115	0.4271	<0.0001	0.0067
450.74	0.2226	0.5942	0.4418	<0.0001	0.0149
1015.85	0.2118	0.6062	0.4466	<0.0001	0.0195
2289.43	0.2323	0.6038	0.4853	<0.0001	0.0259
5159.72	0.2231	0.5964	0.5082	<0.0001	0.1697
11628.54	0.2388	0.5743	0.4949	<0.0001	0.0146
26207.41	0.2943	0.5496	0.5747	<0.0001	0.0468
59064.05	0.3094	0.5509	0.6265	<0.0001	0.2321
133113.50	0.3641	0.6553	0.6900	<0.0001	0.2543
300000.00	0.3815	0.6629	0.6402	<0.0001	0.2683

Table A-26. Continued

Frequency (Hz)	*P*-Values for Indicated Properties				
	Air Content (Set B)	Chloride Concentration (Set B)	Epoxy Condition (Set A, 0 kg/m^3 Chlorides)	Epoxy Condition (Set A, 1.2 kg/m^3 Chlorides)	Epoxy Condition (Set A, 2.4 kg/m^3 Chlorides)
0.10	0.0013	0.2032	0.0002	0.0285	0.0024
0.23	0.0015	0.2671	<0.0001	0.0276	0.0003
0.54	0.0029	0.3106	0.0001	0.0289	0.0044
1.26	0.0009	0.2056	0.0001	0.0286	0.0038
2.93	0.0018	0.1901	0.0001	0.0342	0.0033
6.82	0.0043	0.1286	<0.0001	0.0334	0.0024
15.87	0.0038	0.0626	<0.0001	0.0327	0.0019
36.94	0.0057	0.0513	<0.0001	0.0320	0.0011
85.95	0.0074	0.0391	<0.0001	0.0212	0.0005
200.00	0.0089	0.0283	<0.0001	0.0032	<0.0001
200.00	0.0099	0.0314	<0.0001	0.0039	<0.0001
450.74	0.0116	0.0196	<0.0001	0.0009	0.0002
1015.85	0.0169	0.0158	<0.0001	0.0365	0.0230
2289.43	0.0247	0.0118	0.0002	0.3355	0.2454
5159.72	0.0422	0.0096	0.0462	0.6127	0.4947
11628.54	0.0821	0.0078	0.3378	0.7496	0.6614
26207.41	0.1786	0.0062	0.5115	0.8289	0.8201
59064.05	0.4764	0.0048	0.5738	0.8807	0.9250
133113.50	0.8407	0.0044	0.6811	0.9120	0.9635
300000.00	0.3503	0.0039	0.7260	0.9218	0.9339

APPENDIX B UNCONTROLLED LABORATORY DATA

Table B-1. Data for Slab from Bridge C-357

Location	Impedance (Hz)	Longitudinal Cover (in.)	Transverse Cover (in.)	Rebound Number	Dry Resistivity (kΩ-cm)
A1	16404.0	2.5	1.7	54	100.8
A2	7781.3	2.2	1.7	48	98.2
A3	16297.1	2.1	1.6	49	100.4
A4	14003.4	2.4	1.8	50	100.9
A5	6877.4	2.4	1.7	46	102.0
A6	13633.0	2.2	1.7	49	99.6
A7	7905.4	2.2	1.7	45	101.8
A8	9403.9	2.2	1.6	46	101.6
B1	10498.7	2.5	1.7	59	96.4
B2	7782.8	2.2	1.7	48	97.3
B3	8607.8	2.1	1.5	49	98.7
B4	8536.5	2.2	1.6	51	102.1
B5	7793.3	2.0	1.6	52	100.3
B6	7960.9	2.0	1.6	50	100.5
B7	13788.3	2.2	1.6	44	99.6
B8	9554.8	2.0	1.6	52	98.4
C1	9047.0	2.3	1.7	52	95.2
C2	5406.1	2.0	1.6	50	97.0
C3	8051.4	1.8	1.4	56	99.3
C4	3741.6	2.0	1.5	51	102.7
C5	7353.1	2.0	1.5	50	66.1
C6	6794.3	1.8	1.5	44	99.7
C7	9633.8	1.9	1.5	45	98.5
C8	5472.2	1.9	1.4	44	100.9
D1	10404.4	2.3	1.8	48	96.5
D2	3058.6	1.9	1.6	51	97.8
D3	4369.5	1.7	1.3	45	100.3
D4	4259.8	1.9	1.5	47	94.8
D5	9417.5	1.8	1.5	49	93.8
D6	3147.3	1.8	1.4	51	99.4
D7	5118.9	1.7	1.4	44	57.9
D8	11990.8	1.7	1.4	48	54.9

Table B-1. Continued

Location	Dry Half-Cell Potential (mV)	Dry Linear Polarization A/cm^2	Wet Resistivity (kΩ-cm)	Wet Half-Cell Potential (mV)	Wet Linear Polarization A/cm^2
A1	-17	19093	50.8	-143	4382
A2	2	21360	56.2	-156	5459
A3	-53	18227	55.2	-159	2603
A4	-78	9968	58.0	-148	3694
A5	-75	16207	71.6	-146	3810
A6	-28	7004	93.6	-121	2888
A7	-1	7682	88.1	-139	3846
A8	1	2784	69.5	-139	2012
B1	17	12707	52.7	-140	6038
B2	18	16516	43.3	-162	2727
B3	3	24806	58.5	-162	7716
B4	7	22605	79.7	-156	6547
B5	-86	29674	70.3	-165	4434
B6	-26	31453	71.7	-133	9445
B7	-5	30082	87.5	-138	5259
B8	-19	24455	37.2	-137	9763
C1	5	13826	32.8	-156	7694
C2	-3	17875	55.4	-171	6058
C3	-1	12402	29.0	-180	6305
C4	-79	35938	43.4	-182	6819
C5	-184	4482	33.0	-187	5040
C6	-42	14515	26.3	-177	8854
C7	-15	20672	87.3	-151	11419
C8	-37	38746	61.0	-159	7574
D1	-36	17741	58.4	-170	8075
D2	-47	24711	47.3	-192	6504
D3	-105	8283	39.4	-189	5591
D4	-83	10409	55.7	-191	5676
D5	-104	18498	39.5	-192	1618
D6	-109	11375	12.5	-196	5600
D7	-90	31308	16.2	-178	12230
D8	-85	16179	10.4	-162	5261

Table B-1. Continued

Location	Chloride Concentration (lb Cl^-/yd^3) at Indicated Depth			
	0 - 0.5 in.	0.5 - 1.0 in.	1.0 - 1.5 in.	1.5 - 2.0 in.
A1	2.2	2.6	1.5	1.3
A2	1.8	2.5	1.7	1.0
A3	2.1	2.0	1.0	0.8
A4	2.1	1.6	1.3	1.3
A5	1.5	1.6	1.2	1.0
A6	1.8	2.1	1.7	1.1
A7	2.6	2.4	2.6	1.5
A8	2.0	2.9	2.9	1.7
B1	2.1	2.7	1.7	1.3
B2	1.7	2.7	2.2	1.5
B3	1.6	2.4	2.1	1.2
B4	1.8	1.9	1.9	1.4
B5	2.3	2.4	1.6	1.1
B6	1.8	2.2	1.7	1.1
B7	1.3	2.6	2.2	2.7
B8	1.9	3.1	2.6	1.7
C1	1.3	2.5	2.0	1.3
C2	1.1	2.5	3.0	2.2
C3	1.6	2.0	2.5	2.1
C4	1.6	2.6	2.4	2.1
C5	2.2	2.6	3.1	2.3
C6	2.3	2.9	2.7	2.1
C7	1.7	2.7	2.8	1.8
C8	1.7	2.7	2.7	2.8
D1	2.5	1.8	2.2	1.6
D2	2.2	2.7	2.2	1.3
D3	2.0	3.1	2.8	2.6
D4	1.6	2.7	2.1	1.7
D5	1.9	3.1	2.8	2.6
D6	2.1	2.8	2.7	2.4
D7	1.9	1.4	1.1	1.3
D8	1.0	0.9	1.6	1.8

Table B-1. Continued

Location	Chloride Concentration (lb Cl^-/yd^3) at Indicated Depth			
	2.0 - 2.5 in.	2.5 - 3.0 in.	3.0 - 3.5 in.	3.5 - 4.0 in.
A1	1.2	0.9	0.5	0.4
A2	1.2	1.1	0.8	0.6
A3	1.0	0.7	0.7	0.4
A4	1.0	0.7	0.3	0.3
A5	1.0	0.8	0.5	0.3
A6	0.9	0.8	0.5	0.3
A7	1.3	1.0	0.8	0.6
A8	1.3	1.2	1.1	0.6
B1	0.8	0.9	0.7	0.8
B2	1.7	1.1	1.1	0.8
B3	0.9	0.7	0.8	0.7
B4	1.0	1.0	0.8	0.5
B5	1.2	1.0	0.7	0.6
B6	1.1	0.7	0.7	0.6
B7	1.4	1.1	0.9	0.7
B8	2.0	1.1	1.0	1.0
C1	1.1	0.7	1.0	1.3
C2	1.3	1.1	1.2	1.0
C3	1.6	1.3	1.2	1.2
C4	1.3	1.3	1.0	1.1
C5	2.3	2.0	1.4	1.2
C6	1.3	1.5	1.1	0.9
C7	1.5	1.2	1.0	1.0
C8	2.2	1.5	1.0	1.1
D1	1.3	1.2	1.0	0.7
D2	1.2	1.4	1.1	0.8
D3	1.5	1.2	1.4	1.2
D4	1.4	1.7	1.2	1.6
D5	2.3	1.0	1.1	1.1
D6	1.8	0.9	1.0	1.0
D7	1.1	1.2	0.5	1.0
D8	1.5	1.1	0.9	0.9

Table B-2. Data for Slab from Bridge C-358

Location	Impedance (Hz)	Longitudinal Cover (in.)	Transverse Cover (in.)	Rebound Number	Dry Resistivity (kΩ-cm)
A1	1301.0	3.0	2.2	26	17.5
A2	1181.9	2.6	1.9	40	18.9
A3	1279.5	2.4	1.9	50	21.9
A4	1330.5	2.9	2.1	34	15.6
A5	1301.4	2.7	2.4	30	31.8
A6	1491.4	2.9	2.3	29	19.1
A7	1509.1	2.9	2.4	52	26.4
A8	1538.4	2.9	2.4	53	24.2
B1	1552.7	2.9	2.3	35	12.1
B2	1529.6	2.6	1.9	33	16.2
B3	1636.9	2.1	1.8	32	17.6
B4	1502.1	2.5	2.0	39	14.8
B5	1599.4	2.6	2.1	44	17.9
B6	1610.8	2.8	2.3	45	11.3
B7	1545.1	3.2	2.5	42	16.5
B8	1568.7	3.2	2.7	41	13.6
C1	1654.1	3.0	2.3	50	12.3
C2	1348.5	2.8	1.9	46	16.9
C3	1697.8	2.7	2.0	33	22.9
C4	1848.1	2.8	2.2	25	19.5
C5	1843.4	2.9	2.3	47	13.3
C6	1893.7	3.2	2.5	43	12.5
C7	1683.6	3.1	2.5	52	15.7
C8	1728.1	3.0	2.5	47	11.2
D1	1888.6	2.5	2.3	39	22.5
D2	1696.6	2.7	1.9	56	15.8
D3	2120.0	2.4	2.2	40	19.5
D4	1999.0	2.5	2.2	32	16.5
D5	1922.5	2.6	2.3	39	15.8
D6	2301.4	2.7	2.4	49	14.0
D7	1748.7	2.9	2.7	39	13.9
D8	1907.5	3.0	2.5	43	12.3

Table B-2. Continued

Location	Dry Half-Cell Potential (mV)	Dry Linear Polarization (A/cm^2)	Wet Resistivity (kΩ-cm)	Wet Half-Cell Potential (mV)	Wet Linear Polarization (A/cm^2)
A1	-401	7616	7.3	-461	3046
A2	-370	1780	6.3	-412	1466
A3	-296	1102	6.1	-403	1467
A4	-293	1096	5.4	-328	1319
A5	-293	1183	4.1	-325	1033
A6	-285	4223	13.3	-357	1836
A7	-349	4516	18.2	-458	3236
A8	-382	5672	14.2	-466	2136
B1	-415	1639	7.0	-453	2188
B2	-383	948	5.3	-406	1306
B3	-291	1014	5.9	-407	1327
B4	-290	914	5.5	-297	1257
B5	-290	739	5.0	-300	1010
B6	-210	769	6.8	-293	999
B7	-324	1518	8.1	-382	1319
B8	-354	2593	9.1	-420	1857
C1	-354	799	7.1	-357	1329
C2	-301	1039	6.7	-348	1426
C3	-298	925	8.4	-362	2075
C4	-264	1033	7.4	-279	1418
C5	-223	639	5.3	-255	1221
C6	-160	963	5.6	-253	1181
C7	-263	1227	6.7	-353	1384
C8	-289	1480	6.5	-361	1244
D1	-302	708	6.7	-298	1073
D2	-284	487	6.1	-323	960
D3	-296	566	5.8	-337	1234
D4	-259	1298	6.3	-279	2115
D5	-174	755	6.9	-253	1118
D6	-165	911	7.3	-261	954
D7	-263	1256	6.2	-360	1485
D8	-265	1612	6.2	-339	1362

Table B-2. Continued

Location	Chloride Concentration (lb Cl^-/yd^3) at Indicated Depth			
	0 - 0.5 in.	0.5 - 1.0 in.	1.0 - 1.5 in.	1.5 - 2.0 in.
A1	8.0	6.8	8.0	8.4
A2	9.4	10.1	8.4	7.2
A3	7.4	6.4	6.5	8.0
A4	7.2	7.4	6.9	6.8
A5	6.5	6.7	6.7	8.9
A6	2.4	4.5	5.7	8.2
A7	3.6	5.6	5.8	5.9
A8	3.7	6.3	5.6	6.8
B1	6.8	6.7	4.9	7.1
B2	8.1	7.2	8.0	7.3
B3	7.1	6.2	5.6	6.4
B4	5.7	5.8	5.9	6.1
B5	4.8	5.0	4.8	5.9
B6	3.9	4.4	4.5	5.5
B7	4.2	4.4	4.7	5.0
B8	3.7	3.7	4.1	5.3
C1	4.5	5.1	5.6	6.9
C2	5.2	5.5	6.3	6.0
C3	4.5	5.3	5.4	5.5
C4	6.1	5.1	5.7	4.9
C5	3.8	4.5	4.0	5.1
C6	3.3	3.9	4.1	5.2
C7	2.9	2.9	2.8	4.3
C8	2.8	3.4	3.9	4.3
D1	3.6	3.8	4.4	4.9
D2	4.3	4.1	4.1	3.4
D3	4.8	5.0	4.9	5.4
D4	4.4	4.9	5.3	5.9
D5	3.5	4.6	3.9	5.2
D6	2.7	3.0	3.9	5.1
D7	2.4	2.3	2.7	3.9
D8	3.1	3.2	3.9	4.4

Table B-2. Continued

Location	Chloride Concentration (lb Cl^{-}/yd^{3}) at Indicated Depth			
	2.0 - 2.5 in.	2.5 - 3.0 in.	3.0 - 3.5 in.	3.5 - 4.0 in.
A1	4.5	6.7	6.1	5.2
A2	6.2	6.7	3.7	4.7
A3	6.1	5.8	4.9	5.2
A4	5.1	5.3	8.4	5.7
A5	5.4	3.6	5.4	3.9
A6	5.6	6.0	3.8	3.6
A7	4.9	4.8	5.6	5.5
A8	5.5	5.8	5.7	5.5
B1	5.4	5.5	4.4	6.1
B2	5.3	5.2	5.0	3.7
B3	4.4	5.8	5.2	4.7
B4	4.5	5.7	5.2	5.2
B5	5.5	6.1	4.7	4.6
B6	6.6	4.4	3.7	10.4
B7	5.0	3.8	1.7	5.7
B8	5.4	4.0	4.6	6.5
C1	6.3	5.1	6.2	5.4
C2	6.0	5.6	5.0	4.8
C3	5.0	5.0	4.9	3.7
C4	4.9	3.3	4.8	4.8
C5	4.5	5.1	4.3	4.8
C6	4.6	4.6	4.1	3.5
C7	4.3	4.2	2.8	3.3
C8	4.2	4.8	4.8	5.4
D1	4.1	3.8	4.3	4.7
D2	2.8	2.6	2.2	2.7
D3	3.6	3.4	2.4	3.6
D4	4.1	4.3	3.7	3.7
D5	3.9	6.0	5.0	5.1
D6	4.2	4.5	4.0	4.5
D7	3.7	4.0	3.1	3.1
D8	4.6	3.7	4.9	4.7

Table B-3. Data for Slab from Bridge C-363

Location	Impedance (Hz)	Longitudinal Cover (in.)	Transverse Cover (in.)	Rebound Number	Dry Resistivity (kΩ-cm)	Wet Resistivity (kΩ-cm)
A1	26323.2	1.3	1.1	49	45.8	31.5
A2	23388.1	1.4	1.1	46	50.5	27.3
A3	27424.4	1.7	1.2	43	44.5	28.2
A4	31693.5	1.6	1.4	48	36.8	24.5
A5	21843.1	1.7	1.7	39	45.9	43.1
A6	19143.9	1.9	1.5	40	44.6	27.0
A7	15788.3	1.5	1.5	39	19.6	24.5
A8	16267.4	1.4	1.2	42	73.6	21.5
B1	31930.6	1.6	1.4	44	94.4	21.2
B2	26650.3	1.6	1.2	47	91.4	33.7
B3	30771.7	1.8	1.4	43	93.4	25.2
B4	34006.2	1.9	1.6	43	92.8	22.3
B5	25786.0	1.7	1.7	41	92.4	20.2
B6	19800.3	1.7	1.5	46	90.1	32.1
B7	13332.0	1.5	1.5	41	24.1	34.8
B8	18382.1	1.4	1.4	38	63.2	25.0
C1	36082.3	1.5	1.4	45	81.7	48.9
C2	29032.8	1.7	1.4	43	85.6	42.3
C3	37369.3	1.8	1.6	45	86.4	41.8
C4	37890.9	1.9	1.7	45	77.8	37.4
C5	28785.8	1.7	1.7	42	88.2	43.6
C6	19648.9	1.5	1.4	42	91.9	21.4
C7	15875.9	1.3	1.2	37	97.1	21.4
C8	18539.1	1.5	1.3	43	86.9	23.9
D1	34321.6	1.6	1.2	44	83.1	46.6
D2	34186.0	1.5	1.2	37	69.6	59.5
D3	41505.9	1.6	1.3	42	71.7	51.0
D4	51402.4	1.8	1.4	37	91.3	31.3
D5	31823.9	1.7	1.3	30	93.8	31.3
D6	28430.1	1.6	1.2	37	95.4	28.9
D7	16937.3	1.4	1.2	36	90.3	30.5
D8	23561.7	1.4	1.2	45	75.4	23.0

Table B-3. Continued

Location	Chloride Concentration (lb Cl^-/yd^3) at Indicated Depth			
	0 - 0.5 in.	0.5 - 1.0 in.	1.0 - 1.5 in.	1.5 - 2.0 in.
A1	1.6	0.3	0.4	0.4
A2	1.6	0.3	0.1	0.1
A3	1.6	0.4	0.5	0.4
A4	1.8	0.6	0.3	0.4
A5	1.3	0.5	0.2	0.3
A6	3.5	0.9	0.4	0.4
A7	2.3	0.8	0.5	0.5
A8	1.2	0.3	0.4	0.3
B1	0.9	0.4	0.4	0.4
B2	0.7	0.5	0.4	0.5
B3	0.6	0.3	0.2	0.3
B4	0.7	0.4	0.6	0.7
B5	0.8	0.5	0.4	0.3
B6	1.0	0.5	0.4	0.4
B7	0.8	0.6	0.5	0.1
B8	0.9	0.4	0.3	0.0
C1	1.1	0.5	0.4	0.5
C2	1.2	0.6	0.4	0.2
C3	0.8	0.2	0.2	0.4
C4	1.1	0.2	0.4	0.4
C5	1.2	0.3	0.2	0.5
C6	0.8	0.4	0.2	0.1
C7	0.9	0.4	0.3	0.3
C8	1.2	0.5	0.5	0.5
D1	1.3	0.6	0.6	0.5
D2	1.0	0.7	0.5	0.5
D3	1.5	0.6	0.4	0.3
D4	1.4	0.4	0.2	0.4
D5	0.7	0.2	0.1	0.2
D6	1.1	0.3	0.3	0.4
D7	0.5	0.1	0.2	0.3
D8	1.1	0.6	0.6	0.6

Table B-3. Continued

Location	Chloride Concentration (lb Cl^-/yd^3) at Indicated Depth			
	2.0 - 2.5 in.	2.5 - 3.0 in.	3.0 - 3.5 in.	3.5 - 4.0 in.
A1	0.4	0.3	0.2	0.3
A2	0.1	0.4	0.3	0.1
A3	0.3	0.4	0.4	0.7
A4	0.4	0.3	0.3	0.3
A5	0.4	0.3	0.3	0.3
A6	0.3	0.5	0.4	1.0
A7	0.4	0.3	0.2	0.4
A8	0.3	0.4	0.2	0.4

Table B-4. Data for Slab from Bridge D-413

Location	Impedance (Hz)	Longitudinal Cover (in.)	Transverse Cover (in.)	Rebound Number	Dry Resistivity (kΩ-cm)
A1	4241.6	2.5	2.1	55	24.8
A2	5454.3	2.4	2.2	56	20.7
A3	5577.4	2.4	2.2	57	18.9
A4	7745.5	2.4	2.0	54	20.2
A5	3224.5	2.4	2.1	54	19.3
A6	4181.3	2.4	1.9	47	16.6
A7	3741.0	2.4	1.9	48	19.6
A8	4874.0	2.4	1.4	29	27.6
B1	7503.6	2.5	2.1	56	15.6
B2	7617.1	2.4	2.2	56	21.2
B3	6829.6	2.4	2.0	56	19.4
B4	9005.2	2.4	2.1	53	24.6
B5	3394.5	2.4	2.1	55	14.9
B6	3634.2	2.4	2.2	54	23.4
B7	4250.5	2.2	1.9	59	15.4
B8	4154.4	2.4	2.1	51	17.8
C1	14701.8	2.4	2.2	56	98.1
C2	7036.6	2.6	2.3	53	75.3
C3	7297.2	2.4	2.2	52	51.8
C4	6466.5	2.4	2.1	52	31.2
C5	4959.1	1.0	1.1	56	30.0
C6	5459.6	2.4	2.2	55	31.1
C7	8532.9	2.3	2.1	53	15.7
C8	6451.8	2.4	2.2	53	12.8
D1	6843.8	2.5	2.3	53	97.5
D2	5607.8	2.5	2.2	51	74.2
D3	5468.6	2.5	2.2	51	24.7
D4	4501.3	1.8	2.2	57	28.0
D5	4465.1	2.3	2.2	56	46.8
D6	3593.3	2.4	2.0	57	23.5
D7	5698.6	2.3	2.2	56	13.3
D8	5822.0	2.3	2.0	56	36.2

Table B-4. Continued

Location	Dry Half-Cell Potential (mV)	Dry Linear Polarization (A/cm^2)	Wet Resistivity (kΩ-cm)	Wet Half-Cell Potential (mV)	Wet Linear Polarization (A/cm^2)
A1	-421	2200	26.7	-425	1916
A2	-359	2445	10.2	-314	2080
A3	-365	1759	15.0	-298	2001
A4	-364	2198	10.0	-314	2568
A5	-413	3198	8.7	-388	3290
A6	-441	2787	8.4	-454	2250
A7	-383	30332	9.7	-463	3129
A8	-337	19879	3.0	-511	3084
B1	-391	15718	23.9	-383	1736
B2	-331	2787	12.1	-299	2206
B3	-324	1954	12.2	-278	2216
B4	-355	2559	13.0	-283	2646
B5	-401	2817	14.2	-395	2631
B6	-418	10699	9.6	-434	2307
B7	-459	5029	12.1	-466	2294
B8	-459	3322	10.1	-517	2479
C1	-210	14814	19.7	-283	3076
C2	-244	15530	15.4	-237	3207
C3	-262	5079	15.7	-244	2949
C4	-345	3861	11.4	-279	2722
C5	-387	3668	19.8	-394	3224
C6	-422	2854	13.4	-432	3298
C7	-400	6465	10.0	-383	2193
C8	-384	1643	9.0	-378	2429
D1	-171	13909	55.3	-240	6318
D2	-261	6234	20.1	-244	2310
D3	-332	2385	15.9	-278	2592
D4	-391	2927	12.9	-349	2653
D5	-408	4488	26.5	-399	3316
D6	-454	5644	21.0	-452	2605
D7	-416	11935	21.5	-391	2717
D8	-395	5308	24.2	-390	2609

Table B-4. Continued

Location	Chloride Concentration (lb Cl^-/yd^3) at Indicated Depth			
	0 - 0.5 in.	0.5 - 1.0 in.	1.0 - 1.5 in.	1.5 - 2.0 in.
A1	8.4	9.4	7.8	8.2
A2	7.9	4.8	6.1	3.6
A3	7.3	8.7	6.2	5.7
A4	8.0	6.8	5.4	5.7
A5	5.2	7.9	6.4	6.0
A6	7.7	6.1	8.7	5.0
A7	7.5	7.6	7.4	6.5
A8	6.1	6.7	8.9	6.4
B1	4.2	7.8	7.7	6.6
B2	7.4	7.7	6.2	3.9
B3	4.5	6.4	5.9	6.5
B4	6.6	6.1	6.3	6.8
B5	4.4	6.5	6.1	6.0
B6	5.4	9.7	13.5	19.8
B7	4.4	8.9	9.6	7.1
B8	4.1	6.7	8.9	5.6
C1	5.8	5.1	2.2	0.5
C2	4.1	1.6	0.3	0.2
C3	3.5	2.2	0.8	0.5
C4	5.8	7.1	3.9	2.8
C5	3.7	5.9	5.2	3.1
C6	4.1	5.5	4.3	3.4
C7	3.3	4.5	3.4	2.9
C8	3.3	2.2	1.2	1.2
D1	5.0	4.2	1.7	0.3
D2	4.2	2.3	1.0	0.2
D3	2.9	4.4	3.4	1.3
D4	2.9	5.5	3.2	3.5
D5	2.0	6.5	10.2	8.6
D6	4.8	4.5	5.3	4.4
D7	3.1	6.4	5.0	4.2
D8	4.0	4.4	4.5	4.7

Table B-4. Continued

Location	Chloride Concentration (lb Cl^-/yd^3) at Indicated Depth			
	2.0 - 2.5 in.	2.5 - 3.0 in.	3.0 - 3.5 in.	3.5 - 4.0 in.
A1	6.5	7.3	4.9	5.5
A2	2.5	1.4	0.8	0.5
A3	6.0	4.3	3.7	2.6
A4	4.6	4.4	3.1	1.2
A5	6.0	5.4	3.1	2.3
A6	5.2	7.2	3.5	5.0
A7	6.0	6.6	3.3	4.8
A8	7.4	9.5	6.9	4.9
B1	6.5	5.1	3.7	2.2
B2	3.3	1.6	0.8	0.3
B3	5.6	2.6	0.9	0.6
B4	4.7	4.7	4.0	1.4
B5	6.4	4.7	3.4	4.2
B6	20.6	18.9	14.7	7.7
B7	6.1	6.7	4.6	6.7
B8	4.0	8.0	10.7	9.1
C1	0.2	0.3	0.2	0.1
C2	0.3	0.2	0.2	0.2
C3	0.4	0.3	0.2	0.2
C4	3.9	1.7	0.8	0.5
C5	3.1	1.2	1.1	0.5
C6	3.0	2.7	1.3	1.0
C7	2.5	1.5	0.7	0.7
C8	0.9	0.6	0.4	0.1
D1	0.2	0.1	0.2	0.1
D2	0.2	0.2	0.2	0.2
D3	1.1	1.0	0.6	0.2
D4	0.6	0.7	0.9	0.5
D5	7.2	8.0	5.7	4.3
D6	4.2	2.6	1.7	0.9
D7	2.9	1.6	1.0	0.7
D8	3.2	2.6	1.4	0.8