EVALUATION OF SOIL-CEMENT PROPERTIES WITH ELECTRICAL RESISTIVITY

by

Ahmed Hatem Hammad

Submitted in partial fulfilment of the requirements
for the degree of Master of Applied Science

at

Dalhousie University
Halifax, Nova Scotia
April 2013

DALHOUSIE UNIVERSITY

DEPARTMENT OF CIVIL AND RESOURCE ENGINEERING

The undersigned hereby certify that they have read and recommend to the Faculty of Graduate Studies for acceptance a thesis entitled "Evaluation of Soil-Cement Properties with Electrical Resistivity" by Ahmed Hatem Hammad in partial fulfilment of the requirements for the degree of Master of Master of Applied Science.

Dated: April 30, 2013

Supervisor: ______________________
Dr. Craig B. Lake

Readers: ______________________
Dr. Christopher Barnes

____
Mr. J. Scholte

DALHOUSIE UNIVERSITY

DATE: April 30, 2013

AUTHOR: Ahmed Hatem Hammad

TITLE: Evaluation of Soil-Cement Properties with Electrical Resistivity

DEPARTMENT OR SCHOOL: Department of Civil and Resource Engineering

DEGREE: M.A.Sc. CONVOCATION: October YEAR: 2013

____

Signature of Author

DEDICATION

I dedicate my work………….

To my parents for their endless love and support;

To my wife for her love, patience, and support;

To the most amazing kids in the world,………… my sons Harith and Yezin.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

The quality control of soil-cement during construction would benefit from a cost and time efficient tool for evaluating the soil-cement performance. The degree of cement mixing in ground improvement applications is key to the outcome of the engineering performance of cement-based barrier systems for remediation systems (i.e. strength and hydraulic conductivity) as well as the control of cement and water in the mixture. The potential to use simple, yet accurate, rapid sensors to determine the mixing quality of soil-cement would allow for confidence that the final quality of the soil-cement system will perform as intended. The objective of this research was to examine Electrical Resistivity (ER) measurements of mixed and uncured soil-cement samples and assess whether it can be used to predict strength and hydraulic conductivity properties for hardened soil cement samples.

To fulfill this objective, a series of hydraulic conductivity and unconfined compressive strength tests were performed on hardened samples in parallel with ER testing on uncured soil-cement samples with the same mix designs and bulk densities of the samples used in the hydraulic conductivity and unconfined compressive strength testing. It is generally found that ER is very sensitive to the changes in water content, cement content and density but it is difficult to distinguish between simultaneous changes in cement content and water content. Results of hydraulic conductivity and unconfined compressive strength testing suggest that the molding water play a large role in the resulting hydraulic conductivity and unconfined compression strength for a given cement content. The results show that although ER could detect changes in water content in soil-cement mixtures for given cement content, it would be difficult to relate ER measurements to hydraulic conductivity and unconfined compressive strength tests.

LIST OF ABBREVIATIONS AND SYMBOLS USED

A: cross-sectional area of the sample

A_w: cement content

ER: soil electrical resistivity

H.C.: Hydraulic Conductivity

k: saturated hydraulic conductivity

q_{max}: maximum stress in unconfined compressive strength

S/S: stabilization and solidification

UCS: unconfined compressive strength

w.c.: water content

w/c: water-cement ratio

ρ: soil electrical resistivity

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to my supervisor Dr. Craig Lake for his guidance, patience, encouragement and valuable suggestions throughout the preparation of this research.

Appreciation is extended to Dr. Christopher Barnes and Mr. J. Scholte for serving on my committee and their valuable suggestions.

Special thanks are due to my colleague Reza Jamshidi, and the laboratories technicians Jesse Keane, Blair Nickerson and Brian Kennedy for their constant help in the laboratory experiments.

Chapter 1: Introduction

1.1 General

Continual infrastructure development requires increased use of land that has marginal suitability to support buildings and hence there is an ongoing requirement to improve the strength and stiffness of these soils (Mitchell, 1981). Ground improvement technologies such as soil replacement, densification, consolidation/dewatering, grouting, admixture stabilization, thermal stabilization, or soil reinforcement are available to improve the load carrying capacity of the ground for adequate soil bearing resistance and settlement (Terashi and Juran, 2000). A common admixture stabilization technology involves adding Portland cement to soil to improve its performance characteristics such as strength, leachability and permeability (Terashi and Juran, 2000).

The use of soil-cement in different ground improvement applications such as pavement construction, slope protection, seepage control, foundation stabilization and pipe bedding (Dinchak, 1989) requires evaluating the performance of the "improved" soil by using cost effective testing techniques (i.e. quality control). Most of the conventional testing methods can provide a direct evaluation of the cement-treated soil but these test results are only available after the curing of the soil-cement mixture (Fujii et al., 2010). Other quality control methods performed post-curing such as the Standard Penetration Test (SPT) are considered a destructive testing method of soil-cement (Song et al., 2008). Quality control test results for samples below performance specifications often result in re-working of the treated soil with additional cement binder application required; costing additional time and money. The amount of research developing the early quality evaluation techniques for soil-cement materials is limited compared to the research results available for cured soil-cement materials.

Given that performance properties of soil-cement materials such as strength and hydraulic conductivity are directly related to the amount of cement and water in the soil-cement mixtures as well as the mixing method/compaction method of the treated material, it is hypothesized that techniques which can measure moisture content variations, cement content variations and density variations will be useful for ultimately controlling the performance quality of these mixtures. In this study, electrical resistivity testing of uncured soil cement materials is used in an attempt to predict the performance of soil-cement mixtures with respect to hydraulic conductivity and Unconfined Compressive Strength (UCS). Results are discussed relative to conventional quality control criteria such as moisture control during compaction/mixing of soil cement samples.

The purpose of this chapter is firstly to present a literature review of previous research performed on the quality control of soil cement materials in terms of hydraulic conductivity and strength performance criteria. The second objective is to present previous literature that has investigated the potential applications of electrical resistivity to strength and hydraulic conductivity performance criteria for soil cement materials. The final portion of this chapter provides a summary of the work to be performed throughout this thesis.

1.2 Soil-Cement

1.2.1 History

For most ground improvement scenarios involving cement addition, the existing soil is unsuitable for infrastructure development due to the soil having an inadequate strength or excessive compressibility characteristics. The addition of different combinations of cementitious or chemical additives such as Portland cement, lime, and/or fly ash as a binder to soil often results in a material that is improved in terms of strength and compressibility properties (Milburn and Parsons, 2004). When cement is the primary binder, the resulting material is generally referred to as soil-cement although this terminology also has industry connotations related to compacted soil-cement mixtures. In this thesis, the combination of soil with cement, regardless of mixing method will be referred to as soil-cement.

The first reported use of soil-cement as a ground improvement technology was in 1935 for Highway 41 near Johnsonville, South Carolina (Cement Association of Canada, 2012). Since this time, Portland cement has been used in the stabilization of soils for roadway pavement applications around the world.

In addition to pavement applications, cement and other additives have been mixed with contaminated soil and hazardous wastes to provide improved strength, hydraulic conductivity and leaching characteristics. This application of ground improvement generally has the term "solidification/stabilization (s/s)" associated with it. Cement-based s/s has been used since the 1950s to stabilize nuclear hazardous waste and currently the technology is common in the treatment of different hazardous waste and contaminated sites (Cement Association of Canada, 2012). For contaminated lands, the use of solidification/stabilization (s/s) allows not only provides ground improvement but also the ability to contain contaminants on the site such that excessive treatment or disposal costs can be reduced (Conner and Hoeffner, 1998). As explained by both Conner and Hoeffner (1998) and Kowalski and Starry (2007), the advantages of using cement as a chemical additive to stabilize soil include:

- Can be quicker than other stabilization methods
- Can increase the strength of the stabilized soil
- Can be used for a variety of different soil types
- Can be effective at reducing the leachability of contaminants
- Can exhibit a very good performance with silt and coarse-grained materials
- Can be performed for a relatively low cost and processed without using specialized equipment
- Can expect reasonable long-term stability for physical and chemical performance
- Resistant to biodegradation.

1.2.2 Soil-Cement Definition And Applications

Soil-cement is as defined in ACI 116R as "a mixture of soil and measured amounts of Portland cement and water, compacted to a high density" (ACI, 2000). Soil-cement is more specifically defined in ACI 230.1R-90 as "a material produced by blending, compacting, and curing a mixture of soil/aggregate, portland cement, possibly admixtures including pozzolans, and water to form a hardened material with specific engineering properties. The soil/aggregate particles are bonded by cement paste, but unlike concrete, the individual particle may not be completely coated with cement paste." (ACI, 1990). Most of the applications of this type of soil mixing process are ex-situ. For in-situ mixing of soil and cement, soil can be mixed with a cement-slurry into the ground through rotary mixing machinery (i.e. wet mixing). The slurry is injected into the ground by machinery through hollow mixing shafts containing a head with cutting tool. This technology is often referred to as the Deep Mixing Method (DMM) (Bruce, 2000 and Filz, et al. 2005). When the cement is added to the soil in dry powder-form and then mixed in-situ, this process is referred to as "dry mixing".

1.2.3 Factors Affecting Soil-Cement Properties

There are numerous factors that can affect the properties of soil-cement materials (Felt, 1955):

- The type of soil,
- The proportion of soil, cement, and water in the mixture,
- Compaction and density of the mixture,
- Curing time and conditions, and,
- The use of any additional additives to the soil-cement mixture.

Depending on the mixing method, some of these factors may have more influence on the properties of the soil-cement mixture than others. For example, sufficient water content is necessary for the complete hydration reaction of the portland cement to occur. Cement content affects the unconfined compressive strength of soil-cement as well as the permeability (ACI, 1990).

Felt (1955) found that increases in the moisture content of soil-cement had a very strong influence on the ability to mix the soil with cement.

1.2.4 Soil-Cement Performance Criteria

There are various factors that should be controlled during the construction phase to ensure a soil-cement mixture has adequate properties when mixed ex-situ and re-compacted (ACI, 1990):

- Cement content
- Moisture content
- Mixing quality (uniformity)
- Curing conditions
- Lift thickness and surface tolerance
- Compaction (density)
- Pulverization/gradation

All of these factors are related directly or indirectly to strength, hydraulic conductivity and durability characteristics of soil-cement. The unconfined compressive strength (UCS) test is a widely utilized test for soil-cement because it directly relates to load resistance and it is also correlated with durability (Scullion et al., 2005). Given that obtaining a soil-cement material with a relatively low hydraulic conductivity is one of the most important qualities of cement-based s/s applications, hydraulic conductivity testing of soil-cement is another important performance criteria. Examples of studies showing how the different factors listed above can influence the unconfined compressive strength of a given soil-cement material include Lorenzo and Bergado, 2004 and Fonseca et al., 2009. Several classical papers exist in the literature related to the hydraulic conductivity behaviour of compacted soil for differing densities and molding water content (e.g. Mitchell et al. 1965, Daniel and Benson 1990). In these studies it was shown how increasing the molding water content of compacted soils above their optimum water content will result in a lower hydraulic conductivity due to improved kneading and dispersion of the soil particles during the compaction process. However, for moisture contents beyond 2 to 4% of the optimum water content, the resulting hydraulic conductivity will increase due to the higher void ratios (i.e. lower densities). Similar literature for soil cement is surprising limited, likely due to the primary application of soil-cement to pavement applications. Belleza and Fratalocchi (2006) examined the differences in hydraulic conductivity with 15 different soils (i.e. different grain size) with and without 5% cement addition to the soil. All 15 samples with and without cement were subjected to standard proctor compaction testing and the resulting compaction curves of the soils were found to be relatively similar (i.e. similar optimum water content and density under standard energy compaction). Samples at 2-3% above optimum water content were subjected to hydraulic conductivity testing and it was shown that resultant change in hydraulic conductivity due to cement addition was dependent on the soil index properties of the material. Bahar et al. (2004) examined the effect of the cement addition on the compressive strength of soil-cement. Cement content of 0%, 4%, 6%, 8%, 10%, 12%, 15%, and 20% were added to a fine river sand passing a 0.63 mm sieve. It was found that increases in cement content led to increases in the compressive strength and reduction in the hydraulic conductivity relative to that soil (Bahar et al., 2004).

Based on a review of the literature, it is apparent that both the hydraulic conductivity and strength of soil cement mixtures are related to the water content, compaction energy, soil type, and cement addition. It should be noted that there were surprisingly few systematic studies found beyond that of Belleza and Fratalocchi (2006) that examined the role of these factors with hydraulic conductivity. It is apparent that for compacted soil cement materials, controlling the water content, density and cement contents of these materials in the field is essential for their hydraulic and strength performance. Unlike compacted soil liners however, it is difficult to collect the performance factors of soil cement material after it is cured (usually after the hydraulic conductivity and strength lab results are obtained). It is therefore even more critical to control these factors during construction to avoid costly reconstruction in the field. Traditional moisture density control is a useful mechanism in this regard but given that cement content is also important in the resultant property, it is useful to examine other quality control measures that may be able to detect changes in these properties during construction of these materials. Electrical resistivity measurements represent one such potential method.

1.3 Electrical Resistivity (ER)

1.3.1 Introduction

Soil electrical resistivity testing has been become widely used in geotechnical and geoenvironmental fields due to its non-destructive nature as well as it being a very rapid and, hence, cost effective test method. Literature shows that electrical resistivity measurements are an appropriate tool to be used to investigate mechanical, hydraulic and deformation properties of natural and treated soils (Abu Hassanein et al., 1996, McCarter and Desmazes, 1997, Bryson and Bathe, 2009, Kalinski and Kelly, 1993).

Electrical resistivity generally can be defined as the resistance against the flow of electric current within the soil. Mathematically, soil electrical resistivity, ρ, is defined as:

$$\boldsymbol{\rho} = \frac{\Delta \boldsymbol{U}}{\boldsymbol{I}} \frac{\boldsymbol{A}}{\boldsymbol{L}} \quad [1\text{-}1]$$

Where ΔU is the electrical potential applied to the soil (volts); I is the electrical current passing through the soil (amperes); A is the cross-sectional area (m^2) of the soil sample; and L is the length of the soil sample (m). Electrical resistivity is very sensitive to many material characteristics and hence it has become an increasingly useful tool in civil engineering. It has been found to be sensitive to different soil material indices such as liquid limit, plasticity index, particle size, porosity, and degree of saturation (Abu Hassanein et al., 1996 and Archie, 1942). McCarter (1981) found the electrical resistivity to be dependent on the moisture content and degree of saturation of the soil.

Archie (1942) proposed an empirical equation describing the relationship between the electrical resistivity of soil or rock and porosity (n) as follows:

$$\frac{\rho_0}{\rho_w} = (n)^{-a} \quad [1\text{-}2]$$

Where ρ_0 is electrical resistivity of the saturated soil or rock, ρ_w is the pore fluid electrical resistivity, and a is an empirical exponent depending on the porosity characteristics of a given soil or rock. The ratio on the left side of this equation was defined as the formation resistivity factor, F (Archie 1942).

Archie expanded equation 1-2 for unsaturated soil and rock as:

$$\frac{\rho}{\rho_w} = (S_r)^{-b} \qquad [1\text{-}3]$$

Where S_r is the degree of saturation, ρ the electrical resistivity of the unsaturated soil and b is an empirical constant. For clean, unconsolidated sand, this constant is close to 2.

Keller and Frischknecht (1966) extended Archie's model of saturated sand and rock and developed a slightly different model for unsaturated soil and rock:

$$\frac{\rho}{\rho_w} = n^{-a} S_r^{\ -d} \qquad [1\text{-}4]$$

Where d is the saturation exponent and it is often close to 2 for partially saturated soils and rock.

These early equations developed for soil and rock resistivity measurements are useful for understanding the resistivity measurements of soil and soil-cement materials as it is apparent that the resistivity of a soil cement system will be dependent on its density, conductivity of the pore fluid and particles, and the degree of saturation of the constructed material. Some research on how these relationships have been examined for compacted soils and soil cement materials is provided below.

1.3.2 Factors Affecting Electrical Resistivity Measurements Porosity

Archie's equation for saturated soils (i.e. equation 1-2) describes how electrical resistivity of a saturated soil or rock material changes as the pore fluid concentration and porosity changes. Jackson et al. (1978) concluded that the relationship between formation resistivity factor and porosity is governed by Archie's law (i.e. equation 1-2) and that the exponent a is dependent on the size and shape of the particles. Also, porosity can be dependent on the microstructure of soil, especially concerning to the continuity of pore water. Fukue et al. (1999) concluded that the discontinuity of pore water results in a high resistance to electrical current, making electrical resistivity a very reliable tool to describe the structural characteristics of soils (Fukue et al., 1999). This would mean that unsaturated media or unconnected pore structure would influence the resistivity measured.

Compaction

Electrical resistivity is very sensitive to any change in density of the soil and it has been shown that ER and density are directly proportional to each other (Beck et al., 2011) An increase in density results a decrease in electrical resistivity because of the change in microstructure (i.e. change in porosity) of the soil; the electrical conductance will be increased because the micro-pores would be more connected due to the increase in contact area of the soil particles (Seladji et al., 2010).

Temperature

Previous research by Abu Hassanein et al., (1996) found that the electrical resistivity of a soil decreased with an increase in temperature of the soil.

Water Content and Degree of Saturation

The electrical resistivity has been shown to increase with a decrease in water content of a given soil. A decrease in water content at a constant porosity results in a decrease in degree of saturation, leading to an increase in the soil resistivity (Archie, 1942; McCarter, 1981; Abu Hassanein et al., 1996; Song et al., 2008). This relationship was exhibited for hardened soil-cement samples tested by Song et al. (2008) who found that the electrical resistivity increased with any decrease in degree of saturation. This was attributed to there being less connected pore spaces as well as less pore water.

Cement Content and Curing Time

Given that electrical current predominately passes through the electrolytic pore water within the connected pore space and along the surface of soil particles (Bryson and Bathe, 2009), the electrical resistivity of a soil will likely be changed somewhat after adding cement to the soil because of chemical changes of the pore water, changes in the pore space as well as changes in the particles surface because of the cement hydration reaction (i.e. for hardened samples) (Song et al., 2008). For soil cement samples that are undergoing curing, the electrical resistivity has been shown to increase with increases in cement content as well as curing time, due to cementitious hydration reactions causing changes to the microstructure of the soil. Since the curing process takes time for soil cement samples, the electrical resistivity has been shown to increase with increase in curing time. (Song et al., 2008)

Water-Cement Ratio

For hardened soil cement samples, the electrical resistivity has been shown to decrease when the water-cement ratio increases in soil-cement. When the water-cement ratio decreases, the relative cement content increases and this results in a decrease in void ratio and water content of the soil-cement (Song et al., 2008). Mancio et al. (2009) reported in his study a direct relationship between ER and water-cement ratio of fresh concrete.

1.3.3 Relationship Between ER of Soil-Cement and Unconfined Compressive Strength

As previously mentioned, the unconfined compressive strength test is widely used for quality control and quality assurance of soil-cement performance because it is a relatively simple and reliable test for measuring the strength of soil-cement samples. There are few articles that were found examining this relationship for fresh (uncured) soil-cement. Previous research has largely been focused on cured/hardened soil-cement samples. Song et al. (2008) found that the electrical resistivity of hardened soil-cement increased when the unconfined compressive strength increased. In this study, cured soil-cement samples were tested in a cubic soil resistivity box (70.7×70.7×70.7mm) with various cement contents (8, 10, 12 and 15%) and water-cement ratios (4.7, 3.8, 3.1 and 2.7). A relationship was developed based on the correlations between ER measurement on cured soil-cement samples and the unconfined compressive strength of those samples. A very strong relationship between electrical resistivity and the unconfined compressive strength of the cured samples was produced (Song, et al. 2008). Xiao and Wei (2011) had similar observations and showed the importance of curing time on resistivity measurements compared with unconfined compressive strength.

Zhang et al. (2012) determined that the relationship between electrical resistivity and unconfined compressive strength is not linear as Song et al. (2008) reported in his paper. Zhang et al. (2012) explained that the electrical resistivity of soil primarily depends on ions concentration in pore fluid, pore tortuosity (the continuity of the electrical current path), degree of saturation and the surface charges of the soil particles. Zhang et al. (2012) then suggested that the strength of soil-cement depends primarily on the microstructure of the soil-cement and the product of the chemical reactions during the hydration process. This difference in controlling parameters of the electrical resistivity and the strength was suggested as the reason behind the nonlinear relationship between electrical resistivity and unconfined compressive strength of soil-cement.

A review of the literature shows that most of the studies examining relationships between electrical resistivity and the unconfined compressive strength relate to cured/hardened soil-cement samples. This type of relationship has application to non-destructive testing of hardened soil-cement samples in the field. However, the application of these results to rapid QC testing of soil-cement construction in the field are minimal, especially when it is considered that by the time an unconfined compressive strength test can be performed, the soil-cement material will be hardened in the field and if it doesn't meet strength performance criteria, the material will have to be removed, broken up and remixed with additional cement; a very time and cost consuming task.

1.3.4 Relationship Between ER of Soil-Cement and Hydraulic Conductivity

Hydraulic conductivity is a common performance parameter that is very important for studies related to prediction of contaminant transport through the soils. Examining relationships between the electrical resistivity properties of uncured soil cement samples and the hydraulic conductivity of cured soil cement materials could be a potential useful and rapid technique for quality control applications. As previously mentioned, early literature from Archie (1942), showed that the electrical resistivity of soil or rock depends strongly on the porosity, degree of saturation and the type of the soil. Urish (1981) suggested the surface electrical resistivity as very useful tool for groundwater investigations because its sensitivity to changes in porosity and pore water resistivity and for the soil. Abu Hassanein et al. (1996) performed electrical resistivity measurements on a variety of compacted clay soils and found that there is a unique relationship between the electrical resistivity and the hydraulic conductivity for a given soil yet found that this relationship was not unique for compositional changes in soil type. They suggested that ER was not an ideal method for quality control measurements of hydraulic conductivity in the field.

Based on a review of the literature, it appears as if electrical resistivity could be a potential quality based performance test, such as unconfined compressive strength and hydraulic conductivity, for soil cement materials constructed in the field. However, the sensitivity of the method to changes in cement content will be critical to its usefulness.

1.4 Experimental Hypothesis, Objectives and Tasks

The literature review performed suggests that ER can be used to detect changes in soil and/or soil cement properties. There has been research that has examined specifically cured or hardened soil cement samples. However few if any, publications can be found that have examined the potential for ER measurements of mixed, yet uncured, soil cement samples to predict strength and hydraulic properties for cured, hardened soil-cement samples. Hence, the hypothesis of this research is that *ER measurements of mixed and uncured soil-cement samples can be used to predict strength and hydraulic conductivity properties for hardened soil cement samples*. What will be critical when examining this hypothesis will be whether the measurement will be sensitive enough for differing cement contents and how this sensitivity compares to more conventional methods of quality control in the field (i.e. moisture, density).

To examine this hypothesis, the research is broken down into the following tasks:

- Task 1: Establish an ER testing system and calibrate it according to the ASTM's standard methods.

- Task 2: Prepare soil-cement samples with various water-cement ratios and cement contents for compaction testing, hydraulic conductivity tests and unconfined compressive strength tests.
- Task 3: Examine ER measurements recorded on soil-cement samples with the same mix properties as Task 2.
- Task 4: Use the quantitative results found in Tasks 2 and 3 to demonstrate potential relationship between ER measurements and the soil-cement properties.

1.5 Thesis Organization

This thesis is generally organized in the order of the various tasks listed above in Section 1.4. Chapter 2 focuses on the materials and procedures that were used in this research and establishing the electrical resistivity testing system for the research. Methodologies are presented for the preparation of the 48 samples of soil-cement with 24 different mix designs, moisture-density testing, hydraulic conductivity testing, unconfined compressive strength testing, as well as ER testing. Chapter 3 presents results of the compaction tests, hydraulic conductivity, UCS, and ER testing and provides some discussion on the appropriateness of the ER method to detect changes in UCS and hydraulic conductivity relative to more common QC methods in the field such as moisture and density measurements. Chapter 5 presents the summary, conclusions and recommendations for the future steps to develop this work.

Chapter 2 Experimental Materials And Methods

2.1 Introduction

As outlined in chapter 1, the main objective of this thesis is to examine the potential for Electrical Resistivity (ER) measurements of uncured cement-treated soils to predict hydraulic and strength properties of cured soil-cement samples. It is also of interest to examine whether these ER measurements will be sensitive enough for differing cement contents and how this sensitivity compares to more conventional methods of quality control in the field (i.e. moisture, density). This objective is carried out by performing ER testing on 24 different uncured mixtures of soil-cement and comparing these ER measurements with hydraulic conductivity and unconfined compressive strength of cured soil-cement samples.

The purpose of this chapter is to describe the materials utilized for testing and to describe the various procedures used to perform the testing. These procedures include:

1. Compaction testing, hydraulic conductivity testing and unconfined compressive strength testing on the 24 soil-cement mix designs (two samples for each mix design) after curing, and,
2. ER testing on the same 24 soil-cement mix designs, prior to curing.

2.2 Materials

2.2.1 Soil And Cement

The soil used in this research was taken from a residential construction site located in Bedford, Nova Scotia on June 29, 2011. Prior to any soil characterization testing, all soil was sieved through 4.75 mm sieve to remove gravel size particles for testing. ASTM D1140 (ASTM 2006a) and ASTM D6913-04 (ASTM 2009) were then used to obtain the grain size distribution for a representative sample of this soil, as shown in Figure 2-1.

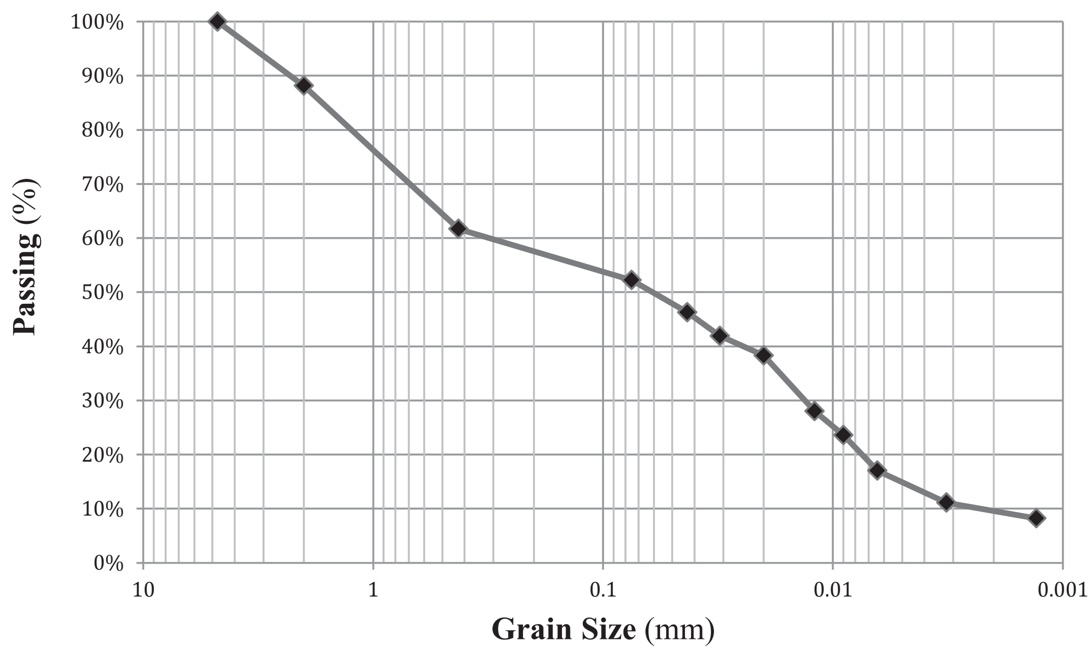

Figure 2-1: Grain size distribution for soil used in soil cement

Additional testing performed on this soil by Pirani (2011) is summarized in Table 2-1.

Table 2-1 Characteristics of soil

Moisture Content	9%
Plasticity Index	0%
Specific Gravity	2.74
USCS Soil Classification	Sandy silt

The oxide analysis and specific gravity test on this soil completed by Dalhousie Minerals Engineering Centre and is shown in Table 2-2.

Table 2-2 Oxide analysis

Analyte	Weight %
Al_2O_3	12.12
BaO	0.06
CaO	0.32
Cr_2O_3	0.01
Fe_2O_3	4.16
K_2O	2.13
MgO	1.16
MnO	0.15
Na_2O	1.70
P_2O_5	0.09
SiO_2	74.25
SrO	0.01
TiO_2	0.77
V_2O_5	0.01
ZrO_2	0.04
LOI	2.46
Total	**99.44**

Cement used in this research was from Lafarge (i.e. type GU cement).

2.2.2 ER Testing

ASTM standard G 187-5 is an established soil resistivity test method to be used in the field or in the laboratory. The method is appropriate for saturated soils or soil at a natural degree of saturation. The standard suggests using a two-electrode soil box to measure the resistance between two opposite faces of a box containing the material or the soil. The resistance of the material in soil resistivity box can be obtained by converting the resistance measurement to resistivity, ρ (ohm-cm), via:

$$\rho = RA/d \qquad [2\text{-}1]$$

Where: A is the cross-sectional area of the soil sample (cm^2), R is the measured resistance (ohm), and d is the distance between electrodes (cm). ASTM standard G 187-05 describes how each individual soil resistivity box will have a multiplier factor that depends on the internal dimension of the box and that factor is represented in Equation 2-1 by the ratio (A/d) (ASTM 2005). An M. C. Miller soil box was used in this research with dimensions 3.94 cm wide, 22.23 cm long, and 3.19 cm deep. These dimensions result a multiplication factor (A/d) equal to 1 cm. Figure 2-3 shows the measuring system as well as M. C. Miller soil box used for the measurement of electrical resistivity in this research. The system was connected to a power source as shown in Figure 2-3 providing 24 volts; the schematic of this test method is shown in Figure 2-2. As shown in Figure 2-3 two multimeters were used in the resistivity testing, one of them (digital) was used to measure the voltage applied between the two electrodes and the black analog multimeter was used to measure the current passing between the two electrodes of the soil box.

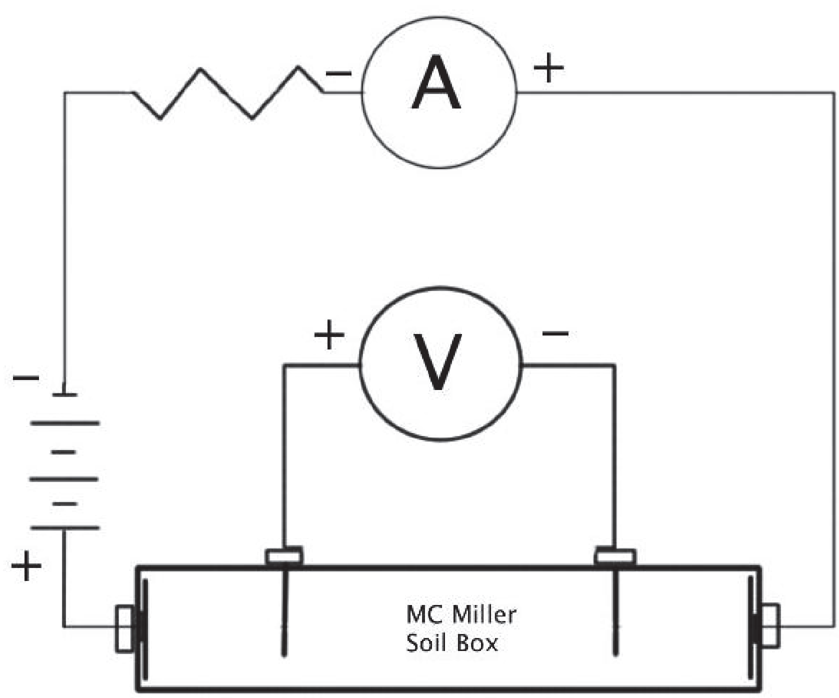

Figure 2-2 Schematic of M.C. Miller Soil Box

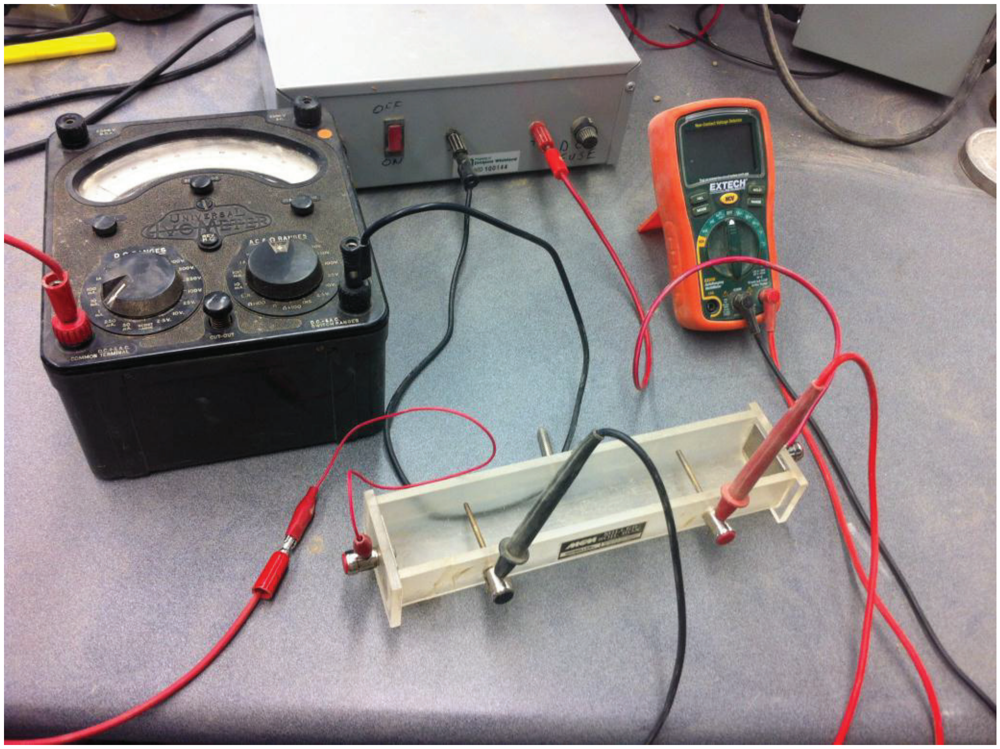

Figure 2-3 Soil Resistivity Testing System Utilized in This Research

2.2.3 Calibration of the ER Testing System

ASTM Standard G 187-5 is recommended for calibration of the soil resistance equipment periodically by using solutions with known resistance. The error in measurements should not exceed 5% over the range of the instrument. In case of error that exceeds this limit, a calibration curve should be prepared and all the measurements should be corrected. Traceable® Conductivity Standard Certified reference material was been used in this research. The reference material is a dilute mixture of potassium chloride (KCL), propanol, and deionized water in equilibrium with atmospheric carbon dioxide and its certificate resistivity was 1003 Ohm.cm at 25 °C. Calibration was performed several times throughout testing. Each calibration showed the error to be acceptable limits.

2.3 Soil Cement Sample Preparation and Testing Program

To examine relationships between the hydraulic conductivity and unconfined compressive strength properties of 28-day cured samples to ER measurements of the fresh soil-cement mixtures, 24 different mix designs were prepared for hydraulic conductivity and unconfined compressive strength testing. The samples used for hydraulic conductivity testing were also used for unconfined compressive strength testing and hence two specimens for each mix design were required. A summary of the various mix designs used is presented in Table 2-3.

Table 2-3 Summary of the mix designs utilized in this research

Mixture ID	Cement Content (%)	Water Content (%)	Water to Cement ratio *w/c*	Bulk Density (kg/m^3)	
				Sample I	Sample II
$A_{2.5}$	2.5	9.3	3.7	2127	2135
$B_{2.5}$	2.5	10.0	4.2	2174	2151
$C_{2.5}$	2.5	11.8	4.7	2096	2073
$D_{2.5}$	2.5	13.0	5.2	2099	2120
$A_{5.0}$	5.0	10.5	2.1	1994	1962
$B_{5.0}$	5.0	13.0	2.6	2121	2092
$C_{5.0}$	5.0	15.5	3.1	2135	2112
$D_{5.0}$	5.0	18.0	3.6	2072	2080
$A_{7.5}$	7.5	11.8	1.6	2061	2045
$B_{7.5}$	7.5	15.5	2.1	2131	2130
$C_{7.5}$	7.5	19.3	2.6	2111	2097
$D_{7.5}$	7.5	23.0	3.1	2055	2069
$A_{10.0}$	10.0	13.0	1.3	2081	2047
$B_{10.0}$	10.0	18.0	1.8	2094	2104
$C_{10.0}$	10.0	23.0	2.3	2061	2067
$D_{10.0}$	10.0	28.0	2.8	2009	2007
$A_{12.5}$	12.5	14.3	1.1	2125	2120
$B_{12.5}$	12.5	20.5	1.6	2103	2079
$C_{12.5}$	12.5	26.8	2.1	2033	2040
$D_{12.5}$	12.5	33.0	2.6	1977	1971
$A_{15.0}$	15.0	15.5	1.0	2126	2127
$B_{15.0}$	15.0	23.0	1.5	2070	2095
$C_{15.0}$	15.0	30.5	2.0	2009	2015
$D_{15.0}$	15.0	38.0	2.5	1937	1909

To prepare the soil-cement specimens for hydraulic conductivity testing, the soil was initially oven dried, after which 8% by dry mass of distilled water was added to the soil to simulate natural moisture content. Cement was then added to the soil and the mixture was mixed manually for approximately 10 minutes before adding water in excess of the natural moisture content. The amount of additional water was to ensure a range of water contents either above and/or below the optimum water content of the soil-cement mixture. The entire mixture was then mixed manually for approximately 15 minutes to ensure homogeneity prior to being compacted in the molds. Standard energy compaction methods (ASTM D558–11) were used for compacting the majority of the soil-cement samples (ASTM 2011). In addition to samples prepared for hydraulic conductivity and unconfined compressive strength testing, standard proctor compaction tests were performed for the soil and each cement content in order to determine maximum dry density and optimum water contents for these material. The preparation of these samples followed a similar procedure.

For some of the samples prepared for hydraulic conductivity and strength testing, due to the amount of water added to some samples (i.e. samples of mix design with water content less than 18%), the bulk density of each sample was recorded after the compaction process so that some control could be maintained for comparison to ER testing. Samples with water content higher than 18% were prepared by using a self-consolidation method because it was impractical to do compaction during the preparation, due to presence of excess water (compared to their optimum moisture content). The self-consolidation method included mixing the soil, cement and water until a homogeneous mixture was achieved. The mixture was transferred to a standard proctor mold in 3 equal thickness layers, and a steel bar was used to consolidate each layer in order to minimize large air voids from the mold. After finishing preparing the samples, specimens were placed in sealed plastic bags for 6 days, then removed from the molds and placed in the moist room for 22 days. The hydraulic conductivity testing took place when the samples had been cured for at least 28 days, followed by unconfined compressive strength testing. Details of the individual tests are provided below.

2.4 Hydraulic Conductivity Testing Procedure

Flexible wall hydraulic conductivity testing (ASTM D 5084) was performed on the 48 specimens. Sample saturation was performed for samples by increasing the cell pressure and backpressure simultaneously in increments of 70 kPa while maintaining a differential of 35 kPa. Each increment was maintained for at least 20 minutes until saturation was achieved. Following saturation, a consolidation phase was performed for each sample by increasing the cell pressure to an effective stress of 103 kPa. After consolidation, permeation of the samples was performed by maintaining the effective stress on the sample and inducing a gradient of 35 across the sample. Inflow and outflow measurements were recorded at least twice per day. The permeation phase was continued until the ratio of outflow to inflow rate was between 0.75 and 1.25 (ASTM 2010).

2.5 Unconfined Compressive Strength (UCS) Testing Procedure

Upon completion of the hydraulic conductivity test, specimens were placed in the moist room until a curing age of 36 days was reached. At this point the specimens were sulphur-capped and tested for unconfined compressive strength. A displacement rate of 0.5 mm/min was maintained during the UCS testing. The dimensions of the samples were not of the length required by ASTM 1633, "Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders" (ASTM 2006b); therefore these test results are not "true" unconfined compressive strength test results. During hydraulic conductivity testing of mixtures $A_{2.5}$, $B_{2.5}$, $C_{2.5}$, and $D_{2.5}$, prolonged wetting of the samples caused sufficient damage to the specimens such that an additional set of specimens were required for the UCS measurements with same mix design.

2.6 ER Testing Procedures

In ER testing three specimens were prepared for each of the 24 mix designs of soil-cement. Samples were mixed similar to that described in section 2.3. After the mixing process was completed, manual compaction in the soil resistivity box was performed in an attempt to reach similar bulk densities to that used in hydraulic conductivity and unconfined compressive strength testing. An attempt was made to keep the same consistency in preparing ER samples by using a similar bulk density compared to the samples for hydraulic conductivity and unconfined compressive strength testing.

Triplicate samples were prepared and ER measurements were performed on these uncured specimens using the ER procedures outlined earlier in section 2.2.2. ER testing was performed as soon as the target densities were achieved. Density measurements for these tests (see Table 2-4) as well as comparison to densities presented in Table 2-3 showed that a maximum of 7% difference in the densities were observed as compared to the target mix design the error was calculated as:

Table 2-4 Summary of the mixtures prepared and utilized in ER testing

Mixture ID	Cement Content %	Water content %	Water to Cement ratio *w/c*	H.C. Bulk Density kg/m^3	Bulk Density Difference between ER & H.C. Samples		
					I	II	III
$A_{2.5}$	2.5	9.3	3.7	2127	6.7%	6.7%	6.6%
$B_{2.5}$	2.5	10.0	4.2	2174	5.3%	3.5%	5.3%
$C_{2.5}$	2.5	11.8	4.7	2096	0.6%	0.6%	0.6%
$D_{2.5}$	2.5	13.0	5.2	2099	1.0%	-0.5%	-0.5%
$A_{5.0}$	5.0	10.5	2.1	1994	1.7%	1.6%	1.5%
$B_{5.0}$	5.0	13.0	2.6	2121	1.5%	0.8%	0.8%
$C_{5.0}$	5.0	15.5	3.1	2135	1.4%	1.2%	1.2%
$D_{5.0}$	5.0	18.0	3.6	2072	-0.2%	-0.2%	-0.3%
$A_{7.5}$	7.5	11.8	1.6	2061	0.4%	0.2%	0.2%
$B_{7.5}$	7.5	15.5	2.1	2131	0.0%	0.1%	0.0%
$C_{7.5}$	7.5	19.3	2.6	2111	0.3%	0.2%	0.3%
$D_{7.5}$	7.5	23.0	3.1	2055	-0.3%	-0.4%	-0.4%
$A_{10.0}$	10.0	13.0	1.3	2081	0.7%	0.7%	0.8%
$B_{10.0}$	10.0	18.0	1.8	2094	-0.2%	-0.3%	-0.1%
$C_{10.0}$	10.0	23.0	2.3	2061	0.0%	-0.1%	0.0%
$D_{10.0}$	10.0	28.0	2.8	2009	0.3%	-0.1%	-0.1%
$A_{12.5}$	12.5	14.3	1.1	2125	8.2%	9.4%	10.1%
$B_{12.5}$	12.5	20.5	1.6	2103	1.1%	0.8%	1.2%
$C_{12.5}$	12.5	26.8	2.1	2033	-0.2%	-0.2%	-0.2%
$D_{12.5}$	12.5	33.0	2.6	1977	0.3%	0.2%	0.1%
$A_{15.0}$	15.0	15.5	1.0	2126	7.6%	7.8%	7.8%
$B_{15.0}$	15.0	23.0	1.5	2070	-0.6%	-0.4%	-0.8%
$C_{15.0}$	15.0	30.5	2.0	2009	-0.1%	-0.1%	-0.1%

Chapter 3: Test Results And Discussion

3.1 Introduction

The first purpose of this chapter is to present the results of the index tests (i.e. plastic limit, compaction testing) as well as performance testing on soil-cement samples to show the sensitivity of cement and water on the hydraulic conductivity and strength measurements for the given soil material under study. The second purpose is to show the sensitivity of electrical resistivity to water and cement addition for this soil (i.e. freshly mixed, unhardened samples). Discussion is then provided on whether ER measurement of soil-cement is a useful tool for quality control in the field.

3.2 Results

3.2.1 Moisture-Density Relationships

Figures 3-1 shows the results of compaction testing on soil cement samples with differing cement contents. The purpose of the testing was to establish optimum moisture contents and resulting maximum dry densities for the soil and cement combinations used in this research. As can be seen from the results in Figures 3-1, the curves utilized for each soil cement mixture are similar with perhaps a slight increase in optimum moisture content and lower dry density with increasing cement content. Increasing the cement content for a given soil tends to increase the optimum moisture content and lower the maximum dry density (ACI 1990), however this relationship is not necessarily always true as the higher specific gravity of cement relative to soil could result in an increase in maximum dry density. Table 3-1 summarizes approximate values of optimum water content and dry density for the samples. Given the slight variability of the results presented herein, it appears as if any differences are minimal. In upcoming sections in this chapter, the moisture content for the mix design will be referenced back to table 3-1. Table 3-2 provides plastic limits results for the various soil-cement mixtures. These plastic limit values may be slightly higher than actual due to difficulties encountered when trying to roll the samples to the required diameters.

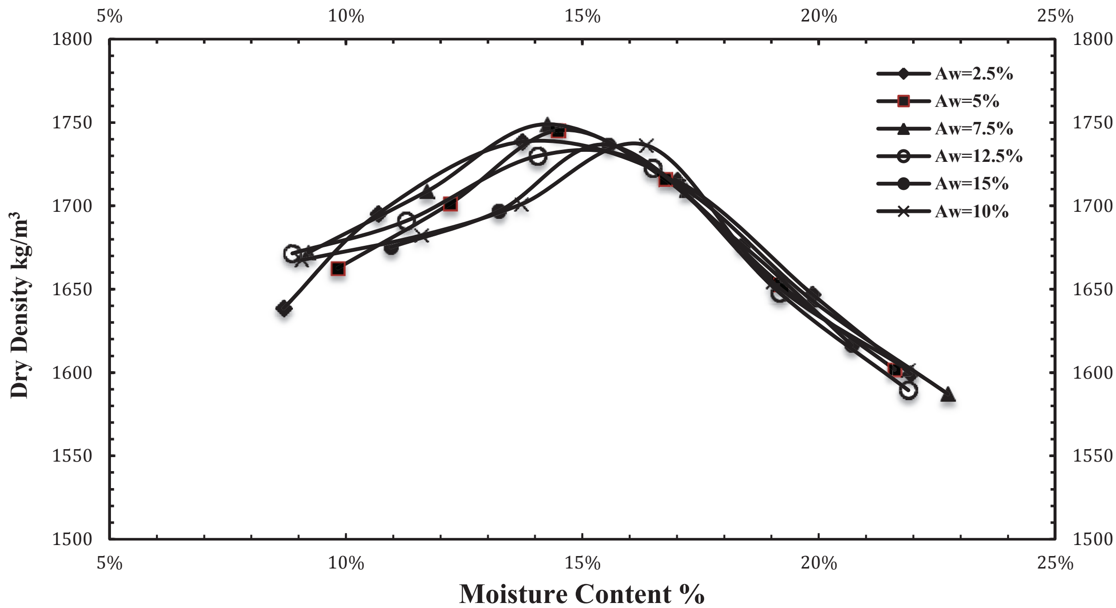

Figure 3-1 Standard Proctor Compaction Test Results

Table 3-1 Optimum moisture contents and maximum densities from soil-cement samples

Cement Content, A_w (%)	Optimum Water Content (To Nearest 0.5 %)	Maximum Dry Density (To Nearest 5 kg/m^3)
2.5	14.0	1740
5.0	14.5	1745
7.5	14.5	1750
10.0	16.0	1740
12.5	15.0	1735
15.0	15.5	1740

Table 3-2 Plastic limit for soil-cement mixtures

Cement Content, A_w (%)	Plastic Limit (%)
2.5	22
5.0	23
7.5	21
10.0	22
12.5	22
15.0	22

3.2.2 Hydraulic Conductivity Results

Table 3-3 presents hydraulic conductivity results for each of the 48 soil-cement samples and their mix designs. The mix design information provided in this table includes the cement content (A_w), total water content of the mixture and the w/c ratio of the resultant mixture. Also included in Table 3-3 is the amount of water content relative to optimum water content (for standard proctor) of the given mix design. These values are included for later discussion. As discussed in Chapter 2, two samples were prepared for hydraulic conductivity measurements using the flexible wall hydraulic conductivity test method. Table 3-3 presents results from each sample as well as the average of the two tests. Overall, there was a fairly wide range of hydraulic conductivity results obtained from the tests performed. Figure 3-2 plots all of the average hydraulic conductivity results (average values) relative to cement content present in the mix. Differences of almost 4 orders of magnitude were observed in the test results. There is a weak correlation of decrease in hydraulic conductivity as cement content increases. This not surprising as the cement content is only one factor that influences the result; the water content at which the sample was prepared is also a determining factor in this relationship.

Table 3-3 Hydraulic conductivity and unconfined compressive strength test results for the 48 soil-cement samples

Mixture ID	A_w (%)	Water content (%)	Water Content Relative To Optimum	*w/c* ratio	**k** (m/sec)			**q_{max}** (kPa)		
					Sample I	Sample II	Average	Sample I	Sample II	Average
$A_{2.5}$	2.5	9.3	-4.7	3.7	$1.1x10^{-7}$	$6.9x10^{-8}$	$8.7x10^{-8}$	435	472	454
$B_{2.5}$	2.5	10.5	-3.5	4.2	$2.2x10^{-8}$	$1.7x10^{-8}$	$2.0x10^{-8}$	639	646	643
$C_{2.5}$	2.5	11.8	-2.2	4.7	$1.5x10^{-7}$	$1.3x10^{-7}$	$1.4x10^{-7}$	343	394	369
$D_{2.5}$	2.5	13.0	-1.0	5.2	$1.8x10^{-8}$	$1.9x10^{-8}$	$1.9x10^{-8}$	289	309	299
$A_{5.0}$	5.0	10.5	-4.0	2.1	$1.5x10^{-7}$	$2.0x10^{-7}$	$1.8x10^{-7}$	1576	1578	1577
$B_{5.0}$	5.0	13.0	-1.5	2.6	$1.9x10^{-9}$	$1.5x10^{-8}$	$8.6x10^{-9}$	1889	2162	2026
$C_{5.0}$	5.0	15.5	+1.0	3.1	$1.1x10^{-9}$	$8.4x10^{-10}$	$9.8x10^{-10}$	930	919	925
$D_{5.0}$	5.0	18.0	+3.5	3.6	$7.4x10^{-10}$	$7.8x10^{-10}$	$7.6x10^{-10}$	877	991	934
$A_{7.5}$	7.5	11.8	-2.7	1.6	$4.0x10^{-7}$	$4.2x10^{-7}$	$4.1x10^{-7}$	2189	2001	2095
$B_{7.5}$	7.5	15.5	+1.0	2.1	$1.3x10^{-10}$	$1.4x10^{-10}$	$1.4x10^{-10}$	1658	2201	1930
$C_{7.5}$	7.5	19.3	+4.8	2.6	$1.2x10^{-10}$	$1.2x10^{-10}$	$1.2x10^{-10}$	2769	2817	2793
$D_{7.5}$	7.5	23.0	+8.5	3.1	$4.7x10^{-10}$	$4.8x10^{-10}$	$4.7x10^{-10}$	1622	1641	1632
$A_{10.0}$	10.0	13.0	-3.0	1.3	$1.4x10^{-7}$	$2.2x10^{-8}$	$8.0x10^{-8}$	4829	4424	4626
$B_{10.0}$	10.0	18.0	+2.0	1.8	$4.5x10^{-11}$	$4.5x10^{-11}$	$4.5x10^{-11}$	4147	4684	4416
$C_{10.0}$	10.0	23.0	+7.0	2.3	$1.8x10^{-10}$	$1.6x10^{-10}$	$1.7x10^{-10}$	3029	2869	2949
$D_{10.0}$	10.0	28.0	+12.0	2.8	$1.1x10^{-9}$	$9.4x10^{-10}$	$9.9x10^{-10}$	1492	1603	1548
$A_{12.5}$	12.5	14.3	-0.7	1.1	$4.5x10^{-10}$	$3.2x10^{-9}$	$1.8x10^{-9}$	7385	7179	7282
$B_{12.5}$	12.5	20.5	+5.5	1.6	$2.8x10^{-11}$	$2.2x10^{-11}$	$2.5x10^{-11}$	6571	6462	6516
$C_{12.5}$	12.5	26.8	+11.8	2.1	$1.5x10^{-10}$	$1.6x10^{-10}$	$1.6x10^{-10}$	2821	3020	2920
$D_{12.5}$	12.5	33.0	+18.0	2.6	$8.5x10^{-10}$	$6.5x10^{-10}$	$7.5x10^{-10}$	1591	1597	1594
$A_{15.0}$	15.0	15.5	0.0	1.0	$4.0x10^{-11}$	$3.0x10^{-11}$	$3.5x10^{-11}$	7546	8145	7845
$B_{15.0}$	15.0	23.0	+7.5	1.5	$3.0x10^{-11}$	$3.0x10^{-11}$	$3.0x10^{-11}$	6875	6895	6885
$C_{15.0}$	15.0	30.5	+15.0	2.0	$1.9x10^{-10}$	$2.1x10^{-10}$	$2.0x10^{-10}$	3160	3057	3109
$A_{2.5}$	15.0	38.0	+22.5	2.5	$2.2x10^{-9}$	$2.0x10^{-9}$	$2.1x10^{-9}$	1634	1615	1625

Note: underlined values represent water contents at lowest hydraulic conductivity for the four samples within each cement content.

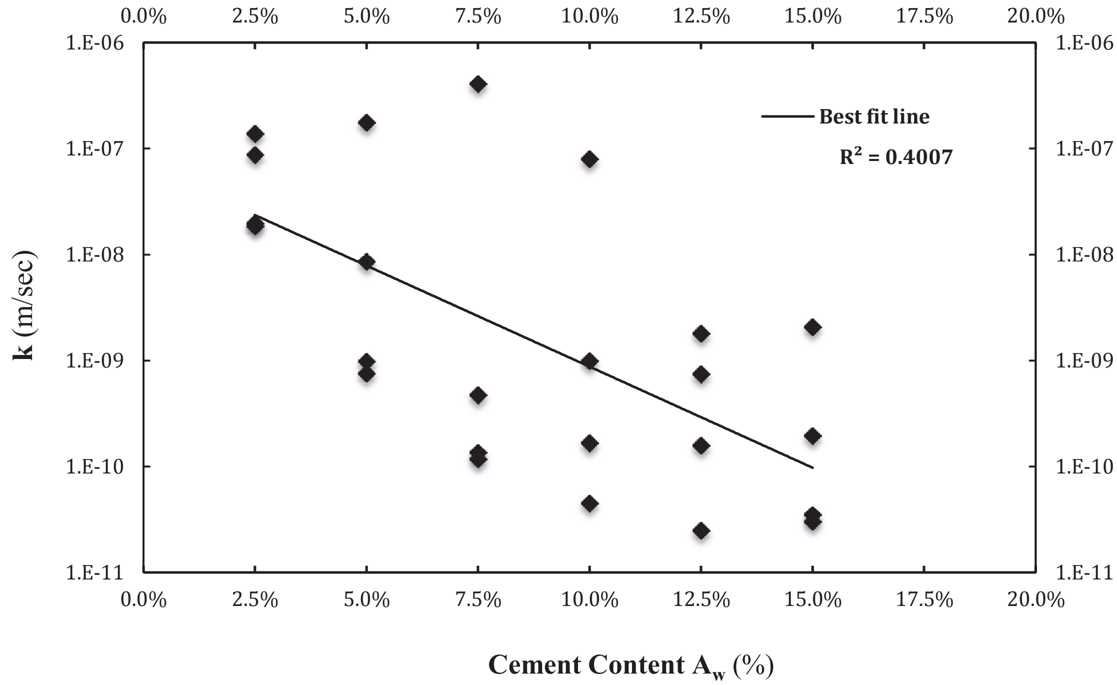

Figure 3-2 Effect of Cement Content, A_w, on Hydraulic Conductivity, k, of Soil-Cement Samples

Figure 3-3 shows the average sample hydraulic conductivity data plotted versus with water to cement ratio. As would be expected, this data exhibits an even weaker trend, as the cement content would be expected to have an important role to play in the resultant k determined from testing. The same results are presented in Figure 3-4 with all different cement contents grouped together. As can be seen in the Figure 3-4, although individual trends of changes in hydraulic conductivity versus water to cement ratio are present, the water to cement ratio that provides the lowest hydraulic conductivity (for a given cement content) decreases as the cement content increases. For example, when comparing A_w of 5% with A_w of 10 %, the water to cement ratio that results in the lowest hydraulic conductivity shifts from 3.6 to 1.8. Figure 3-5 further examines the variation of hydraulic conductivity with the water content of the final soil-cement mixture. Shown on this figure are results separated by cement content as the molding water content of the mixture is increased. These results look similar to those found for compacted soils (Mitchell et al., 1965 and Daniel and Benson, 1990) in which for a given compactive effort of the samples (i.e. standard compactive effort), there is a mixing water content (~2 to 5% above optimum water content) for each cement content that produces a minimum hydraulic conductivity.

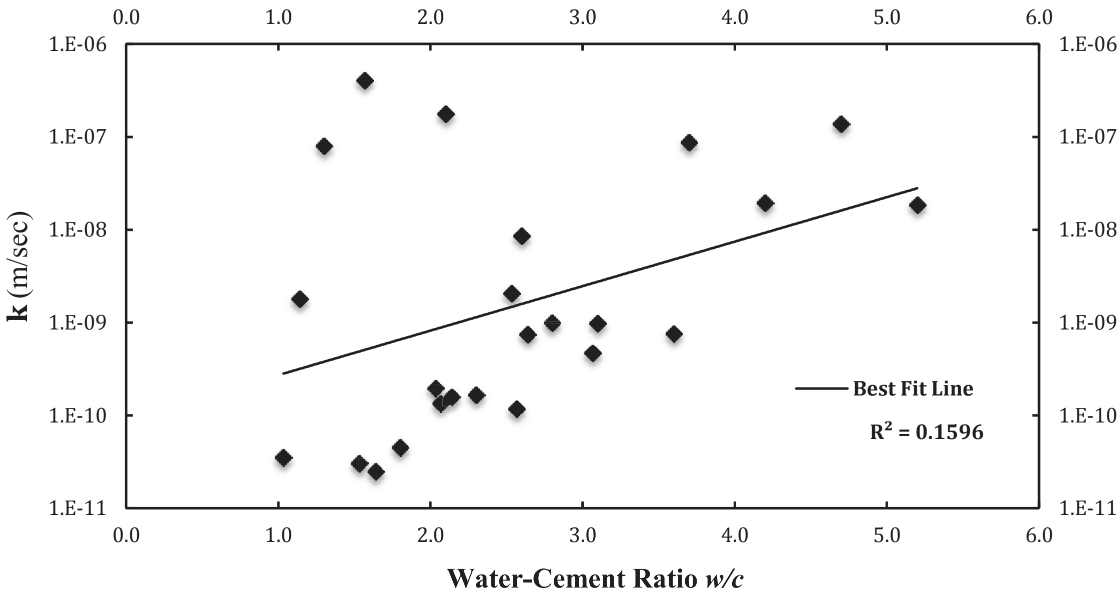

Figure 3-3 Effect of Water-Cement Ratio *w/c* on k of Soil-Cement Samples

As explained by Mitchell et al. (1965) this is due to samples wet of optimum producing a more dispersed structure and the soil kneading action being optimum at this moisture level (i.e. near its plastic limit). Even though the results shown in Figure 3-5 are for cured, hardened samples, the initial mixing at water content appears to have a significant effect on soil-cement sample hydraulic conductivity after curing. Firstly it is noted that increases in hydraulic conductivity occur above the plastic limit. Secondly, there is a significant drop in hydraulic conductivity as the samples were wetted dry of optimum to this plastic limit (i.e. note the steepness of the hydraulic conductivity drop from water contents of 10-15%). Thirdly, the lowest of the hydraulic conductivity values for each cement content are underlined in Table 3-3 and this corresponds to water contents 2 to 7% above optimum. It is noted that as the cement content increases, there is a general drop in hydraulic conductivity from 5% to 7.5% to 10% to 12.5% at this "ideal" water content (i.e. the bottom of the curves decrease in hydraulic conductivity). The 2.5 % samples were not tested at high enough water content and there is very little difference between the underlined values of 12.5% and 15%. This shows the interdependence of both molding water content and cement content on the resultant hydraulic conductivity of the samples.

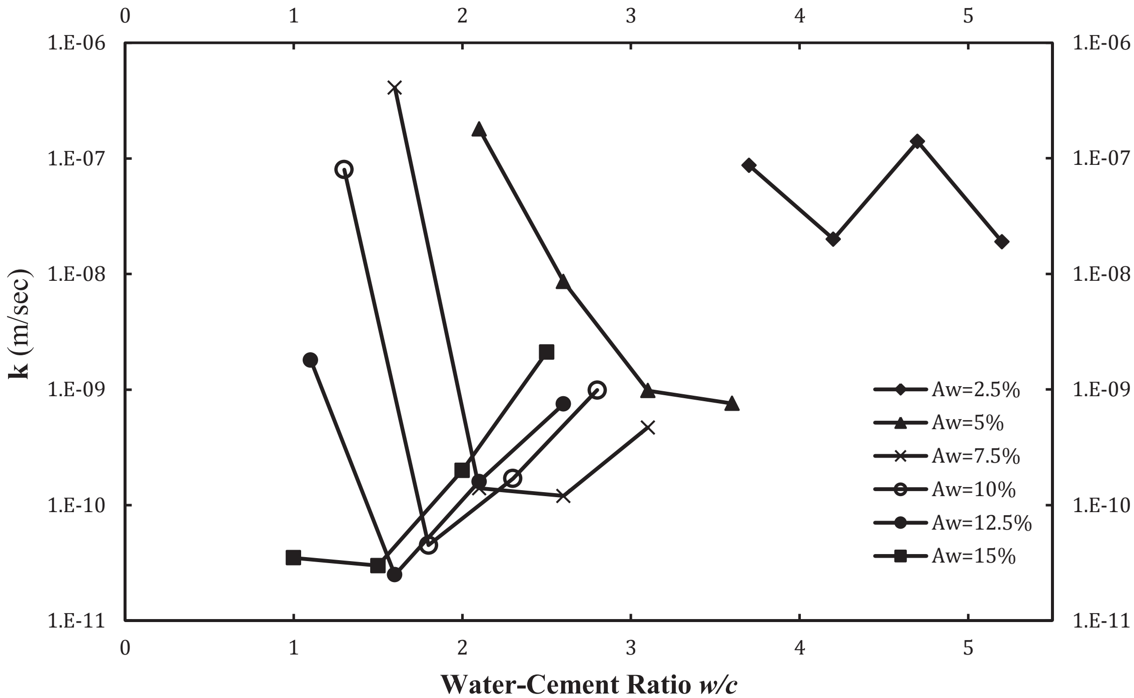

Figure 3-4 Effect of Water-Cement Ratio w/c on Hydraulic Conductivity of Samples Grouped By Cement Content

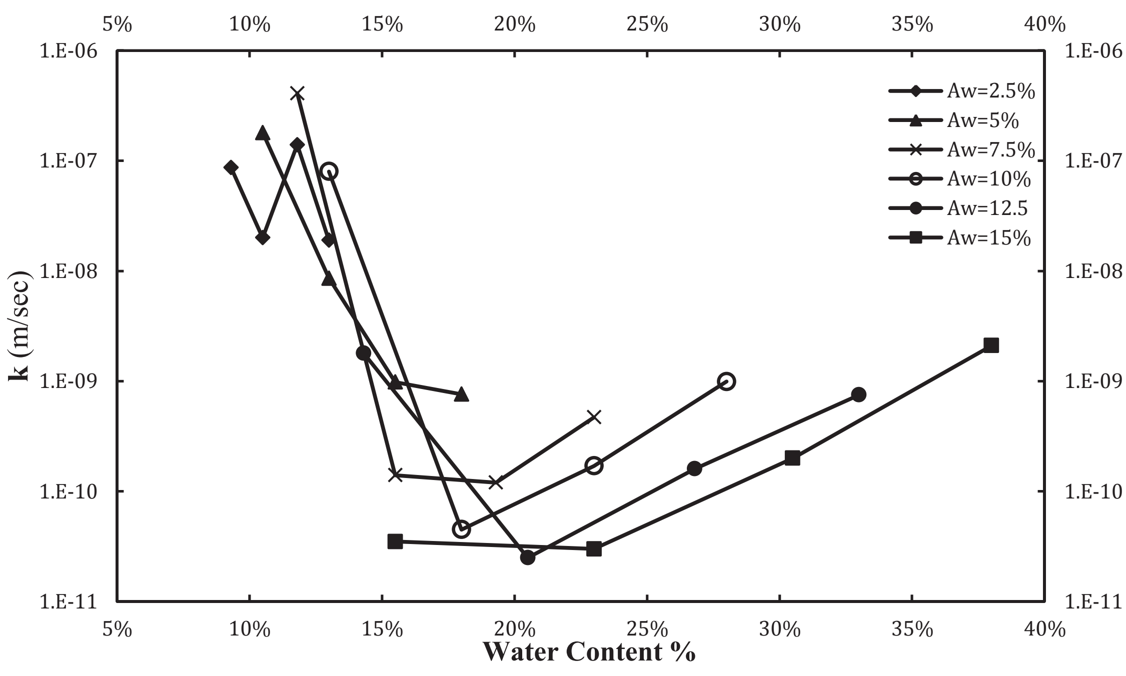

Figure 3-5 Effect of Water Content on Hydraulic Conductivity of Samples Grouped by Cement Content

3.2.3 Unconfined Compressive Strength Results

Table 3-3 produces all the results of 48 soil-cement samples, aged for 36 days, in terms of unconfined compressive strength. To visually examine the data shown in Table 3-3, all 48 test results are plotted in Figure 3-6 in terms of cement content, A_w. For the soil tested, there is relatively more correlation of the dependence of strength on cement content compared to the hydraulic conductivity results presented in the previous section, however the results still exhibit a significant amount of scatter for the different water to cement ratios examined. Figure 3-7 plots the same unconfined compressive strength test data versus water-cement ratio and a much stronger correlation is found for this set of data. There is a definitive drop in strength as the water-cement ratio of the sample increases, consistent with literature (e.g. Song et al., 2008). This is due to adding water in excess required for cement hydration.

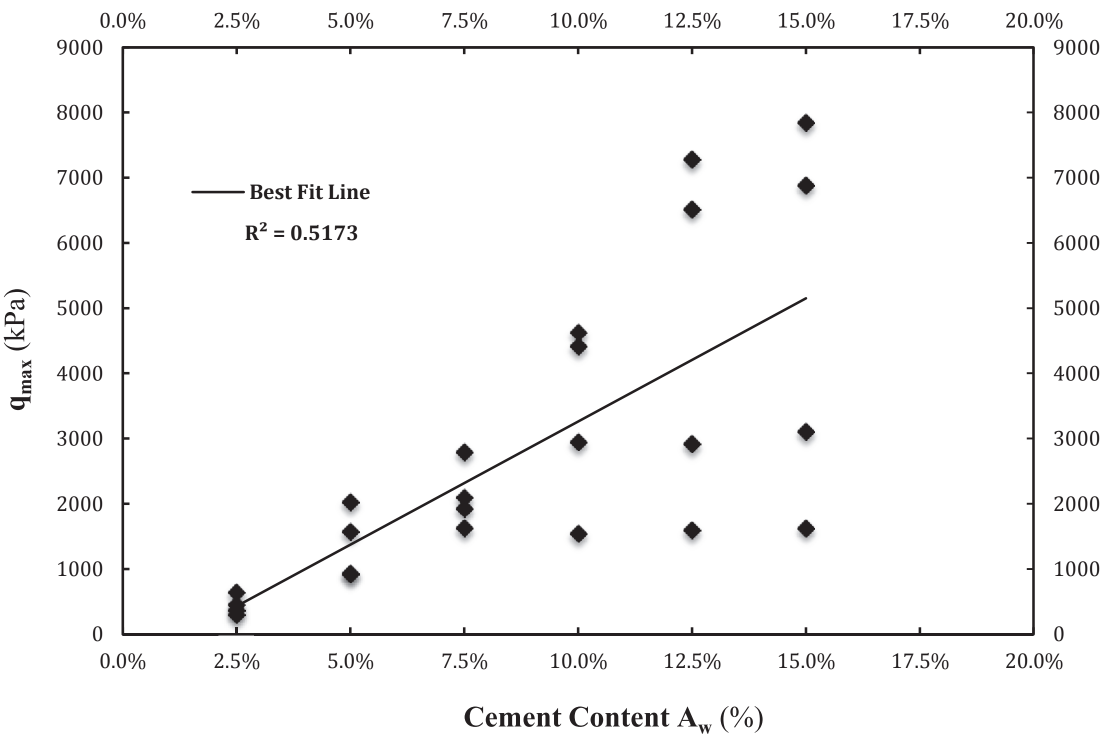

Figure 3-6 Effect of Cement Content A_w on The Unconfined Compressive Strength q_{max} of Soil-Cement Samples

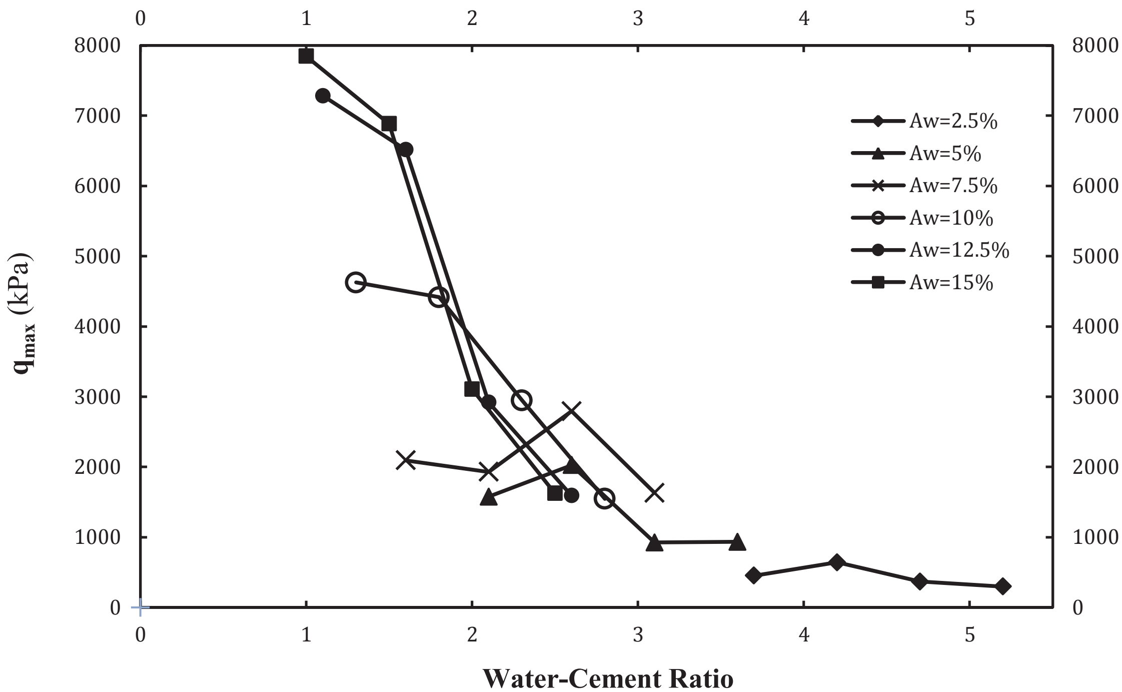

Figure 3-7 Effect of Water-Cement Ratio on The Unconfined Compressive Strength q_{max} of Samples Grouped by Cement Content

Similar to the previous section, the unconfined compressive strength test results were plotted versus the molding water content of the final mixture (see Figure 3-8). Shown on this figure are results separated by cement content as the molding water content of the mixture is increased. It is noted that for the exception of one cement content, most of the highest values of unconfined compressive strengths occurred dry of optimum water content and that there is a clear separation of strengths between cement contents. This is similar to early work presented by Bahar et al. (2004) and Zhang et al. (2012). Also noted, there was a decrease in strength for most of the samples from the optimum water content range to the higher molding water contents. As with compacted clay soils, this highlights the "tradeoff" of increasing the molding water content that may provide some benefit from a hydraulic conductivity standpoint. There will decrease in strength for this increase water content. From a field compaction perspective this makes it harder to place and compact the material with heavy construction equipment as the moisture content increases significantly past the optimum water content.

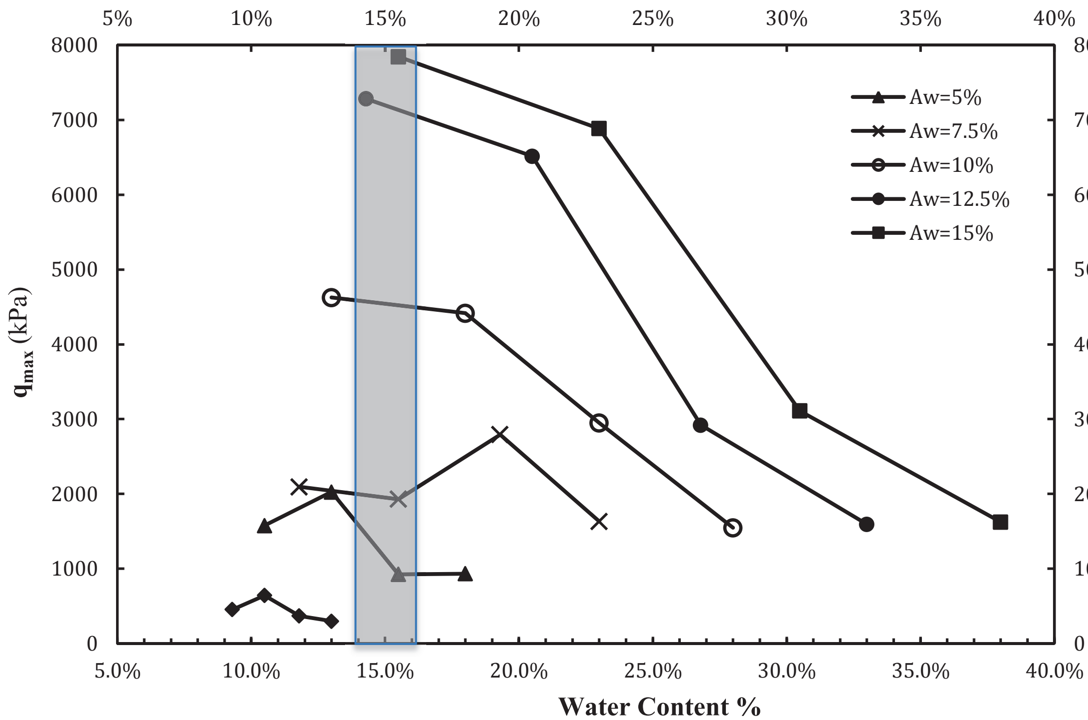

Figure 3-8 Effect of Water Content on Unconfined Compressive Strength q_{max} of Samples Grouped by Cement Content

Based on the results presented in this section (at least for the soil samples examined in this thesis). The following can be concluded from the mix designs examined relative to hydraulic conductivity and unconfined compressive strength:

1. The amount of water added to the soil cement mixtures in an unhydrated state had a definitive effect on the resultant hydraulic conductivity of the hardened samples. Hydraulic conductivities varied by almost 4 orders of magnitude for some cement contents throughout the range of water contents.
2. The amount of cement added to the soil cement mixtures in an unhydrated state appeared to have lesser influence on the hydraulic conductivity at low water contents, but more effect as the water content of the sample approached the plastic limit of the soil.
3. Both the amount of water and cement added to the soil cement mixtures had an influence on the resultant unconfined compressive strengths.

Given that the amount of water and cement appear to contribute to significant changes in hydraulic conductivity and strength of the sample, it is useful to examine the ability of electrical resistivity results to detect these changes in cement content and water content during mixing in order to evaluate whether ER would be a useful test for QC of such materials in the field.

3.2.4 Electrical Resistivity (ER) Test Results

Electrical Resistivity (ER) testing was performed in order to examine correlations with the results of hydraulic conductivity and unconfined compressive strength testing presented in previous sections. Table 3-4 shows each of the ER results obtained for the three test samples prepared, for each mix design. The triplicate samples provided good repeatability of the ER testing for each measurement. This reproducibility in ER measurement is encouraging when considering the potential for ER as a QC test for soil-cement mixtures.

Table 3-4 ER results for all mix designs

Mixture ID	A_w	Water content %	*w/c* ratio	ER (Ohm.cm)			
				Sample I	Sample II	Sample III	Average
$A_{2.5}$	2.5%	9.3	3.7	5429	5865	6053	5782
$B_{2.5}$	2.5%	10.5	4.2	3222	3303	3303	3276
$C_{2.5}$	2.5%	11.8	4.7	3079	3412	3688	3393
$D_{2.5}$	2.5%	13.0	5.2	2318	2255	2314	2295
$A_{5.0}$	5.0%	10.5	2.1	4222	4075	3867	4055
$B_{5.0}$	5.0%	13.0	2.6	2250	2204	2279	2244
$C_{5.0}$	5.0%	15.5	3.1	1939	1818	1848	1868
$D_{5.0}$	5.0%	18.0	3.6	1373	1432	1476	1427
$A_{7.5}$	7.5%	11.8	1.6	2300	2160	2300	2253
$B_{7.5}$	7.5%	15.5	2.1	1532	1556	1503	1530
$C_{7.5}$	7.5%	19.3	2.6	1263	1238	1209	1236
$D_{7.5}$	7.5%	23.0	3.1	946	961	965	958
$A_{10.0}$	10.0%	13.0	1.3	1701	1674	1676	1684
$B_{10.0}$	10.0%	18.0	1.8	1045	1023	1029	1032
$C_{10.0}$	10.0%	23.0	2.3	815	830	825	824
$D_{10.0}$	10.0%	28.0	2.8	718	677	678	691
$A_{12.5}$	12.5%	14.3	1.1	2040	1991	1981	2004
$B_{12.5}$	12.5%	20.5	1.6	1013	946	917	959
$C_{12.5}$	12.5%	26.8	2.1	681	704	682	689
$D_{12.5}$	12.5%	33.0	2.6	633	644	648	642
$A_{15.0}$	15.0%	15.5%	1.0	1522	1557	1569	1549
$B_{15.0}$	15.0%	23.0%	1.5	851	877	799	842
$C_{15.0}$	15.0%	30.5%	2.0	636	609	612	619
$A_{2.5}$	15.0%	38.0%	2.5	556	572	557	562

It is useful to examine the results in Table 3-4 relative to commonly utilized mix characteristics such as cement content, w/c ratio and molding water content. Figure 3-9 shows the relationship between the electrical resistivity and cement content, for the various water-cement ratios. It is clear from examining the results of Figure 3-9 that ER measured for the uncured samples follows a decreasing trend with increase in cement content. However, the rate of the decrease varies, based on the water to cement ratio of the sample. Even though there is a noticeable trend shown on this figure, it should be noted that the results presented are for one soil of a given grain size distribution. Variations in grain size and mineralogy would influence this relationship.

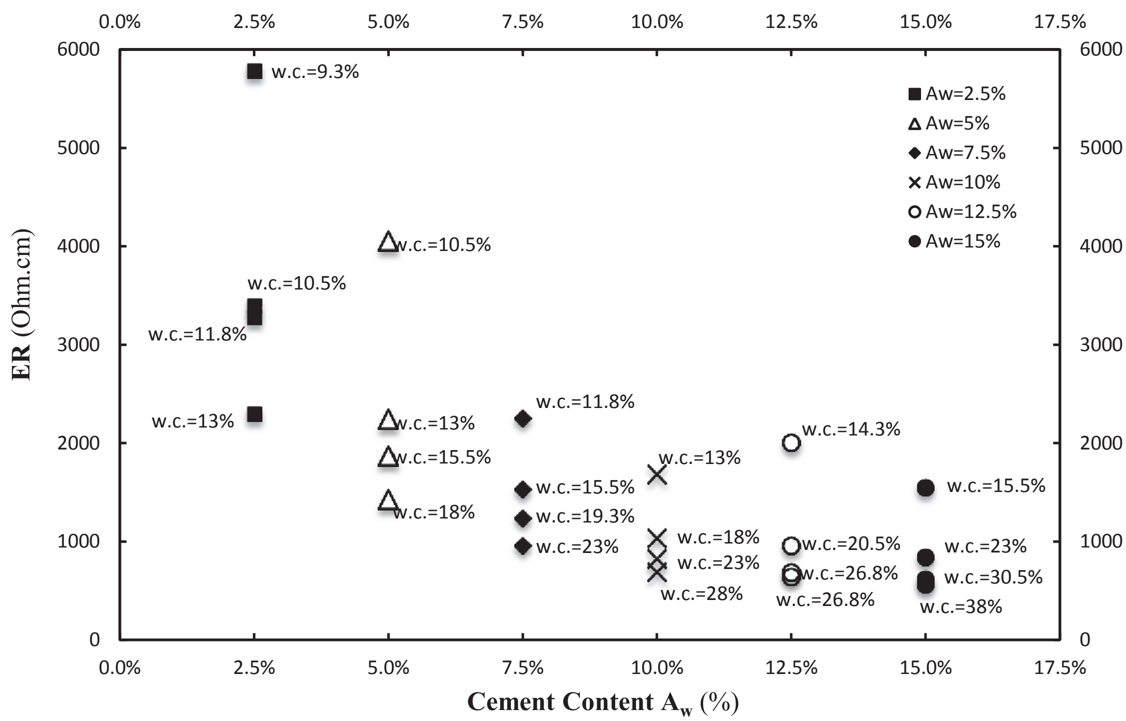

Figure 3-9 Effect of Cement Content A_w on Electrical Resistivity (ER) For Soil-Cement Samples

If these results are plotted as w/c versus ER for each cement content tested, one can observe similar trends. At the higher cement contents examined, there are relatively indistinguishable changes in ER for increases in water to cement ratio (i.e. moving towards the bottom left corner of the graph).

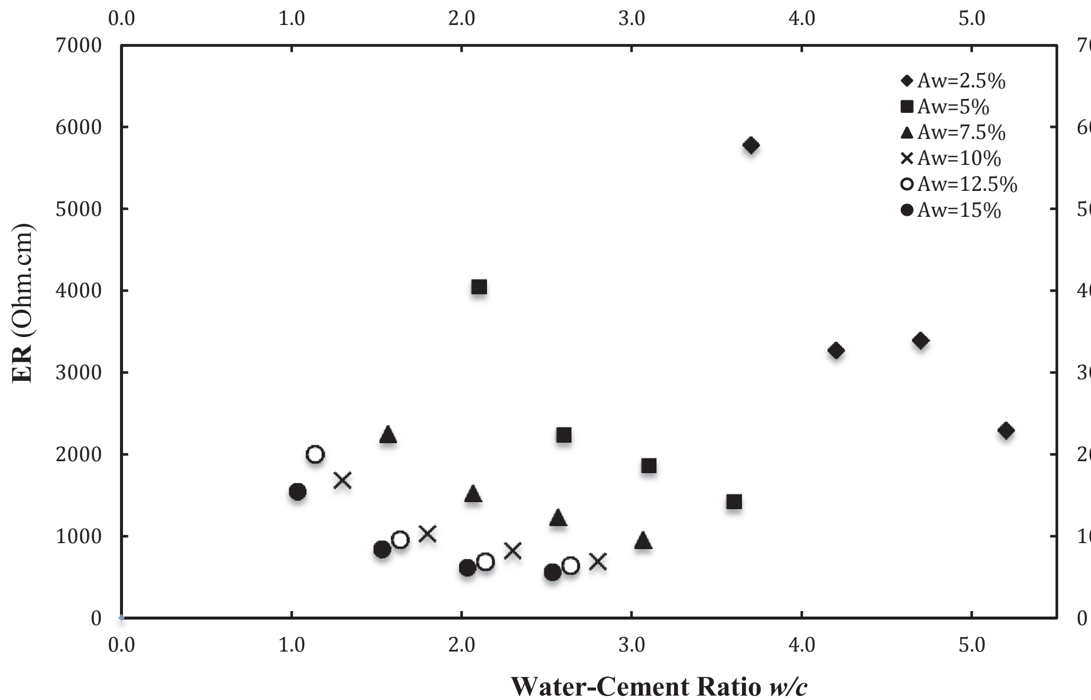

Figure 3-10 Effect of Water-Cement Ratio *w/c* on Electrical Resistivity (ER) of Soil-Cement Samples at Different Cement Content A_w

When plotting the results of the ER testing simply versus water content in the sample as shown in Figure 3-11, a distinct relationship is observed between water content and ER, irrespective of the cement content used. The strong power law relationship observed is not entirely unexpected, as suggested by Archie's Law (i.e. equation 1-2). Given that Figure 3-10 plots all the cement contents together and such a good trend is observed, it appears as if ER may be a good technique for detecting changes in moisture content in soil-cement in the field for a variety of cement contents. Although the ability to detect changes in water content in the field is an important criteria, the inability to see differences in cement content for a given water content is not encouraging for observing relationships between ER and k or ER and UCS given that cement content plays a large role in the performance of the material.

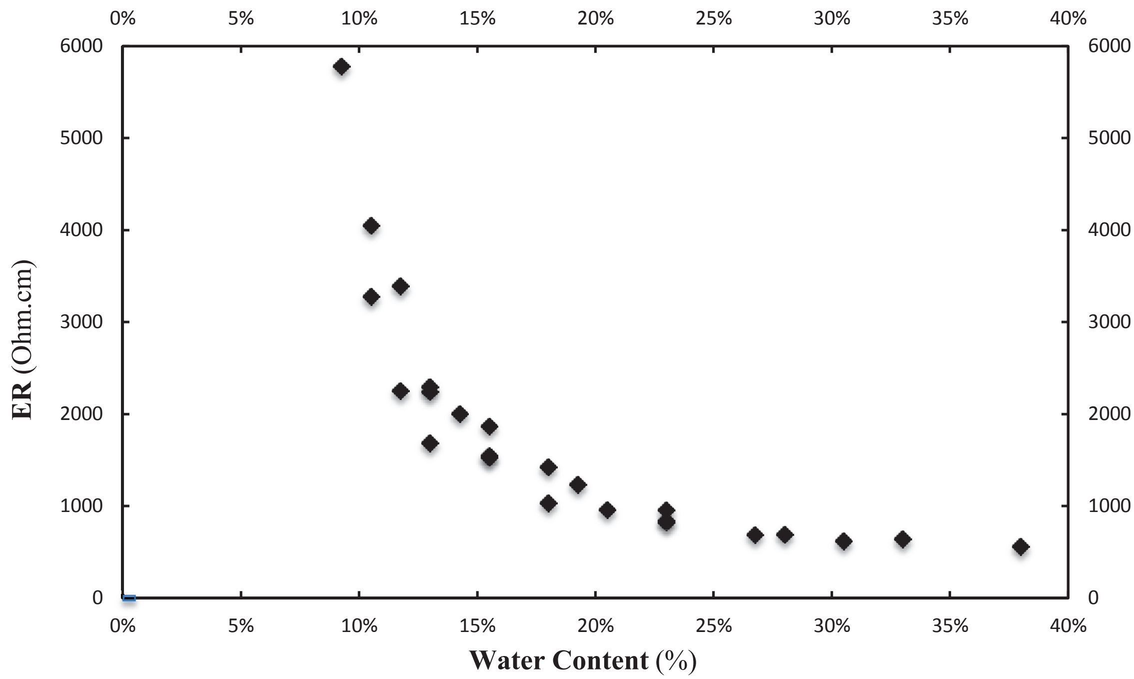

Figure 3-11 Effect of Water Content on Electrical Resistivity (ER) For Soil-Cement Samples

3.3 Relationships Between ER and Hydraulic Conductivity/UCS

3.3.1 ER and Hydraulic Conductivity Test Results:

Table 3-5 shows the average value of the three ER measurements for each mixture along with the average results of hydraulic conductivity tests for the same mixture. Figure 3-12 plots this same information in graphical form. As shown in Figure 3-12 there is a weak trend of decrease in hydraulic conductivity with decrease in ER when all of the results are plotted together. Examining the results for the individual cement contents in Figure 3-13, it can be seen that similar trends observed for water content versus hydraulic conductivity were observed as shown in Figure 3-5. Given that the previous section showed the strong relationship between ER and water content, it is not surprising that this is the case. What Figure 3-13 does indirectly capture is the dependence on the molding water content on the resultant hydraulic conductivity. As the moisture content increases beyond the 2-7% range for optimum hydraulic conductivity results, the hydraulic conductivity begins to increase.

Table 3-5 The Average of ER Results and Hydraulic Conductivity

Mixture ID	A_w	**Water content %**	***w/c* ratio**	**Average ER** (Ohm.cm)	**Average k** (m/sec)
$A_{2.5}$	2.5%	9.3%	3.7	5782	$8.7x10^{-8}$
$B_{2.5}$	2.5%	10.5%	4.2	3276	$2.0x10^{-8}$
$C_{2.5}$	2.5%	11.8%	4.7	3393	$1.4x10^{-7}$
$D_{2.5}$	2.5%	13.0%	5.2	2295	$1.9x10^{-8}$
$A_{5.0}$	5.0%	10.5%	2.1	4055	$1.8x10^{-7}$
$B_{5.0}$	5.0%	13.0%	2.6	2244	$8.6x10^{-9}$
$C_{5.0}$	5.0%	15.5%	3.1	1868	$9.8x10^{-10}$
$D_{5.0}$	5.0%	18.0%	3.6	1427	$\underline{7.6x10^{-10}}$
$A_{7.5}$	7.5%	11.8%	1.6	2253	$4.1x10^{-7}$
$B_{7.5}$	7.5%	15.5%	2.1	1530	$1.4x10^{-10}$
$C_{7.5}$	7.5%	19.3%	2.6	1236	$\underline{1.2x10^{-10}}$
$D_{7.5}$	7.5%	23.0%	3.1	958	$4.7x10^{-10}$
$A_{10.0}$	10.0%	13.0%	1.3	1684	$8.0x10^{-8}$
$B_{10.0}$	10.0%	18.0%	1.8	1032	$\underline{4.5x10^{-11}}$
$C_{10.0}$	10.0%	23.0%	2.3	824	$1.7x10^{-10}$
$D_{10.0}$	10.0%	28.0%	2.8	691	$9.9x10^{-10}$
$A_{12.5}$	12.5%	14.3%	1.1	2004	$1.8x10^{-9}$
$B_{12.5}$	12.5%	20.5%	1.6	959	$\underline{2.5x10^{-11}}$
$C_{12.5}$	12.5%	26.8%	2.1	689	$1.6x10^{-10}$
$D_{12.5}$	12.5%	33.0%	2.6	642	$7.5x10^{-10}$
$A_{15.0}$	15.0%	15.5%	1.0	1549	$3.5x10^{-11}$
$B_{15.0}$	15.0%	23.0%	1.5	842	$\underline{3.0x10^{-11}}$
$C_{15.0}$	15.0%	30.5%	2.0	619	$2.0x10^{-10}$
$A_{2.5}$	15.0%	38.0%	2.5	562	$2.1x10^{-9}$

Note: underlined values represent water contents at lowest hydraulic conductivity for the four samples within each cement content.

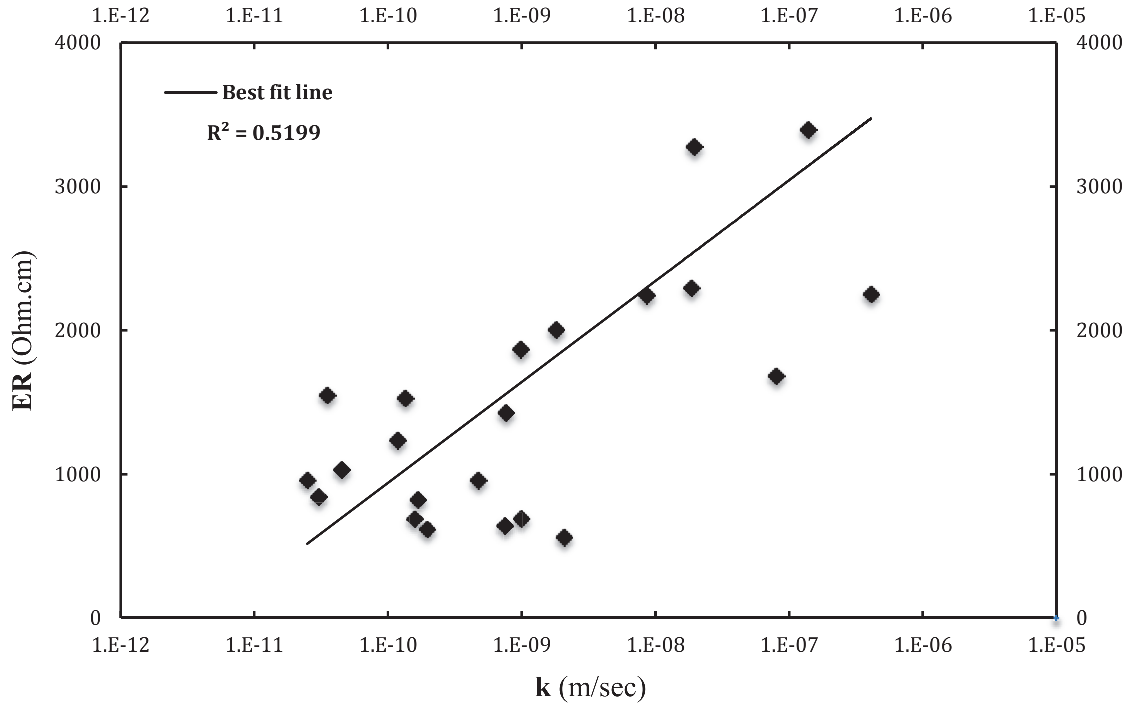

Figure 3-12 Correlation between Results of Electrical Resistivity (ER) and Hydraulic Conductivity

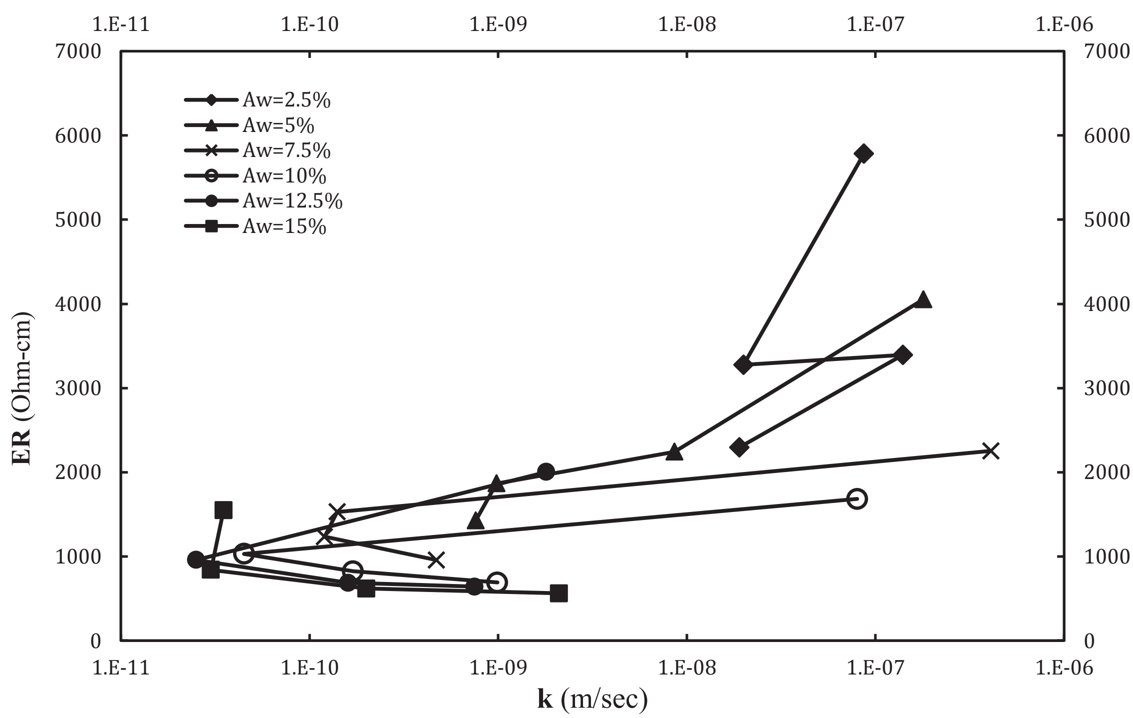

Figure 3-13 Electrical Resistivity (ER) vs Hydraulic Conductivity for Samples Grouped by Cement Content

3.3.2 Correlation of ER And Unconfined Compressive Strength results:

Table 3-6 shows the average of the three ER measurements for each mixture as well as average unconfined compressive strength q_{max} of two samples for each mixture. Figure 3-14 plots this data in graphical form. The trend between ER and UCS is weakly inverse as noted on the figure. This is opposite to the some literature findings such as Song, et al. (2008) who reported a positive non-linear relationship but his experiment was based on ER testing on cured soil-cement samples and the results shown above was for fresh (uncured) soil-cement samples.

Table 3-6 The average of ER results and UCS

Mixture ID	A_w	**Water content %**	***w/c* ratio**	**Average ER**	**Average** q_{max} (kPa)
$A_{2.5}$	2.5%	9.3%	3.7	5782	454
$B_{2.5}$	2.5%	10.5%	4.2	3276	643
$C_{2.5}$	2.5%	11.8%	4.7	3393	369
$D_{2.5}$	2.5%	13.0%	5.2	2295	299
$A_{5.0}$	5.0%	10.5%	2.1	4055	1577
$B_{5.0}$	5.0%	13.0%	2.6	2244	2026
$C_{5.0}$	5.0%	15.5%	3.1	1868	925
$D_{5.0}$	5.0%	18.0%	3.6	1427	934
$A_{7.5}$	7.5%	11.8%	1.6	2253	2095
$B_{7.5}$	7.5%	15.5%	2.1	1530	1930
$C_{7.5}$	7.5%	19.3%	2.6	1236	2793
$D_{7.5}$	7.5%	23.0%	3.1	958	1632
$A_{10.0}$	10.0%	13.0%	1.3	1684	4626
$B_{10.0}$	10.0%	18.0%	1.8	1032	4416
$C_{10.0}$	10.0%	23.0%	2.3	824	2949
$D_{10.0}$	10.0%	28.0%	2.8	691	1548
$A_{12.5}$	12.5%	14.3%	1.1	2004	7282
$B_{12.5}$	12.5%	20.5%	1.6	959	6516
$C_{12.5}$	12.5%	26.8%	2.1	689	2920
$D_{12.5}$	12.5%	33.0%	2.6	642	1594
$A_{15.0}$	15.0%	15.5%	1.0	1549	7845
$B_{15.0}$	15.0%	23.0%	1.5	842	6885
$C_{15.0}$	15.0%	30.5%	2.0	619	3109
$A_{2.5}$	15.0%	38.0%	2.5	562	1625

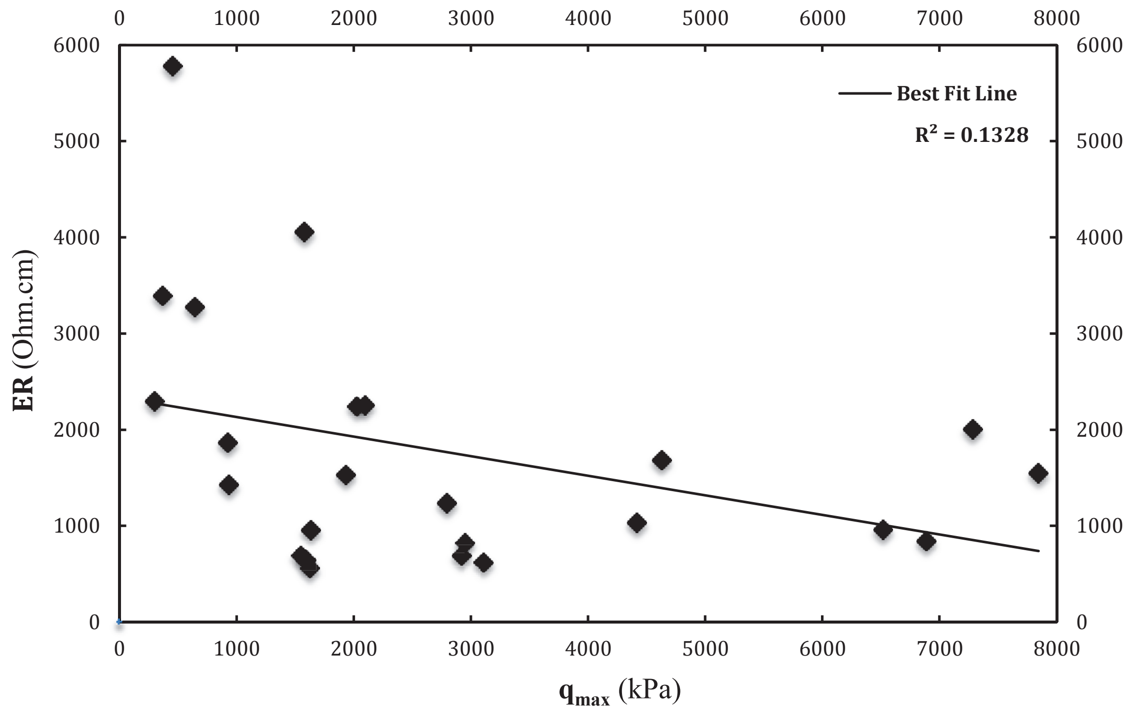

Figure 3-14 Correlation Between Results of Electrical Resistivity (ER) and Unconfined Compressive Strength q_{max}

Examining the results in terms of each cement content in Figure 3-15, it can be observed that for the higher cement contents, there is a relatively slight change in ER for large changes in UCS, while at the lower cement contents, the change in ER for small changes in UCS is quite noticeable.

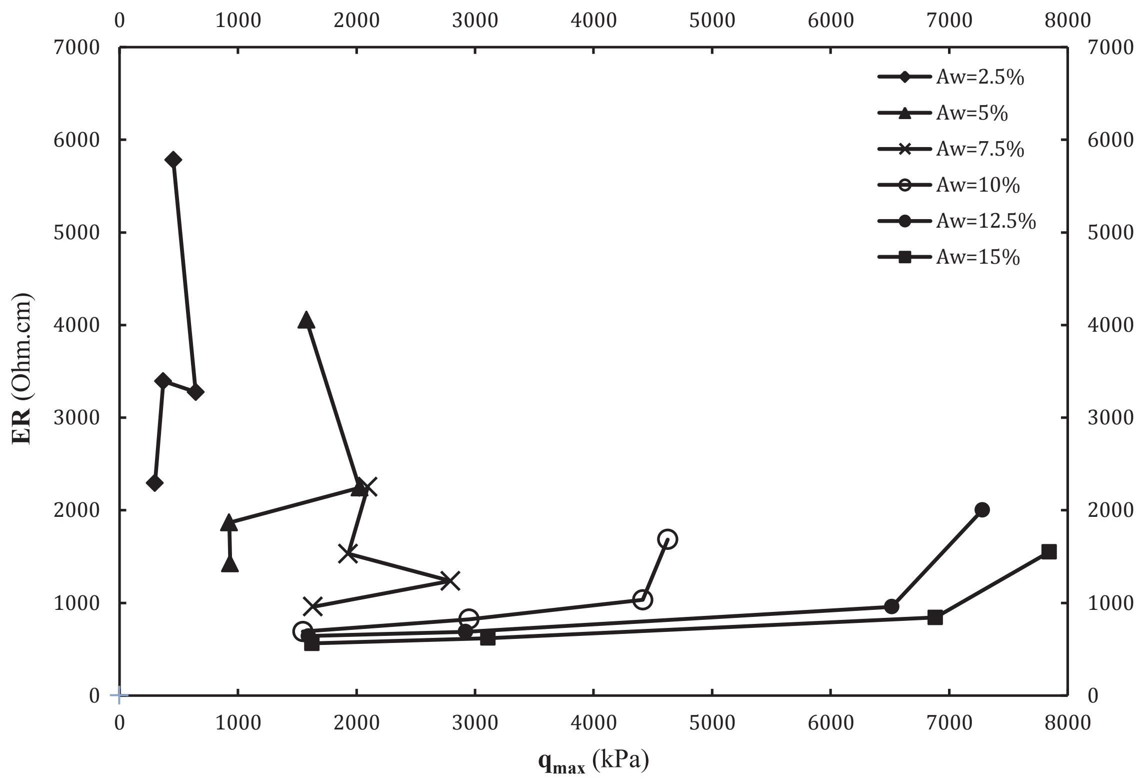

Figure 3-15 ER vs UCS for Samples Grouped by Cement Content

3.4 Discussion

The results provided in this chapter have provided some insight into the hydraulic behaviour of soil-cement that has not been previously described or observed in the literature. It has been shown that molding water content plays a large role in the resulting k, perhaps even more than cement content. This is likely related to the structure of the samples produced when the material is below and above its plastic limit. Samples compacted significantly drier than its plastic limit will have large micro pores and perhaps cracks due to the compaction process. As the water content increases towards its plastic limit, the soil-cement sample undergoes more kneading action during the compaction process. This creates a more oriented plastic structure which provides for a lower hydraulic conductivity. Near the plastic limit, the increase in cement content causes a reduction in hydraulic conductivity due to hydration.

In terms of the potential to use ER as QC method for soil-cement, it is difficult to envision it as a stand alone tool because it appears to be much more sensitive to water content and density changes than changes in the pore water conductivity due to the addition of cement. Given that traditional nuclear methods of non-destructive testing are currently widely used in this regard, it is unlikely that ER testing would provide any value in this regard. As was shown in the previous results there is such a dependency on water content, density and cement content that really a chemical means of measuring cement content in combination with moisture and density would be the ideal means to proceed with QC testing of soil-cement samples.

Chapter 4: Summary, Conclusions, and Recommendations for Future Work

4.1 Summary

As discussed in Chapter 1, the main hypothesis of this research was that ER measurements of uncured soil-cement samples could be used for quality control purposes for hardened soil cement samples. Specifically in this thesis, this hypothesis pertains to UCS and hydraulic conductivity measurements of hardened mixtures.

To assess this hypothesis, the following tasks were carried out:

- Task 1: Establish an ER testing system and calibrate it according to the ASTM's standard methods.
- Task 2: Prepare samples of soil-cement admixtures with various water-cement ratios and cement contents for hydraulic conductivity and unconfined compressive strength testing.
- Task 3: Examine ER for the soil-cement mixtures examined in Task 2.
- Task 4: Use the quantitative results found in Tasks 2 and 3 to demonstrate the potential relationship between ER measurements and the soil-cement properties.

Task 1 results are routine and hence the focus on the next section is the summary of the results obtained from tasks 2, 3, and 4, identified above.

4.1.1 Laboratory Results

4.1.1.1 Hydraulic Conductivity Results (Task 2)

It was generally found that when the water content of the mixture was 2 to 6 percent above optimum, proportional increments in cement content decreased the hydraulic conductivity. When water content was used to group the samples, this finding becomes more apparent. It was also shown that the rate of hydraulic conductivity decrease was noticeable when the water content was increased past the optimum water content. However, the hydraulic conductivity begins to increase if water in excess of the 2 to 6% range was exceeded.

4.1.1.2 Unconfined Compressive Strength Results (Task 2)

It was found that the compressive strength increased with increments of cement content (at a given water content). This finding was observed for most the 48 samples tested. Also it was also noted increasing water contents past the 2 to 6% range as noted in the previous section resulted in loss of strength of the sample. As expected, the results showed that the unconfined compressive strength decreased with increases in water-cement ratio.

4.1.1.3 Electrical Resistivity Results (Task 3)

The testing program in Task 3 focused on the effect of water content, cement content, and the water-cement ratio on ER measurements of uncured soil-cement samples. Samples were prepared with the same mix designs, bulk density of the samples which were used in hydraulic conductivity and unconfined compressive strength testing. Results showed that ER decreased with increases in water content, cement content, and water-cement ratio (when either water or cement content was isolated).

4.1.2 Comparison of Task 2 and Task 3 Results

Comparing results between electrical resistivity and hydraulic conductivity/unconfined compressive strength results showed that ER results were, in essence, similar to plots showing relationships between water content and hydraulic conductivity/unconfined compressive strength.

4.2 Conclusions

The results of soil and soil-cement samples used in this research have demonstrated the following:

- For the soil type used in this research, ER testing results in Task1 and Task 3 show that the electrical resistivity is very sensitive tool for the changes in the parameters examined in testing programs of this thesis (density, water content, cement content, and water-cement ratio) and there is a potential possibility to develop the electrical resistivity to be a tool can estimate those parameters. Unfortunately for soil-cement applications, unlike controlled concrete batch mixing applications, both cement and water contents can vary during the mixing process. This creates issues with the ER interpretation performed in this research.
- The results of hydraulic conductivity and the unconfined compressive strength testing show that the same examined parameters (water content, cement content, and water-cement ratio) are considered key parameters controlling the soil-cement performance. This is especially true of water content which plays a large role in resulting k and UCS for a given cement content.
- For a given cement content, the variation in water content results in different k and q_{max} values which leads to conclude that controlling the water is very important in the field to get acceptable hydraulic and physical performance.

4.3 Recommendations for Future Work

It appears as if ER as a measurement technique is not very effective for quality control for soil-cement samples. Future work should concentrate on chemical techniques which can approximately estimate cement contents and use in combination with traditional water content and moisture density criteria. Resistivity measurements may be somewhat useful as a way for measuring water addition in deep mixing processes but still cement content control is desired in this process. In addition, further examination of the

Archie equations may assist in separating the contribution of cement and water in the interpretation of ER results for soil-cement materials.

References

Abu Hassanein, Z. S., Benson, C. H. and Blotz, L. R. (1996). Electrical Resistivity of Compacted Clays. Journal of Geotechnical Engineering (American Society of Civil Engineers) 122(5), pp. 397-406.

ACI Committee 230 (1990). Report on Soil Cement. American Concrete Institute, American Concrete Institute, 23 pages. Retrieved from ACI website (www.concrete.org).

ACI Committee 116 (2000). Cement and Concrete Terminology. American Concrete Institute ACI, 73 pages. Retrieved from ACI website (www.concrete.org).

Archie, G. E. (1942) The electrical resistivity log as an aid in determining some reservoir characteristics. Transactions of The American Institute of Mining, Metallurgical, and Petroleum Engineers Inc. 146(1), pp. 54-62.

ASTM Standard G187–05 (2005). Standard Test Method for Measurement of Soil Resistivity Using the Two-Electrode Soil Box Method. American Society for Testing and Materials, West Conshohocken, PA. Retrieved from ASTM Digital Library.

ASTM standard D1140. (2006a). Standard Test Methods for Amount of Material in Soils Finer than No. 200 (75-μm) Sieve. American Society for Testing and Materials, West Conshohocken, PA. Retrieved from ASTM Digital Library.

ASTM Standard D1633 (2006b). Standard test methods for compressive strength of molded soil-cement cylinders. American Society for Testing and Materials, West Conshohocken, PA. Retrieved from ASTM Digital Library.

ASTM Standard D6913-04 (2009). Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis. American Society for Testing and Materials, West Conshohocken, PA. Retrieved from ASTM Digital Library.

ASTM Standard D5084 (2010). Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter. American Society for Testing and Materials, West Conshohocken, PA. Retrieved from ASTM Digital Library.

ASTM Standard D558-11 (2011). Standard Test Methods for Moisture-Density (Unit Weight) Relations of Soil-Cement Mixtures. American Society for Testing and Materials, West Conshohocken, PA. Retrieved from ASTM Digital Library.

Bahar, R., Benazzoug, M. and Kenai, S.(2004). Performance of Compacted Cement-Stabilised Soil. Cement & Concrete Composites (ELSEVIER) 26, pp. 811-820.

Beck, Y. L., Lopes, S. P., Ferber, V., and Côte, P. (2011). Microstructural Interpretation of Water Content and Dry Density Influence on the DC-Electrical Resistivity of a Fine-Grained Soil. Geotechnical Testing Journal, American Society for Testing and Materials, West Conshohocken, PA. Retrieved from ASTM Digital Library, 34(6), pp. 1-14.

Belleza, I., and Fratalocchi, E. (2006). Effectiveness of Cement on Hydraulic Conductivity of Compacted Soil–Cement Mixtures. Ground Improvement (Thomas Telford Ltd) 10(2), pp. 77-90.

Bruce, D. A. (2000). An Introduction to the Deep Soil Mixing Methods as Used in Geotechnical Aplications. Report FHWA-RD-99-138, Federal Highway Administration, U.S. Department of Transportation, Mclean, VA, 150 pages.

Bryson, L. S., and Bathe, A. (2009). Determination of Selected Geotechnical Properties of Soil Using Electrical Conductivity Testing. Geotechnical Testing Journal, American Society for Testing and Materials, West Conshohocken, PA. Retrieved from ASTM Digital Library. 32(3), pp. 252-261.

Cement Association of Canada (2012). Cement Applications: Engineered Soil. Retrieved on: December 18, 2012. From: http://www.cement.ca/en/Engineered-Soil.html

Conner, J. R., and Hoeffner, S. L. (1998). The History of Stabilization / Solidification Technology. Critical Reviews in Environmental Science and Technology (Taylor & Francis) 28(4), pp. 325-396.

Daniel, D. E., and Benson C. H. (1990). Water Content-Density Criteria for Compacted Soil Liners. Journal of Geotechnical Engineering (ASCE) 116(12) (1990), pp. 1811-1830.

Dinchak, W. B. (1989). Soil-cement: It's Not Just For Highways Anymore. Energy and Water Resources Department, Portland Cement Association, The Aberdeen Group.

Felt, E. J. (1955). Factors Influencing Physical Properties of Soil-Cement Mixtures. Highway Research Board Bulletin 108, (National Academy of Sciences-National Research Council), pp. 138-162.

Filz, G. M. and Hodges, D. K. and Weatherby, D. E. and Marr, W. A. (2005). Standardized Definitions and Laboratory Procedures for Soil-Cement Specimens Applicable to the Wet Method of Deep Mixing. Innovations in Grouting and Soil Improvement. American Society of Civil Engineers. pp. 1643-1656.

Fonseca, A. V., Cruz, R. C., and Consoli, N. C. (2009). Strength Properties of Sandy Soil–Cement Admixtures. Geotechnical and Geologecal engineering (Springer Science) 27, pp. 681-686.

Fujii, M., Watabnabe, K., Kubo, Y., Keizo, M., Arai, M. J., Kitamura, K., Yamashita, T. (2010). Applicability of Electric Resistivity Method for Quality Evaluation of Soil-Cement Column. Proceedings of the Twentieth International Offshore and Polar Engineering Conference, The International Society of Offshore and Polar Engineers.

Fukue, M., Minato, T., Horibe, H. and Taya, N. (1999). The Micro-Structures of Clay Given by Resistivity Measurements. Engineering Geology (ScienceDirect). 54, no. 1-2, pp. 42-53.

Jackson, P. D., Smith, D. T. and Stanford, P. N. (1978). Resistivity-Porosity-Particle Shape Relationships For Marine Sands. GEOPHYSICS (Society of Exploration Geophysicists) 43(6), pp. 1250-1268.

Kalinski, R. J., and Kelly, W. E. (1993). Estimating Water Content of Soils from Electrical Resistivity. Geotechnical Testing Journal American Society for Testing and Materials, West Conshohocken, PA. Retrieved from ASTM Digital Library, 16(3), pp. 232-329.

Keller, G., and Frischknecht, F. (1966). Electrical methods in geophysical prospecting. New York, NY: Pergamon Press.

Kowalski, T. E., and Starry, D. W. Jr. (2007). Modern Soil Stabilization Techniques. Annual Conference of the Transportation Association of Canada. Saskatoon, Saskatchewan, pp. 1-16.

Lorenzo, G. A., and Bergado, D. T. (2004). Fundamental Parameters of Cement-Admixed Clay—New Approach. Joornal of Geotechnical and Geoenvironmental Engineerirng (ASCE) 130(10), pp. 1042-1050.

Mancio, M., Moore, J. R., Brooks, Z., Monteiro, P. J. M. and Glaser, S. D. (2009). Instantaneous In-Situ Determination of Water-Cement Ratio of Fresh Concrete. ACI Materials Journal. ACI. 107, no. 6, pp. 586-592.

McCarter, W. (1981). The electrical resistivity characteristics of compacted clays. (Géotechnique). 34(2), pp. 263 –267.

McCarter, W. J., and Desmazes, P. (1997). Soil characterization using electrical measurements. (Géotechnique). 47(1), pp. 179-183.

Milburn, J. P., and Parsons, R. L.(2004). Performance of Soil Stabilization Agents. Report No. K-TRAN: KU-01-8, Bureau of Materials and Research, Research Unit, Kanasa Department of Transpotation, Springfield, Virginia: National Technical Information Service, 117 pages.

Mitchell, J. K., Hooper, D. R. and Campanella, R. G. (1965). Permeability of Compacted Clay. Journal of Soil Mechanics & Foundations Div (ASCE) 91(SM4), pp. 41-65.

Mitchell, J. K. (1981). Soil lmprovement- State-of-the-Art Report. Proceedings of the 10th International Conference on Soil Mechanics and Foundation Engineering. Stockholm, pp. 509-565.

Pirani, Z. (2011). Examination The Feasibility of Portland Limestone Cement For Cement-Based Stabilization and Solidification Applications. Dalhousie University.

Scullion, T., Sebesta, S., Harris, J. P., and Syed, I. (2005). Evaluating the Performance of Soil-Cement and Cement- Modified Soil for Pavements: A Laboratory Investigation. Portland Cement Association PCA, Skokis, Illinois, 142 pages.

Seladji, S., Cosenza, P., Tabbagh, A., Ranger, J., and Richard, G. (2010). The effect of compaction on soil electrical resistivity: a laboratory investigation. European Journal of Soil Science (British Society of Soil Science) 61, pp. 1043-1055.

Song, Y. L., Yan, J., Han, L. H., and Gu, M. F. (2008). Experimental study on the electrical resistivity of soil–cement admixtures. Environmental Geology (Springer-Verlag). 54(6), pp. 1227-1233.

Terashi, M., and Juran, I. (2000). Ground Improvement-State of the Art. An International Conference on Geotechnical and Geological Engineering. Melbourne, Australia: Technomic Inc, Lancaster, pp. 461–519.

Urish, D. W. (1981). Electrical Resistivity-Hydraulic Conductivity Relationships in Glacial Outwash Aquifers. Water Resources Research 17, no. 5, October 1981, pp. 1401-1408.

Wei, Xiaosheng and Xiao, Lianzhen. (2011). Effect of temperature on the electrical resistivity of Portland cement pastes. Advances in Cement Research (Institution of Civil Engineers ICE) 24, no. 2, April 2011, pp. 69-76.

Xiao, L., and Wei, X. (2011) Early Age Compressive Strength of Pastes by Electrical Resistivity Method and Maturity Method. Journal of Wuhan University of Technology-Mater, 26(5), pp. 983-989.

Zhang, Ding-wen, Lei Chen, and Song-yu Liu. (2012). Key parameters controlling electrical resistivity and strength of cement treated soils. Journal of Central South University. (Springer) 19, no. 10, March 2012, pp. 2991-2998.

APPENDIX

A.1 ER Preliminary Testing - Soil

Based on the literature review findings in Chapter 1, it is apparent that sample characteristics such as density, water content, pore water chemistry, and temperature can potentially influence the measurement of ER for soil samples. To properly develop the ER testing methodologies in this thesis for soil-cement samples, it was determined that some preliminary ER testing would be undertaken in the laboratory with soil samples to be used for future ER testing with soil-cement samples. As well, results of this preliminary testing would assist in interpreting future soil-cement testing.

To examine the influence of density on the results of ER measurements, the soil was prepared to a range of densities in the soil resistivity box (i.e. 1000, 1250, 1500, 1750, 2000 kg/m3) at 10% moisture content. The 10% moisture content was near the natural moisture content of the soil and provided for measureable current flow through the samples. At a given temperature, washed or unwashed soil was used for testing. Washed samples were initially washed with distilled water in plastic centrifuge containers with size of 250 ml for each, after the soil water mixture placed in those containers. The containers placed in a centrifuge to allow separation of the soil-water mixture and the washing process was performed three times. After centrifugation, the soil was dried in the oven at 110 °C to be ready for testing. Unwashed samples were used immediately after oven drying.

Figure A-1 shows the relationship between ER and the bulk density at the 10% water content. Square symbols represent the washed soil samples and triangular symbols represent unwashed soil samples. It is apparent from the graph that regardless of the pore water chemistry (washed or unwashed); ER decreases as the bulk density increases for the range of densities examined. As explained earlier in the literature review by Beck et al. (2011) and Seladji et al. (2010), the increase in density leads to particles that are more tightly packed and hence leads to an increase in electrical conductance in the soil. The washing of the soil does appear to affect the ER measurement at low densities but differences are minimal at higher densities. The trends are approximately similar and the points of the unwashed soil are higher because the change in pore water chemistry, which was caused by the washing process.

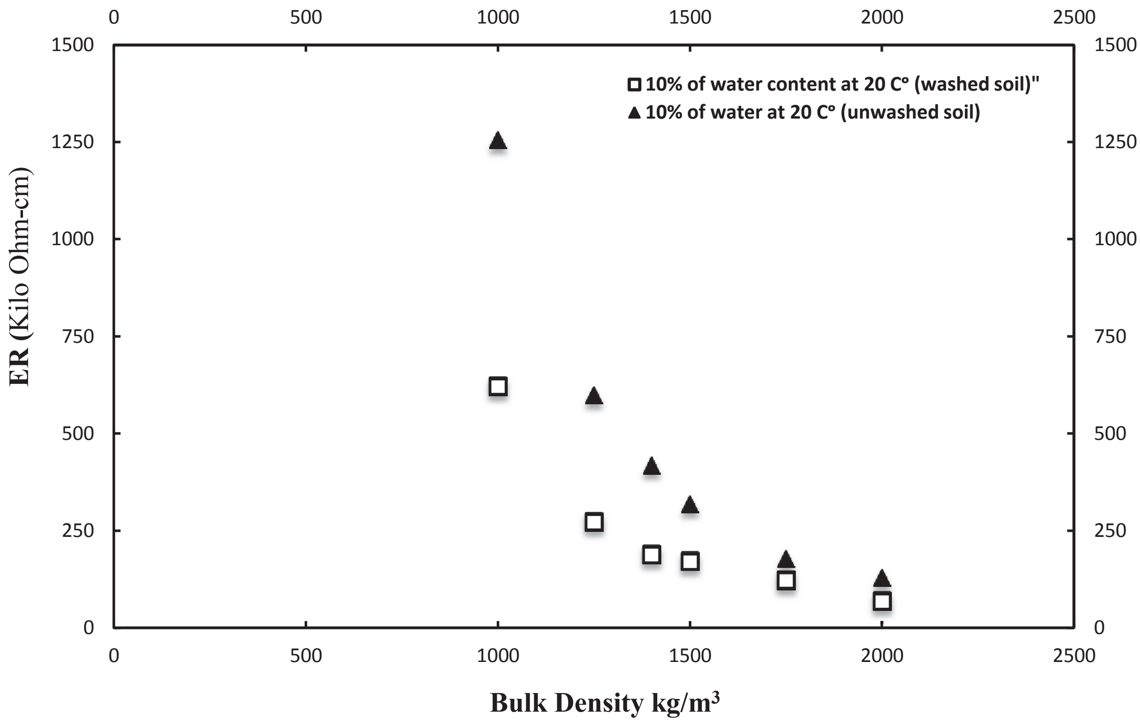

Figure A-1 ER of Washed and Unwashed Soil Compacted To Different Bulk Densities

To further examine the sensitivity of the ER measure with water content, both washed and unwashed soil samples were prepared at a constant bulk density (i.e. 1400 kg/m3) and subjected to ER testing. Figure A-2 summarizes the results of ER testing and it is clear that the electrical resistivity is sensitive to increases in water content for both the washed and unwashed soil.

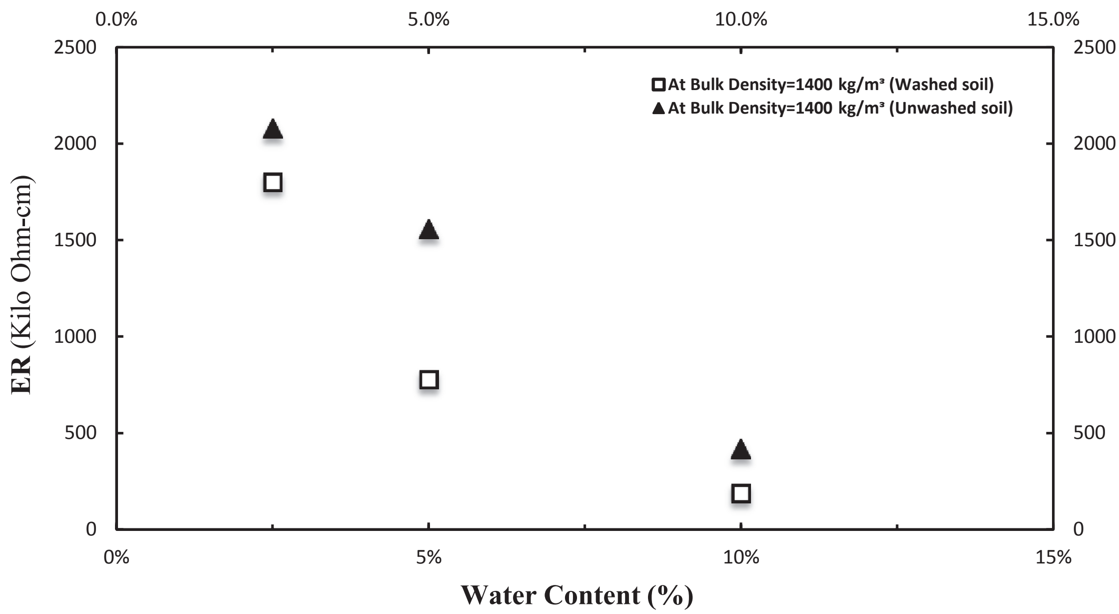

Figure A-2 ER of Washed and Unwashed soil at Different Water Content

The influence of test temperature on ER results was examined by performing ER measurements of the soil at various temperatures (i.e. 3 °C, 10 °C, and 20 °C), compacted to the same target bulk densities and moisture contents described above in section 0 (i.e. 1000, 1250, 1500, 1750, and 2000 kg/m^3). These tests were repeated for two different water contents (5% and 10%). Results of this testing is provided in Figure A-3 and Figure A-4. It can be seen that temperature effects appeared to influence the 5% water content soil more than the 10% water content soil. For the 10% moisture content soil, it appears as if the range in temperatures examined had little effect on the ER measured for densities greater than 1250 kg/m3.

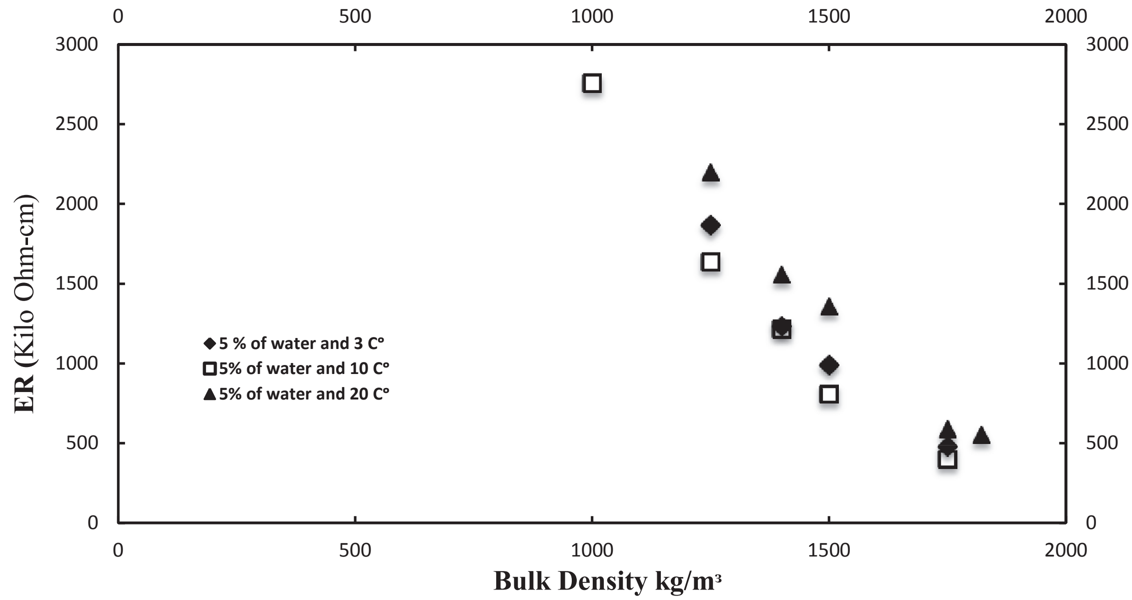

Figure A-3 Effect of The Temperature on ER of Soil-Cement at 5% of Water Content

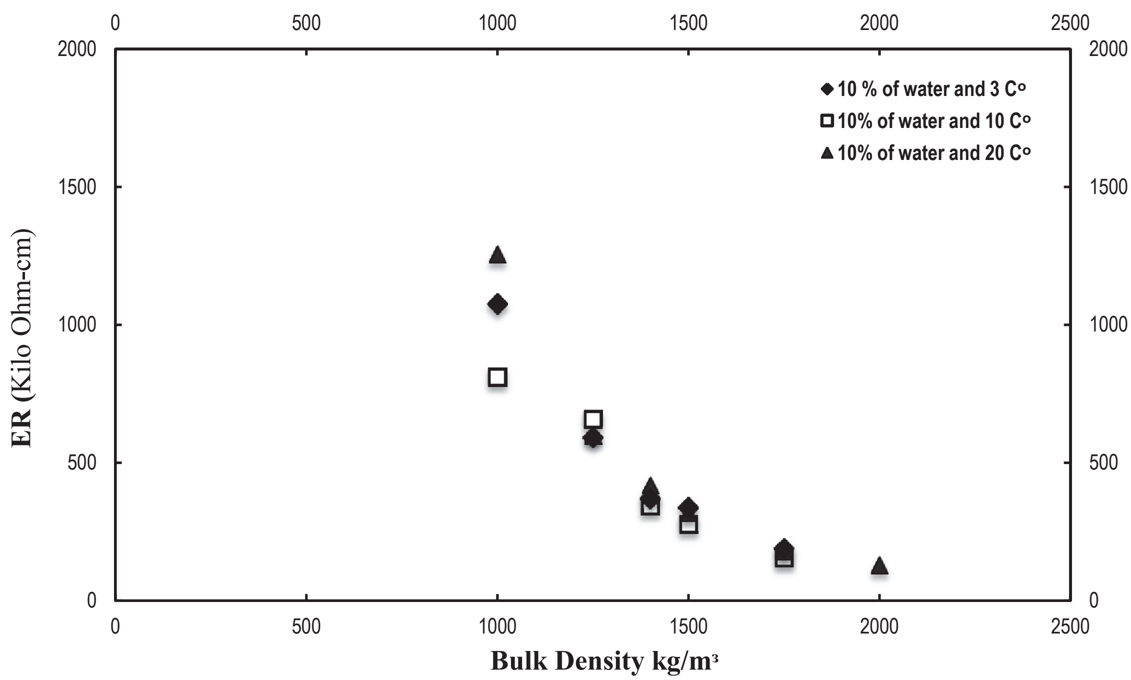

Figure A-4 Effect of Temperature on ER of Soil-Cement at 10% of Water Content

In summary, as suggested in the literature (i.e. Beck et al., 2011 and Seladji et al., 2010), soil density and moisture content have fairly significant influence on the ER measure for the soil tested. Temperatures differences between 3 C° and 20 C° had some influence on ER measurements but little at densities higher than 1250 kg/m3. It also appears that washed samples exhibit different ER values than unwashed samples at a given density and water content however, at higher densities, the differences are slight. Given this, it was determined use one target bulk density for future testing to eliminate potential variability associated with bulk density affecting ER measurements. It was also determined that compacted soils at higher densities would be the focus of this research (normal field application) and that the temperature for future testing was held constant at 20 C°.