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Sensitivity of Resistivity Measurements on Concrete Bridge Decks to Operator-Controlled and Concrete Material Variables

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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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ABSTRACT

Sensitivity of Resistivity Measurements on Concrete Bridge Decks to Operator-Controlled and Concrete Material Variables

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Master of Science

The objectives of this research were to investigate the sensitivity of two-prong and four-prong resistivity measurements to certain operator-controlled variables and to conduct a direct comparison of the sensitivity of two-prong and four-prong resistivity measurements to certain concrete material variables. Four full-factorial experiments were designed for this research. In the experimentation on operator-controlled variables with two-prong resistivity testing, main effects that are both statistically significant and practically important include hole depth and surface water. In the experimentation on operator-controlled variables with four-prong resistivity testing, probe position, surface water, and prong spacing are all neither statistically significant nor practically important. This high degree of unexplained variation may be of concern to practitioners. In the experimentation on concrete material variables with two-prong and four-prong resistivity testing, main effects that are both statistically significant and practically important include chloride concentration and temperature, both of which exhibit inverse relationships with resistivity. These research findings support several important recommendations for resistivity testing. Operators of the two-prong resistivity device should use an accurately positioned drill stop to ensure that the prepared holes are consistently the correct depth, and they should expect to obtain different values depending on the presence of surface water on the deck surface. Operators considering use of the four-prong resistivity device should not expect the measurements to be sensitive to probe position with respect to rebar, presence of surface water, or prong spacing for conditions similar to those investigated in this research. Operators interested in monitoring resistivity values over time to ascertain material changes in a bridge deck should develop protocols for measuring concrete temperature in the field and subsequently normalizing resistivity measurements to a standard temperature.

Key words: bridge deck testing, chloride concentration, concrete durability, electrical resistivity, non-destructive testing, reinforcing steel corrosion

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1 INTRODUCTION

1.1 Problem Statement

A primary cause of premature failure of concrete bridge decks is corrosion caused by deicing salts applied during winter maintenance. The intrusion of chlorides from deicing salts initiates corrosion of the reinforcing steel, which is an important failure mechanism in concrete bridge decks (*1, 2, 3, 4, 5, 6, 7*). To investigate the condition of bridge decks, non-destructive tests can be performed. An increasingly popular non-destructive method for evaluating chloride-induced corrosion of concrete bridge decks is electrical resistivity testing (*1, 2, 3, 4, 8, 9, 10*). Resistivity testing indirectly measures the ability of concrete to resist chloride ion penetration (*2, 4, 8, 11*) and therefore to prevent corrosion of embedded reinforcing steel (*1, 2, 8, 10*). The rate of corrosion is inversely proportional to the electrical resistivity of concrete (*1, 2, 8, 10*).

Multiple instruments exist for measuring the electrical resistivity of concrete (*1, 11*). Two common hand-held devices are the two-prong and four-prong resistivity instruments (*1, 11, 12, 13*). The two-prong resistivity instrument requires two shallow holes to be drilled into the concrete before testing. Conductive gel, most commonly liquid soap, is inserted into the holes to provide a conductive interface between the probe, which has a fixed prong spacing, and the concrete. In contrast, predrilled holes are not necessary for measuring resistivity with the four-prong instrument. Instead, the four-prong instrument is fitted with saturated wooden tips that provide electrical coupling between the probe, which has an adjustable prong spacing, and the concrete surface (*3, 6, 10, 14*). Frequent saturation of the wooden tips is necessary to compensate for water loss from the tips that occurs through absorption by the concrete and through evaporation (*10, 12*). Because measurements with the four-prong resistivity instrument are non-destructive, rapid, and simple, that device is reportedly more popular than the two-prong instrument (*12, 13*).

Two-prong and four-prong resistivity measurements are sensitive to operator-controlled variables and concrete material variables. Potentially important operator-controlled variables for two-prong resistivity measurements include:

- drilled hole depth
- probe position with respect to rebar
- presence of surface water
- liquid soap volume or quantity

Potentially important operator-controlled variables for four-prong resistivity measurements include:

- probe position with respect to rebar
- presence of surface water
- prong spacing

Chloride concentration and temperature are potentially important concrete material variables that affect measurements obtained using either resistivity instrument.

Although understanding how these variables may affect resistivity measurements is important, the sensitivity of two-prong resistivity measurements to operator-controlled variables has not been previously investigated, and the sensitivity of four-prong resistivity measurements to certain operator-controlled variables has been studied only marginally (*3, 10, 14, 15, 16, 17,* *18*); a thorough evaluation has not been conducted. Additionally, while the effects of certain concrete material variables on resistivity measurements have been investigated (*3, 10, 11, 14, 15, 17*), a direct comparison of the sensitivity of two-prong and four-prong resistivity measurements to operator-controlled and concrete material variables has not been conducted. Therefore, the objectives of this research were to investigate the sensitivity of two-prong and four-prong resistivity measurements to certain operator-controlled variables and to conduct a direct comparison of the sensitivity of two-prong and four-prong resistivity measurements to certain concrete material variables.

1.2 Scope

This research included preparation and testing of nine concrete slabs at the Brigham Young University (BYU) Highway Materials Laboratory. One concrete mixture was utilized for all of the slabs, but the configuration of reinforcing steel and the concentration of cast-in-place chlorides were altered from slab to slab. Six slabs were created for testing the sensitivity of resistivity measurements to operator-controlled variables, including three slabs for two-prong testing and three slabs for four-prong testing. These slabs each contained three uncoated reinforcing bars placed at a depth of 5.1 cm (2.0 in.) and had a uniform chloride concentration of 5.9 kg of Cl^-/m^3 of concrete (10.0 lb of Cl^-/yd^3 of concrete). The remaining three slabs were created for testing the sensitivity of resistivity measurements to concrete material variables. These unreinforced slabs contained levels of chloride concentrations varying from 0.0 to 11.9 kg of Cl^-/m^3 of concrete (0.0 to 20.0 lb of Cl^-/yd^3 of concrete).

1.3 Outline of Report

This report contains five chapters. Chapter 1 presents the objectives and scope of this research. Chapter 2 presents information from a literature review on the use of resistivity measurements in evaluating corrosion of reinforcing steel in concrete bridge decks. Chapter 3 discusses the experimental methodology employed for determining the sensitivity of two-prong and four-prong resistivity measurements to specific operator-controlled and concrete material variables. Chapter 4 presents the results, and Chapter 5 gives the conclusions and recommendations derived from this research.

2 BACKGROUND

2.1 Overview

The following sections present information from a literature review on resistivity theory, resistivity testing devices, and resistivity studies as these topics apply to evaluating corrosion rates of reinforcing steel in concrete bridge decks.

2.2 Resistivity Theory

Electrical resistivity is a material's resistance per unit length to the flow of an electrical current through a defined area (*10*). Resistivity is directly proportional to the cross-sectional area of a material and inversely proportional to its effective length. The electrical resistivity of concrete is largely a function of the properties of the concrete matrix and the pore water (*17*). A concrete matrix with high porosity characterized by high interconnectivity and low tortuosity allows for the passage of high amounts of electrical current and would have low resistivity compared to a concrete with low porosity characterized by low interconnectivity and high tortuosity, all other factors constant (*6*, *11*). Regarding the pore water, high ion concentrations and high temperatures allow for the passage of high amounts of electrical current through the concrete due to the high abundance and mobility of current carriers (*17*); as temperature increases, the activity of the ions increases and the viscosity of the pore solution within the concrete decreases, causing an increase in ion mobility that corresponds to lower concrete resistivity measurements (*6, 11*).

Electrical resistivity measurements are based on Ohm's law, which states that the direct current through a conductor is directly proportional to the applied potential and inversely proportional to the resistance of the conductor (*11, 15*). Equation 1 presents Ohm's law:

$$R = \frac{V}{I} \tag{2-1}$$

where R = resistance, Ω

V = potential, V

I = current, A

Resistivity testing is an appropriate method for estimating the likelihood of reinforcing steel corrosion because the development of corrosion currents in concrete is also largely a function of the properties of the concrete matrix and the pore water (*3, 10, 18*). Higher porosities, moisture contents, chloride concentrations, and temperatures are all consistently correlated with higher corrosion rates and are manifest by lower resistivity values (*3, 10, 18, 19*). Resistivity values can consequently be useful for isolating areas of deteriorating concrete.

Table 2-1 shows the interpretation of resistivity measurements with respect to the potential risk of corrosion in the concrete (*1, 10, 12, 17*). Although resistivity testing measures the likelihood of corrosion to occur, it does not measure actual corrosion rates or the amount of corrosion that has already occurred (*18*).

Table 2-1: Interpretation of Resistivity Measurements (*2*)

Resistivity (kΩ-cm)	Corrosion Rate
> 20	Low
10 to 20	Low to Moderate
5 to 10	High
< 5	Very High

2.3 Resistivity Testing Devices

Two devices commonly used to measure resistivity are the two-prong and four-prong resistivity instruments (*1, 10, 13*). Both the two-prong and four-prong instruments operate by passing an alternating current between the prongs, or electrodes, measuring the corresponding potential drop, and then computing the resistance of the concrete (*2, 8*). Alternating current is used instead of direct current for resistivity measurements to minimize polarization at the electrode tips (*1, 7, 13*). For the four-prong instrument, a known alternating current is applied to the two outer prongs, and the resulting potential drop is measured between the spring-loaded inner prongs for calculation of resistivity (*1, 3, 7, 9, 11, 13, 14, 16*). The resistivity values measured using this method represent the average concrete resistivity at a depth approximately equivalent to the probe spacing (*1, 16*). Typically, the prongs are uniformly spaced 3.0 to 5.1 cm (1.2 to 2.0 in.) apart (*9, 16*). Equation 2 presents the calculation of resistivity from four-prong resistance measurements (*1, 14*):

$$\rho = 2 \cdot \pi \cdot a \cdot R \qquad (2\text{-}2)$$

where ρ = resistivity, kΩ-cm

a = electrode spacing, cm

R = resistance, kΩ

Concrete surface conditions such as laitance and carbonation can affect resistivity measurements depending on how the measurements are obtained (*14*). When the two-prong instrument is used, two shallow holes are commonly drilled into the concrete surface for probe placement, allowing the probe tips to bypass the affected layers (*17*). However, predrilled holes are not utilized in four-prong resistivity testing; instead, the probe is placed directly on the concrete surface for testing (*18*). As a result, four-prong resistivity readings may be more affected by laitance and carbonation.

2.4 Resistivity Studies

Researchers have conducted several studies on the sensitivity of resistivity measurements to selected factors, including age, type of curing, temperature, moisture content, type of cement, presence of rebar, and chloride concentration (*13, 18*). Both two-prong and four-prong resistivity instruments were evaluated in several of these studies.

On the relationship between electrical resistivity and age, the electrical resistivity of concrete produced with Type I cement was found to double from 7 to 90 days when the concrete was cured in lime water (*10, 15*). The researchers concluded that, as the concrete ages, the moisture content decreases due to the decreasing amount of porosity, which increases the resistivity measurement (*7, 10, 11, 15*).

In previous experimentation, resistivity measurements were also determined to be sensitive to the type of curing applied to the concrete (*15*). The types of curing that were studied included autoclave, steam, and moist curing. In that research, with curing durations of less than 10 days, the highest resistivity values were measured on concrete cured in an autoclave. After 100 days of curing, however, steam curing produced the highest resistivity measurements. Moist curing consistently produced the lowest resistivity measurements (*15*).

Other researchers have evaluated the sensitivity of resistivity measurements to temperature. Resistivity measurements were found to decrease with increasing temperature due to the increasing activity of the ions in the pore solution (*1, 11, 17*). A relationship between resistivity measurements and the temperature of the concrete at the time of testing was developed. A temperature range of 4.4°C to 37.8°C (40.0 to 100.0°F) was studied, and a 1 to 3 percent decrease in resistivity was observed to occur per 0.6°C (1.0°F) increase in temperature (*11, 15, 17*).

Researchers have shown that resistivity values are sensitive to the moisture content of the concrete (*2, 8, 10, 11, 15, 17, 20*). As the moisture content of concrete decreases, less pore water is available to carry electrical current, resulting in an increase in resistivity values (*6, 10, 14, 16*). On the other hand, an increase in free water results in decreased resistivity measurements (*17*). In particular, surface water, resulting from precipitation or deliberately applied during testing, can cause the operator to underestimate the resistivity of the concrete because high amounts of electrical current can travel through the surface water relative to that carried through the pore water inside the concrete.

Resistivity measurements have also been shown to be sensitive to the type of cement and additives used in concrete. The different types and amounts of cement change the chemical and physical properties of the concrete, which can affect resistivity measurements (*10, 17*). Different types of cement have different hydration rates and generate different pore solution chemistries, which can affect resistivity measurements (*10*). Fly ash increases the resistivity of concrete by a factor of 3 or 4 because of its optimization of the cement hydration process (*9, 17*).

Research has shown that the presence of rebar can also result in an underestimation of concrete resistivity in certain testing configurations (*3, 14, 15, 16, 21*). When the resistivity probe is oriented parallel to embedded rebar, the resistivity value is about 40 percent lower than that measured in the absence of rebar because the rebar, evident within the zone of interrogation, facilitates a higher flow of current between the prongs (*21*). However, when the resistivity probe is placed perpendicular to embedded rebar, the embedded rebar did not significantly affect the resistivity measurements (*21*).

Previous research has shown that resistivity measurements are sensitive to the concrete material variable of chloride concentration (*14*). Not only does the presence of chlorides increase the concentration of current carriers in the pore solution, it can also cause the concrete to retain more water, on average, than concrete without chlorides. Both of these effects increase the ability of the concrete to conduct electrical current, which results in decreased resistivity measurements (*1, 10, 14*).

2.5 Summary

A literature review on resistivity theory, resistivity testing devices, and resistivity studies as these topics apply to evaluating corrosion rates of reinforcing steel in concrete bridge decks was performed for this research. Electrical resistivity is a material's resistance per unit length to the flow of an electrical current through a defined area. Resistivity is directly proportional to the cross-sectional area of a material and inversely proportional to its effective length. Electrical resistivity measurements are based on Ohm's law, which states that the direct current through a conductor is directly proportional to the applied potential and inversely proportional to the resistance of the conductor. Resistivity testing is an appropriate method for estimating the likelihood of reinforcing steel corrosion because the development of corrosion currents in concrete is also largely a function of the properties of the concrete matrix and the pore water. Two devices commonly used to measure resistivity are the two-prong and four-prong resistivity instruments. Concrete surface conditions such as laitance and carbonation can affect resistivity measurements depending on how the measurements are obtained. Researchers have conducted several studies on the sensitivity of resistivity measurements to selected factors, including age, type of curing, temperature, moisture content, type of cement, presence of rebar, and chloride concentration.

3 EXPERIMENTAL METHODOLOGY

3.1 Overview

The sensitivity of resistivity measurements to operator-controlled and concrete material variables was evaluated in two phases. The following sections describe the experimental design, specimen preparation and testing, and data analyses for each phase.

3.2 Experimental Design

Four full-factorial experiments were designed with varying factors and levels to determine the sensitivity of two-prong and four-prong resistivity measurements to operator-controlled factors and concrete material variables as discussed in the following sections.

3.2.1 Operator-Controlled Variables

In the process of designing formal experimentation to investigate the sensitivity of resistivity measurements to operator-controlled factors, several preparatory tests were conducted. The purpose of the preparatory tests was to determine which factors merited inclusion in a full-factorial experiment. The preparatory tests for the two-prong resistivity instrument included evaluations of type of soap, volume of soap, time after soap application, and time after surface water application. The factors evaluated in the preparatory testing for the four-prong instrument included weight applied to the probe and time after surface water application. The procedures and results associated with these preparatory tests are given in Appendix A.

Although research has shown that the concrete material variables of chloride concentration and temperature affect resistivity measurements (*10, 14, 15, 17*), constant values of chloride concentration and testing temperature were specified to focus this experimentation on operator-controlled variables. A chloride concentration of 5.9 kg of Cl^-/m^3 of concrete (10.0 lb of Cl^-/yd^3 of concrete) and an air temperature of 15.6˚C (60.0˚F), typical for concrete bridge decks in Utah, were chosen for experimentation.

3.2.1.1 Two-Prong Resistivity Testing

One full-factorial experiment was designed with four factors and varying levels to determine the sensitivity of two-prong resistivity measurements to the potentially important operator-controlled variables of drilled hole depth, probe position with respect to rebar, presence of surface water, and liquid soap volume or quantity. The recommended hole depth for two-prong resistivity testing is 0.9 cm (0.375 in.) (*18*), but insufficient research exists about the sensitivity of two-prong instrument readings to shallower or deeper holes. To evaluate this sensitivity, the hole depths selected for evaluation were 0.64 cm (0.25 in.) and 1.27 cm (0.50 in).

Research has shown that the presence of rebar can influence concrete resistivity measurements (*3, 14, 15, 16*), but a thorough evaluation of the sensitivity of resistivity measurements to various probe positions with respect to the rebar has not been conducted. As illustrated in Figure 3-1, five levels of probe position with respect to the rebar were evaluated in this study: (1) transverse, (2) longitudinal, (3) diagonal, (4) 3.8-cm (1.5-in.) offset from the center of the rebar, and (5) 7.6-cm (3.0-in.) offset from the center of the rebar.

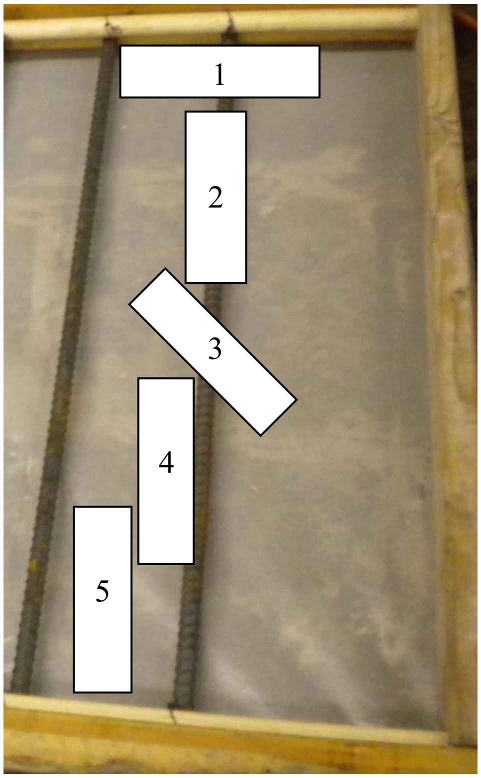


Figure 3-1: Probe position with respect to rebar.

Research has suggested that resistivity measurements are highly sensitive to the presence of surface water (*6, 16*). Two levels of surface water were evaluated in this experiment: absence or presence of surface water. The absence of surface water simulated a dry in-situ condition, while the presence of surface water simulated a wet in-situ condition.

Although the user's manual for the two-prong device highlights the importance of not spilling soap between the two drilled holes, the amount of soap to be placed in the holes is not specified (*18*). The two soap levels chosen for this research were full and half full. Full describes a condition in which sufficient soap is applied so that the holes are full but not overflowing when the prongs are placed in the holes. Half full describes a condition in which sufficient soap is applied so that the holes are half full after the prongs are inserted.

Figure 3-2 illustrates the slab design, rebar placement, and layout of resistivity measurements specified for this experimentation. Fully crossing all levels of all experimental factors yielded a total of 40 unique combinations. To facilitate three replicate measurements for each unique combination, three identical slabs were needed that would allow for 40 measurements each. Each unique combination of factors was randomly assigned to available testing locations on each concrete slab so that the results would be statistically valid. Locations of individual resistivity measurements are labeled in Figure 3-2 with unique letters that

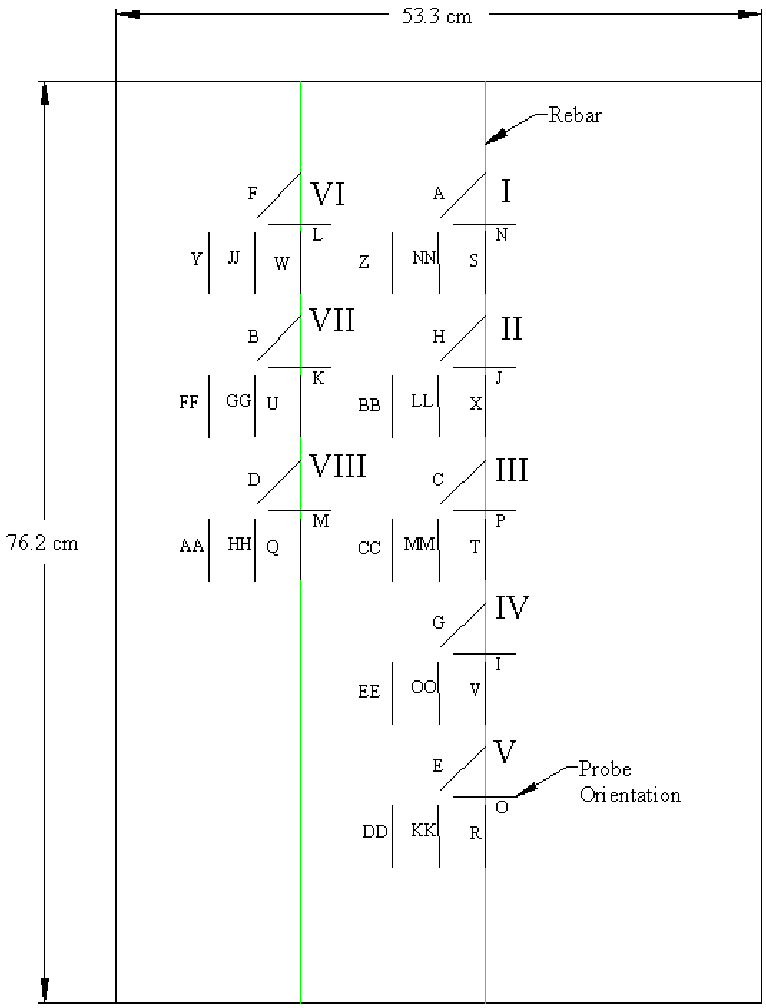


Figure 3-2: Slab design for experimentation on operator-controlled variables with two-prong resistivity testing.

correspond to specific combinations of experimental factors as indicated in Appendix B. For example, Figure B-1 indicates that the levels of factors at location Q include longitudinal probe placement, a 1.27-cm (0.50-in.) hole depth, full soap volume, and no surface water. No resistivity measurements were made closer than 7.6 cm (3.0 in.) to a slab edge.

3.2.1.2 Four-Prong Resistivity Testing

Another full-factorial experiment was designed to determine the sensitivity of four-prong resistivity measurements to the potentially important operator-controlled variables of probe position with respect to the rebar, presence of surface water, and prong spacing. As depicted in Figure 3-3, the same five levels of position with respect to the rebar that were evaluated in the two-prong resistivity testing were also investigated in the four-prong resistivity testing: transverse, longitudinal, diagonal, 3.8-cm (1.5-in.) offset from the center of the rebar, and 7.6-cm (3.0-in.) offset from the center of the rebar. The same two levels of surface water that were evaluated in the two-prong resistivity experiment were also investigated for this experiment, including absence or presence of surface water. For prong spacing, which affects the depth of interrogation (*10, 21*), the two levels selected for investigation in this research were 3.8 cm (1.5 in.) and 5.1 cm (2.0 in.). These levels were considered because both are typical values of prong spacing that generally reflect the depth of cover on a concrete bridge deck.

Figure 3-3 illustrates the slab design, rebar placement, and layout of resistivity measurements specified for this experimentation. Fully crossing all levels of all experimental factors yielded a total of 60 unique combinations. To facilitate three replicate measurements for each unique combination, three identical slabs were needed that would allow for 60 measurements each. Each unique combination of factors was randomly assigned to available

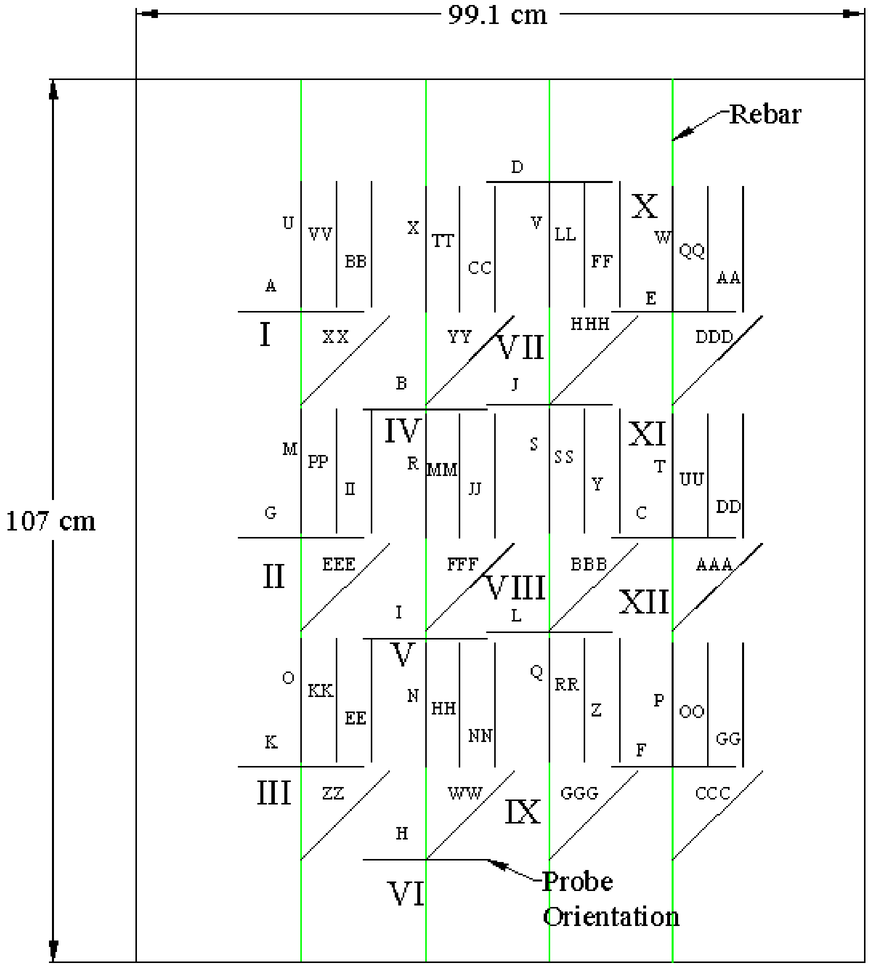


Figure 3-3: Slab design for experimentation on operator-controlled variables with four-prong resistivity testing.

testing locations on each concrete slab so that the results would be statistically valid. Locations of individual resistivity measurements are labeled in Figure 3-3 with unique letters that correspond to specific combinations of experimental factors as indicated in Appendix B. For example, Figure B-2 indicates that the levels of factors at location N include longitudinal probe placement, a 5.1-cm (2.0-in.) prong spacing, and no surface water. Again, no resistivity measurements were made closer than 7.6 cm (3.0 in.) to a slab edge.

3.2.2 Concrete Material Variables

Two full-factorial experiments were designed to conduct a direct comparison of the sensitivity of two-prong and four-prong resistivity measurements to the potentially important concrete material variables of chloride concentration and temperature. Many of the operator-controlled factors from the other experiments performed in this research were held constant during this experimentation. For testing with the two-prong resistivity device, a drilled hole depth of 1.3 cm (0.375 in.), absence of surface water, and full soap volume were utilized. Rebar was not included in this experimentation.

While the sensitivity of two-prong resistivity measurements to chloride concentration has been investigated with respect to the use of calcium chloride accelerator in concrete slabs (*15*), the sensitivity of four-prong resistivity measurements to chloride concentration has apparently not been studied. Chloride concentration was included as a factor in this experimentation in order to compare two-prong and four-prong resistivity measurements across a range of chloride concentrations. The levels that were evaluated in this experiment were 0.0 kg of Cl^-/m^3 of concrete (0.0 lb of Cl^-/yd^3 of concrete), 5.9 kg of Cl^-/m^3 of concrete (10.0 lb of Cl^-/yd^3 of concrete), and 11.9 kg of Cl^-/m^3 of concrete (20.0 lb of Cl^-/yd^3 of concrete). These levels were chosen to simulate bridge decks with no chlorides and excessive chlorides. Chloride concentrations of 1.2 kg of Cl^-/m^3 of concrete (2.0 lb of Cl^-/yd^3 of concrete) or higher can initiate corrosion of reinforcing steel (*4*). Research indicates that, during their normal service life, bridge decks in Utah can attain chloride concentrations approaching 11.9 kg of Cl^-/m^3 of concrete (20.0 lb of Cl^-/yd^3 of concrete) within the typical depth of cover above the top mat of reinforcing steel, well above the threshold of 1.2 kg of Cl^-/m^3 of concrete (2.0 lb of Cl^-/yd^3 of concrete) (*2*).

The literature also suggests that resistivity measurements are sensitive to temperature, with a decrease of 1 to 3 percent in resistivity for every 0.6°C (1.0°F) of increasing temperature (*6, 15, 17*). In order to investigate the effects of temperature in this experiment, temperatures of 4.4°C (40.0°F), 15.7°C (60.0°F), and 26.7°C (80.0°F) were evaluated.

Each unique combination of factors was randomly assigned to available testing locations on each concrete slab as depicted in Figure 3-4. Fully crossing all levels of all experimental factors yielded a total of 18 unique combinations. To facilitate three replicate measurements for each unique combination, three similar slabs, with varying chloride concentrations, were needed that would allow for 18 measurements each. Locations of individual resistivity measurements are labeled in Figure 3-4 with unique letters that correspond to specific combinations of experimental factors as indicated in Appendix B. For example, Figure B-3 indicates that the levels of factors at location BB include testing with the four-prong instrument at 4.4°C (40.0° F).

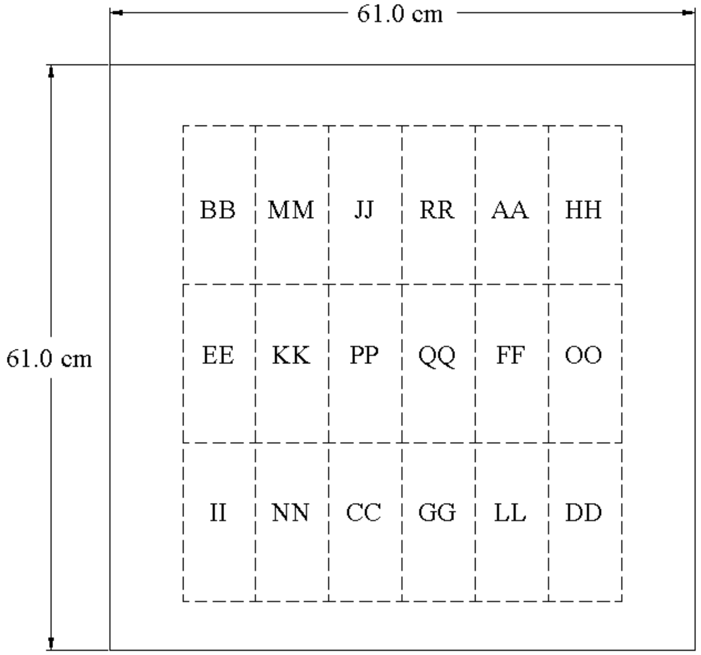


Figure 3-4: Slab design for experimentation on concrete material variables with two-prong and four-prong resistivity testing.

3.3 Specimen Preparation

Six slabs were prepared for determining the sensitivity of resistivity measurements to operator-controlled variables, while three slabs were prepared for investigating concrete material variables. The construction of the slabs for each objective is described in the following sections.

3.3.1 Operator-Controlled Variables

One of the objectives of this research was to investigate the sensitivity of two-prong and four-prong resistivity measurements to certain operator-controlled variables. To accomplish this objective, three concrete batches were cast, each containing sufficient material for two slabs, one for two-prong resistivity testing and one for four-prong resistivity testing.

The three concrete slabs prepared for two-prong resistivity testing each had a length of 76.2 cm (30.0 in.), a width of 53.3 cm (21.0 in.), and a depth of 8.9 cm (3.5 in.). Each of these slabs was designed with three lengths of rebar, all oriented parallel to the longer side and spaced 15.2 cm (6.0 in.) on center at a depth of 5.1 cm (2.0 in.) to the top of the rebar. The three concrete slabs prepared for four-prong resistivity testing each had a length of 107.0 cm (41.0 in.), a width of 99.1 cm (39.0 in.), and a depth of 8.9 cm (3.5 in.). Each of these slabs was designed with four lengths of rebar, all oriented parallel to the longer side and spaced 21.6 cm (8.5 in.) on center at a depth of 5.1 cm (2.0 in.) to the top of the rebar. Polyvinyl chloride (PVC) pipes were placed perpendicular to the lengths of rebar along the short ends of the forms to facilitate the insertion of longer lengths of rebar as handles for carrying the slabs from the curing location to the environmental chamber. The forms in the upper left corner and right side of Figure 3-5 are some of the forms created for two-prong resistivity testing and four-prong resistivity testing, respectively.

The concrete mixture used in this research met Utah Department of Transportation specifications for bridge decks and was developed in previous research at BYU (*9*). The quantity of ingredients for each of the three batches is shown in Table 3-1, where the required amounts of both coarse aggregate (CA) and fine aggregate (FA) are given in the saturated-surface-dry (SSD) condition. The concentration of sodium chloride added to each batch is presented in Table 3-2. The concrete mixture design required six bags of Type I/II portland cement per cubic yard of concrete and a water-cement ratio of 0.44. Class F fly ash was also incorporated as a supplementary cementitious material. Coarse and fine aggregates meeting the requirements of American Society for Testing and Materials (ASTM) C33 (Standard Specification for Concrete Aggregates) were utilized. In addition to casting slabs for both two-prong and four-prong resistivity testing, three cylinders were prepared from each batch for compression testing.

Figure 3-5: Forms prepared for concrete slabs.

Table 3-1: Concrete Mixture Design for Experimentation on Operator-Controlled Variables

Ingredient	Specific Gravity	Design Weight Per Cubic Meter (kg)	Design Volume Per Cubic Meter (m^3)	Design Weight Per Batch (kg)	Measured-Out Weight Per Batch (kg)
Free Water	1.00	166.1	0.166	19.7	22.0*
Cement	3.15	307.9	0.100	36.5	36.5
CA (SSD)	2.63	1016.9	0.397	120.5	119.9
FA (SSD)	2.40	635.4	0.247	75.3	74.7
Fly Ash	2.30	68.2	0.030	8.1	8.1
Air Entrainer	1.00	0.297	0.060	0.035	0.035
Total		2194.8	1.000	260.1	261.2

* An additional 0.91 kg of water was added to Batch 1.

Table 3-2: Sodium Chloride Batch Quantities for Experimentation on Operator-Controlled Variables

Sodium Chloride (NaCl)	Batch		
	1	2	3
Concentration (kg of Cl^-/m^3 of Concrete)	5.93	5.93	5.93
Weight (kg)	1.16	1.16	1.16

The concrete batches were prepared in a drum mixer following the procedure developed in previous research at the Brigham Young University Highway Materials Laboratory (*5*). Casting and curing were performed in general accordance with ASTM C192 (Standard Practice of Making and Curing Concrete Test Specimens in the Laboratory). Slump, air content, and unit weight tests were performed immediately after mixing of the concrete, after which the concrete was placed into the forms. Figure 3-6 shows some of the concrete slabs during the placement process.

Thermocouples were cast into the slabs prepared for testing with the four-prong instrument to enable measurement of the internal slab temperatures during testing. After final set had occurred, a moist burlap covering and a sheet of plastic were placed on top of each concrete slab. The burlap was moistened with fresh water as needed to keep the surface of the concrete

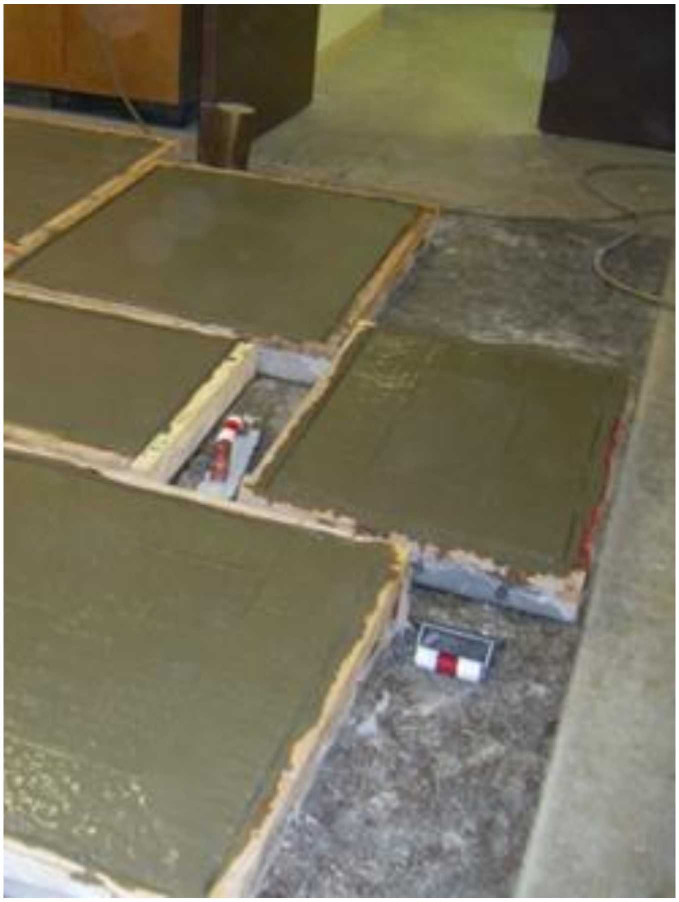


Figure 3-6: Concrete slabs during placement process.

slabs wet. After 14 days of moist curing, the burlap and plastic were removed, and the slabs were allowed to cure in open air for another 14 days. After 28 days of curing, the slabs were relocated to a staging area just outside the environmental chamber, where they were allowed to air-dry at room temperature until the surface dielectric values across the slabs remained constant, which indicated that the moisture contents had stabilized.

3.3.2 Concrete Material Variables

Another objective of this research was to conduct a direct comparison of the sensitivity of two-prong and four-prong resistivity measurements to concrete material variables. To accomplish this objective, three concrete batches were prepared, each containing sufficient material for one slab to be used for both two-prong and four-prong resistivity testing and three cylinders to be used for compression testing.

Each of the three concrete slabs had a length of 61.0 cm (24.0 in.), a width of 61.0 cm (24.0 in.), and a depth of 8.9 cm (3.5 in.). Each of these slabs was prepared without any rebar. As in the slabs prepared for investigating operator-controlled variables, PVC pipes were placed along the short ends of the forms to facilitate the insertion of longer lengths of rebar as handles for carrying the slabs from the curing location to the environmental chamber.

The concrete mixture is documented in Table 3-3 with the different chloride concentrations were used in this experimentation on concrete material variables as shown in Table 3-4. The same mixing and casting procedures previously described were utilized for construction of these slabs, and the same concrete curing condition previously described was also applied to these slabs.

Table 3-3: Concrete Mixture Design for Experimentation on Concrete Material Variables

Ingredient	Specific Gravity	Design Weight Per Cubic Meter (kg)	Design Volume Per Cubic Meter (m^3)	Design Weight Per Batch (kg)	Measured-Out Weight Per Batch (kg)
Free Water	1.00	166.1	0.166	14.5	15.4
Cement	3.15	307.9	0.100	26.9	26.9
CA (SSD)	40.31	1016.9	0.397	88.9	88.4
FA (SSD)	25.19	635.4	0.247	55.5	55.1
Fly Ash	2.30	68.2	0.030	6.0	6.0
Air Entrainment	1.02	0.297	0.060	0.026	0.026
Total		2194.8	1.000	191.8	191.8

Table 3-4: Sodium Chloride Batch Quantities for Experimentation on Concrete Material Variables

Sodium Chloride (NaCl)	Batch		
	4	5	6
Concentration (kg of Cl^-/m^3 of Concrete)	0.00	5.93	11.90
Weight (kg)	0.00	0.39	0.78

3.4 Specimen Testing

Four full-factorial experiments were performed to determine the sensitivity of resistivity measurements to operator-controlled and concrete material variables as described in the following sections.

3.4.1 Operator-Controlled Variables

Two full-factorial experiments were performed to investigate the sensitivity of two-prong and four-prong resistivity measurements to certain operator-controlled variables. Before testing began, the slabs prepared for this purpose were placed in an environmental chamber to equilibrate as shown in Figure 3-7. The slabs prepared for two-prong resistivity testing were placed on the right, while the slabs prepared for four-prong resistivity testing were placed on the left.

The temperature and relative humidity inside the environmental chamber were set at constant values of 15.6˚C (60.0˚F) and 50 percent, respectively, for evaluation of operator-controlled variables. The chosen temperature and relative humidity are approximately representative of average environmental conditions experienced by Utah bridge decks in the field. All of the specimens and testing equipment were allowed to equilibrate for 24 hours to the desired temperature and humidity before resistivity testing commenced as described in the following sections. As measured with the embedded thermocouples, the internal slab temperatures were confirmed to be equal to the air temperature in the environmental chamber at the end of the equilibration period.

Figure 3-7: Concrete slabs prepared for experimentation on operator-controlled variables.

3.4.1.1 Two-Prong Resistivity Testing

For two-prong resistivity testing, a full-factorial experiment was performed with four factors. The factors included hole depth with levels of 0.64 cm (0.25 in.) and 1.27 cm (0.50 in.); probe position with respect to the rebar with levels of transverse, longitudinal, diagonal, 3.8-cm (1.5-in.) offset from the center of the rebar, and 7.6-cm (3.0-in.) offset from the center of the rebar; presence of surface water with levels of no surface water and surface water; and soap volume with levels of full and half full.

For each measurement, two holes of equal depth were drilled, as shown in Figure 3-8, and a vacuum was used to remove the powder from the hole. Accurate hole depths were ensured in this experimentation through the use of an adjustable stop on the drill bit. As illustrated in Figure 3-9, the appropriate amount of soap volume was placed into the holes using a pharmaceutical-type dispenser. One drop and two drops of soap at a hole depth of 0.64 cm (0.25

in.) and two drops and four drops at a hole depth of 1.27 cm (0.50 in.) were needed to achieve the half-full and full condition, respectively, as determined in the preparatory testing described in Appendix A. The probe was then placed into the holes as depicted in Figure 3-10, and a reading was taken. The probe was then removed from the holes, turned end-for-end, and re-positioned in the holes so that a second reading could be taken. Beginning with the application of the soap, this process was consistently performed in less than 60 seconds at each testing location. When required, water was applied at individual locations one at a time to the top surface of each concrete slab with a pressure sprayer, immediately before drilling.

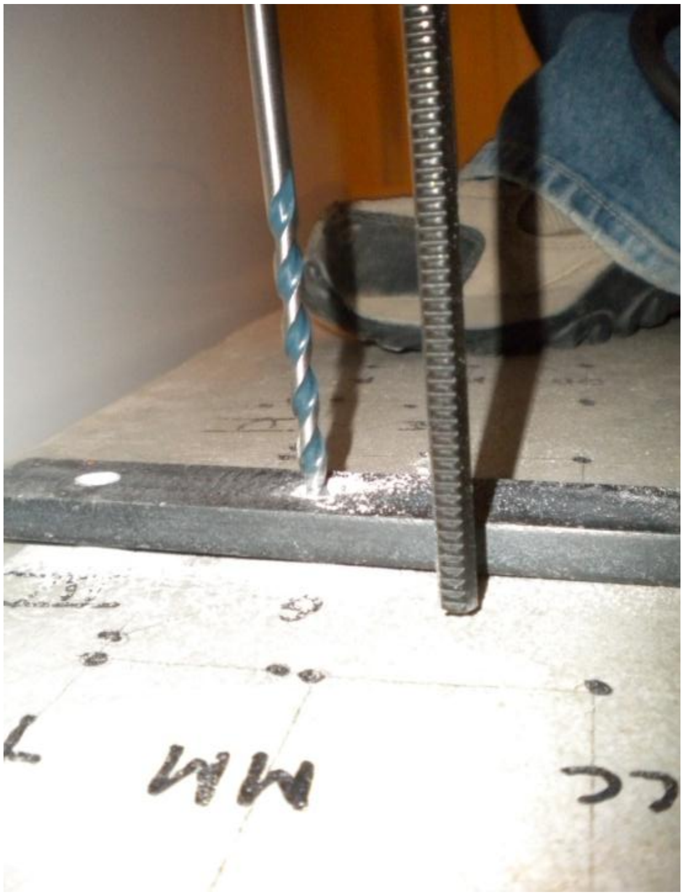


Figure 3-8: Hole-drilling for two-prong resistivity testing.

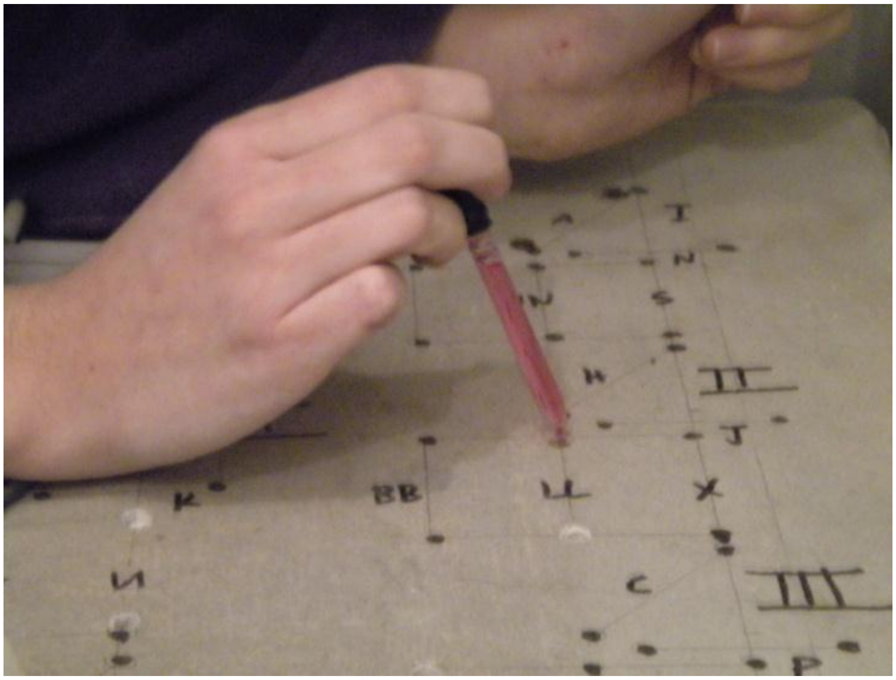


Figure 3-9: Soap insertion for two-prong resistivity testing.

Figure 3-10: Two-prong resistivity testing.

The collection of data was accomplished in the following sequence:

- No surface water with 1.27-cm (0.50-in.) hole depth
- No surface water with 0.64-cm (0.25-in.) hole depth
- Surface water with 1.27-cm (0.50-in.) hole depth
- Surface water with 0.64-cm (0.25-in.) hole depth

The researchers finished all testing on one slab before beginning testing on subsequent slabs. Each slab was tested identically to ensure repeatability.

3.4.1.2 Four-Prong Resistivity Testing

For four-prong resistivity testing, a full-factorial experiment was performed with three factors. The factors included probe position with respect to the rebar with levels of transverse, longitudinal, diagonal, 3.8-cm (1.5-in.) offset from the center of the rebar, and 7.6-cm (3.0-in.) offset from the center of the rebar; presence of surface water with levels of no surface water and surface water; and prong spacing with levels of 3.8 cm (1.5 in.) and 5.1 cm (2.0 in.).

Motivated by the results of the preparatory testing described in Appendix A, a customized, free-standing probe holder was designed and fabricated to ensure greater uniformity in testing. The preparatory testing also showed that a minimum force of about 4.5 kg (10 lb) on the probe tips was required to achieve constant readings. Therefore, appropriate weights were situated on the probe handle so that the total weight of the probe, weights, and holder was 4.5 kg (10 lb), and the original springs on the middle two prongs of the four-prong resistivity probe were replaced with stiffer ones to ensure that the applied weight was distributed equally across all of the prongs. Prior to each measurement, the wooden tips on the ends of the prongs were dipped in soapy water to ensure adequate saturation. The probe assembly was then placed at the appropriate location on the concrete surface as depicted in Figure 3-11, and a reading was taken. The assembly was then lifted from the concrete surface, turned end-for-end, and re-positioned on the concrete surface so that a second reading could be taken. This process was consistently performed in less than 60 seconds at each testing location. When required, water was applied at individual locations immediately before drilling, consistent with the procedure used during two-prong resistivity testing, and the same procedure previously used for quantifying the surface water distribution was also utilized. Once all the resistivity measurements were recorded for the 3.8-cm (1.5-in.) prong spacing, the prong spacing was adjusted to 5.1 cm (2.0 in.), and the testing was repeated.

The collection of data was accomplished in the following sequence:

- No surface water with 3.8-cm (1.5-in.) prong spacing
- No surface water with 5.1-cm (2.0-in.) prong spacing

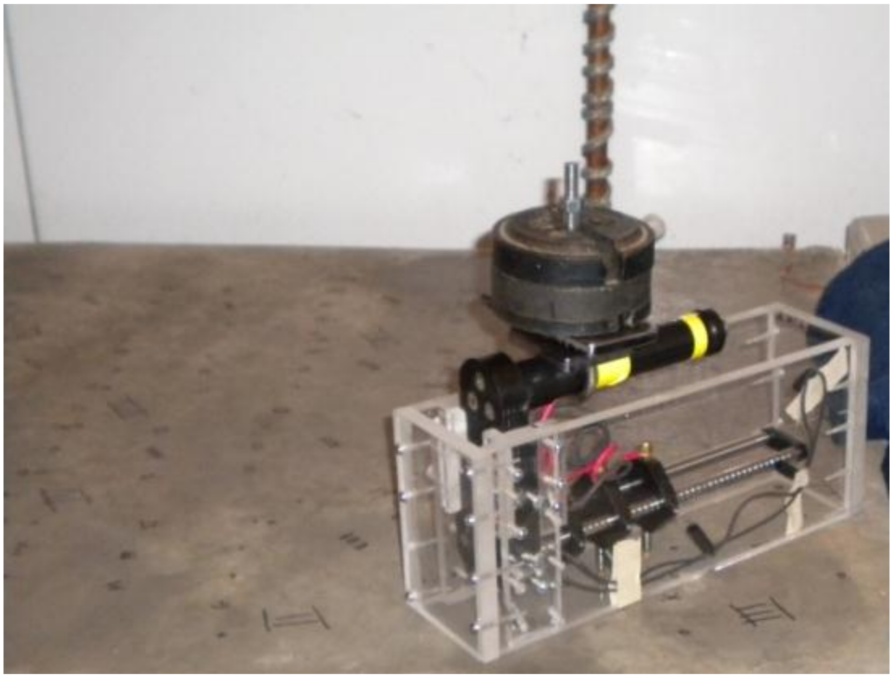


Figure 3-11: Four-prong resistivity testing.

- Surface water with 3.8-cm (1.5-in.) prong spacing
- Surface water with 5.1-cm (2.0-in.) prong spacing

The researchers finished all testing on one slab before beginning testing on subsequent slabs. Each slab was tested identically to ensure repeatability.

3.4.2 Concrete Material Variables

In order to perform a direct comparison between the sensitivity of two-prong and four-prong resistivity measurements to certain concrete material variables, two full-factorial experiments were performed with the same two factors. The factors included chloride concentration with levels of 0.0 kg of Cl^-/m^3 of concrete (0.0 lb of Cl^-/yd^3 of concrete), 5.9 kg of Cl^-/m^3 of concrete (10.0 lb of Cl^-/yd^3 of concrete), and 11.9 kg of Cl^-/m^3 of concrete (20.0 lb of Cl^-/yd^3 of concrete) and temperature with levels of 4.4°C (40.0°F) , 15.6°C (60.0°F), and 26.7°C (80.0°F). Both of these experiments were performed on the same three slabs. Each slab was intended to be same as the others in every way except the chloride concentration.

Before testing began, the slabs were placed in a computer-controlled environmental chamber at 26.7°C (80.0°F). The slabs were allowed to equilibrate for 48 hours in the environmental chamber before testing began as shown in Figure 3-12. Equilibration was determined by monitoring surface dielectric values as described previously.

After the completion of all resistivity testing at 26.7°C (80.0°F), the environmental chamber was set to 4.4°C (40.0°F), and the slabs were again allowed to equilibrate for 48 hours before testing resumed. After the completion of testing at 4.4°C (40.0°F), the environmental chamber was set to 15.6°C (60.0°F), and the process was repeated. The researchers finished all testing on one slab before beginning testing on subsequent slabs, and all of the two-prong and four-prong

Figure 3-12: Concrete slabs prepared for experimentation on concrete material variables.

resistivity testing was completed at each temperature within a 24-hour period in every case. The testing procedures followed for two-prong and four-prong resistivity testing at each temperature are given in the following sections.

3.4.2.1 Two-Prong Resistivity Testing

For each two-prong resistivity measurement obtained in this experimentation on concrete material variables, two holes were consistently drilled to a depth of 0.9 cm (0.375 in.), and a vacuum was used to remove the powder from the hole. Again, accurate hole depths were ensured in this experimentation through the use of an adjustable stop on the drill bit. Three drops of soap were placed into the holes using a pharmaceutical-type dispenser to achieve a full soap volume. The probe was then placed into the holes as depicted in Figure 3-10, and a reading was taken. The probe was then removed from the holes, turned end-for-end, and re-positioned in the holes so that a second reading could be taken. This process was consistently performed in less than 60 seconds at each testing location.

3.4.2.2 Four-Prong Resistivity Testing

Prior to each four-prong resistivity measurement, the wooden tips on the ends of the prongs were dipped in soapy water to ensure adequate saturation. The probe was then placed at the appropriate location on the concrete surface as depicted in Figure 3-11, and a reading was taken. The device was then removed from the concrete surface, turned end-for-end, and re-positioned on the concrete surface so that a second reading could be taken. This process was consistently performed in less than 60 seconds at each testing location.

3.5 Statistical Analyses

After data collection was complete for each full-factorial experiment, an analysis of variance (ANOVA) was performed. Two ANOVAs were performed to evaluate operator-controlled variables, and two ANOVAs were performed to evaluate concrete material variables.

The null hypothesis applied to each factor in the ANOVAs was that no difference in resistivity measurements existed between the levels of that factor, while the alternative hypothesis was that a difference did exist (5). The results of each ANOVA included a *p*-value, which indicated the level of significance of each factor in the experiment. A full model was originally fit to each data set, and a *p*-value was then computed for each main effect, two-way interaction, and three-way interaction. Consistent with common practice, a reduced model was then created by sequentially excluding factors with *p*-values greater than 0.15 so that the remaining factors would have *p*-values less than or equal to 0.15. A factor having a *p*-value less than or equal to 0.05 was considered to be statistically significant. The least squares means

(LSMs) were then computed for all of the factors in each reduced model. In addition, the coefficient of determination, or R^2 value, was calculated for each reduced model. The R^2 value presents the fraction of variation in the dependent variable that can be explained by variation in the independent variables (*5*). An R^2 value of 1.0 represents a perfect model.

The research results were also evaluated in terms of practical importance. Differences in LSMs for different levels were considered to be practically important if they were greater than the smallest threshold in Table 2-1 of 5 kΩ-cm (2000 Ω-in.).

3.6 Summary

Four full-factorial experiments were designed with varying factors and levels to determine the sensitivity of two-prong and four-prong resistivity measurements to operator-controlled factors and concrete material variables. In the process of designing formal experimentation to investigate the sensitivity of resistivity measurements to operator-controlled factors, several preparatory tests were conducted to determine which factors merited inclusion in a full-factorial experiment.

One full-factorial experiment was designed with four factors and varying levels to determine the sensitivity of two-prong resistivity measurements to the potentially important operator-controlled variables of drilled hole depth with levels of 0.64 cm (0.25 in.) and 1.27 cm (0.50 in.); probe position with respect to the rebar with levels of transverse, longitudinal, diagonal, 3.8-cm (1.5-in.) offset from the center of the rebar, and 7.6-cm (3.0-in.) offset from the center of the rebar; presence of surface water with levels of no surface water and surface water; and soap volume with levels of full and half full. To facilitate three replicate measurements for each unique combination, three identical slabs were prepared that would allow for 40 measurements each.

Another full-factorial experiment was designed to determine the sensitivity of four-prong resistivity measurements to the potentially important operator-controlled variables of probe position with respect to the rebar with levels of transverse, longitudinal, diagonal, 3.8-cm (1.5-in.) offset from the center of the rebar, and 7.6-cm (3.0-in.) offset from the center of the rebar; presence of surface water with levels of no surface water and surface water; and prong spacing with levels of 3.8-cm (1.5-in.) and 5.1-cm (2.0-in.). To facilitate three replicate measurements for each unique combination, three identical slabs were prepared that would allow for 60 measurements each.

Two full-factorial experiments were designed to conduct a direct comparison of the sensitivity of two-prong and four-prong resistivity measurements to the potentially important concrete material variables of chloride concentration with levels of 0.0 kg of Cl^-/m^3 of concrete (0.0 lb of Cl^-/yd^3 of concrete), 5.9 kg of Cl^-/m^3 of concrete (10.0 lb of Cl^-/yd^3 of concrete), and 11.9 kg of Cl^-/m^3 of concrete (20.0 lb of Cl^-/yd^3 of concrete) and temperature with levels of 4.4°C (40.0°F) , 15.6°C (60.0°F), and 26.7°C (80.0°F). To facilitate three replicate measurements for each unique combination, three identical slabs were prepared that would allow for 18 measurements each.

After data collection was complete for each full-factorial experiment, an ANOVA was performed. In each ANOVA, factors in the reduced model having *p*-values less than or equal to 0.05 were considered to be statistically significant, and LSMs were then computed for those factors. In addition, the R^2 value was calculated for each reduced model. Differences in LSMs for different levels were considered to be practically important if they were greater than 5 kΩ-cm (2000 Ω-in.).

4 RESULTS

4.1 Overview

A discussion of the test results and statistical analyses associated with the experiments completed in this research on operator-controlled and concrete materials variables is presented in the following sections.

4.2 Concrete Properties

The slump, air content, unit weight, and 60-day compressive strength for each batch of concrete prepared in this research are shown in Table 4-1. Batches 1 to 3 were used for experimentation on operator-controlled variables; one slab for two-prong resistivity testing and one slab for four-prong resistivity testing were created from each batch. Batches 4 to 6 were

Table 4-1: Concrete Mixture Properties

Batch	Slump (cm)	Air Content (%)	Unit Weight (kg/m^3)	60-day Compressive Strength (MPa)
1	16.5	3.9	2275	36.7
2	20.3	6.4	2275	32.7
3	11.4	2.5	2225	45.8
4	15.2	4.0	2225	38.3
5	7.6	2.9	2318	44.6
6	14.6	4.5	2318	43.1

used for experimentation on concrete material variables; one slab, prepared at a specified chloride concentration, was created from each batch.

4.3 Operator-Controlled Variables

This section presents the results of statistical analyses related to operator-controlled variables, including main effects and interactions. Particular focus is placed on factors that are both statistically significant and practically important.

4.3.1 Two-Prong Resistivity Testing

Table 4-2 presents the main effects and interactions from the reduced ANOVA model for experimentation on operator-controlled variables with two-prong resistivity testing. Interactions are denoted with asterisks. The R^2 value for the reduced model indicates that 80 percent of the variation in two-prong resistivity measurements can be explained by variation in the operator-controlled variables evaluated in this research.

Table 4-2: ANOVA Results for Experimentation on Operator-Controlled Variables with Two-Prong Resistivity Testing

Factor	*p* -value
Hole Depth	<0.0001
Position	0.0744
Soap Volume	0.0263
Surface Water	<0.0001
Hole Depth*Soap Volume	0.1034
Hole Depth*Surface Water	<0.0001
Position*Soap	0.1311
Surface Water*Soap Volume	0.0729
Hole Depth*Soap Volume*Surface Water	0.0457
Position*Soap*Water	0.0264
$R^2 = 0.80$	

The *p*-values for three of the main effects and three of the interactions are less than or equal to 0.05. Consequently, for the main effects, sufficient evidence exists to reject the null hypothesis that no difference exists between the levels of each factor and to accept the alternative hypothesis that variation among the levels of each factor has a significant impact on two-prong resistivity measurements in this experimentation. For the statistically significant interactions, sufficient evidence exists to conclude that the effects of particular factors depend on the levels of other factors.

Table 4-3 presents the LSMs for the main effects shown in Table 4-2. The corrosion classification, from the data in Table 2-1, is also given for each level. Corrosion was improbable for all conditions except for when surface water was present.

The statistically significant main effects are displayed graphically in Figures 4-1 to 4-3. Figure 4-1 shows that, as hole depth increased, resistivity measurements decreased, presumably due to the increased moisture that exists at deeper hole depths. The average resistivity for the

Table 4-3: Main Effects for Experimentation on Operator-Controlled Variables with Two-Prong Resistivity Testing

Factor	Level	Resistivity Value (kΩ-cm)	Corrosion Classification
Hole Depth	0.64 cm	34.3	Improbable
	1.27 cm	25.1	Improbable
Position	1	27.9	Improbable
	2	30.7	Improbable
	3	27.5	Improbable
	4	30.9	Improbable
	5	31.4	Improbable
Soap Volume	Full	28.4	Improbable
	Half Full	30.9	Improbable
Surface Water	No	44.6	Improbable
	Yes	14.8	Moderate

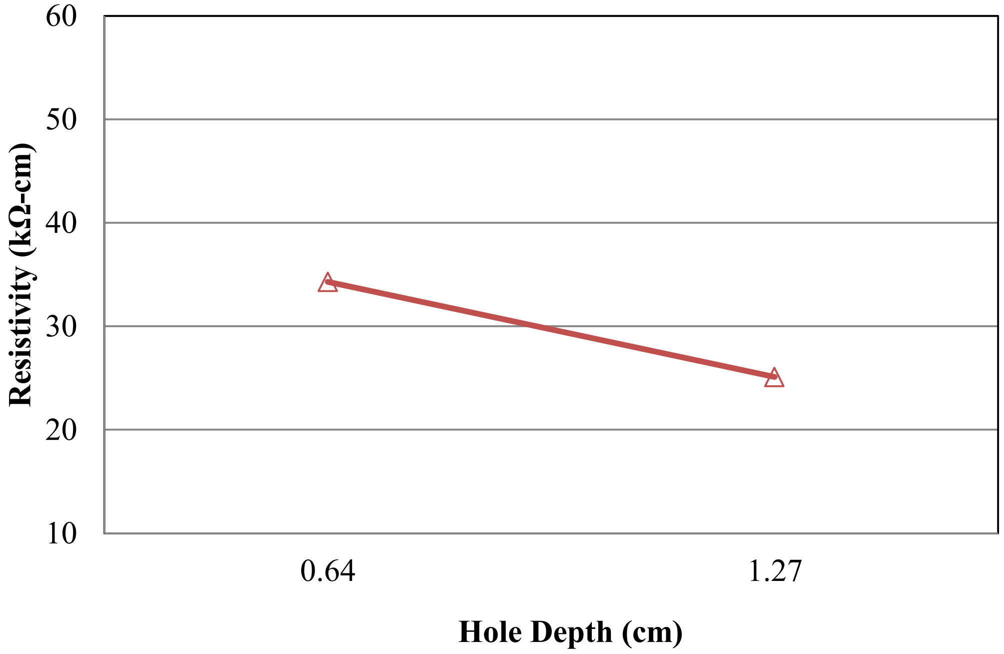


Figure 4-1: Main effect of hole depth for experimentation on operator-controlled variables with two-prong resistivity testing.

shallower hole depth was about 10 kΩ-cm (3940 Ω-in.) higher than that for the deeper hole depth, suggesting that this factor is practically important. Figure 4-2 shows that, as soap volume increased, resistivity measurements decreased; however, the change in resistivity is less than the threshold established in this research for practical importance. Figure 4-3 shows that, when water was placed on the surface before testing, resistivity measurements decreased. This main effect is both statistically significant and practically important.

Tables 4-4 to 4-7 present the LSMs for the two-way interactions shown in Table 4-2, and the statistically significant interactions are displayed graphically in Figures 4-4 to 4-6. The lines connecting data points do not imply that interpolation can be performed; they simply highlight slope differences to assist in showing interactions.

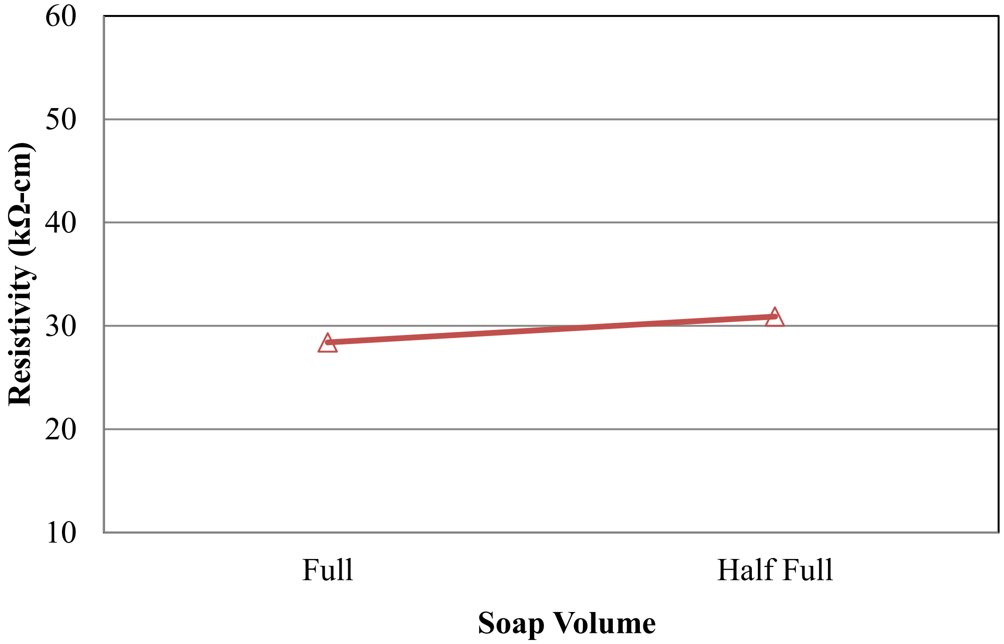


Figure 4-2: Main effect of soap volume for experimentation on operator-controlled variables with two-prong resistivity testing.

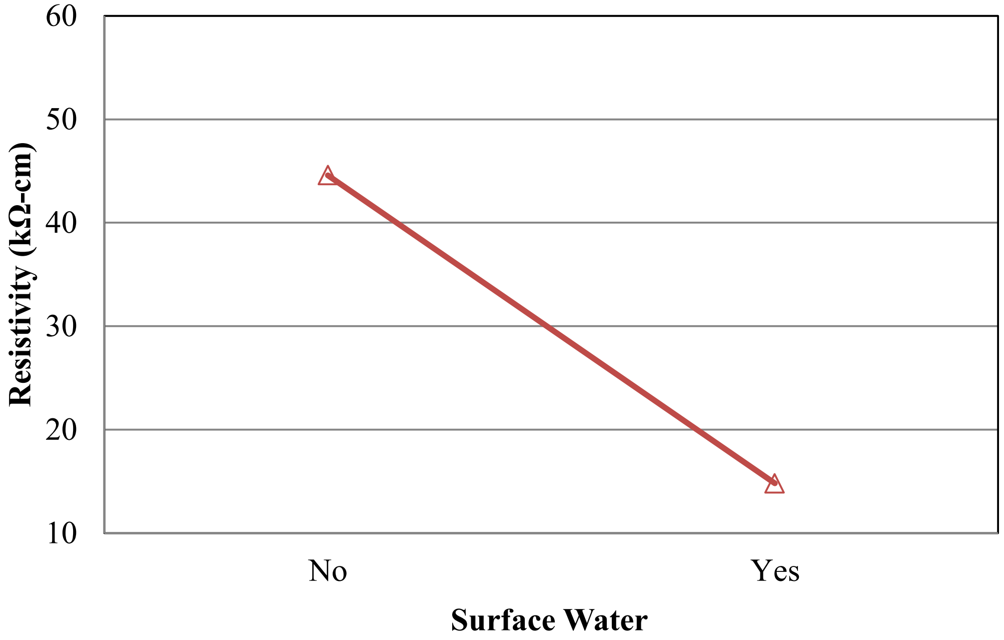


Figure 4-3: Main effect of surface water for experimentation on operator-controlled variables with two-prong resistivity testing.

Tables 4-8 and 4-9 present the LSMs for the three-way interactions shown in Table 4-2, and Figures 4-6 and 4-7 display those that are statistically significant. Among all these interactions, only the interaction between hole depth and surface water is both statistically significant and practically important. At the shallower hole depth of 0.64 cm (0.25 in.), the effect of surface water on resistivity was more pronounced than at the deeper hole depth of 1.27 cm (0.50 in.), with a greater decrease in resistivity occurring in the presence of surface water at the shallower hole depth.

Table 4-4: Two-Way Interaction between Hole Depth and Soap Volume for Experimentation on Operator-Controlled Variables with Two-Prong Resistivity Testing

Hole Depth	Soap Volume	
	Full	Half Full
0.64 cm	33.9	34.6
1.27 cm	22.9	27.3

Table 4-5: Two-Way Interaction between Position and Soap Volume for Experimentation on Operator-Controlled Variables with Two-Prong Resistivity Testing

Position	Soap Volume	
	Full	Half Full
1	25.3	30.4
2	30.1	31.3
3	27.9	27.2
4	27.4	34.3
5	31.5	31.4

Table 4-6: Two-Way Interaction between Hole Depth and Surface Water for Experimentation on Operator-Controlled Variables with Two-Prong Resistivity Testing

Hole Depth	Surface Water	
	No	Yes
0.64 cm	52.1	16.4
1.27 cm	37.1	13.1

Table 4-7: Two-Way Interaction between Soap Volume and Surface Water for Experimentation on Operator-Controlled Variables with Two-Prong Resistivity Testing

Soap Volume	Surface Water	
	No	Yes
Full	42.3	14.5
Half Full	46.9	15.0

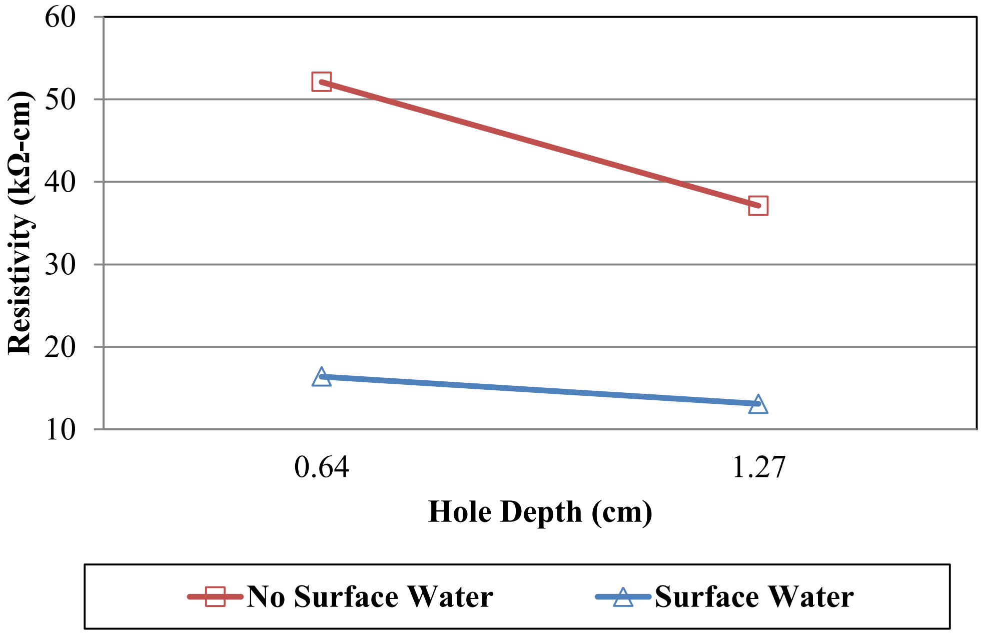


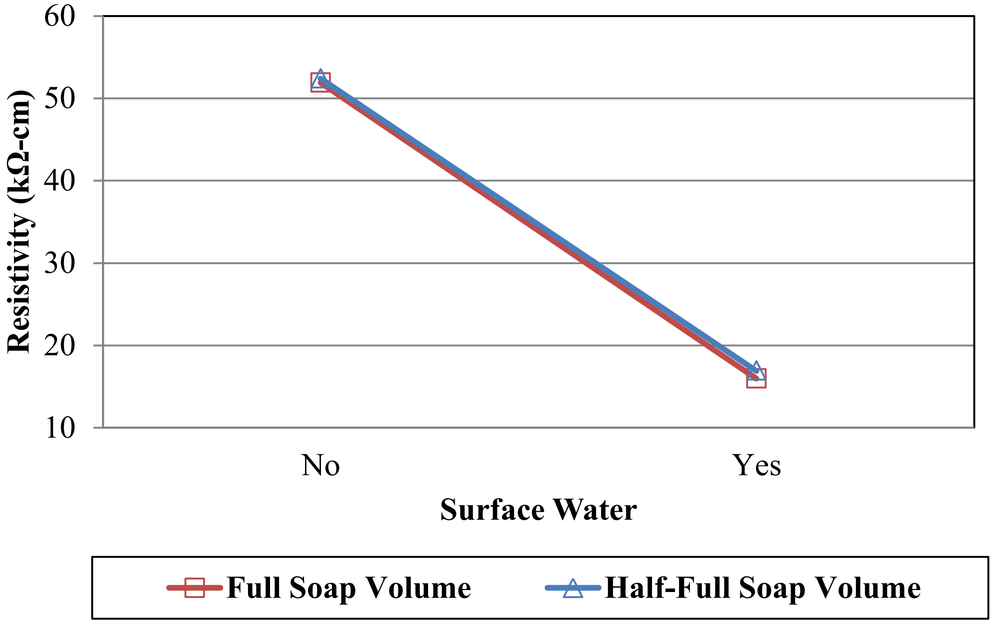
Figure 4-4: Two-way interaction between hole depth and surface water for experimentation on operator-controlled variables with two-prong resistivity testing.

Table 4-8: Three-Way Interaction between Hole Depth, Soap Volume, and Surface Water for Experimentation on Operator-Controlled Variables with Two-Prong Resistivity Testing

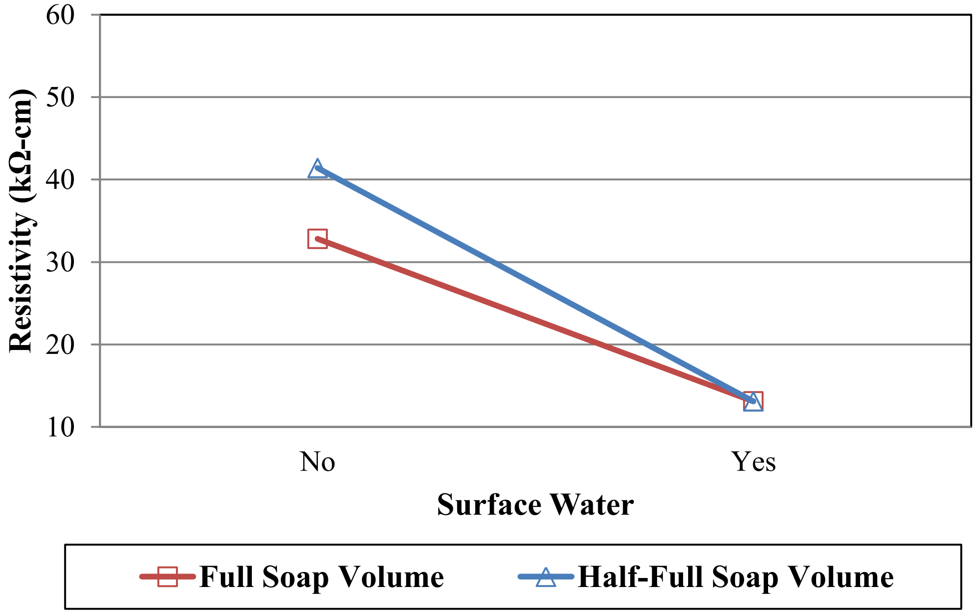
Hole Depth (cm)	Soap Volume	Surface Water	Resistivity Value (kΩ-cm)
0.64	Full	No	51.9
	Half Full		52.4
1.27	Full	No	32.8
	Half Full		41.4
0.64	Full	Yes	16.0
	Half Full		16.9
1.27	Full	Yes	13.1
	Half Full		13.1

Table 4-9: Three-Way Interaction between Position, Soap Volume, and Surface Water for Experimentation on Operator-Controlled Variables with Two-Prong Resistivity Testing

Position	Soap Volume	Surface Water	Resistivity Value (kΩ-cm)
1	Full	No	38.2
	Half Full		46.4
	Full	Yes	12.4
	Half Full		14.4
2	Full	No	44.8
	Half Full		49.2
	Full	Yes	15.4
	Half Full		13.4
3	Full	No	42.7
	Half Full		38.8
	Full	Yes	13.1
	Half Full		15.6
4	Full	No	38.5
	Half Full		54.2
	Full	Yes	14.5
	Half Full		13.1
5	Full	No	47.6
	Half Full		45.8
	Full	Yes	15.4
	Half Full		17.1

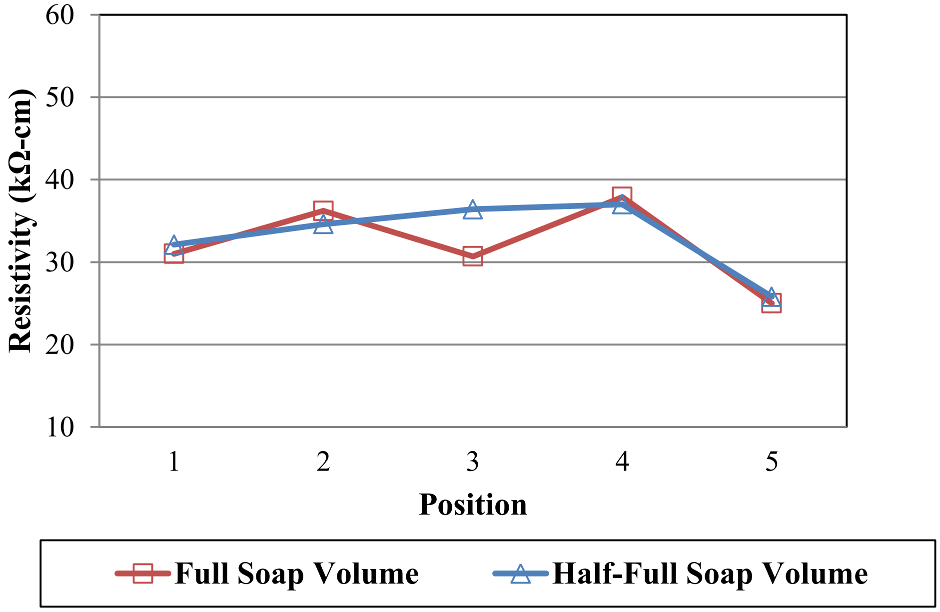


a) Depth of 0.64 cm.

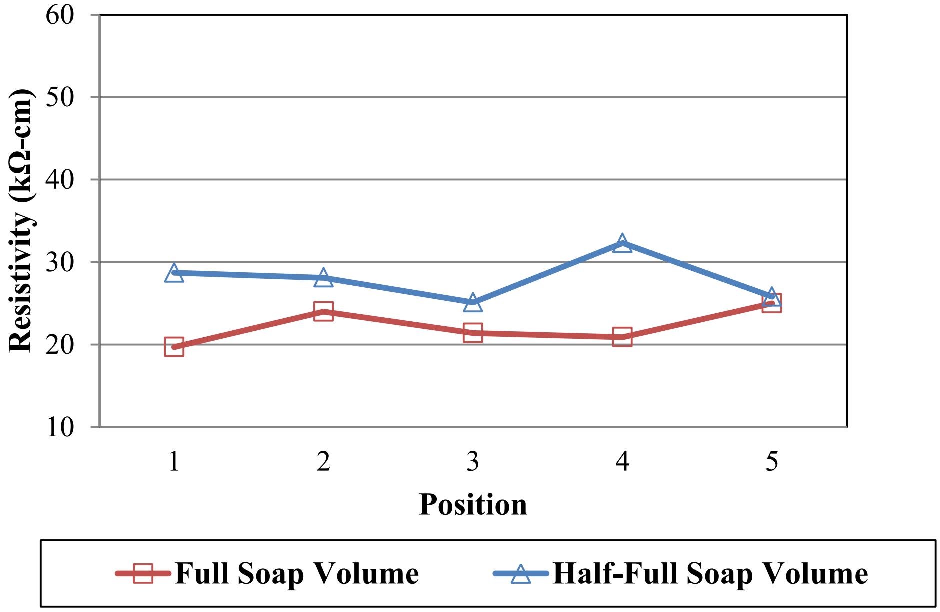


b) Depth of 1.27 cm.

Figure 4-5: Three-way interaction between hole depth, soap volume, and surface water for experimentation on operator-controlled variables with two-prong resistivity testing.



a) Depth of 0.64 cm.



b) Depth of 1.27 cm.

Figure 4-6: Three-way interaction between hole depth, position, and soap volume for experimentation on operator-controlled variables with two-prong resistivity testing.

4.3.2 Four-Prong Resistivity Testing

Table 4-10 presents the main effects from the reduced ANOVA model for experimentation on operator-controlled variables with four-prong resistivity testing. No interactions were included in the reduced model. The R^2 value for the model indicates that only 4 percent of the variation in four-prong resistivity measurements can be explained by variation in the operator-controlled variables evaluated in this research; the remaining variation remains unexplained, not being attributable to any particular source. This high degree of unexplained variation may be of concern to practitioners. Table 4-11 presents the LSMs for the main effects shown in Table 4-10. The corrosion classification, from the data in Table 2-1, is also given for each level. Corrosion was improbable for all conditions except for when surface water was present.

Table 4-10: ANOVA Results for Experimentation on Operator-Controlled Variables with Four-Prong Resistivity Testing

Factor	*p* -value
Prong Spacing	0.1262
Surface Water	0.0953
$R^2 = 0.04$	

Table 4-11: Main Effects for Experimentation on Operator-Controlled Variables with Four-Prong Resistivity Testing

Factor	Level	Resistivity Value (kΩ-cm)	Corrosion Classification
Prong Spacing	3.8 cm	25.2	Improbable
	5.1 cm	20.8	Improbable
Surface Water	No	25.4	Improbable
	Yes	20.6	Improbable

The *p*-values for both of the main effects are larger than 0.05, which indicates that insufficient evidence exists to reject the null hypothesis that no difference exists between the levels of each factor. Therefore, neither of the main effects is statistically significant.

4.4 Concrete Material Variables

This section presents the results of statistical analyses related to concrete material variables, including main effects and interactions. Particular focus is placed on factors that are both statistically significant and practically important.

4.4.1 Two-Prong Resistivity Testing

Table 4-12 presents the main effects from the reduced ANOVA model for experimentation on concrete material variables with two-prong resistivity testing. No interactions were included in the reduced model. The R^2 value for the reduced model indicates that 80 percent of the variation in two-prong resistivity measurements can be explained by variation in the concrete material variables evaluated in this research.

The *p*-values for the main effects of chloride concentration and temperature are less than or equal to 0.05. Consequently, for the main effects, sufficient evidence exists to reject the null

Table 4-12: ANOVA Results for Experimentation on Concrete Material Variables with Two-Prong Resistivity Testing

Factor	*p*-value
Chloride Concentration	<0.0001
Temperature	<0.0001
$R^2 = 0.80$	

hypothesis that no difference exists between the levels of each factor and to accept the alternative hypothesis that variation among the levels of each factor has a significant impact on two-prong resistivity measurements in this experimentation.

Table 4-13 presents the LSMs for the main effects shown in Table 4-12. The corrosion classification, from the data in Table 2-1, is also given for each level. Corrosion was improbable for all conditions.

Figures 4-7 and 4-8 illustrate the inverse relationships between resistivity and both chloride concentration and temperature, where resistivity decreased by about 30 kΩ-cm (12,000 Ω-in.) as chloride concentration increased from 0.0 kg of Cl^-/m^3 of concrete (0.0 lb of Cl^-/yd^3 of concrete) to 11.9 kg of Cl^-/m^3 of concrete (20.0 lb of Cl^-/yd^3 of concrete) or as temperature increased from 4.4°C (40.0°F) to 26.7°C (80.0°F). Both of these factors are therefore practically important.

Table 4-13: Main Effects for Experimentation on Concrete Material Variables with Two-Prong Resistivity Testing

Factor	Level	Resistivity Value (kΩ-cm)	Corrosion Classification
Chloride Concentration	0.0 kg of Cl^-/m^3 of Concrete	66.7	Improbable
	5.9 kg of Cl^-/m^3 of Concrete	54.6	Improbable
	11.9 kg of Cl^-/m^3 of Concrete	36.1	Improbable
Temperature	4.4˚C	68.5	Improbable
	15.6˚C	52.4	Improbable
	26.7˚C	36.4	Improbable

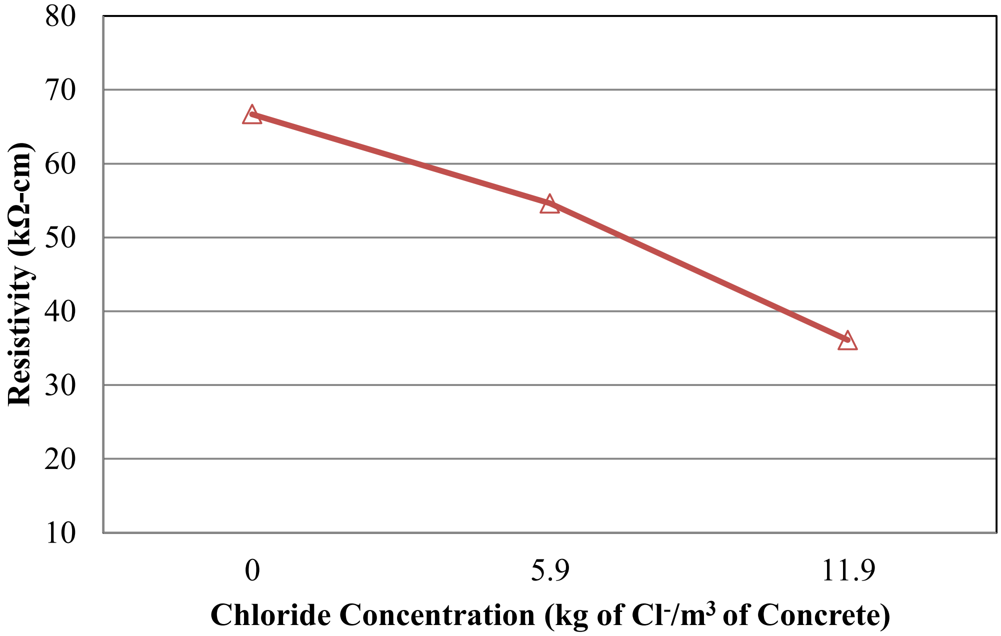


Figure 4-7: Main effect of chloride concentration for experimentation on concrete material variables with two-prong resistivity testing.

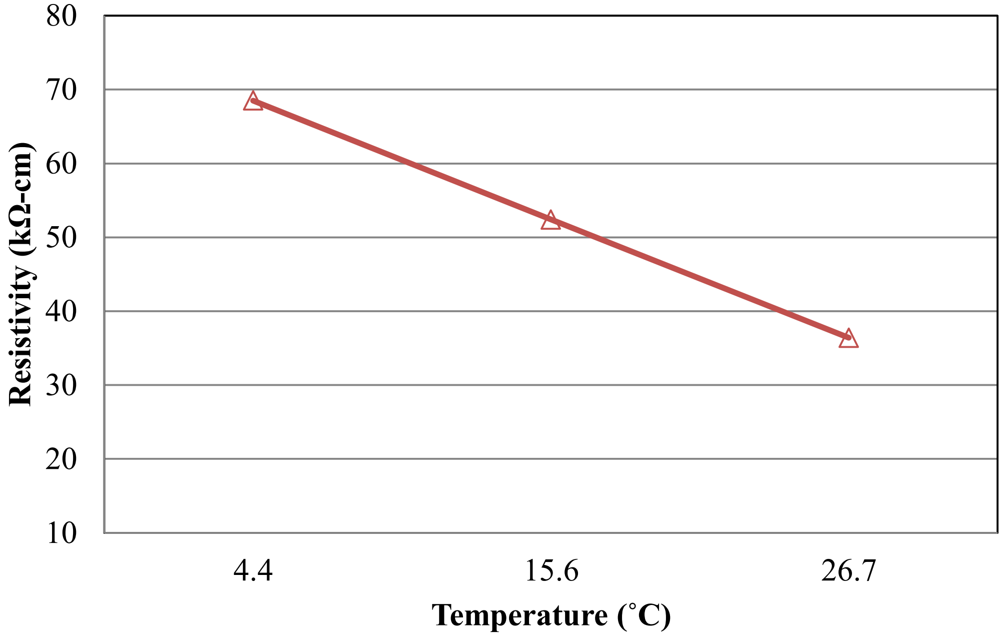


Figure 4-8: Main effect of temperature for experimentation on concrete material variables with two-prong resistivity testing.

4.4.2 Four-Prong Resistivity Testing

Table 4-14 presents the main effects from the reduced ANOVA model for experimentation on concrete material variables with four-prong resistivity testing. No interactions were included in the reduced model. The R^2 value for the reduced model indicates that 88 percent of the variation in four-prong resistivity measurements can be explained by variation in the concrete material variables evaluated in this research.

The *p*-values for the main effects of chloride concentration and temperature are less than or equal to 0.05. Consequently, for the main effects, sufficient evidence exists to reject the null hypothesis that no difference exists between the levels of each factor and to accept the alternative hypothesis that variation among the levels of each factor has a significant impact on four-prong resistivity measurements in this experimentation.

Table 4-15 presents the LSMs for the main effects shown in Table 4-14. The corrosion classification, from the data in Table 2-1, is also given for each level. Corrosion was improbable for all conditions.

Similar to Figures 4-7 and 4-8, Figures 4-9 and 4-10 illustrate the inverse relationships between resistivity and both chloride concentration and temperature, although in this case the differences in resistivity across the levels of chloride concentration are not as large. Resistivity decreased by about 10 kΩ-cm (3900 Ω-in.) as chloride concentration increased from 0.0 kg of

Table 4-14: ANOVA Results for Experimentation on Concrete Material Variables with Four-Prong Resistivity Testing

Factor	*p* -value
Chloride Concentration	<0.0001
Temperature	<0.0001
$R^2 = 0.88$	

Table 4-15: Main Effects for Experimentation on Concrete Material Variables with Four-Prong Resistivity Testing

Factor	Level	Resistivity Value (kΩ-cm)	Corrosion Classification
Chloride Concentration	0.0 kg of Cl^-/m^3 of Concrete	45.8	Improbable
	5.9 kg of Cl^-/m^3 of Concrete	38.6	Improbable
	11.9 kg of Cl^-/m^3 of Concrete	33.7	Improbable
Temperature	4.4˚C	57.6	Improbable
	15.6˚C	35.6	Improbable
	26.7˚C	24.9	Improbable

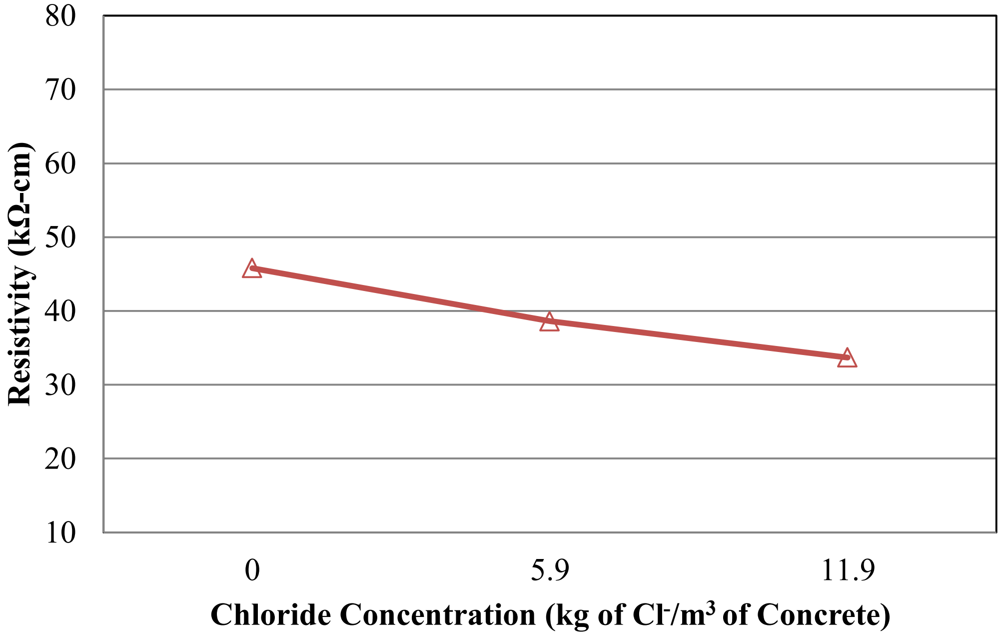


Figure 4-9: Main effect of chloride concentration for experimentation on concrete material variables with four-prong resistivity testing.

Cl^-/m^3 of concrete (0.0 lb of Cl^-/yd^3 of concrete) to 11.9 kg of Cl^-/m^3 of concrete (20.0 lb of Cl^-/yd^3 of concrete) while decreasing by about 30 kΩ-cm (12,000 Ω-in.) as temperature increased from 4.4°C (40.0°F) to 26.7°C (80.0°F). Both of these factors are therefore practically important.

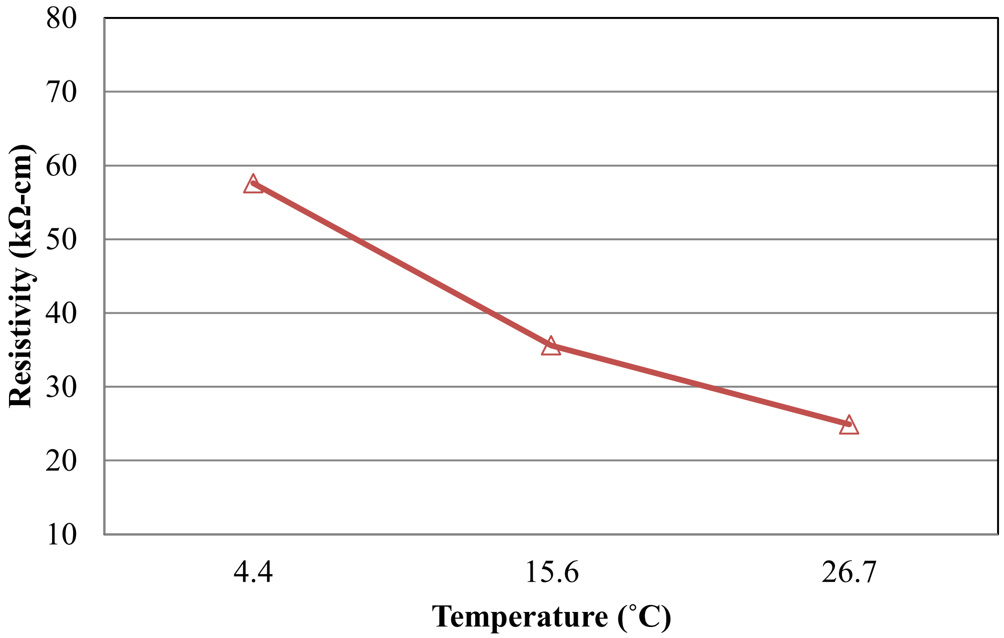


Figure 4-10: Main effect of temperature for experimentation on concrete material variables with four-prong resistivity testing.

4.5 Summary

In the experimentation on operator-controlled variables with two-prong resistivity testing, the R^2 value for the reduced ANOVA model indicates that 80 percent of the variation in two-prong resistivity measurements can be explained by variation in the operator-controlled variables evaluated in this research. Main effects that are both statistically significant and practically important include hole depth and surface water. The data show that, as hole depth increased, resistivity measurements decreased, presumably due to the increased moisture that exists at deeper hole depths. The data also show that, when water was placed on the surface before testing, resistivity measurements decreased. Only the interaction between hole depth and surface water is both statistically significant and practically important. At the shallower hole depth, the effect of surface water on resistivity was more pronounced than at the deeper hole depth, with a greater decrease in resistivity occurring in the presence of surface water at the shallower hole depth. Neither probe position nor soap volume is both statistically significant and practically important.

In the experimentation on operator-controlled variables with four-prong resistivity testing, the R^2 value for the reduced ANOVA model indicates that only 4 percent of the variation in four-prong resistivity measurements can be explained by variation in the operator-controlled variables evaluated in this research; the remaining variation remains unexplained, not being attributable to any particular source. Probe position, surface water, and prong spacing are all neither statistically significant nor practically important. This high degree of unexplained variation may be of concern to practitioners.

In the experimentation on concrete material variables with two-prong and four-prong resistivity testing, the R^2 values for the reduced ANOVA models indicate that 80 and 88 percent, respectively, of the variation in two-prong and four-prong resistivity measurements can be explained by variation in the concrete material variables evaluated in this research. In both cases, main effects that are both statistically significant and practically important include chloride concentration and temperature, both of which exhibit inverse relationships with resistivity.

5 CONCLUSION

5.1 Summary

A primary cause of premature failure of concrete bridge decks is corrosion caused by deicing salts applied during winter maintenance. An increasingly popular non-destructive method for evaluating chloride-induced corrosion of concrete bridge decks is electrical resistivity testing. Two common hand-held devices for testing the resistivity of concrete are the two-prong and four-prong resistivity resistivity instruments. The objectives of this research were to investigate the sensitivity of two-prong and four-prong resistivity measurements to certain operator-controlled variables and to conduct a direct comparison of the sensitivity of two-prong and four-prong resistivity measurements to certain concrete material variables.

Four full-factorial experiments were designed with varying factors and levels to determine the sensitivity of two-prong and four-prong resistivity measurements to operator-controlled factors and concrete material variables. In the process of designing formal experimentation to investigate the sensitivity of resistivity measurements to operator-controlled factors, several preparatory tests were conducted to determine which factors merited inclusion in a full-factorial experiment.

One full-factorial experiment was designed with four factors and varying levels to determine the sensitivity of two-prong resistivity measurements to the potentially important operator-controlled variables of drilled hole depth with levels of 0.64 cm (0.25 in.) and 1.27 cm

(0.50 in.); probe position with respect to the rebar with levels of transverse, longitudinal, diagonal, 3.8-cm (1.5-in.) offset from the center of the rebar, and 7.6-cm (3.0-in.) offset from the center of the rebar; presence of surface water with levels of no surface water and surface water; and soap volume with levels of full and half full. To facilitate three replicate measurements for each unique combination, three identical slabs were prepared that would allow for 40 measurements each.

Another full-factorial experiment was designed to determine the sensitivity of four-prong resistivity measurements to the potentially important operator-controlled variables of probe position with respect to the rebar with levels of transverse, longitudinal, diagonal, 3.8-cm (1.5-in.) offset from the center of the rebar, and 7.6-cm (3.0-in.) offset from the center of the rebar; presence of surface water with levels of no surface water and surface water; and prong spacing with levels of 3.8-cm (1.5-in.) and 5.1-cm (2.0-in.). To facilitate three replicate measurements for each unique combination, three identical slabs were prepared that would allow for 60 measurements each.

Two full-factorial experiments were designed to conduct a direct comparison of the sensitivity of two-prong and four-prong resistivity measurements to the potentially important concrete material variables of chloride concentration with levels of 0.0 kg of Cl^-/m^3 of concrete (0.0 lb of Cl^-/yd^3 of concrete), 5.9 kg of Cl^-/m^3 of concrete (10.0 lb of Cl^-/yd^3 of concrete), and 11.9 kg of Cl^-/m^3 of concrete (20.0 lb of Cl^-/yd^3 of concrete) and temperature with levels of 4.4°C (40.0°F) , 15.6°C (60.0°F), and 26.7°C (80.0°F). To facilitate three replicate measurements for each unique combination, three identical slabs were prepared that would allow for 18 measurements each.

After data collection was complete for each full-factorial experiment, an ANOVA was performed. In each ANOVA, factors in the reduced model having *p*-values less than or equal to 0.05 were considered to be statistically significant, and LSMs were then computed for those factors. In addition, the R^2 value was calculated for each reduced model. Differences in LSMs for different levels were considered to be practically important if they were greater than 5 kΩ-cm (2000 Ω-in.).

5.2 Findings

In the experimentation on operator-controlled variables with two-prong resistivity testing, the R^2 value for the reduced ANOVA model indicates that 80 percent of the variation in two-prong resistivity measurements can be explained by variation in the operator-controlled variables evaluated in this research. Main effects that are both statistically significant and practically important include hole depth and surface water. The data show that, as hole depth increased, resistivity measurements decreased, presumably due to the increased moisture that exists at deeper hole depths. The data also show that, when water was placed on the surface before testing, resistivity measurements decreased. Only the interaction between hole depth and surface water is both statistically significant and practically important. At the shallower hole depth, the effect of surface water on resistivity was more pronounced than at the deeper hole depth, with a greater decrease in resistivity occurring in the presence of surface water at the shallower hole depth. Neither probe position nor soap volume is both statistically significant and practically important.

In the experimentation on operator-controlled variables with four-prong resistivity testing, the R^2 value for the reduced ANOVA model indicates that only 4 percent of the variation in four-prong resistivity measurements can be explained by variation in the operator-controlled variables evaluated in this research; the remaining variation remains unexplained, not being attributable to any particular source. Probe position, surface water, and prong spacing are all neither statistically significant nor practically important. This high degree of unexplained variation may be of concern to practitioners.

In the experimentation on concrete material variables with two-prong and four-prong resistivity testing, the R^2 values for the reduced ANOVA models indicate that 80 and 88 percent, respectively, of the variation in two-prong and four-prong resistivity measurements can be explained by variation in the concrete material variables evaluated in this research. In both cases, main effects that are both statistically significant and practically important include chloride concentration and temperature, both of which exhibit inverse relationships with resistivity.

5.3 Recommendations

These research findings support several important recommendations for resistivity testing. Since the two-prong resistivity device is sensitive to hole depth, operators should use an accurately positioned drill stop to ensure that the prepared holes are consistently the correct depth. Furthermore, operators using the two-prong resistivity device should expect to obtain different values depending on the presence of surface water on the deck surface; thus, to ensure proper interpretation of collected data, protocols for resistivity testing should include instructions about whether or not the operator should apply surface water prior to a test. When testing bridge decks with concrete material properties and cover depths similar to those investigated in this research, operators using the two-prong resistivity device should not be concerned about probe position with respect to rebar. Furthermore, although the operator must be trained not to spill soap between the two drilled holes, tight control over the level to which the holes are filled, between full and half full after the prongs are inserted, is not required.

Operators considering use of the four-prong resistivity device should not expect the measurements to be sensitive to probe position with respect to rebar, presence of surface water, or prong spacing for conditions similar to those investigated in this research. Depending on the objectives of the testing, this device may therefore be unsuitable for use even when specific improvements to the probe have been incorporated to increase the repeatability of the measurements as demonstrated in this research.

Both the two-prong and four-prong resistivity devices are sensitive to chloride concentration and may therefore be useful non-destructive tools for evaluating chloride-induced corrosion of concrete bridge decks. However, since both the two-prong and four-prong resistivity devices are sensitive to concrete temperature, operators interested in monitoring resistivity values over time to ascertain material changes in a bridge deck should develop protocols for measuring concrete temperature in the field and subsequently normalizing resistivity measurements to a standard temperature. Accounting for differences in deck temperature from testing time to testing time will ensure more meaningful comparisons of resistivity values in deck monitoring programs.

REFERENCES

1. Song, H. W., and V. Saraswathy. Corrosion Monitoring of Reinforced Concrete StructuresA Review. *International Journal of Electrochemical Science*, Vol. 2, 2007, pp. 1-28.

2. Guthrie, W. S., and R. S. Tuttle. *Condition Analysis of Concrete Bridge Decks in Utah*. Report UT-06.01. Department of Civil and Environmental Engineering, Brigham Young University, Provo, UT, February 2006.

3. Bungey, J. H., and S. G. Millard. *Testing of Concrete in Structures*. Chapman and Hall, Cambridge, United Kingdom, 1996.

4. Guthrie, W. S., E. T. Linford, and D. Eixenberger. Development of an Index for Concrete Bridge Deck Management in Utah. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1991, Transportation Research Board of the National Research Academies, Washington, DC, 2007, pp. 35-42.

5. Guthrie, W. S., and T. M. Pinkerton. *Sensitivity of Half-Cell Potential Measurements to Properties of Concrete Bridge Decks*. Report UT-08.21. Department of Civil and Environmental Engineering, Brigham Young University, Provo, UT, October 2008.

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

7. Böhni, H. *Corrosion in Reinforced Concrete Structures*. CRC Press, Inc., Boca Raton, FL, 2005.

8. Hema, J., W. S. Guthrie, and F. Fonseca. *Concrete Bridge Deck Condition Assessment and Improvement Strategies*. Report UT-04.16. Department of Civil and Environmental Engineering, Brigham Young University, Provo, UT, 2005.

9. Morris, W., E. I. Moreno, and A. A. Sagüés. Practical Evaluation of Resistivity of Concrete in Test Cylinders Using a Wenner Array Probe. *Cement and Concrete Research*, Vol. 26, No. 12, 1996, pp. 1779-1787.

10. Whiting, D. A., and M. A. Naji. *Electrical Resistivity of Concrete—A Literature Review*. PCA R&D Serial No. 2457. Portland Cement Association, Skokie, IL, 2003.

11. Malhotra, V. M., and N. J. Carino. *Handbook on Nondestructive Testing of Concrete*. CRC Press, Inc., Boca Raton, FL, 1991.

12. *RM-8000 Resistivity Meter Instruction Manual*. James Instruments, Inc., Chicago, IL, 2004.

13. Pullar-Strecker, P. *Concrete Reinforcement Corrosion*. Thomas Telford Publishing, Heron Quay, London, United Kingdom, 2002.

14. Broomfield, J. P. *Corrosion of Steel in Concrete—Understanding, Investigating and Repair*. E&FN Spon, New York, NY, 1997.

15. Monfore, G. E. The Electrical Resistivity of Concrete. *Journal of the PCA Research and Development Laboratories*, Vol. 10, No. 2, May, 1968, pp. 35-48.

16. Malhotra, V. M. *Testing Hardened Concrete: Nondestructive Methods*. American Concrete Institute, Detroit, MI, 1976.

17. Brameshuber, I. W., and I. M. Raupach. Nondestructive Determination of the Water-Content in the Concrete Cover Using the Multiring-Electrode. In *Proceedings of the International Symposium of Non-Destructive Testing in Civil Engineering*, Berlin, Germany, September 16-19, 2003.

18. *RM MK II Concrete Resistivity Meter Model U95 Manual*. CNS Farnell Limited, Hertfordshire, United Kingdom, 2008.

19. Nolan, C. *Effect of Initial Scarification and Overlay Treatment Timing on Chloride Concentrations in Concrete Bridge Decks*. M.S. thesis. Department of Civil and Environmental Engineering, Brigham Young University, Provo, UT, 2008.

20. Rupnow, T. D., and P. Icenogle. Evaluation of Surface Resistivity Measurements As an Alternative to the Rapid Chloride Permeability Test for Quality Assurance and Acceptance. In *Proceedings of the Louisiana Transportation Conference*, Baton Rouge, LA, January 9-11, 2011.

21. Sengul, O., and O. Gjorv. Effect of Embedded Steel on Electrical Resistivity Measurements on Concrete Structures. *ACI Materials Journal*, Vol. 106, January-February 2009, pp. 11-18.

22. *Guideline for the Selection of Snow and Ice Control Materials to Mitigate Environmental Impacts*. NCHRP Report No. 577. Levelton Consultants Limited, Richmond, British Columbia, Canada, 2007.

APPENDIX A. PREPARATORY TESTING

A.1 Overview

Preparatory testing was conducted in order to determine which operator-controlled variables had a significant effect on resistivity measurements and merited inclusion in full-factorial experimentation. Both the two-prong and four-prong resistivity instruments were evaluated.

A.2 Two-Prong Resistivity Measurements

The preparatory tests for two-prong resistivity measurements included evaluations of type of soap, volume of soap, time after soap application, and time after surface water application. Information regarding the procedures and results are given in the following sections.

A.2.1 Procedures

The operator-controlled variables investigated in the preparatory testing for two-prong resistivity measurements included type of soap, volume of soap, time after soap application, and time after surface water application. To evaluate type of soap, electrical conductivity testing was performed on each of seven different liquid dishwashing soaps. The electrical conductivity of the soap was measured at room temperature with a pH/conductivity probe.

For volume of soap testing, two levels of soap volume, full and half-full, were investigated to determine a specific number of soap drops for the corresponding level. For this analysis, three sets of 0.9-cm (0.375-in.) holes were drilled around the edge of each slab designed for full-factorial testing. A soap-filled, pharmaceutical-type dispenser was then used to insert one drop of soap into each drilled hole before the two-prong resistivity probe was inserted. Subsequent drops were added individually until the full and half-full soap volume was quantified. This testing was performed at a constant temperature of 15.6°C (60.0°F) inside an environmental chamber.

To evaluate time after soap application, one set of 0.9-cm (0.375-in.) holes was drilled on the edge of each of the three slabs prepared for two-prong resistivity testing. In order to accurately reach the required hole depth, a drill stop was placed on the masonry drill bit. After drilling was complete, the concrete powder was removed from the hole with a vacuum. Immediately after the hole was cleaned, three drops of soap were placed in each hole before the two-prong resistivity probe was inserted. Measurements continued at specified time intervals for a 24-hr period, during which no additional soap drops were added to the holes. This testing procedure was repeated for the remaining two slabs. Again, the work was performed at a constant temperature of 15.6°C (60.0°F) inside an environmental chamber.

Two approaches were used to evaluate time after surface water application. The first procedure, the spray method, was a one-time application of surface water. The second procedure, the towel method, was the constant application of surface water. The spray and towel methods simulate the application of surface water on a bridge deck after a dry spell or after a rainstorm, respectively. Both of these approaches were evaluated simultaneously by partitioning each slab and testing one method on each side. Each half was further partitioned into three sections, one for each of three repetitions. This experimentation was conducted at a temperature of 15.5°C (60.0°F) in the environmental chamber; about 0.2 kg (0.4 lb) of distilled water was sprayed onto each concrete slab, covering a third of the slab at a time. Immediately after the surface was saturated with water, two holes were drilled on each half. Three drops of soap were placed in each hole, and resistivity measurements were recorded. This testing continued at specified time intervals for an 8-hr period. For the spray method, a plastic covering was placed on the surface of the slab immediately after it was sprayed to minimize evaporation of the surface water. For the towel method, a water-soaked towel was placed on the surface of the slab immediately after each reading.

A.2.2 Results

Results were obtained for the operator-controlled variables of type of soap, volume of soap, time after soap application, and time after surface water application. For type of soap, the electrical conductivities of the soaps ranged from 16.9 mS/cm (0.00670 S/in.) to 24.2 mS/cm (0.00950 S/in.). However, since the electrical conductivity of concrete, even at highly corrosive rates, is much lower at 0.2 mS/cm (0.00008 S/in.) than the electrical conductivity of any of the soaps tested, type of soap was not included in the full-factorial testing. The soap exhibiting the average electrical conductivity was selected for experimentation.

For volume of soap, two drops and one drop were necessary to achieve full and half-full conditions, respectively, for a hole depth of 0.64 cm (0.25 in.). Four drops and two drops were necessary to achieve full and half-full conditions, respectively, for a hole depth of 1.27 cm (0.5 in.). Since the depth of 1.27 cm (0.5 in.) is twice the depth of 0.64 cm (0.25 in.), the number of drops required for the former was twice that required for the latter.

For time after soap application, measured resistivity values are presented in Figure A-1. Each resistivity value measured after the initial value was compared to the initial value. The threshold for evaluation was defined as the time at which a subsequent reading was different than the initial value by more than 5 kΩ-cm (2000 Ω-in.), which is the smallest threshold in Table 2-1. After one minute, the difference in resistivity measurements exceeded the threshold, which which suggests that readings taken before that time will be essentially the same under circumstances similar to those investigated in this research.

For time after surface water application, measured resistivity values are presented in Figure A-2. When the spray method was used for testing, resistivity values decreased during the first 15 minutes and then gradually increased over the remainder of the testing period. When the towel method was used, resistivity values decreased gradually throughout the testing period. For

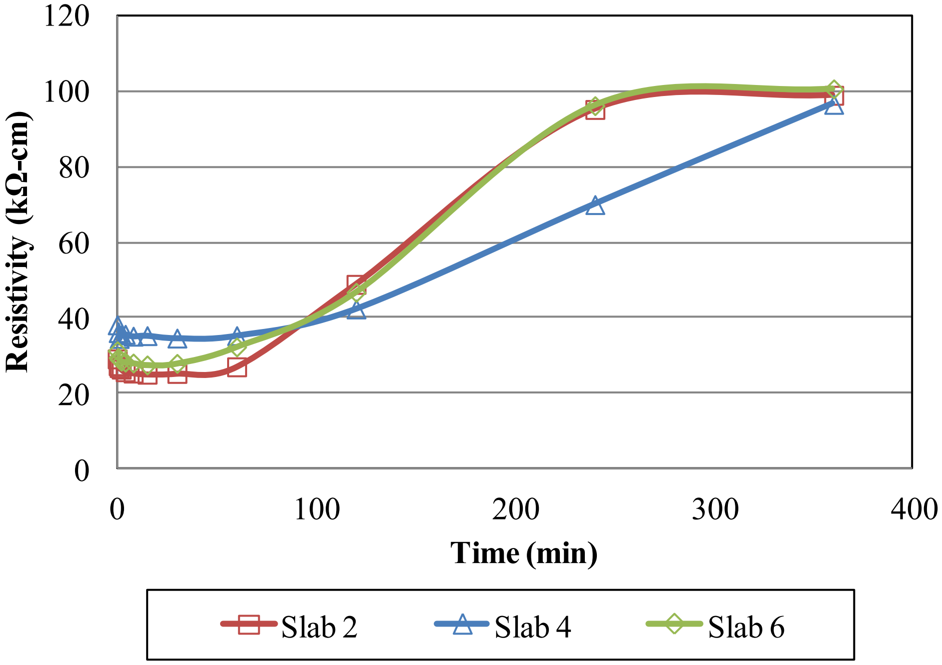


Figure A-1: Time effect of soap application on two-prong resistivity values.

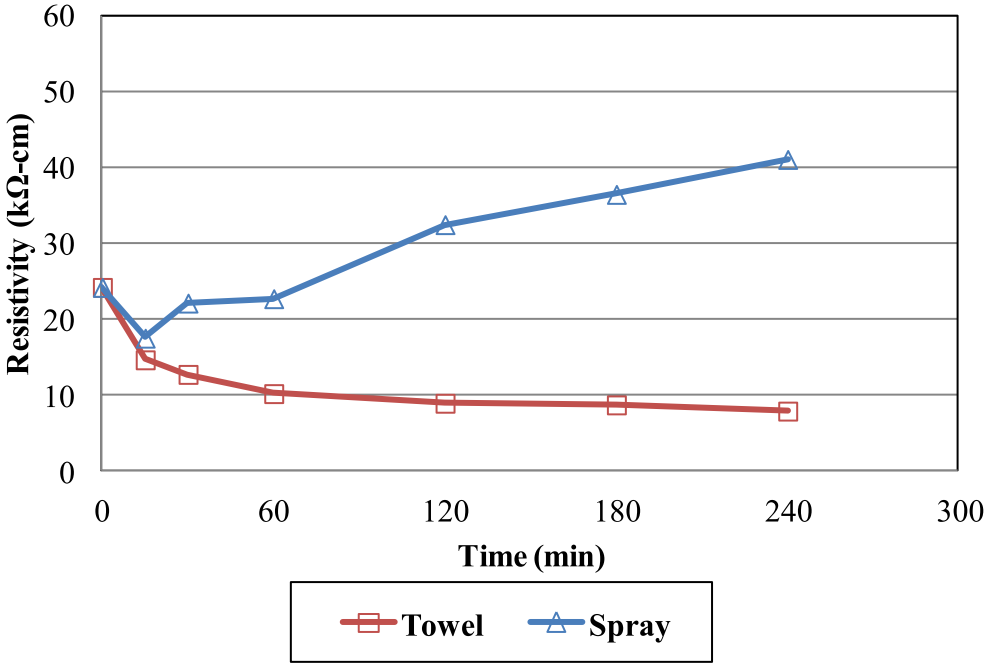


Figure A-2: Time effect of surface water application on two-prong resistivity values.

evaluation of these data, the same threshold of 5 kΩ-cm (2000 Ω-in.) was utilized. After 20 minutes, the difference in resistivity measurements between the two methods exceeded the threshold, which suggests that readings taken before that time will be essentially the same under circumstances similar to those investigated in this research.

A.3 Four-Prong Resistivity Measurements

The preparatory tests for four-prong resistivity measurements included evaluations of weight applied to the probe and time after surface water application. Information regarding the procedures and results are given in the following sections.

A.3.1 Procedures

The operator-controlled variables investigated in the preparatory testing for four-prong resistivity measurements included weight applied to the probe and time after surface water application. Before preparatory testing commenced, a customized, free-standing probe holder was designed and fabricated to ensure greater uniformity in testing. Appropriate weights were situated on the probe handle so that the total weight of the probe, weights, and holder was 2.3 kg (5.0 lb), 4.5 kg (10.0 lb), or 6.8 kg (15.0 lb). In addition, the original springs on the middle two prongs of the probe were replaced with stiffer ones to ensure that the applied weight was distributed more uniformly across all of the prongs. In order to measure the distribution of applied weight, two scales were leveled and aligned side by side as depicted in Figure A-3.

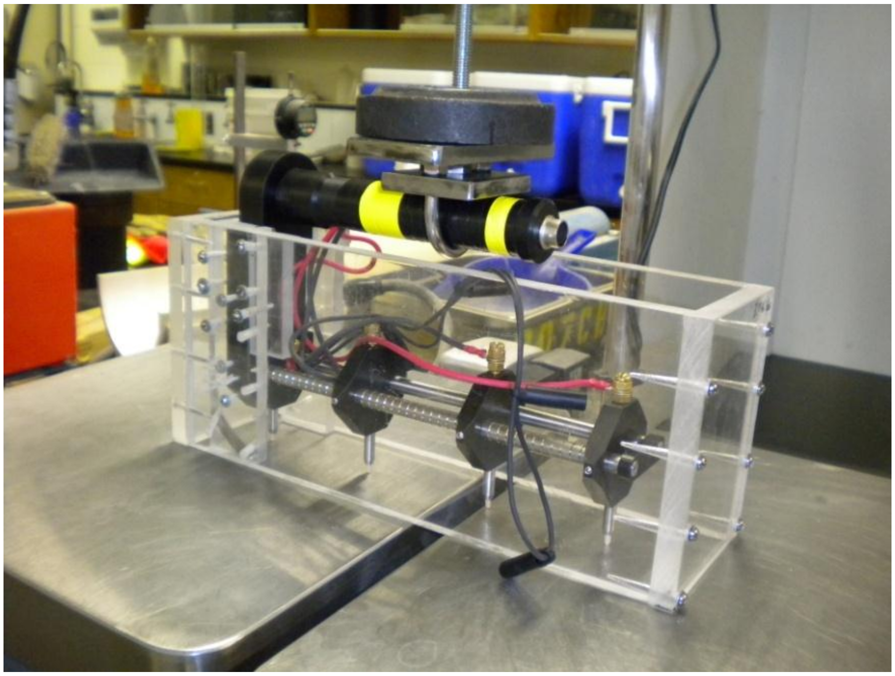


Figure A-3: Measurement of weight distribution on four-prong resistivity probe.

For testing, the wooden tips were saturated in distilled water for 24 hours before insertion into the prongs. The tips were also sanded to ensure a uniform pressure distribution. The prong spacing was manually adjusted to 3.8 cm (1.5 in.).

To evaluate weight applied to the probe, a location was chosen deliberately away from any rebar on each of the slabs prepared for four-prong resistivity testing. The levels of applied weight used for this experimentation were 2.3 kg (5.0 lb), 4.5 kg (10.0 lb), and 6.8 kg (15.0 lb), which were evaluated in the order listed. Testing of all weight levels was performed with and without surface water, with the latter condition being evaluated first. For the former condition, resistivity measurements were made within 5 minutes after application of the surface water.

The procedure for investigating the time after surface water application on four-prong resistivity measurements was the same as that used during preparatory testing on two-prong resistivity measurements. The spray method and the towel method were again used to evaluate the slabs in the environmental chamber at 15.5°C (60.0°F).

A.3.2 Results

Results were obtained for the operator-controlled variables of weight applied to the probe, which was evaluated with and without surface water,and time after surface water application. When the resistivity measurements were taken with the 2.3-kg (5.0-lb) weight, the readings were unstable in the absence of surface water, fluctuating during each measurement so that manual observation over a period of three minutes was required to observe an average value. However, an applied weight of 4.5 kg (10.0 lb) or more provided sufficient contact between the concrete and the prongs to produce steady readings. The measured resistivity values are presented in Figure A-4. While the effect of surface water was most pronounced when the 2.3-kg (5.0-lb) weight was applied, the trend is inconsistent with theory, suggesting that the data collected using the 2.3-kg (5.0-lb) weight are invalid; when the 4.5-kg (10.0-lb) or 6.8-kg (15.0-lb) weights were applied, the effect of surface water was negligible.

For time after surface water application, the results were similar to those obtained from two-prong resistivity testing. Figure A-5 presents the measured resistivity values. After 15 minutes, the difference in resistivity measurements between the two methods exceeded the threshold, which suggests that readings taken before that time will be essentially the same under circumstances similar to those investigated in this research.

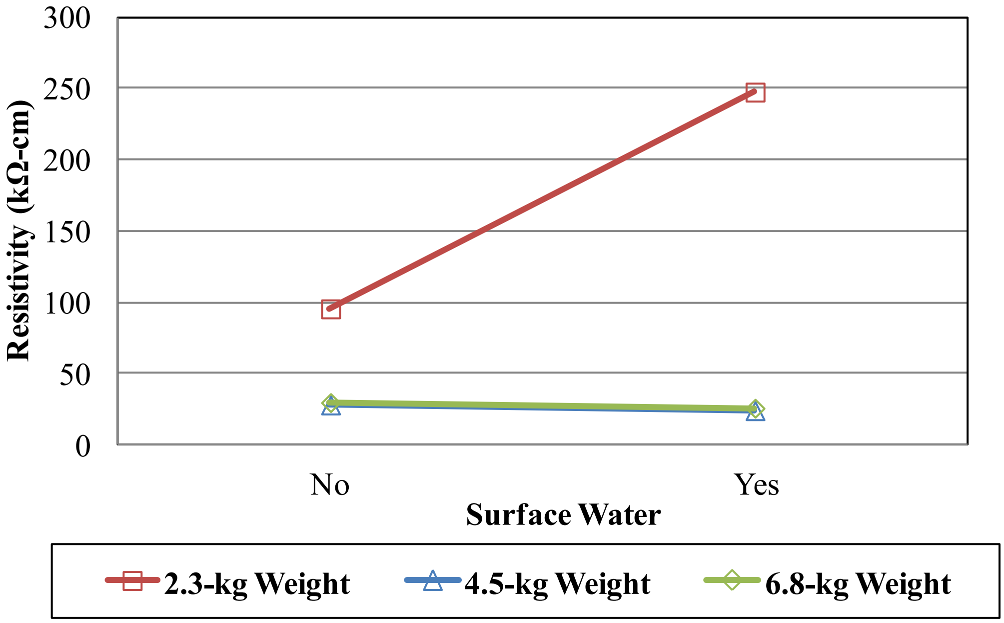


Figure A-4: Effect of probe weight and surface water on four-prong resistivity values.

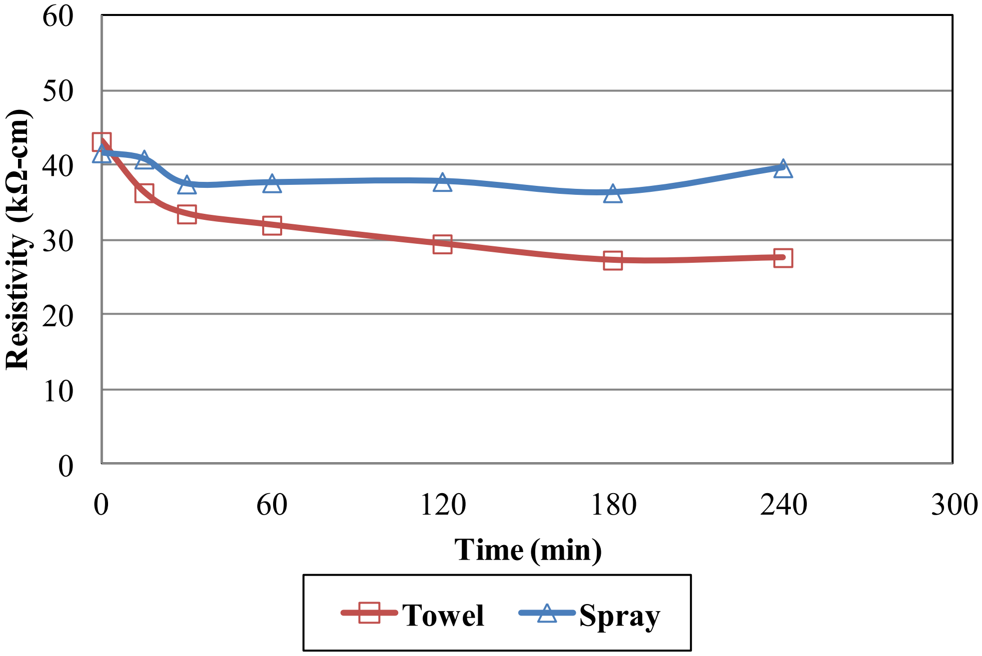


Figure A-5: Time effect of surface water application on four-prong resistivity values.

APPENDIX B. SLAB TESTING CONFIGURATIONS

B.1 Operator-Controlled Variables

Tables B-1 and B-2 indicate the levels of individual factors specified for each location on the concrete slabs prepared for two-prong and four-prong resistivity measurements, respectively. The location labels designated in the tables correspond to those given in Figures 3-2 and 3-3.

Table B-1: Slab Testing Configurations for Experimentation on Operator-Controlled Variables with Two-Prong Resistivity Testing

Location	Hole Depth (cm)	Position	Soap Volume	Surface Water
A	1.27	3	Full	No
B	0.64	3	Full	No
C	1.27	3	Full	Yes
D	0.64	3	Full	Yes
E	1.27	3	Half Full	No
F	1.27	3	Half Full	Yes
G	0.64	3	Half Full	No
H	1.27	3	Half Full	Yes
I	1.27	2	Full	No
J	0.64	2	Full	No
K	1.27	2	Full	Yes
L	0.64	2	Full	Yes
M	1.27	2	Half Full	No
N	1.27	2	Half Full	Yes
O	0.64	2	Half Full	No
P	0.64	2	Half Full	Yes
Q	1.27	1	Full	No

Table B-1 (Continued)

Location	Hole Depth	Position	Soap Volume	Surface Water
R	0.64	1	Full	No
S	1.27	1	Full	Yes
T	0.64	1	Full	Yes
U	1.27	1	Half Full	No
V	1.27	1	Half Full	Yes
W	0.64	1	Half Full	No
X	0.64	1	Half Full	Yes
Y	1.27	5	Full	No
Z	0.64	5	Full	No
AA	1.27	5	Full	Yes
BB	0.64	5	Full	Yes
CC	1.27	5	Half Full	No
DD	1.27	5	Half Full	Yes
EE	0.64	5	Half Full	No
FF	0.64	5	Half Full	Yes
GG	1.27	4	Full	No
HH	0.64	4	Full	No
JJ	1.27	4	Full	Yes
KK	0.64	4	Full	Yes
LL	1.27	4	Half Full	No
MM	1.27	4	Half Full	Yes
NN	0.64	4	Half Full	No
OO	0.64	4	Half Full	Yes

Table B-2: Slab Testing Configurations for Experimentation on Operator-Controlled Variables with Four-Prong Resistivity Testing

Location	Position	Prong Spacing (cm)	Surface Water
B	1	5.1	No
E	1	3.8	No
H	1	5.1	Yes
K	1	3.8	Yes
N	2	3.8	No
Q	2	5.1	No
T	2	3.8	Yes
W	2	5.1	Yes
Z	5	3.8	No
CC	5	3.8	No
FF	5	3.8	Yes
II	5	5.1	Yes
LL	4	3.8	No
OO	4	5.1	No
RR	4	3.8	Yes
UU	4	5.1	Yes
XX	3	3.8	No
AAA	3	5.1	No
DDD	3	3.8	Yes
GGG	3	5.1	Yes

B.2 Concrete Material Variables

Tables B-3 and B-4 indicate the levels of individual factors specified for each location on the concrete slabs prepared for two-prong and four-prong resistivity measurements, respectively. The location labels designated in the tables correspond to those given in Figure 3-4.

Table B-3: Slab Testing Configurations for Experimentation on Concrete Material Variables with Two-Prong Resistivity Testing

Location	Temperature (°C)
AA	4.4
CC	4.4
EE	4.4
GG	15.7
II	15.7
KK	15.7
MM	26.7
OO	26.7
QQ	26.7

Table B-4: Slab Testing Configurations for Experimentation on Concrete Material Variables with Four-Prong Resistivity Testing

Location	Temperature (°C)
BB	4.4
DD	4.4
FF	4.4
HH	15.7
JJ	15.7
LL	15.7
NN	26.7
PP	26.7
RR	26.7

APPENDIX C. RAW DATA

TABLE C-1: Raw Data for Experimentation on Operator-Controlled Variables with Two-Prong Resistivity Testing

Slab	Surface Water	Position	Hole Depth (cm)	Soap Volume	Repetition	Resistivity (kΩ-cm)
1	No	1	0.64	Full	1	37.6
					2	36.5
				Half Full	1	36.9
					2	36.3
			1.27	Full	1	28.3
					2	27.5
				Half Full	1	38.5
					2	37.4
		2	0.64	Full	1	41.6
					2	40.7
				Half Full	1	64.5
					2	63.9
			1.27	Full	1	34.5
					2	29.5
				Half Full	1	32.9
					2	31.3
		3	0.64	Full	1	47.2
					2	46.9
				Half Full	1	52.9
					2	50.6
			1.27	Full	1	38.8
					2	37.5
				Half Full	1	22.6
					2	21.6
		4	0.64	Full	1	53.5
					2	52.9
				Half Full	1	45.5
					2	42.7
			1.27	Full	1	21.8
					2	21.5
				Half Full	1	25.0
					2	24.4
		5	0.64	Full	1	50.9
					2	50.3
				Half Full	1	55.2
					2	53.7
			1.27	Full	1	38.8
					2	38.2
				Half Full	1	35.2
					2	23.5

TABLE C-1: (Continued)

Slab	Surface Water	Position	Hole Depth	Soap Volume	Repetition	Resistivity (kΩ-cm)
1	Yes	1	0.64	Full	1	18.5
					2	18.1
				Half Full	1	18.6
					2	18.0
			1.27	Full	1	7.5
					2	7.3
				Half Full	1	12.6
					2	12.0
		2	0.64	Full	1	24.5
					2	20.8
				Half Full	1	20.0
					2	17.1
			1.27	Full	1	10.3
					2	8.8
				Half Full	1	7.0
					2	6.7
		3	0.64	Full	1	13.0
					2	12.4
				Half Full	1	13.6
					2	13.0
			1.27	Full	1	11.9
					2	11.0
				Half Full	1	18.8
					2	16.6
		4	0.64	Full	1	22.5
					2	13.2
				Half Full	1	15.8
					2	15.3
			1.27	Full	1	13.4
					2	12.6
				Half Full	1	11.9
					2	11.3
		5	0.64	Full	1	16.2
					2	14.3
				Half Full	1	22.3
					2	21.8
			1.27	Full	1	14.4
					2	13.7
				Half Full	1	10.7
					2	11.1

TABLE C-1: (Continued)

Slab	Surface Water	Position	Hole Depth	Soap Volume	Repetition	Resistivity (kΩ-cm)
3	No	1	0.64	Full	1	58.5
					2	52.5
				Half Full	1	59.0
					2	58.5
			1.27	Full	1	28.0
					2	27.3
				Half Full	1	51.8
					2	49.5
		2	0.64	Full	1	76.2
					2	75.5
				Half Full	1	52.7
					2	51.3
			1.27	Full	1	35.5
					2	32.7
				Half Full	1	62.8
					2	59.7
		3	0.64	Full	1	55.5
					2	53.2
				Half Full	1	35.1
					2	33.8
			1.27	Full	1	55.5
					2	44.3
				Half Full	1	32.9
					2	31.7
		4	0.64	Full	1	48.6
					2	63.6
				Half Full	1	89.7
					2	88.1
			1.27	Full	1	27.8
					2	25.8
				Half Full	1	73.0
					2	72.0
		5	0.64	Full	1	81.5
					2	80.5
				Half Full	1	54.5
					2	53.6
			1.27	Full	1	34.7
					2	30.0
				Half Full	1	38.0
					2	35.6

TABLE C-1: (Continued)

Slab	Surface Water	Position	Hole Depth	Soap Volume	Repetition	Resistivity (kΩ-cm)
3	Yes	1	0.64	Full	1	8.9
					2	8.7
				Half Full	1	19.6
					2	19.0
			1.27	Full	1	16.5
					2	16.7
				Half Full	1	15.0
					2	14.2
		2	0.64	Full	1	22.3
					2	21.2
				Half Full	1	12.9
					2	12.9
			1.27	Full	1	17.0
					2	16.9
				Half Full	1	17.7
					2	16.5
		3	0.64	Full	1	21.7
					2	20.6
				Half Full	1	25.5
					2	24.8
			1.27	Full	1	11.1
					2	10.7
				Half Full	1	13.4
					2	13.1
		4	0.64	Full	1	24.8
					2	24.1
				Half Full	1	19.5
					2	19.2
			1.27	Full	1	18.8
					2	18.1
				Half Full	1	15.5
					2	15.1
		5	0.64	Full	1	21.8
					2	21.6
				Half Full	1	20.3
					2	18.6
			1.27	Full	1	19.6
					2	19.3
				Half Full	1	19.0
					2	18.1

TABLE C-1: (Continued)

Slab	Surface Water	Position	Hole Depth	Soap Volume	Repetition	Resistivity (kΩ-cm)
5	No	1	0.64	Full	1	54.8
					2	53.0
				Half Full	1	47.1
					2	45.7
			1.27	Full	1	27.9
					2	27.0
				Half Full	1	49.5
					2	46.3
		2	0.64	Full	1	47.6
					2	47.0
				Half Full	1	44.8
					2	43.1
			1.27	Full	1	38.9
					2	37.8
				Half Full	1	42.8
					2	41.1
		3	0.64	Full	1	39.0
					2	37.6
				Half Full	1	58.8
					2	57.3
			1.27	Full	1	28.8
					2	28.1
				Half Full	1	36.6
					2	31.2
		4	0.64	Full	1	41.8
					2	39.2
				Half Full	1	38.8
					2	38.3
			1.27	Full	1	31.8
					2	33.2
				Half Full	1	58.8
					2	53.9
		5	0.64	Full	1	47.2
					2	46.4
				Half Full	1	59.8
					2	58.3
			1.27	Full	1	36.9
					2	35.2
				Half Full	1	41.6
					2	40.1

TABLE C-1: (Continued)

Slab	Surface Water	Position	Hole Depth	Soap Volume	Repetition	Resistivity (kΩ-cm)
5	Yes	1	0.64	Full	1	13.8
					2	11.4
				Half Full	1	13.2
					2	12.8
			1.27	Full	1	11.1
					2	10.8
				Half Full	1	8.9
					2	8.6
		2	0.64	Full	1	8.7
					2	8.5
				Half Full	1	16.4
					2	15.1
			1.27	Full	1	13.3
					2	12.7
				Half Full	1	9.7
					2	9.3
		3	0.64	Full	1	10.9
					2	10.4
				Half Full	1	15.8
					2	14.7
			1.27	Full	1	11.9
					2	11.3
				Half Full	1	9.0
					2	8.8
		4	0.64	Full	1	11.0
					2	10.9
				Half Full	1	12.3
					2	11.7
			1.27	Full	1	13.5
					2	12.4
				Half Full	1	13.5
					2	13.0
		5	0.64	Full	1	12.4
					2	11.8
				Half Full	1	14.0
					2	12.3
			1.27	Full	1	9.9
					2	9.4
				Half Full	1	19.8
					2	17.0

TABLE C-2: Raw Data for Experimentation on Operator-Controlled Variables with Four-Prong Resistivity Testing

Slab	Surface Water	Prong Spacing (cm)	Position	Repetition	Resistivity (kΩ-cm)
2	No	3.8	1	1	18
				2	16
			2	1	25
				2	23
			3	1	23
				2	22
			4	1	20
				2	18
			5	1	22
				2	23
		5.1	1	1	15
				2	17
			2	1	26
				2	24
			3	1	23
				2	22
			4	1	23
				2	23
			5	1	20
				2	19
	Yes	3.8	1	1	16
				2	19
			2	1	27
				2	26
			3	1	23
				2	23
			4	1	17
				2	19
			5	1	26
				2	26
		5.1	1	1	16
				2	16
			2	1	20
				2	24
			3	1	21
				2	23
			4	1	22
				2	22
			5	1	17
				2	22

TABLE C-2: (Continued)

Slab	Surface Water	Spacing	Position	Repetition	Resistivity (kΩ-cm)
4	No	3.8	1	1	21
				2	23
			2	1	28
				2	28
			3	1	26
				2	27
			4	1	189
				2	27
			5	1	25
				2	26
		5.1	1	1	19
				2	18
			2	1	25
				2	24
			3	1	21
				2	20
			4	1	22
				2	24
			5	1	21
				2	21
	Yes	3.8	1	1	26
				2	21
			2	1	21
				2	21
			3	1	31
				2	12
			4	1	21
				2	20
			5	1	33
				2	19
		5.1	1	1	22
				2	22
			2	1	18
				2	18
			3	1	23
				2	23
			4	1	15
				2	16
			5	1	21
				2	22

TABLE C-2: (Continued)

Slab	Surface Water	Spacing	Position	Repetition	Resistivity (kΩ-cm)
6	No	3.8	1	1	21
				2	19
			2	1	27
				2	28
			3	1	27
				2	26
			4	1	23
				2	23
			5	1	23
				2	25
		5.1	1	1	18
				2	18
			2	1	29
				2	29
			3	1	26
				2	25
			4	1	21
				2	20
			5	1	19
				2	19
	Yes	3.8	1	1	19
				2	20
			2	1	20
				2	19
			3	1	24
				2	22
			4	1	16
				2	16
			5	1	19
				2	17
		5.1	1	1	16
				2	15
			2	1	23
				2	24
			3	1	19
				2	20
			4	1	20
				2	19
			5	1	19
				2	20

TABLE C-3: Raw Data for Experimentation on Concrete Material Variables with Two-Prong Resistivity Testing

Slab	Chloride Concentration (kg of Cl$^-$/m^3 of Concrete)	Temperature (°C)	Location	Repetition	Resistivity (kΩ-cm)
7	0	4.4	1	1	62.5
				2	62.5
			2	1	91.7
				2	91.5
			3	1	91.8
				2	91.6
		15.6	1	1	64.8
				2	64.3
			2	1	66.2
				2	66.0
			3	1	68.8
				2	68.6
		26.7	1	1	45.0
				2	44.6
			2	1	71.7
				2	71.1
			3	1	39.5
				2	38.9
8	5.9	4.4	1	1	64.8
				2	64.4
			2	1	82.7
				2	81.7
			3	1	77.4
				2	76.6
		15.6	1	1	65.5
				2	64.1
			2	1	46.0
				2	46.0
			3	1	50.2
				2	49.4
		26.7	1	1	28.8
				2	28.1
			2	1	36.1
				2	34.8
			3	1	39.5
				2	38.9

TABLE C-3: (Continued)

Slab	Chloride Concentration (kg of Cl^-/m^3 of Concrete)	Temperature (°C)	Location	Repetition	Resistivity (kΩ-cm)
9	11.9	4.4	1	1	42.9
				2	42.6
			2	1	38.7
				2	38.2
			3	1	66.2
				2	65.7
		15.6	1	1	38.0
				2	37.1
			2	1	42.9
				2	41.6
			3	1	32.0
				2	31.7
		26.7	1	1	25.6
				2	25.0
			2	1	19.5
				2	19.0
			3	1	21.3
				2	21.0

TABLE C-4: Raw Data for Experimentation on Concrete Material Variables with Four-Prong Resistivity Testing

Slab	Chloride Concentration (kg of Cl^-/m^3 of Concrete)	Temperature (°C)	Location	Repetition	Resistivity (kΩ-cm)
7	0	4.4	1	1	56
				2	44
			2	1	78
				2	62
			3	1	67
				2	67
		15.6	1	1	41
				2	38
			2	1	36
				2	36
			3	1	60
				2	38
		26.7	1	1	38
				2	35
			2	1	28
				2	27
			3	1	36
				2	37
8	5.9	4.4	1	1	60
				2	60
			2	1	60
				2	60
			3	1	52
				2	56
		15.6	1	1	34
				2	38
			2	1	33
				2	38
			3	1	34
				2	35
		26.7	1	1	23
				2	24
			2	1	22
				2	20
			3	1	22
				2	24

TABLE C-4: (Continued)

Slab	Chloride Concentration (kg of Cl^-/m^3 of Concrete)	Temperature (°C)	Location	Repetition	Resistivity (kΩ-cm)
9	11.9	4.4	1	1	56
				2	53
			2	1	53
				2	57
			3	1	49
				2	47
		15.6	1	1	32
				2	33
			2	1	27
				2	26
			3	1	31
				2	31
		26.7	1	1	21
				2	19
			2	1	17
				2	17
			3	1	19
				2	19