Impact of Deicing Salts on Corrosion Rates of MSE Reinforcement – Phase 1

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16. ABSTRACT

This research involved a detailed laboratory study of available test procedures for evaluating corrosive potential of granular MSE backfill. The research examined standard AASHTO and ASTM test procedures that are widely used in current practice as well as several new test procedures that aim to overcome the limitations in the existing test procedures. Special emphasis was placed on electrical resistivities of the material under fully saturated conditions and the pore solution extract. A new test device, INA219 was developed and used throughout the test series so that continuous data collection and recording could be achieved. The experimental program included MSE backfill material obtained from three different local sources. Two separate gradations, i.e. AASHTO standard gradation and AASHTO No.57 gradation, of each source were included in the test program. In addition, tests were also performed on glass beads with three different sizes.

The key findings from the SPTC Project 14.6-36: Phase I are as follows: (a) a new empirical relationship was established between the electrical resistivity of the pore solution extract and that of the saturated bulk material. This relationship can be used to estimate the electrical resistivity of MSE backfill with large particles when the material porosity is known, (b) The minimum electrical resistivity of saturated backfill varies significantly with elapsed time. This effect was particularly noticeable in MSE backfill with coarse gradation. Such material typically required 15hrs before the resistivity stabilized and reached its minimum value.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	Mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl	fluid ounces	29.57	milliliters	mL
oz	gallons	3.785	liters	L
gal	cubic feet	0.028	cubic meters	m^3
ft^3	cubic yards	0.765	cubic meters	m^3
yd^3	NOTE: volumes greater than 1000 L shall be shown in m^3			
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 (F-32)/1.8	Celsius or	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inc h	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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Impact of Deicing Salts on Corrosion Rates of MSE Reinforcement

Final Report
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by

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Executive Summary

SPTC Project 14.6-36 examined corrosion rates of MSE steel reinforcement specimens embedded in granular MSE backfill with and without salt exposure. Salt exposure was simulated by permeating the backfill material with a salt solution that represented runoff from deicing salt applications and/or coastal flooding. This research study was completed in two separate phases. This report documents the work completed in Phase I of the research.

SPTC Project 14.6-36: Phase I involved a detailed laboratory study of available test procedures for evaluating corrosive potential of granular MSE backfill. The research examined standard AASHTO and ASTM test procedures that are widely used in current practice as well as several new test procedures that aim to overcome the limitations in the existing test procedures. Phase I test program primarily focused on electrochemical properties of the material as these properties are considered the industry standard for evaluating backfill with respect to corrosive potential. Special emphasis was placed on electrical resistivity of the material under fully saturated conditions and the electrical resistivity of the pore solution extract. A new test device, INA219 was developed and used throughout the test series so that continuous data collection and recording could be achieved. The experimental program included MSE backfill material obtained from three different local sources, namely Vulcan, Sand Mills and R. E. Janes. Two separate gradations, i.e. AASHTO standard gradation and AASHTO No.57 gradation, of each source were included in the test program. In addition to tests conducted on the three natural backfill sources mentioned above, tests were also performed on glass beads with three different sizes. The tests on glass beads enabled the effects of particle size to be isolated from effects of pore solution chemistry.

The key findings from the SPTC Project 14.6-36: Phase I are as follows: (a) a new empirical relationship was observed between the electrical resistivity of the pore solution extract and that of the saturated bulk material. This relationship can be used to estimate the electrical resistivity of MSE backfill with large particles when the material porosity is known, (b) The minimum electrical resistivity of saturated backfill varies significantly with elapsed time. This effect was particularly noticeable in MSE backfill with coarse gradation. Such material typically required 15hrs before the resistivity stabilized and reached its minimum value.

Chapter 1 - Introduction

1.1 General Background

Mechanically stabilized earth (MSE) retaining walls support numerous structures used in transportation such as bridge abutments, access ramps and retaining walls. MSE structures use wall panels attached to galvanized steel reinforcement that is inserted directly into the soil backfill. Galvanized steel reinforcement offers numerous benefits in MSE retaining wall construction projects such as high strength, inextensibility and reasonable cost, but they also have some drawbacks. When steel is buried within soil mass the refined iron will revert back to its natural ore-like state by a process known as oxidation. The oxidation process chemically reacts with the refined iron of steel reinforcement and the MSE retaining can become structurally compromised.

The service life of Mechanically Stabilized Earth (MSE) retaining walls is governed by the rate of corrosion of metallic reinforcements used in wall construction. In current design practice, the service life of the structure is estimated assuming rates of metal loss that correspond to mild or moderate corrosive conditions in the soil backfill. The assumption is deemed to be valid when certain electrochemical properties of the soil backfill, namely electrical resistivity, pH, chloride and sulfate contents are within specified limits. There are several major drawbacks in the approach currently used for the purpose of evaluating MSE backfill for corrosive potential. First, the current practice only offers a means of testing for the corrosive potential of backfill that consists of soil or fine aggregate only. However, modern MSE wall projects often use coarse aggregate backfill to achieve better strength and drainage behavior. In fact, a material that drains easily provides a less corrosive environment than a fine backfill that holds moisture for extended periods of time. Second, the method does not consider the potential changes in the material that may when occur when exposed to roadway deicing salts during service. The electrochemical conditions within the backfill can change significantly as salt contaminated runoff permeates through the reinforced fill and accumulates within the backfill soil. Evaluation of corrosion rates under these circumstances requires a more comprehensive approach.

The current standard practice based on American Association of State Highway and

Transportation Officials (AASHTO) and American Society for Testing and Materials (ASTM International) specifications rely on key electrochemical properties of backfill materials namely resistivity (ρ), pH, chlorides (Cl-), sulfates (SO42-), and organic content to evaluate MSE backfill for corrosive potential. Of all these electrochemical properties, soil resistivity is considered as the primary parameter that determines corrosive behavior within MSE wall backfills (Fitzgerald, 1989; Palmer, 1989). This report documents the work conducted under SPTC research study 14.1-36 to evaluate current AASHTO and ASTM methodology for evaluating MSE backfill material for corrosive potential. It will address the limitations and propose improvements.

1.2 Research Objective

The main objectives of this study can be summarized as follows:

- Evaluate and understand the concept of resistivity as it pertains to corrosivity of soil material;
- Evaluate current AASHTO and ASTM standard test methods and assess limitations with regard to their applicability for coarse-aggregate backfill materials;
- Test and analyze resistivity parameters for specific effects such as particle- size; drainage characteristics and salt intrusion from extraneous sources
- Propose an alternative means for measuring resistivity of both coarse- and fine-aggregate backfill materials.

1.3 Research Approach

This research began with a comprehensive review of relevant documents pertaining to assessment of soil corrosivity. The literature review process undertaken included the evaluation of current national association and organization documents on following topics: electrochemical characteristics and parameters used for measuring corrosive potential of MSE soil backfill material, limitations in the current AASHTO and ASTM standard test methods for resistivity measurements, alternative coarse-aggregate resistivity test methods such as the Field Leaching Test (FLT) method, fundamentals of corrosion of metals in soil environment, and measurement of rate of corrosion using electrical methods.

Resistivity measurement testing conducted for this report was based in part on the AASHTO 288-12 and ASTM G187–12a standard test methods for estimating the minimum soil resistivity of select material. Because AASHTO (2012) limits the testing of soil resistivity to material passing the No. 10 sieve (2.00 mm) using a soil resistivity box that cannot accommodate large particle-sized material, a new approach for measuring the minimum resistivity was developed using the relationship between the resistivity of bulk material (ρa) and the resistivity of that material's pore solution (ρw).

This approach was tested by first measuring resistivity of water to make sure all resistance-measuring devices were consistent with each other and reliable, then by testing the effects of physical characteristics like particle size of material through resistivity testing on inert material (glass beads), and finally performing resistivity tests on actual backfill materials with two separate gradations. Other factors that were found to be relevant to actual backfill resistivity effects included the time required for the material/water to reach equilibrium, which was tested using continuous data collection from the INA219 device that was developed as a part of this research project. Once the experimental program was completed, the data was collected and analyzed to develop new relationships and models.

1.4 Report Organization

The report consists of five chapters. Chapter 2 includes an extensive literature review on the subject of MSE retaining wall steel reinforcement corrosion with the inclusion of pertinent documents covering areas such as the corrosive potential of embedded steel in soil, resistivity characteristics and corresponding test methods for the use of establishing soil corrosive potential in MSE wall backfill material selection, and the concepts regarding coarse-aggregate resistivity measurements and the associated specific test method options. Chapter 3 focuses on the experimental program process and the associated procedures conducted by researchers at Texas Tech University. Results obtained from the experimental program are summarized and interpreted in Chapter 4. Chapter 5 consists of all conclusions deduced from the research results and contains recommendations derived from the project.

Chapter 2 – Literature Review

2.1 General Overview

This chapter includes an extensive literature review over Mechanically Stabilized Earth (MSE) soil backfill concepts and resistivity test methods. The chapter begins with the review of national publication documents that focus on the corrosive potential parameters of select MSE backfill material, and is followed by the specific test methods implemented by national transportation associations and societies. After discussing the importance of corrosive potential in selecting appropriate backfill material, this chapter focuses on topics about the fundamentals of soil resistivity, and how they can be used to uncover innovative ways of establishing a bulk soil resistivity value through resistivity testing of pore-water mixture solutions. This chapter concludes with the reviews of previous research on the matter of soil resistivity measurements that help establish a connection with the experimental program conducted in the experimental program of this report.

2.2 MSE Wall Backfill

Many, if not all, MSE Retaining Wall structures are designed and constructed by following the United States Department of Transportation Federal Highway Administration (USDOT FHWA) regulation guidelines. A program from the USDOT FHWA, called The National Highway Institute (NHI), published course document (Elias, Fishman, Christopher, & Berg, 2009), which details the design and construction process and criteria of several MSE Walls and Reinforced Soil Slopes. Section 3.2.3 of this document establishes specific recommendation limits on several electrochemical properties for reinforced fills with steel reinforcement. Elias et al., (2009) states these electrochemical properties include resistivity (ρ), pH, chloride ($Cl2$), sulfate ($SO4$), and organic content criteria limitations. These properties are displayed in Table 1, and include the corresponding criteria limitations for each property, as well as an appropriate laboratory test method to be used for obtaining each parameter's value.

Table 1: Recommended Limits of Electrochemical Properties for Reinforced Fills with Steel Reinforcement

Parameter	Criteria Limitations	Test Method
Resistivity	3000 ohm-cm	AASHTO T-288
pH	>5 and < 10	AASHTO T-289
Chlorides	<100 PPM	ASTM D4327
Sulfates	< 200 PPM	ASTM D-4327
Organic Content	1% maximum	AASHTO T-267

The corrosive potential, or degradation, of soil backfill material determines the rate in which steel member thickness deteriorates by a chemical or electrochemical reaction. Elias et al. (2009) states that, "Corrosion is fundamentally a return of metals to their native state as oxides and salts" (p. 2-1). ASTM Committee G-1, Subcommittee G1.10 assigned a task group in 1989 to discover an answer to the synergistic effect of several soil characteristics in regards to corrosion of metals in soils. In one paper published in the committee's final report, Escalante, (1989), the underground corrosion process is described as being "Similar to the electrochemical action that takes place in an ordinary dry cell of a flashlight during use," (p. 81). The corrosion process described by Escalante (1989) is as follows:

A galvanic cell must have three components for it to function. These are:

(1) an anode/cathode system;

(2) an electrically conducting path between the anode and the cathode; and

(3) an electrolyte in contact with the anode/cathode system. In the dry cell illustrated in Figure 1, the zinc case and the carbon rod make up the anode/cathode system. The electrolyte is the chemical medium, normally an aqueous gel, between the zinc case and the carbon rod. The conducting path between the anode and the cathode is provided externally by the flashlight body which passes the current through the bulb for illumination.

In this type of dry cell, the zinc case is the anode which goes into solution in the electrolyte and thus corrodes in the process of giving up electrons for the production of electricity. This dissolution at the anode is referred to as an oxidation reaction. At this electrode, a zinc atom gives up two electrons and becomes a positive ion. The electrons flow toward the cathode through the conducting metallic path while the positively charged ions either chemically combine with some other species or diffuse through the electrolyte toward the cathode where they gain electrons and are reduced. Thus, the current is directly related to the dissociation of zinc, the corrosion process taking place at the anode. (p. 81-82).

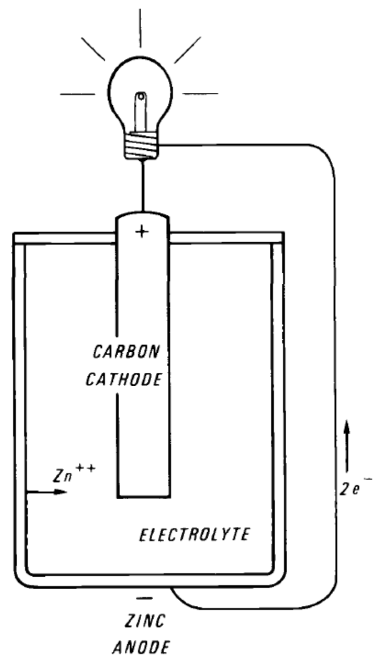


Figure 1: Galvanic cell (dry cell).

Note. From "Concepts of Underground Corrosion," by Edward Escalante, 1989, *Effects of Characteristics on Corrosion*, p.82. Copyright 1989 by ASTM International.

Several key conclusions were made that indicate resistivity as being indicative of a soil's corrosivity. In one report, Fitzgerald (1989), soil resistivity is described as being, "Easy to measure and, being an electrical quantity and thus related to corrosion current flow through Ohm's Law, is probably the parameter most often looked upon as indicative of a soil's corrosivity" (p. 2). According to Palmer (1989), experiments conducted in a field study consisted of several parameters that could affect corrosion, but resistivity measurements were the one controlling parameter. Palmer (1989) also states "only resistivity appears to be generally relevant," when explaining the validity of several variables given consideration in a corrosion rating formula by the American Water Works Association for the selection of pipe materials and protective measures, and states the other variables "may be pertinent where differences in corrosion rate are experienced with otherwise similar conditions" (p. 16). After such discoveries about resistivity in relation to corrosion effects on metals in soil, it was concluded that resistivity would become the primary parameter to be measured for this project.

2.3 Resistivity Test Methods

Resistivity Testing on Fine Aggregate

Resistivity, the reciprocal of conductivity, is defined as, “The resistance between opposite faces of a one-centimeter cube of given material” (“Dictionary.com”, n.d.).

Resistivity is the measure of this resistance (R), given as a ratio of electric intensity to the cross-sectional area, with units measured in ohm-centimeters (Ω-cm). For MSE retaining walls with steel reinforcement, the resistivity of a soil backfill material must exceed 3000 Ω-cm in order for the material to be sufficient enough for construction purposes (Elias et al., 2009). As stated in Table 1, the laboratory test method used for evaluating resistivity follows the American Association of State Highway and Transportation Officials (AASHTO) test standard designation: “Determining Minimum Laboratory Soil Resistivity” (American Association of State Highway and Transportation Officials [AASHTO], 2012).

The principal behind test method AASHTO (2012) is to, “Determine a soil’s corrosivity and thereby identify the conditions under which the corrosion of metals in soil may be sharply accentuated” (p. T 288-1). This two-part test method first requires the preparation of 1500 grams (g) of soil material which passes a 2.00 millimeter (mm) sized sieve, called the No. 10 Sieve. This material is mixed with distilled water that has a resistivity greater than 20,000 Ω-cm and placed in either a soil box with inside dimensions of 152.4 mm (length) x 101.6 mm (width) x 44.5 mm (height), or a soil box with inside dimensions of 152.3 mm (length) x 101.5 mm (width) x 44.4 mm (height), each with two electrodes on either ends of the box (AASHTO, 2012). A current from a resistivity meter is run from one end of an electrode, through the soil, to the other end of another electrode and the resistance (R) is measured. This observed R value, in Ohms (Ω), is then multiplied by a soil box factor (obtained by dividing the surface area of one electrode (cm^2) by the measured average distance between electrodes (cm)), which gives the minimum soil resistivity value.

There are several problems when using AASHTO (2012) for measuring the minimum resistivity of coarse-grained soil material. As noted in AASHTO (2012), “When less than 5 percent of a material passes the No. 10 sieve, this test method may not be indicative of the corrosion potential of the material" (p. T 288-1). The Unified Soil Classification System [USCS] (2011) classifies coarse-grained soils as more than 50% material retained on the No. 200 (0.075 mm) sieve using the American Society for Testing and Materials (ASTM) International standard D2487 – 11 (American Society for Testing and Materials [ASTM] International, 2011). Course-Grained material retained on the No. 200 sieve can be further classified as Sands, where 50% or more of the coarse fraction passes the No. 4 (4.75 mm) sieve, and Gravels, where more than 50 % of coarse fraction is retained on the No. 4 sieve (ASTM International, 2011). This research project includes resistivity testing on soil backfill with less than 5% of material passing the No. 10 (2 mm) sieve, which is described later in Chapter 3 of this report. Due to this anomaly, further research into the testing of resistivity with coarse-grained aggregate was inquired.

Another limitation of AASHTO (2012) is the AASHTO Standard Soil Box.

AASHTO (2012) gives two options for the use of a soil box when determining minimum resistivity values of backfill material. Both of the soil box options have inside dimensions of 6 in (152.3 mm) x 4 in (101.5 mm) x 1.75 in (44.4 mm) to adequately test backfill material finer than the No. 10 (2.00 mm) sieve. Because the AASHTO T 288-12 standard tests the minimum resistivity of fine-aggregate backfill materials, the soil boxes described would not accommodate a representative sample of coarse-aggregate backfill material.

As the aggregate sizes of select backfill material increases, the amount of sample able to be used for resistivity testing using AASHTO (2012) decreases. In fact, AASHTO (2012) describes an initial preparation of test samples that warrants splitting or quartering material greater than the No. 10 (2.00 mm) sieve. Because of this limitation, a new process was implemented for this document that would allow laboratory testing of coarse-aggregate backfill material, as well as fine-aggregate material.

ASTM International issued a standard for measuring soil resistivity of soil samples collected from the ground and for the assessment and control of corrosion of buried structures (ASTM International, 2012). This standard includes a Two-Electrode Soil Box Method procedure that resembles similar characteristics to the AASHTO T 288- 12 standard. ASTM G187 – 12a utilizes a two-electrode soil box much like the AASHTO Standard Box that is used in AASHTO T 288-12, but does not specify certain dimensions for the construction of a box. Instead, the ASTM International (2011) two-electrode soil box, "Can be constructed in various sizes provided the inside dimensions are known" (page 2). Other equipment required for soil resistivity measurement in the laboratory include a soil resistance meter (like the Nilsson Meter), with appropriate wiring to connect the soil resistance meter to the soil box. The procedure of ASTM G187 – 12a reflects closely that of AASHTO T 288-12 as well, with some differences. Unlike AASHTO T 288-12, which requires the procurement of 1500 g of material, ASTM G187- 12a (2012) simply instructs to gather enough soil to accommodate the size of the soil box being used. The procedure then asks to add the soil sample to the soil box in increments with the addition of distilled or deionized water to saturate the soil. Soil resistivity is measured only under saturated conditions in ASTM G187 – 12a, whereas AASHTO T 288-12 requires several resistivity measurements, starting with a small amount of distilled or deionized water, and ultimately ending with resistivity measurement when fully saturated conditions occur. Equation 1, used in ASTM G187 – 12a (2012) for calculating resistivity (ρ), in Ω-cm is as follows:

$$\rho = \frac{AR}{d} \qquad (1)$$

where A is equal to the cross-sectional area of an electrode, in cm2; R is the resistance measured using the soil resistance meter, in Ω; and d equals the distance measured between the two electrode plates, in cm. ASTM G187 – 12a (2012) does not explicate soil particle-size limitations for resistivity testing, but it does specify that the soil sample being tested be free of any "foreign materials such as gravel, small stones, roots, and twigs" (page 4), which implies that this method might be unsuitable for the testing of coarse-grained aggregate material. This limitation leads to the need for other publications or documents that pertain exclusively to resistivity testing of coarse-aggregate backfill material.

Resistivity Testing on Coarse Aggregate

Since the first introduction of MSE wall construction projects in the 1970s, there has been need for further research into the concept of corrosion and its effect on galvanized steel reinforcement. Today, MSE wall projects have opted for more coarse- based aggregate backfill materials in lieu of fine-aggregate soil. The use of coarse- aggregate for backfill materials allows for better drainage when events such as rain introduce water into the MSE wall backfill. The use of coarse-aggregate also relieves hydrostatic pressure buildup that would occur through the use of finer aggregate as water saturates the backfill.

The United States Geological Survey (USGS) published a document that offers a means of characterizing electrochemical parameters of soil specimens by a method called the Field Leach Test (FLT). The FLT presents a quick procedure that can be tested on soil samples of any aggregate size, both fine and coarse, through a process of leaching, which occurs constantly in the natural environment. This 5-minute test exposes a soil material sample to a certain amount of deionized water (20 parts leachate to one part soil leaching ratio) that is then disturbed and mixed through the process of vigorous shaking in a container. Once the sample is allowed to settle for a period of 10 minutes, subsamples of the mixed leachate are collected and used for individual parameter testing such as pH and specific conductance (the reciprocal of R) (Hageman, 2007).

Thapalia, Borrok, Nazarian, and Garibay (2011) assessed the corrosion potential of MSE coarse-based aggregate backfill using leaching techniques describe by the USGS FLT. In Thapalia et al., (2011), the USGS FLT is described to be a faster, less expensive, method for testing a wide array of aggregate sized backfill for electrochemical properties. Because of these attributes, the USGS FLT method warrants a viable means for testing the coarser aggregate backfill material in this research, in addition to testing the fine-aggregate backfill. The only drawback Tapalia et al., (2011) found when using the USGSFLT method was that a fine-aggregate material sample did not represent the same electrochemical properties as the bulk counterpart. According to Taplalia et al., (2011), some of the bulk (coarse) material used for electrochemical testing were crushed in the laboratory with a Massco crusher so as to "isolate the chemical differences through the elimination of size-related kinetic leaching effects" (page 65). The comparisons between the bulk material and "laboratory-crushed samples," behaved differently because "Chemicals typically leach into a solution more rapidly from smaller-sized aggregates because the surface-to-volume ratios increased with the decreasing aggregate size" (page 65). This phenomenon is addressed in this report through the use of inert materials (glass beads) with different diameters to exclusively compare the surface-to-volume ratios without other contributing effects from soil backfill material.

2.4 EC Relationships between Bulk Soil and Pore-Water Solution

Although many research projects have been conducted on the resistivity and conductivity of soil throughout numerous disciplines such as the agricultural and engineering fields, there is still no clear indicator of a laboratory test that results in a representative resistivity value of the bulk in-situ (field) conditions. The following chapters will utilize current standard test methods for the laboratory testing of select MSE soil backfill material, but will also seek to address an alternative method for testing resistivity of both coarse and fine materials by establishing a relationship between the resistivity of a soil's bulk material and the resistivity of a soil's pore-water solution.

Friedman (2005) reviews theoretical relationships between electrical conductivity (EC) of a soil's solution, ECW (or σw), apparent electrical conductivity of the bulk soil, ECa (or σa), and the soil's water content (θ). These σw(σa,θ) relationships, although complex, are represented in the form of empirical and theoretical models, and include the effects of various soil and environmental attributes on these relationships. In Friedman (2005), it is stated that there are three major categories of factors that affect ECa; the first category describes the respective volumetric fractions occupied by the three phases (solid, water, and air) and the porosity (η), water content (θ), and structure of the bulk soil; the second category encompasses the factors related to solid particle quantifiers, such as particle shape and orientation, particle-size distribution, cation exchange capacity (CEC), and wettability; the third and final category of factors includes the soil solution attributes and environmental factors, such as ionic strength (σw), cation composition, and temperature (Friedman, 2005). According to Friedman (2005), the only conducting phase of a given soil sample is the aqueous solution, σw, and is measured in S/m (Siemens per meter). In water-saturated soils, such as the conditions used within this research, Friedman (2005) states that Archie's empirical law and the Maxwell model can be used to measure σa or σw.

Archie's empirical law utilizes a soil's porosity (η) and a soil-dependent empirical exponent, m in Eq. 2 to describe the reciprocal of the formation factor, F, which is synonymous to the reduced EC, σa/σw (Friedman, 2005).:

$$\frac{\sigma_a}{\sigma_w} = \frac{1}{F} = \eta^m \qquad (2)$$

The empirical exponent, m, also called "Archie's Law Exponent" consists of values ranging from 1.2 to approximately 4.0, depending on the cementation and consolidation characteristics (Friedman, 2005). For the purposes of this report, the values of m used for glass bead EC calculations were 1.2 and 1.35. Friedman (2005) explains that particle shape can have a significant effect on σa/σw(η) calculations, with m values ranging from 1.35 (spheres) to 1.65 (prismatic and angular tuff particles), and special care should be exerted when selecting an appropriate m value.

As described by Friedman (2005), the Maxwell model simplifies Archie's empirical law by eliminating the m value altogether and uses only η to calculate σa and σw. For non-conducting solid particles, the Maxwell formula is shown in Equation 3:

$$\frac{\sigma_a}{\sigma_w} = \frac{2\eta}{3-\eta} \qquad (3)$$

The Maxwell formula is only meant for the simplest two-phase case (fully saturated soils with water) involving similar-sized spheres. Friedman (2015) explains that the Maxwell formula is over-simplified and often over-predicts the measured EC value; therefore, the formula should only be used as a predicting tool for two-phase mixtures. The following chapters will utilize both Archie's empirical law and the Maxwell method for preliminary and comparative resistivity measurements. The use of these two equations will help establish a connection between ρa and ρw, the reciprocals of σa and σw, respectively.

2.5 Other Research on Soil Resistivity

Borrock, Bronson, Nazarian, and Rocha (2013) conducted a research report for the Texas Department of Transportation (TxDOT) that dealt with the matter of characterizing coarse-aggregate material for prevention of corrosion on the steel reinforcement members used for MSE wall projects. Objectives outlined by Borrock et al., (2013) follow several guidelines: evaluate electrochemical test methods from TxDOT standards, characterize the coarse backfill material in regards to geochemical properties, establish a test method for evaluating corrosion potential of coarse backfills, and evaluate the corrosion rate of steel reinforcement members used for MSE walls with coarse backfill and study the corresponding geochemistry and environmental conditions. The following paragraphs will summarize the test program conducted by Borrock *et al*., and will explain all pertinent information that directly relates with the research conducted for this report.

The test program performed by Borrock et al., (2013) started with several geotechnical and geochemical characterization tests in order to provide a baseline of relevant parameters that would contribute to corrosion. Characterization began with the evaluation of each backfill material particle-size distribution curve to clarify that each material consisted of a majority of coarse-aggregate (all materials had gravel contents greater than 80%). Each material was characterized for other geotechnical properties, including Atterberg Limit tests for plasticity characteristics, and measurements of aggregate resistance to disintegration in water using the Wet Ball Mill Method (Tex- 116E), optimum moisture content (OMC), and maximum dry density (MDD). For geochemistry characterization, Borrock et al., (2013) followed several TxDOT standard test methods to provide a baseline to compare those results with values obtained using the USGS FLT method. The specific TxDOT electrochemical property test methods followed are included in Table 2. For the purposes of this report, only resistivity was evaluated because of the close relation it has to actual corrosion on steel reinforcement members for MSE wall projects (Fitzgerald, 1989 and Palmer, 1989). The focus on resistivity provides a relative means of evaluating corrosion without the need of large quantities of backfill material, which would be necessary for the numerous tests of other, less controlling of the overall corrosion rate, electrochemical parameters.

Table 2: Electrochemical Property Tests Conducted by Borrock et al., (2013)

Electrochemical Property	TxDOT Test Method Used
Resistivity (Ohm-cm)	Tex-129-E
pH	Tex-128-E
Chloride (mg/kg)	Tex-620-J
Sulfate (mg/kg)	Tex-620-J

The TxDOT test methods mentioned in Table 2 follow very closely to that of AASHTO and ASTM standards and were therefore not used for the purposes of this research project. This project will utilize national organizations and associations standards on resistivity testing for a more recognizable on a national level. When electrochemical characteristics were established using TxDOT test methods, Borrock et al., (2013) performed kinetic leaching experiments on the same materials to compare results obtained from the leaching experiments with that of TxDOT test obtained values. Because current TxDOT backfill selection standards utilize the evaluation of fine- aggregate material, Borrock et al. (2013) suggest the use of the FLT method, which allows the assessment of larger backfill material aggregate electrochemical properties.

For experimentation purposes, Borrock et al. (2013) followed the USGS FLT method that is described previously in Section 2.3 of this Chapter, with the slight alteration of increasing the sample size used for experimentation form 50 g to 100 g in order to accommodate the coarser aggregates without having to crush them.

Borrock et al. (2013) focused on three areas of the FLT experiment; the first area focused on the particle-size effects on the electrochemical properties like pH, resistivity, and chemistry; the second area focused on the amount of time used for kinetic leaching, and it's corresponding effects on the electrochemical properties; and the third area focus was on the validity of the assumption that TXDOT, as well as most national organizations and associations, has that the finest fractions of the backfill material is chemically representative of the entire bulk material.

For the purposes of this research project, the USGS FLT was implemented for resistivity tests on the coarser backfill material, while keeping in mind the focuses explained by Borrock et al. (2013). Additional focus was taken on the particle-size of aggregate and the corresponding effect it has on the resistivity value measured in lieu of the first area focus described by Borrock et al. (2013). The particle-size parameter was tested in Borrock et al. (2013) by performing FLT tests on different sieve-size backfill materials and on a mixed grab sample. The samples tested were analyzed as a function of time for approximately 200 hours while testing the electrochemical characteristics of the different aggregate sizes. The scope of this research furthered the principles followed by Borrock et al. (2013), by constricting resistivity measurement effects to only particle sizes. The use of inert material such as glass beads allows resistivity values of different particle-sized materials to be compared without the added effects found from soil chemistry and geotechnical characteristics. Once resistivity results were gathered from glass bead testing, actual backfill was tested for resistivity parameters to establish a connection found with the results on glass bead resistivity patterns. The patterns seen when testing glass beads allowed a better understanding of resistivity effects seen in actual backfill because the coarse and fine aggregate backfill resistivity values were vastly different.

The second focus of Borrock et al. (2013) was analyzed by using a data acquisition system that collected the several electrochemical and geochemical parameter data with regards to time. The system used by Borrock et al. (2013) consisted of several intricate parts such as data acquisition cards, a function generator, an uninterruptible power supply (UPS), and all the necessary circuitry to programmatically test the different materials in several cylindrical containers. For the purposes of the research conducted in this report, the effect of time on only the resistivity parameter was tested using continuous data collection via a special device created by the Texas Tech University research team. This device, called INA219, will be covered in Chapter 3. The device allows for the continuous collection of resistivity data at a designated interval for a prescribed amount of time established by the team. The principle behind the use of the INA219 device was to allow a more simplistic means of testing soil backfill material in the laboratory. The INA219 data collection program can be easily programmed to allow for brief one-minute testing, or for an extended period of resistivity testing time. The adaptability and ease of this device was determined to be a more viable option for laboratory testing of soil backfill resistivity.

Chapter 3 – Experimental Program

3.1 General Overview

Researchers at Texas Tech University desired an alternative means of measuring resistivity in a laboratory that would allow for testing potential MSE Retaining Wall backfill material with any gradation of particle-sizes, coarse-grained or fine-grained.

Laboratory testing was conducted over various mediums including distilled water solutions, an inert material (glass beads), and select backfill materials for the purpose of answering several different questions about soil resistivity and how different properties of a select material can affect the overall value of R measured. This chapter covers experimental procedures developed to appropriately measure the minimum resistivity of each medium being tested, and presents a relationship between the ρ of bulk material (ρa) and the ρ of that material's pore-water solution (ρw). The chapter begins with the testing on distilled water solutions, then leads to the test program on glass beads, and ends with the resistivity testing of different MSE Retaining Wall backfill materials. These resistivity tests comprised of comparisons between two soil resistivity boxes with different dimensions, and were conducted using a Nilsson Model 400 4-Pin Soil Resistance Meter (called the Nilsson Meter), shown in Figure 2, the Hanna Instrument's HI9814 GroPro Waterproof Portable pH/EC/TDS/Temperature Meter for Hydroponics (called the GroPro), shown in Figure 3, and a new device developed by the researchers at Texas Tech University (called INA219), shown in Figure 4.

Figure 2: Nilsson Soil Resistivity Meter Model 400

Figure 3: GroPro HI9814

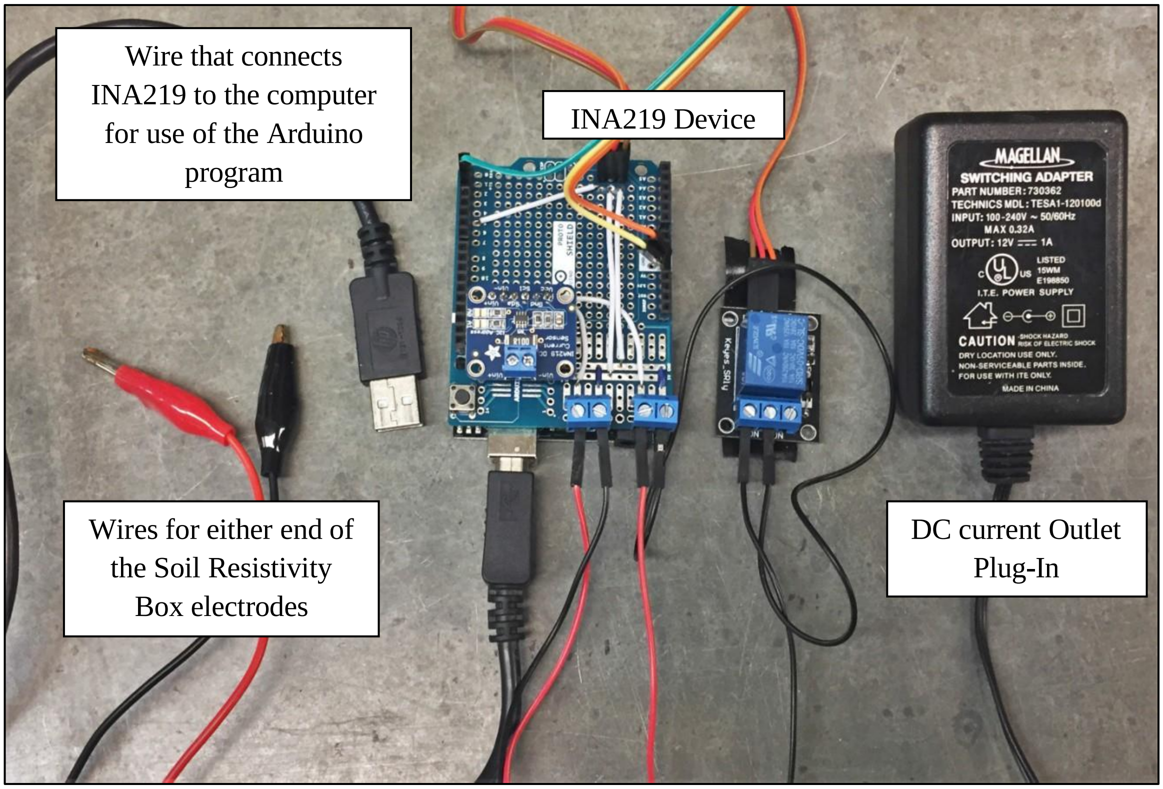


Figure 4: INA219 Device and Components

3.2 Resistivity Tests on Water Solutions

Soil properties can be very diverse within a given sample of material, which can cause discrepancy in measurements when tested for a particular variable, like resistivity. Many properties attribute to the composition of soil, like organic matter, electrochemical properties, and mineralogy, which creates complications when trying to measure resistivity in the laboratory. Therefore, the beginning of this research was to first test the resistivity of a more controlled substance, namely distilled water of several different resistivity values. AASHTO T-288-12 states specifically to use distilled water, or deionized water, when saturating a soil material for resistivity measurements. Testing distilled water, sometimes called "pure" water, or water without ions, allows for a more controlled homogenous medium than soil, with invariable characteristics. The lack of ions in distilled water makes the solution an insulator, or a material of low conductivity, because the electrical current is only transported by ions in solution. When distilled water is used for resistivity laboratory tests, current flow is limited to the ions presented by the soil material, and therefore gives a more accurate reading of the soil's resistivity. Because of this characteristic, the resistivity testing of water distilled water used in this report involved testing distilled water mixed with salt in order to give different resistivity readings. These water solutions gave a wider array of values of resistivity to be measured by the three devices, and also provided a means of comparing the devices for accuracy.

All resistivity tests were conducted using two boxes of different dimensions. The first box, called the AASHTO Resistivity Box, was based on the design criteria implemented by AASHTO T-288-12 for the testing of soil resistivity. A second soil box, called the Texas Tech Resistivity box, was designed and constructed to account for resistivity measurements of materials with larger aggregate sizes. A third resistivity box, called The Miller Soil Box, was used during the process of testing ρw for AASHTO Standard material. Table 3 shows the inside dimensions of each soil box used for resistivity testing, and Figure 5 and Figure 6 show the schematic drawings used to construct the Large and AASHTO Resistivity Box. All three of the resistivity boxes are shown beside each other for size comparison in Figure 7 and Figure 8, while Figure 9 shows the size comparison between the Texas Tech Resistivity box and the AASHTO Resistivity Box only. The Large and AASHTO Resistivity Boxes were constructed using acrylic plastic sheets, for the walls and base, and 0.9 mm (20 Gauge) stainless steel electrodes, which were bolted to the acrylic walls of the boxes. The Miller Box construction materials include a Plexiglas body with rounded corners, and stainless steel current distribution plates.

Table 3: Specifications of Soil Boxes used for Resistivity Testing

	Length	Width	Height	Volume
Texas Tech Resistivity Box	30.48 cm (12 in)	15.24 cm (6 in)	10.16 cm (4 in)	4719.47 cm^3
AASHTO Resistivity Box	15.24 cm (6 in)	10.16 cm (4 in)	4.45 cm (1.75 in)	688.26 cm^3
Miller Soil Box	15.87 cm (6.25 in)	6.35 cm (2.5 in)	3.17 cm (1.25 in)	80 cm^3

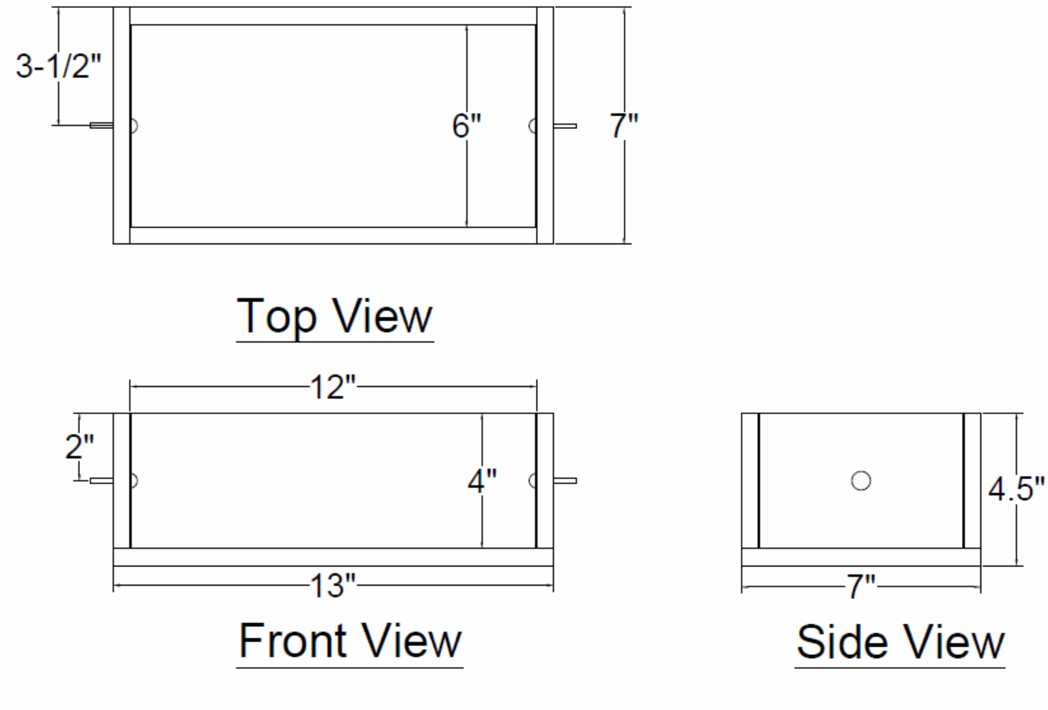


Figure 5: Large Soil Resistivity Box Schematic

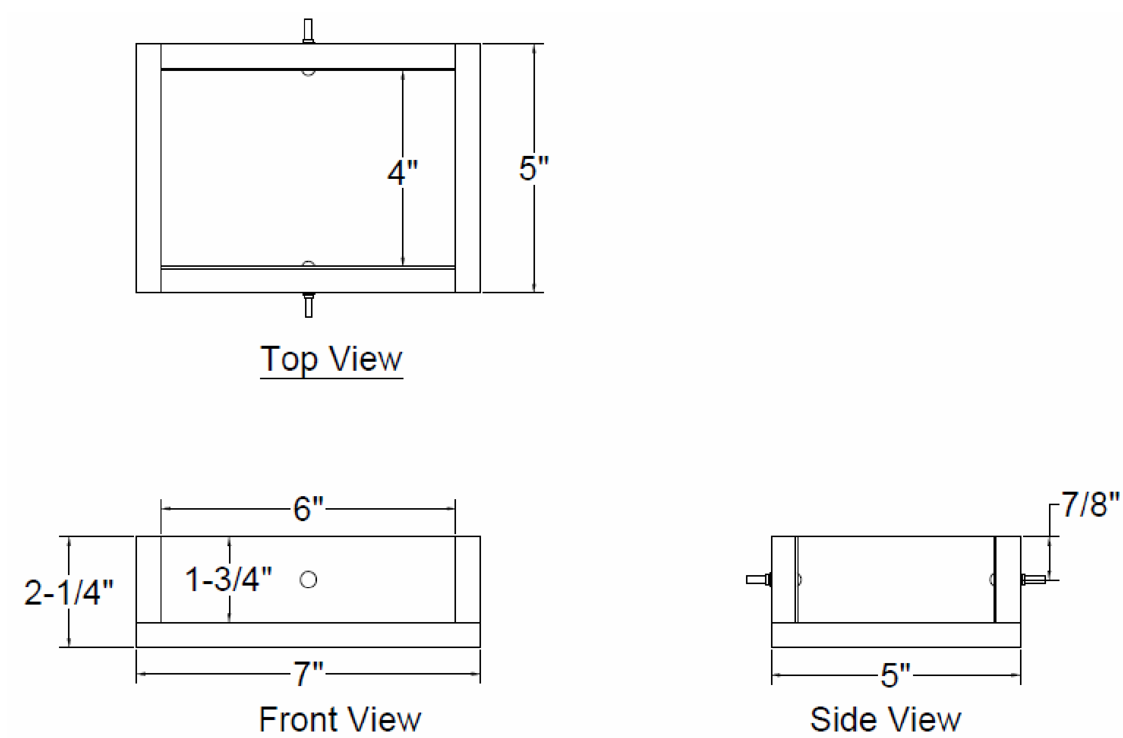


Figure 6: Small Soil Resistivity Box Schematic

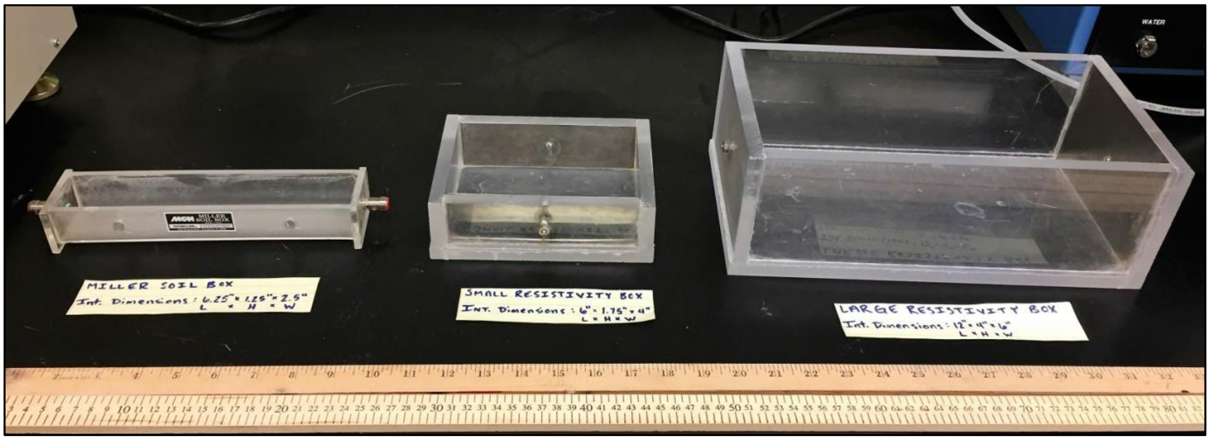


Figure 7: All Soil Resistivity Boxes in Side View

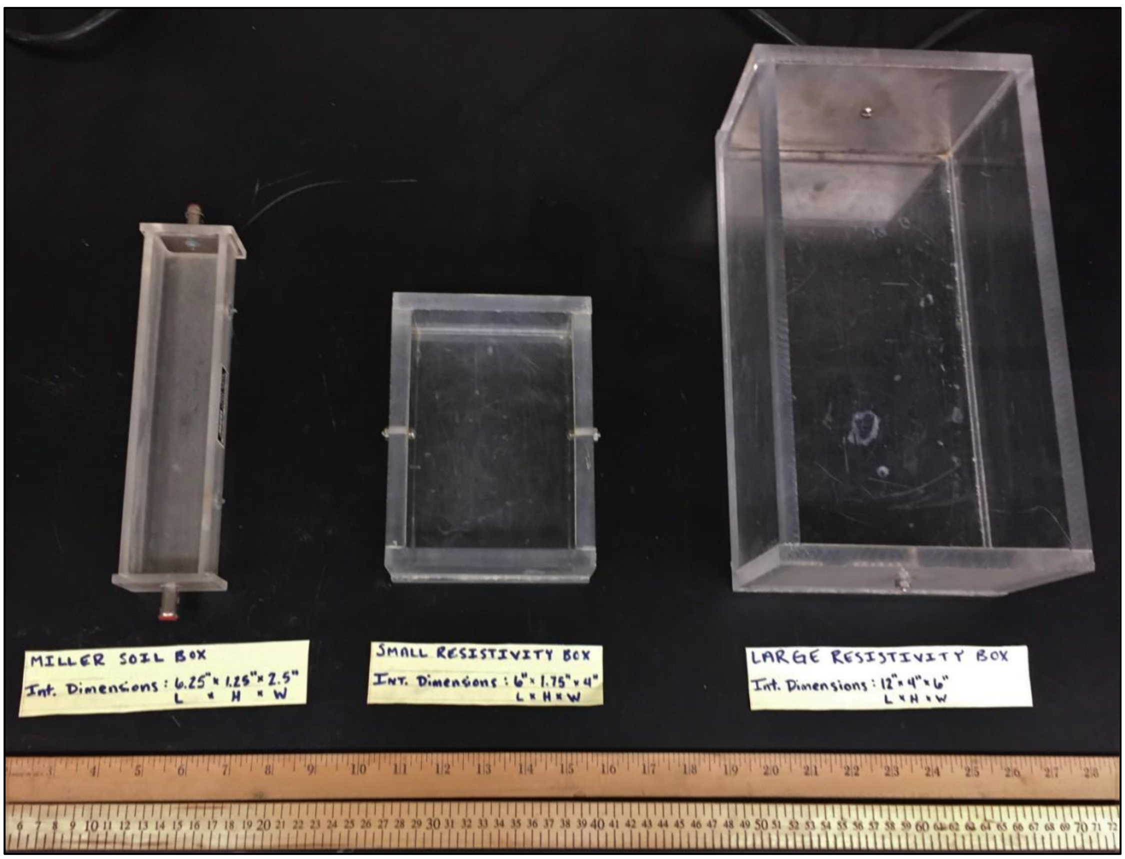


Figure 8: All Soil Resistivity Boxes in Top View

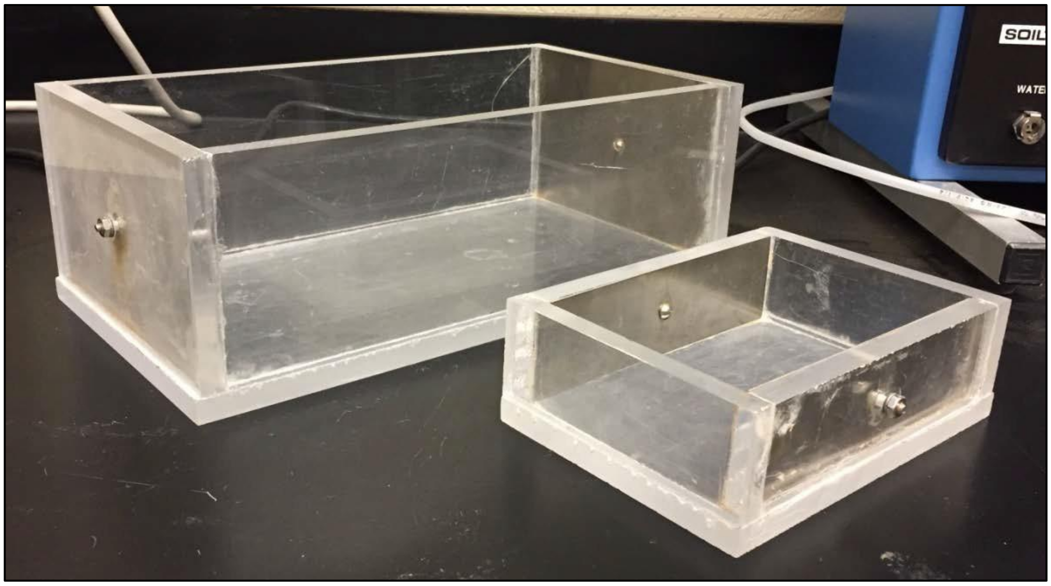


Figure 9: Large and Small Soil Resistivity Box Comparisons

To begin resistivity testing on water solution, distilled water was poured into the Large and AASHTO Resistivity Boxes until it reached the top of each box. Each device was attached to or placed directly into in the case of the GroPro probe, the electrode screws on either side of the box, and the resistivity was measured in accordance to the corresponding device manual. Once the resistivity was obtained from the devices, the solution was mixed with different salt concentrations to create a more conductive medium for the devices to measure resistivity with. The following paragraphs describe the process of measuring resistivity of several water solutions using all devices.

Test method AASHTO T-288-12 instructs to use a resistivity meter with a 12-Volt (V) direct current (DC) meter that utilizes a Wien Bridge with a phase sensitive detector and a square wave inverter that produces a nominal alternating signal at 97 Hertz (Hz). To follow these guidelines for all testing procedures, the Nilsson Model 400 Meter was selected as one of the devices because it fulfills all requirements. The Nilsson Meter, as stated in Corrosion Control Products Co. (1984), has wires that connect from the unit's four binding posts to the soil resistivity box electrode screws. Two binding posts are connected which allow for current to flow between both ends of the soil resistivity box, through the material (water), while a detector, which is made up of the other two binding posts, senses the voltage drop between each binding post and compares that drop to internal standard resistors, indicating a R value, in Ohms (Ω).

The process of determining water solution resistivity began by appropriately mixing a concentration of distilled water and sodium chloride (also known as common salt, NaCl). Because the resistivity of distilled water is close to zero, sodium chloride in the form of common salt was added to water. Salt adds ions into the distilled water, which in effect allows for the water to be more conductive (the inverse of R). Three different distilled-water-to-salt ratios were used and are shown in Table 4. Following the AASHTO T-288-12 standard procedure for determining minimum laboratory soil resistivity, the Nilsson Meter was calibrated and attached to the soil resistivity box and the resistance (R) of the water was measured. That measured R was then multiplied by a soil box factor. This soil box factor was calculated by dividing the surface area of one electrode by the measured average distance between the two electrodes. The Small Soil Resistivity Box has a soil box factor of 6.67 cm (2.625 in), and the Texas Tech Resistivity box has a soil box factor of 5.08 cm (2 in). The resistivity value, measured in Ω-cm, was then calculated by multiplying the measured R by the corresponding soil box factor.

Table 4: Distilled Water to Sodium Chloride (Salt) Water Ratios

Tests	Amount of NaCl, (g)	Amount of Distilled Water (mL)
1	7.0	5415
2	12.0	5415
3	17.0	5415

Once the Nilsson Meter resistivity value was obtained, the Nilsson Meter was detached from the soil resistivity box and the INA219 was attached. The INA219 device contains a Bidirectional Current/Power Monitor microchip made by Texas Instruments, which allows the device to utilize Ohm's Law of resistance (R= V/I) by measuring the current shunt, in milliamperes (mA), and voltage, in Volts (V), from one end of the resistivity box electrode, through the soil material, to the other electrode at the opposite end of the resistivity box. The device also monitors the power being used through the resistivity box with a 12C- (SMBUS-) compatible interface. The device is controlled through a program on a computer that includes a data logger and relay. This program controls the duration and timing that power is sent through the resistivity box. All data obtained through the INA219 is collected and cataloged on an Arduino Uno Serial Monitor and an SD card. The program was initiated after properly connected to the corresponding ends of the resistivity box, and was commenced for a period of 15 hours. After the desired time passed, the program seized collecting current and voltage measurements and the data was copied onto an Excel Spreadsheet. Resistivity calculations were made by first converting the current values from mA to A, by multiplying the mA values by a unit of 0.001. The voltage data was then divided by the new current values to obtain a resistance value (Ω). By multiplying the corresponding soil resistivity box factor, in cm, by the resistance value, resistivity was obtained for each data point, in Ω-cm.

For resistivity testing using the GroPro, a probe was inserted directly into the top 2.54 cm (1 in.) of the water and allowed to stabilize. The GroPro device probe measures the electrical conductivity (EC) value of the water, in units of millisiemens-per-cm (mS/cm). This EC value represents the inverse of resistivity and was therefore converted directly into Ohm-cm (Ω-cm) by first dividing the EC value by 1000 to convert the value from mS/cm to S/cm, and then dividing 1 Ω by that S/cm value.

3.3 Resistivity Tests on Glass Beads

Because of the complex nature of soil backfill material, several tests were conducted on particular properties of soil that could be more controlled. For the instance of particle-size and its effects on the resistivity measurements, different sized glass beads were used for the next testing phase of resistivity. To reduce the multiple variables to only particle size parameters, an inert material was used that would allow for resistivity measurements to be based independent of soil characteristics and chemistry. Three differently sized glass beads were tested for particle-size effects on resistivity. The beads with diameters of 0.50 cm (0.20 in.) are called Small Beads, the 1.54 cm (0.61 in.) diameter beads are called Medium Beads, and the 3.45 cm (1.36 in.) diameter beads are called Large Beads. Figure 10 shows the three different marbles and each of their diameters for comparison. Three resistivity tests were conducted for each glass bead size, using both resistivity boxes, and the procedure for testing each resistivity measurement was followed in the same manner as done for the water solution resistivity tests.

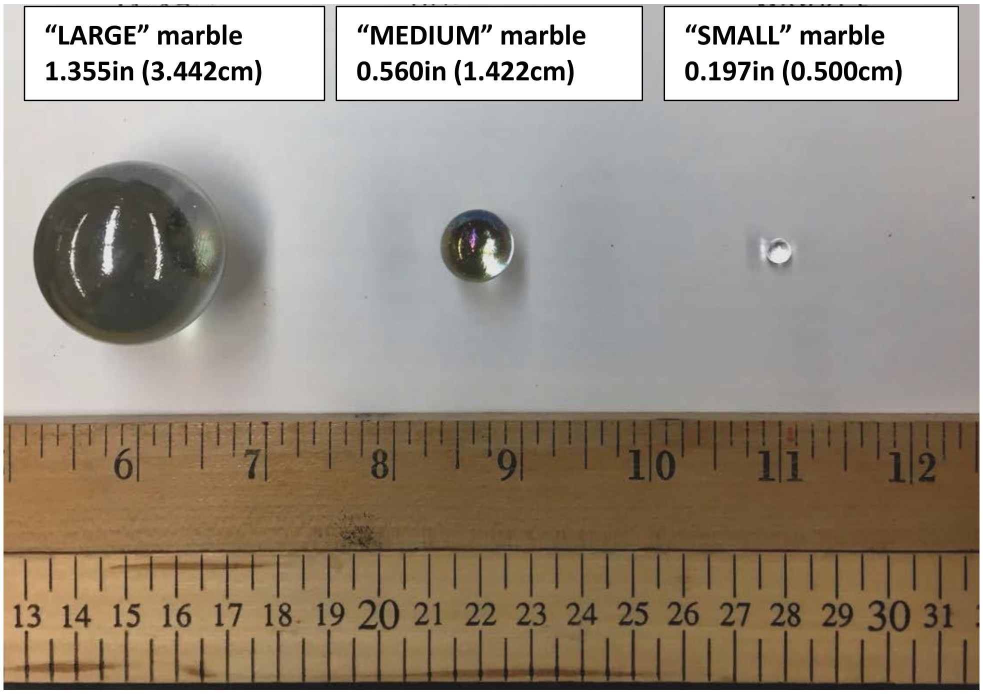


Figure 10: All Marbles Used for Resistivity Testing

To begin this phase of the experimental program, 5415 ml of distilled water was poured into a 2-gallon bucket. An amount of common salt was added and mixed in the bucket depending on the test number being conducted: 7.0 grams (g) of salt for the first test, 12.0 g of salt for the second test, and 17.0 g of salt for the third test. To revalidate that water solution resistivity (ρw) conclusions tested in the first phase, the GroPro was inserted into the top 2.54 cm (1 in.) of the bucket and an EC value was obtained and documented in an Excel spreadsheet. The two resistivity boxes were then filled to the top with the distilled water/salt solution mixture until the water level reached to top of the soil resistivity box. The weight of each full resistivity box was then found using a scale and documented on the Excel spreadsheet. The INA219 device was connected to a resistivity box and computer using the appropriate wires and cord. Using the Arduino program, the corresponding resistivity parameters were collected at one-second intervals for a total of one minute. The data collected and shown on the Arduino program Serial Monitor screen was then copied and pasted onto an Excel spreadsheet for the given test number. Once both resistivity boxes were tested for water solution resistivity, the solutions were poured back into the 2-gallon bucket. Resistivity values and calculations for the EC value obtained from the GroPro device were conducted on the Excel spreadsheet.

To begin glass bead resistivity measurement tests, each resistivity box was first carefully filled to the brim with one of the glass bead sizes. The weight of each resistivity box (with the glass beads only) was taken and documented on the corresponding Excel spreadsheet. The water mixture for that given test was then poured into each resistivity box until the boxes were fully saturated. Each resistivity box filled with corresponding glass beads are shown in Figure 11. The weight of each saturated resistivity box was then obtained using a scale and documented on the Excel spreadsheet. The contents inside the resistivity boxes were allowed to stabilize for a total of 5 minutes, then the Nilsson meter was connected to each soil resistivity box and an R value was measured. The ρa value was then calculated using the same approach used in the water solution resistivity tests: the measured R value was multiplied by the corresponding soil box factor, giving ρa values with the unit Ω-cm. The Nilsson Meter was then disconnected from the soil resistivity box and the INA219 device was attached. The INA219 device was connected to the computer and the Arduino program was initiated. The Arduino program measured resistivity parameters at one-second intervals for a total of one minute. After such time, the program seized to take measurements and was disconnected from the soil resistivity box. The data collected on the Serial Monitor screen was then copied and pasted into the Excel spreadsheet for analytical purposes. A clearing was carefully made in the soil resistivity box solution and the GroPro was placed inside the clearing. This clearing was made in a manner that would not allow glass beads to accidentally be pushed inside the GroPro probe. Once the EC values seen on the GroPro device screen stabilized to one unique value for a period of 1 minute, that EC value was documented on the spreadsheet. This EC was then converted directly into a ρa value by first converting the EC value from mS/cm to S/cm, and then dividing 1 Ω by that S/cm value. The resulting ρ_a value gives resistivity in units of Ω-cm.

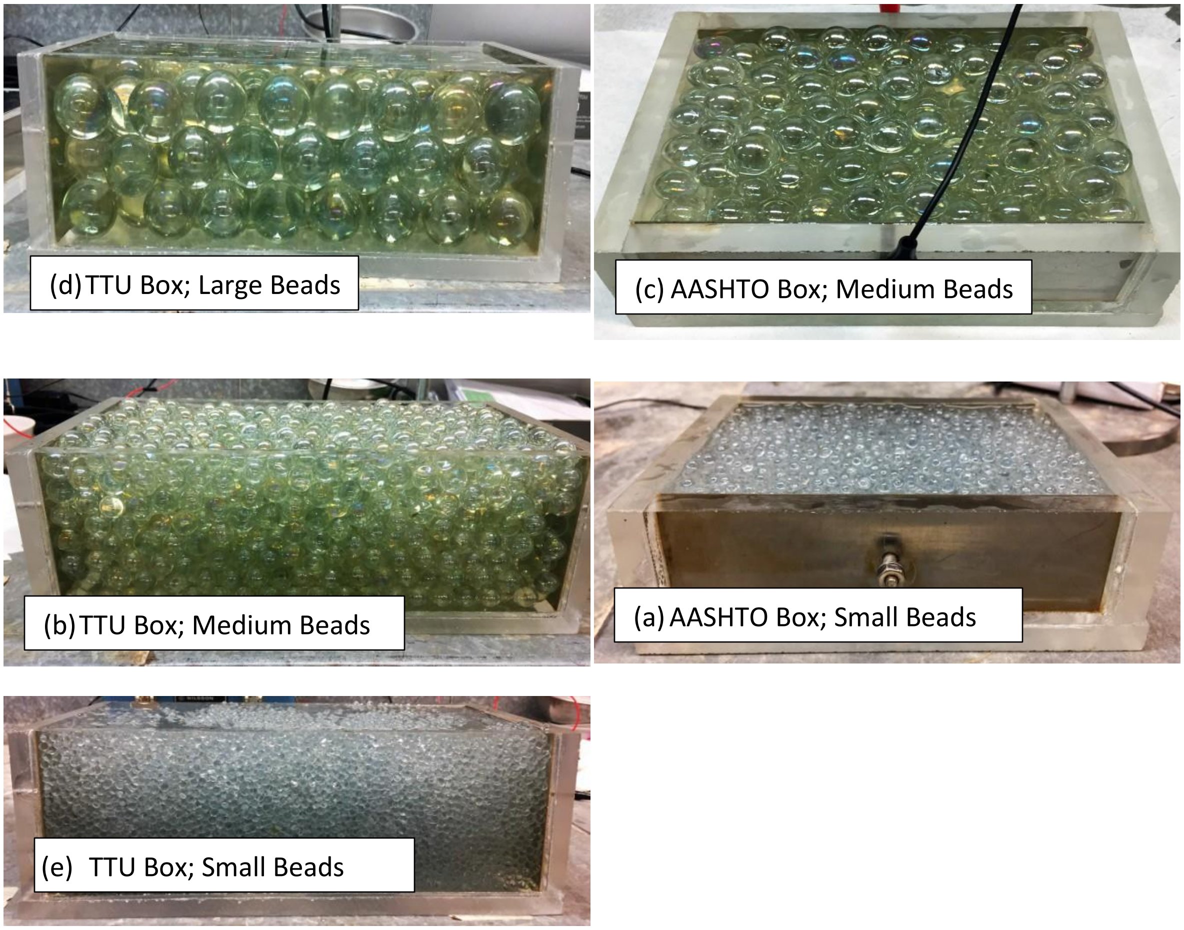


Figure 11: Texas Tech and AASHTO Resistivity Boxes with Large, Medium, and Small Beads

3.4 Resistivity Tests on Backfill Materials

Once specific properties of soil backfill material were tested and analyzed for their effects on resistivity values, tests were then conducted on select soil backfillmaterial used in MSE retaining wall projects. The soil backfill material selected for this part of the research used two different gradation-requirements based on AASHTO Number 57 (No. 57) and AASHTO Standard materials. The gradation criteria for each AASHTO soil backfill material are shown in **Table 5** and **Table 6**. AASHTO Standard material comprises mostly of fine-grained material, while AASHTO No. 57 material comprises mostly of coarse-grained material. **Figure 12** shows the gradation limits for AASHTO Standard backfill, gradation band for AASHTO No. 57 backfill (in dotted lines) as well as actual gradation curves for AASHTO Standard and AASHTO No. 57 materials used throughout this research (solid lines). Three different sources for each gradation were selected for resistivity testing to better understand how the material compositions affect resistivity values and also to gather more data to compare resistivity with. The source materials were collected from local stockpiles at a Vulcan Materials Company facility and from stockpiles at West Texas Paving, Inc. The three sources created were labeled Sandmills, Vulcan, and RE Janes. All three source materials comprise of limestone material to further control resistivity measurement effects on just one type of material.

These three source materials were used to create the AASHTO Standard and No. 57 Gradations for resistivity testing on backfill materials and are shown in **Figure 13**.

Table 5: AASHTO No. 57 Material Gradation

Gradation Criteria	AASHTO No. 57 Gradation (%)
Passing 25 mm (1 in.) sieve	100
Between 25 mm (1 in.) and 19 mm	25
Between 19 mm (3/4 in.) and 12.5	30
Between 12.5 mm (1/2 in.) and 6.3	40
Between 6.3 mm (1/4 in.) and 2.00	5
Passing 2.00 mm (No. 10) sieve	0

Table 6: AASHTO Standard Material Gradation

Gradation Criteria	AASHTO Standard Gradation (%)
Passing 0.841mm (No. 20) sieve	100
Between 0.841 mm (No. 20) and 0.420 mm (No. 40) sieve	45
Between 0.420 mm (No. 40) and 0.075 mm (No. 200) sieve	45
Passing 0.075 (No. 200) sieve	10

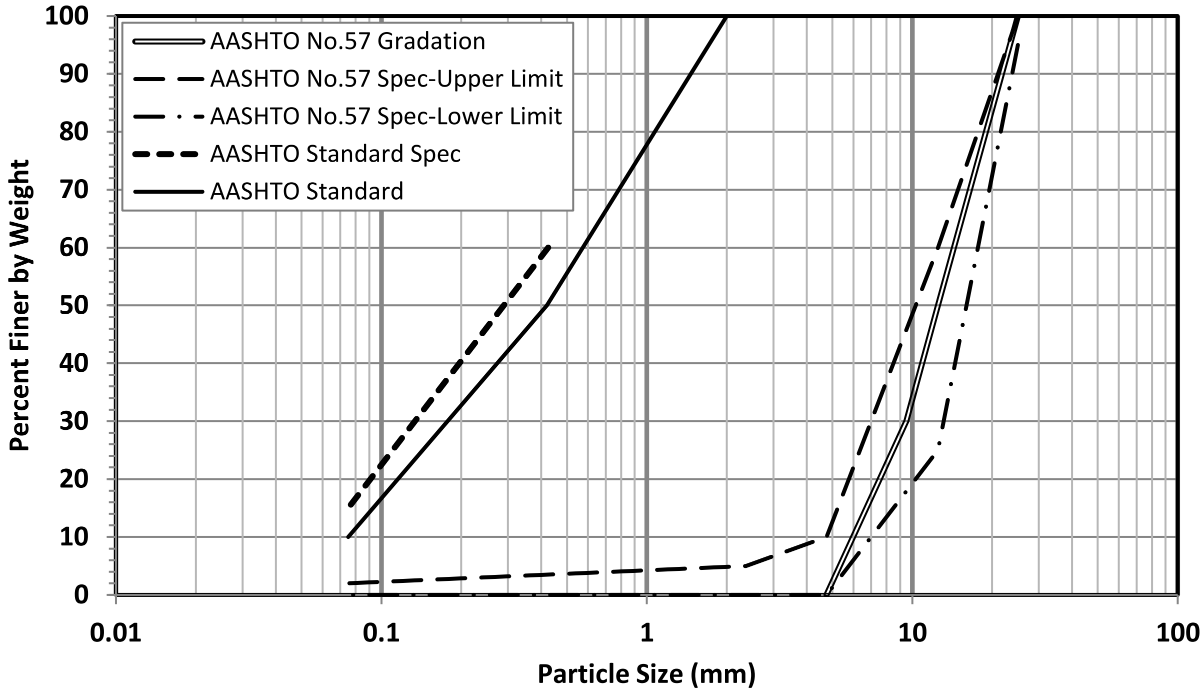
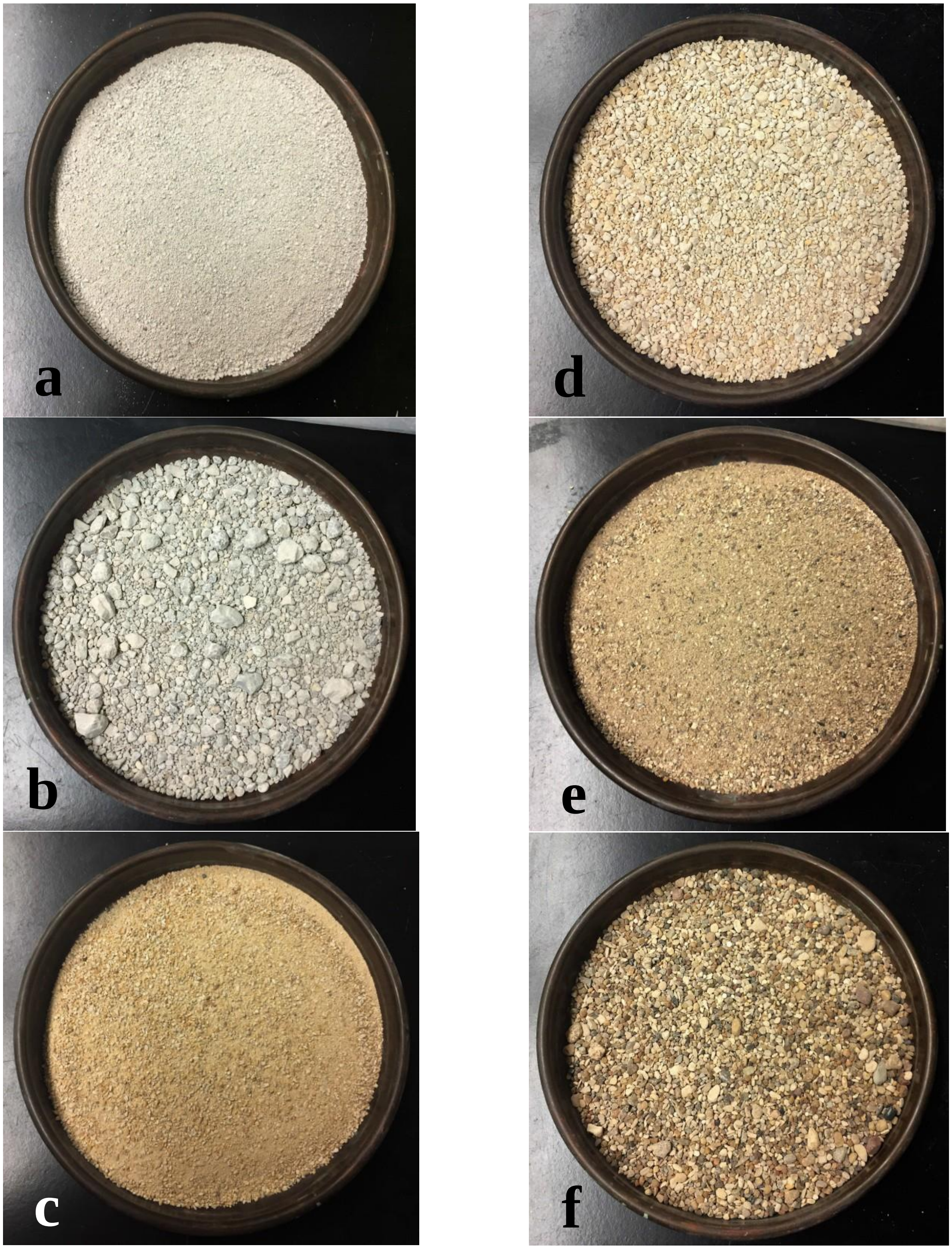


Figure 12: Gradation Curves for AASHTO Standard and No. 57 Materials



a) AASHTO Standard Gradation for Vulcan Material, b) No. 57 Gradation for Vulcan Material, c) AASHTO Standard Gradation for Sandmill Material, d) No. 57 Gradation for Sandmill Material, e) AASHTO Standard Gradation for RE Janes Material, f) No. 57 Gradation for RE Janes Material

Figure 13: Gradation Samples for All Source Materials

Each resistivity test started with the preparation of 10 kilograms (kg) of backfill material for AASHTO Standard material, and 14 kg of AASHTO No. 57 backfill material. AASHTO Standard material comprised of 4.5 kg of material retained on the 0.420 mm (No. 40) sieve, 4.5 kg of material retained on the 0.075 mm (No. 200) sieve, and 1 kg of material that passes the 0.075 mm (No. 200) sieve. AASHTO No. 57 material comprised 3.5 kg of material retained on the 19 mm (0.75 in) sieve, 4.2 kg of material retained on the 12.7 mm (0.50 in) sieve, 5.6 kg of material retained on the 6.35 mm (0.25 in) sieve, and 0.7 kg of material retained on the 2 mm (No. 10) sieve. All gradation segments for each of the two materials were mixed together in a 5-gallon bucket labeled for the corresponding AASHTO material so as to obtain homogeneity for each test.

Resistivity testing on AASHTO No. 57 backfill material began by placing the material into the large and AASHTO Resistivity Boxes until the material reached the top of the box (without protruding over the top). Distilled water was then poured over the material until the water level was observed at the surface of the material (fully saturated), as seen in Figure 14. The INA219 device was connected to a resistivity box using wires from the device mainframe, which were attached to both ends of the resistivity box, and the device was plugged into an outlet for electricity. Then the program on the computer, which measures the amperage and voltage being sent through the resistivity box electrodes to calculate the bulk material resistivity (ρ_a), was started. The device was programmed to send a current from one end of the resistivity box electrode, through the material mixture, to the electrode on the other end of the resistivity box for a period of two seconds at intervals of one minute, for a total of 15 hours. Once the 15 hours elapsed, the program stopped and the device wires were disconnected from the resistivity box. The recorded data from the INA219 was transferred to an Excel Spreadsheet for resistivity calculations and graphing purposes. Once the resistivity values were calculated from the voltage and current measurements, a graph was constructed, as seen in Figure 15. The graph features resistivity values measured at the given two-second interval, for the entire 15 hours. Once the graph was completed, a minimum resistivity value was established and used as the representative ρa value for that particular test material. For ρ_w calculations, the pore water solution was filtered from the bulk material mixture, through the use of two filtration methods: through a 0.074 mm (No. 200) sieve, and through Grade 42 sized filter paper in a Büchner flask that is attached to a vacuum. These two methods of filtration were used to better understand whether simple filtration through a sieve would warrant the same ρw value as filtering through filter paper with 2.5 micrometer (μm) particle retention. The water from each filtration method was collected into a plastic container, where the GroPro device probe was inserted into the solution.

The GroPro device measured the EC value of each solution, which, in turn, was converted into the resistivity value of the solution. This calculated resistivity value is called the pore-water solution resistivity (ρ_w). This procedure was followed for all AASHTO No. 57 Gradation tests on RE Janes, Sandmill, and Vulcan source material.

Figure 14: Fully Saturated AASHTO No. 57 Gradation of RE Janes Material Sample connected to INA219 Device

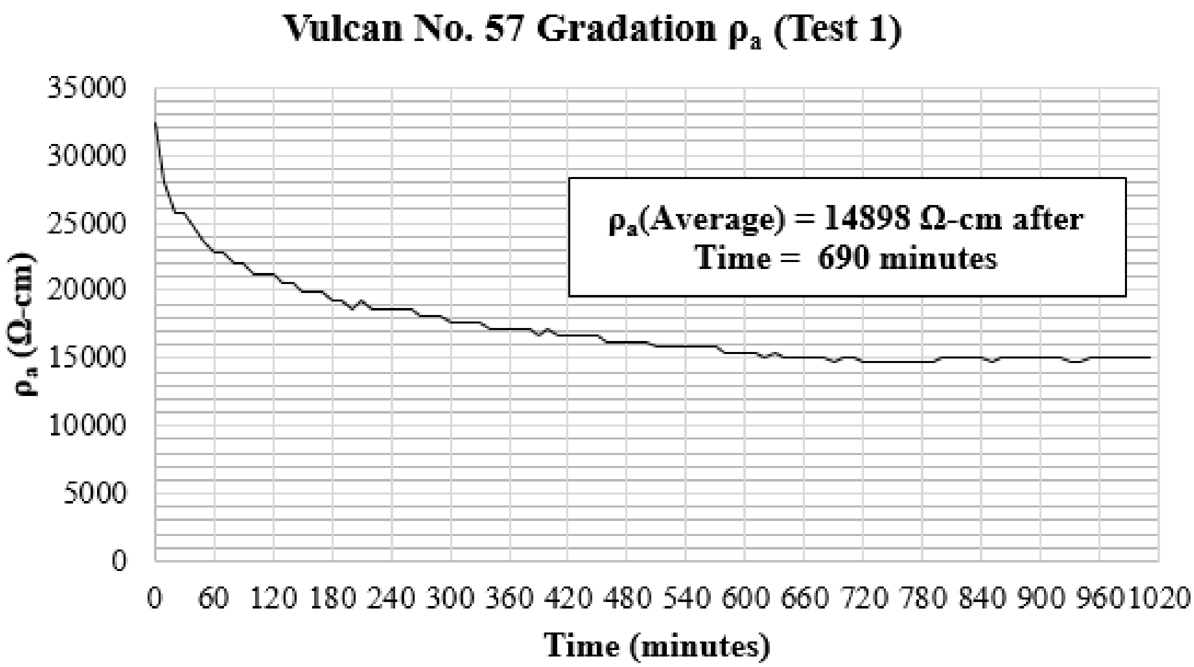


Figure 15: Sample Resistivity Plot using INA219 Device

Because AASHTO Standard consists mostly of fine aggregate material, both ρa and ρw required a more intricate process to evaluate resistivity. The pore-water solution of the AASHTO No. 57 mixture does not consist of as many absorbed or mixed fine aggregate particles when distilled water is added to the material, but when distilled water is mixed with AASHTO Standard material, the resulting concoction creates a mixture which makes testing ρw virtually impossible, shown in Figure 16. After the 15-hour test has completed taking resistivity measurements, the material has completely absorbed the distilled water. The GroPro device is unable to test EC properties in slurry solutions because the probe sensors are too delicate and sensitive to accommodate aggregate-like material, therefore ρw testing involved diluting AASHTO Standard Gradation material using a specific dry material-to-water ratio to first obtain a ρ'_w value, and then using properties and equations explained from Archie's empirical law to convert that ρ'_w to a representative ρ_w value.

Figure 16: AASHTO Standard Gradation for RE Janes Material after 15 Hour Test is completed.

At the beginning of testing, the weight of each empty resistivity box was measured on a scale. Dry material was weighed on the scale and transferred to a 2.5- gallon plastic bucket for mixing purposes. Using the weight of the dry material and specific ratios outlined in Table 7, an appropriate amount of distilled water was calculated and added to the dry material and mixed. The slurry mixture was placed back in the resistivity box and the INA219 device was connected to the box and computer. The same program used for AASHTO No. 57 testing commenced collecting data about resistivity properties for approximately 15 hours, and then the device was disconnected from the resistivity box. The program data was copied to an Excel Spreadsheet file for resistivity calculations and graphing.

Table 7: Dry Material to Water Ratio for each Material Source

Source Material	Dry Material: Water Ratio
Vulcan Material	1:1
Sandmill Material	1:2
RE Janes Material	1:2

For ρ'_w resistivity testing, the mixture was removed from the resistivity box and filtered through Grade 42 sized filter paper. This process further removes various dissolved solids from the diluted slurry mixture so the GroPro device measures the resistivity of the pore-water solution only. The filtered water was poured into the Miller Soil Box, the GroPro probe was submerged into the topmost part of solution, and an EC value was measured. The obtained EC value was recorded on the Excel spreadsheet file, and then converted into a value for ρ’w.

The process of establishing a connection between ρ'_w and ρ_w involved established relationships between the molar conductivity (Λm), which is the ratio of measured conductivity (K) and the concentration (c) of distilled water and material used during a specific test, and the square root concentration. These principles are explained in Kohlrausch’s Law. Λm and the square root of c-values were calculated for several material-to-water ratios and were plotted against each other in order to find a relationship between the dilution ratio and conductivity. These graphs serve as a basis of understanding the effects of dilution on a given material and show the effects that distilled water amounts have on the overall resistivity value a diluted sample produces. A sample table that shows the corresponding calculations from several dilution ratios for RE Janes material is shown in Table 8, and a sample graph formed using results from Table 8 are shown in Figure 17. A Power Trendline was added to each source material test graph to express the relationship in a numerical equation. Each trendline equation was then used to convert the measured ρ'_w into a representative ρw value by first using the equation to calculate a corresponding K/c value, multiplying that value by the c-value obtained during a specific backfill resistivity test to form a value for K, and then taking the inverse of the K value to obtain a ρ value for that specific backfill material resistivity test. A ratio was established comparing each ρ value calculated from each of the three backfill material resistivity tests with the ρ value calculated using the specific material-to-water ratio used for each source material AASHTO Standard test seen in Table 7. The ρ'_w values obtained for each resistivity test was multiplied by this ratio and a representative ρ_w value was obtained.

Table 8: Sample Λ_m and Sqrt(c) Parameter Calculations for several Material-to- Water Dilution Ratios using AASHTO Standard Gradation on RE Janes Material

Material:Water Dilution Ratio	1:2	1:1.5	1:1	1:075	1:0.5	1:0.25
ρ measured (Ω-cm)	14,285	12,500	11,111	10,000	8,333	5,263
Concentration (c)	0.50 0	0.667	1.000	1.333	2.000	4
Conductivity (K)	7.00E-05	8.00E-05	9.00E-05	1.00E-04	1.20E-04	1.90E-04
Λm = K/c	1.40E-04	1.20E-04	9.00E-05	7.50E-05	6.00E-05	4.75E-05
Sqrt(c)	0.707	0.816	1.000	1.155	1.414	2

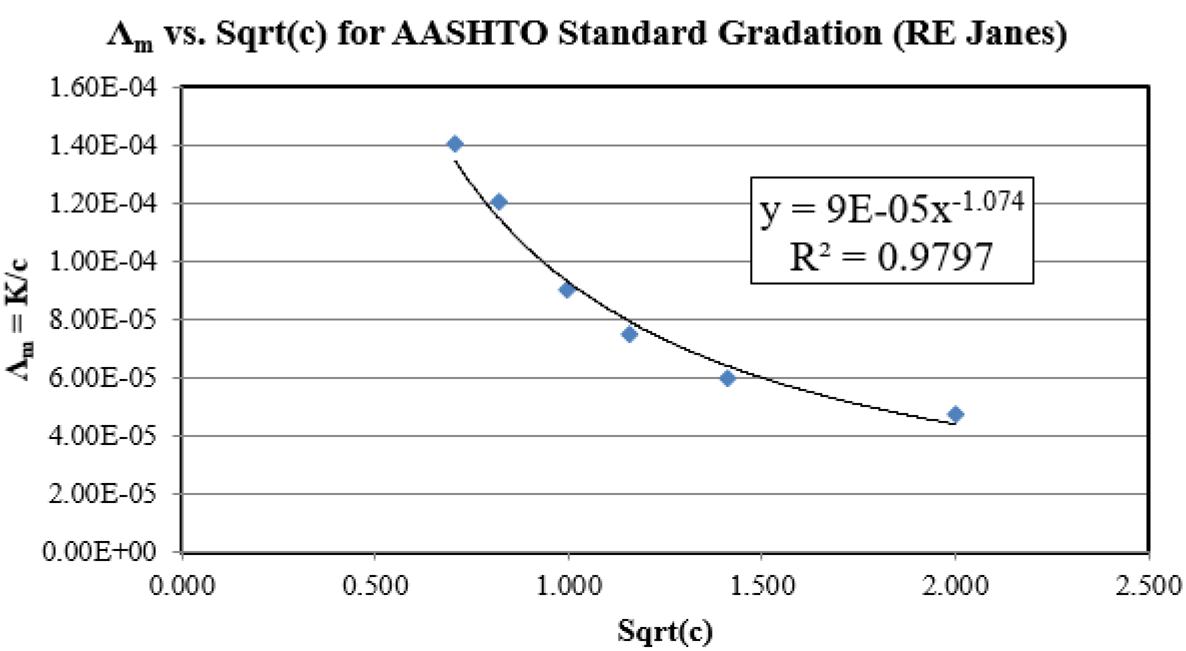


Figure 17: Sample Graph of Λ_m and Sqrt(c) Results obtained for Material-to-Water Dilution Ratios of AASHTO Standard Gradation on RE Janes Material

3.6 Influence Backfill Drainage Characteristics on Corrosion Rates

The experimental program described in previous sections was entirely focused on the measurement of electrical resistivity of the backfill when is under fully saturated conditions. However, in actual in-service MSE structures, the backfill materials may reach full saturation conditions only for limited periods of time. Full saturation may occur when the MSE structure gets inundated or after heavy rainfall. Once specific properties of soil backfill material were tested and analyzed for their effects on resistivity values, tests were then conducted on select soil backfill material used in MSE retaining wall projects. The soil backfill material selected for this part of the research used two different gradation-requirements based on AASHTO Number 57 (No. 57) and AASHTO Standard materials. The gradation criteria for each AASHTO soil backfill material are shown in Table 5 and Table 6. AASHTO Standard.

Chapter 4 – Results and Data Analysis

4.1 General Overview

This chapter presents the findings from the experimental program commenced by Texas Tech University researchers. The chapter is organized in a chronological order, beginning with the results and data analysis discovered from water solution resistivity tests. The chapter then proceeds with the results obtained from the glass beads resistivity tests and the following data analysis discussion. This chapter concludes with the data results and analysis from actual backfill resistivity tests. The organization of each presented data was established in a sequential manner: the presentation of results from each test conducted and the corresponding process of understanding resistivity characteristics, including the effects that certain parameters have on these characteristics, is answered through analytical reflections discovered from beginning to end of the experimental program. The several steps conducted by the research team are presented as such findings were discovered.

4.2 Water Solution Resistivity Results and Data Analysis

Resistivity test studies began with the testing of each resistance measuring devices for accuracy and consistency purposes. As stated in the experimental program of Chapter 3, each device was connected to both the large and AASHTO Resistivity Box with a known concentration of distilled water and salt. These series of tests were implicated to compare resistivity results obtained from the Nilsson meter, INA219 device, and GroPro meter. Table 9 displays resistivity results obtained using the three resistivity measuring devices with different distilled-water-to-salt ratios. Figure 18 shows a graphical representation comparing the resistivity results measured with the Nilsson Meter and INA219 Device. Figure 19 shows a graphical representation comparing the resistivity results measured with the Nilsson Meter and GroPro Meter. Figure 20 shows a graphical representation comparing the resistivity results measured with the GroPro Meter and INA219 Device.

Table 9: Resistivity Result Comparisons between Resistivity Measuring Devices

GroPro Meter (Ω-cm)	Nilsson Meter (Ω-cm)	INA219 Device (Ω-cm)
6250	5867	6588
2703	2534	2931
1724	1600	1820
962	933	1018
510	473	554

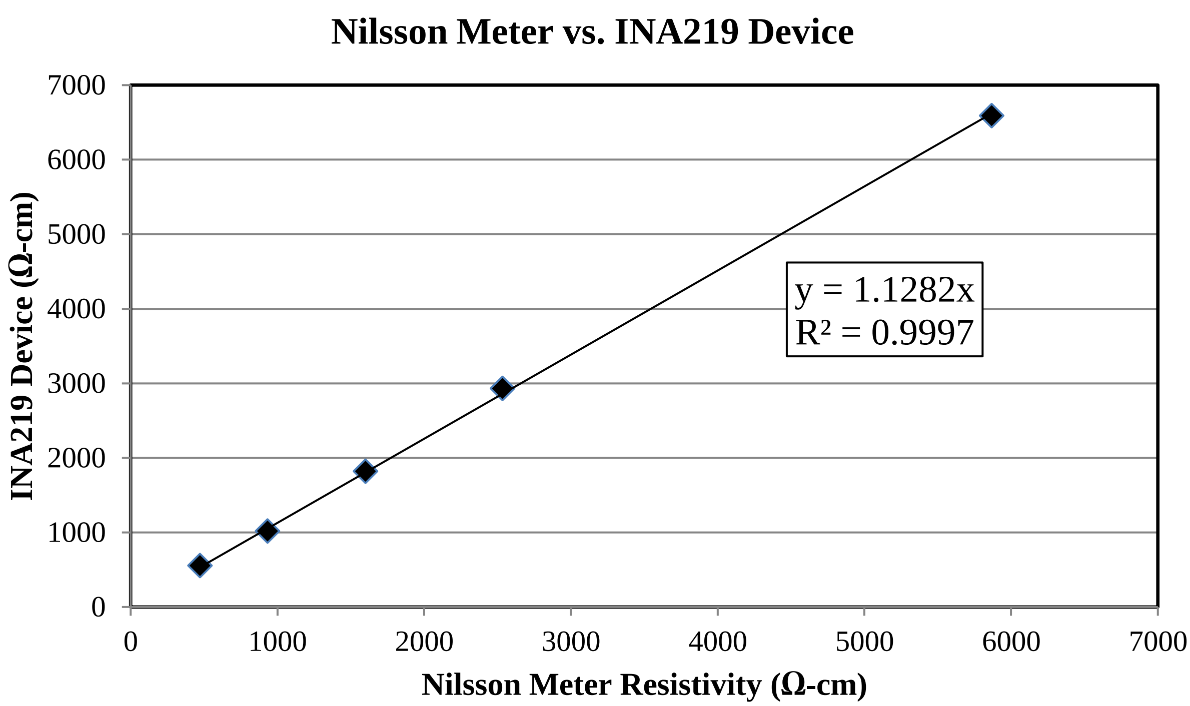


Figure 18: Resistivity Comparison between Nilsson Meter and INA219 Device

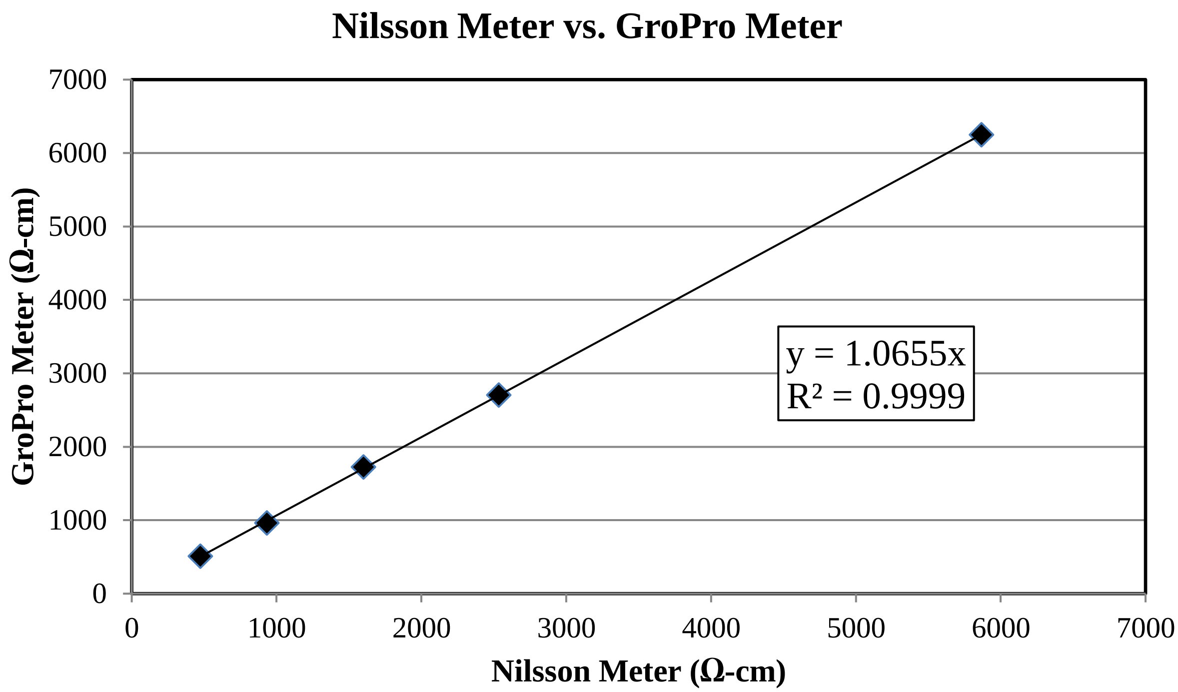


Figure 19: Resistivity Comparison between Nilsson Meter and GroPro Meter

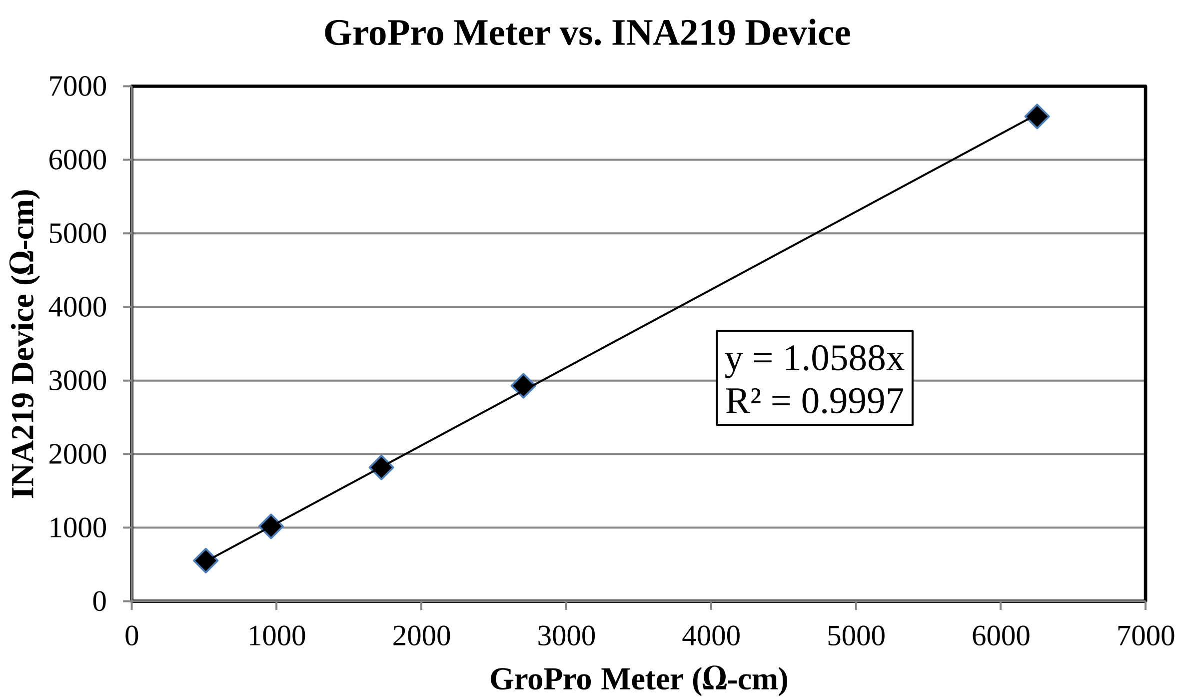


Figure 20: Resistivity Comparison between GroPro Meter and INA219 Device

Although the three devices did not measure a unique resistivity value for a given distilled-water-to-salt solution, the results obtained are within a reasonable margin to conclude that resistivity values obtained using one device is representative of all other devices. The greatest discrepancy between resistivity results occurred between the Nilsson Meter and INA219 device. In Figure 18, the slope of the line represents the percent difference between the two devices. Had the two devices measured the exact same values for each water solution sample, the slope of the line would be equal to one, but because the devices measured two separate values for a given solution, the slope of the line is off by roughly 13%, overall. The difference between the two devices can be attributed to the accuracy of one being less acute than the other, causing some of the values to differ more widely when measured. Other comparisons between two devices show a significantly smaller percent difference (7% between the GroPro Meter and Nilsson Meter and 6% between the GroPro Meter and INA219 Device). From these observations and results, it was concluded that the INA219 Device, which offers continuous data collection and recoding, would be the only device used for the purposes of resistivity measurements.

Another factor needed for comparison before resistivity testing could further was the comparisons between the Texas Tech Resistivity Box and the smaller AASHTO Resistivity Box. Tests were conducted using several distilled water with different salt concentrations. The primary objective for these tests was to understand the box size effect on resistivity values measured. Because the Texas Tech Resistivity box does not follow any specific standard currently implemented by national associations or organizations, there was also a necessity to try and compare measured values with a resistivity box that is implemented by national associations (the AASHTO Resistivity Box). Results obtained from a series of five tests were collected and are shown in Table 10. Specific resistivity testing between the two resistivity boxes and a resistivity measuring device are shown in Figure 21, 22, and 23. The values measured using the GroPro Meter were the exact same between the Texas Tech Resistivity Box and AASHTO Resistivity Box. The probe utilized by the GroPro Meter measures resistivity within a very small spherical area, which justifies the relationship observed between the two resistivity boxes. The values obtained using the Nilsson Meter and INA219 were not tantamount, but are closely related in value. There are no definitive factors that sufficiently explain why the resistivity values measured between the two resistivity boxes are different, but the way the resistivity devices measure resistivity can explain in part the reasoning behind the different values. The amount of resistance measured between the two electrodes can alter as the charged ions within the solution move when current flows through the water solution. The solution is energetic which causes pathways between particles to change constantly, leading to electrodes to measure slightly different resistance values at any given moment. With this understanding, it was concluded that the even though there were slightly different values obtained between the two resistivity boxes, the overall resistivity of a given water solution (without the presence of organic material) is not affected by the size of the resistivity box.

Table 10: Texas Tech Resistivity Box and AASHTO Resistivity Box Comparisons U sing All Resistivity Measuring Devices

	GroPro	GroPro	Nilsson	Nilsson	INA219	INA219
	Texas Tech Resistivity Box	AASHTO Resistivity Box	Texas Tech Resistivity Box	AASHTO Resistivity Box	Texas Tech Resistivity Box	AASHTO Resistivity Box
Test 1	12500	12500	12700	11335	13371	11860
Test 2	10000	10000	9652	10001	10440	10325
Test 3	4762	4762	4318	4267	4848	4784
Test 4	1786	1786	1676	1534	1858	1813
Test 5	524	524	483	487	552	558

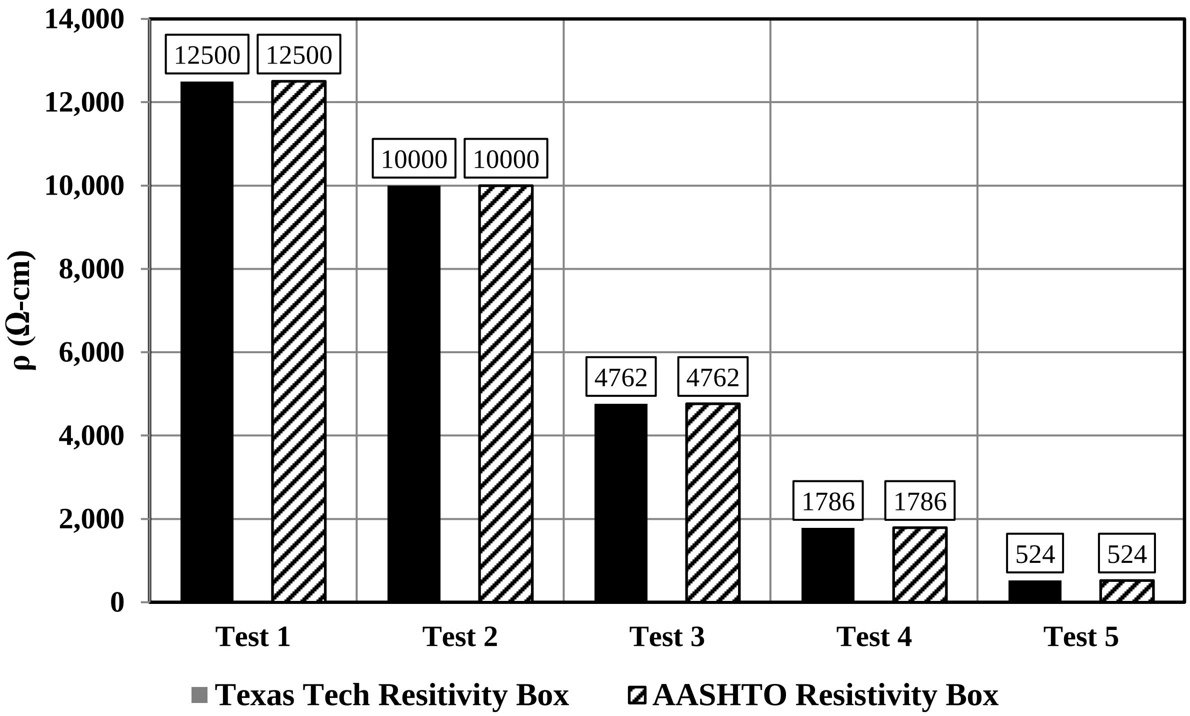


Figure 21: Comparison between Texas Tech Resistivity Box and AASHTO Resistivity Box using the GroPro Meter

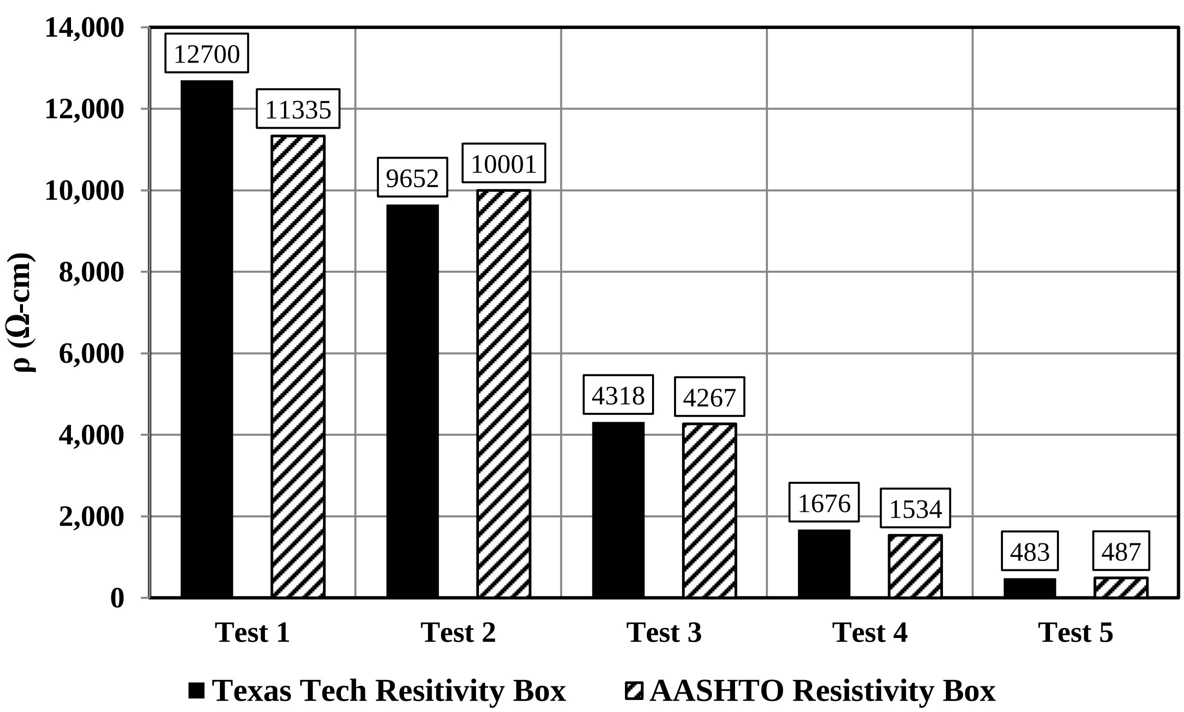


Figure 22: Comparison between Texas Tech Resistivity Box and AASHTO Resistivity Box using the Nilsson Meter

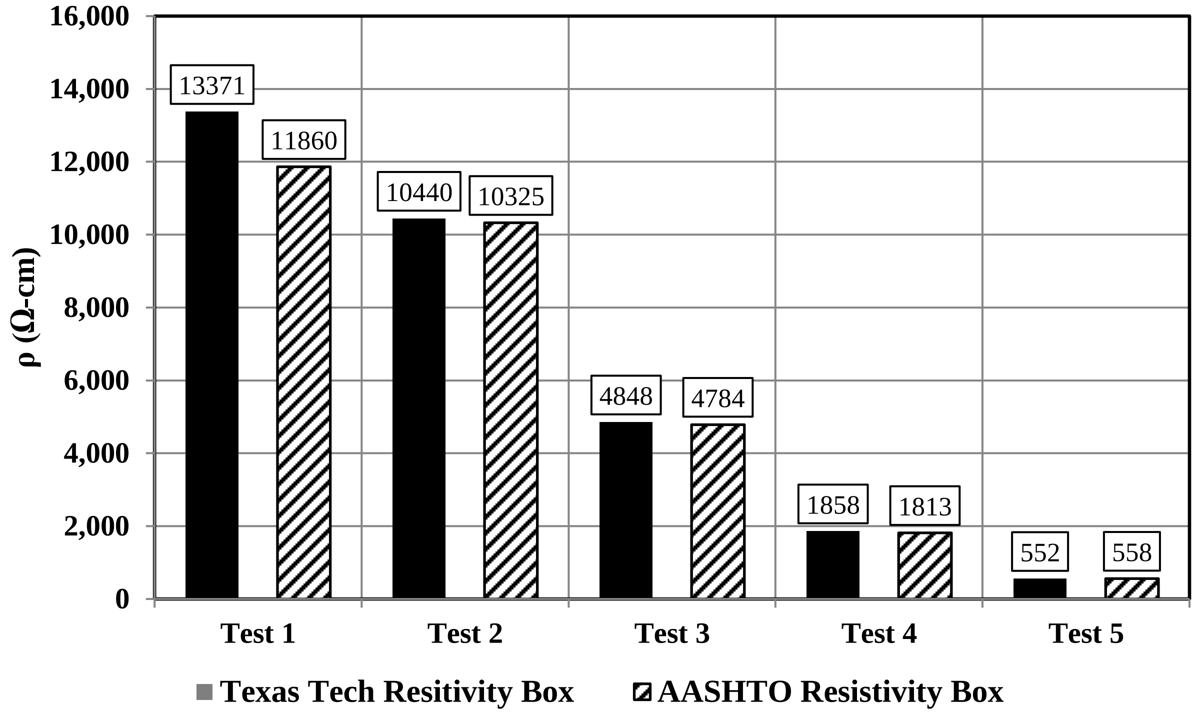


Figure 23: Comparison between Texas Tech Resistivity Box and AASHTO Resistivity Box using the INA219 Device

4.3 Glass Bead Resistivity Results and Data Analysis

The experimental phase conducted on glass beads focused on the effect of particle size on the resistivity of a given material. To limit resistivity test results effects to include only particle size, an inert material in the form of three differently sized glass beads was used. Because the INA219 device obtained similar resistivity value results as the Nilsson Meter whilst providing a means of continuous readings and organized data logging, three tests were carried out on the three glass beads using only the INA219 device and GroPro meter with the Texas Tech and AASHTO Resistivity Boxes. **Table 11** summarizes the results obtained from three glass bead resistivity tests. **Figures 24**, **25**, and **26** show the three different glass beads resistivity measurements obtained for the series of three tests using the INA219 device and both resistivity boxes for a time period of one minute.

Individual graphs for each glass bead size and corresponding resistivity box used are presented in **Appendix A - Glass Bead Resistivity Tests**.

Table 11: Resistivity Summary Results for Glass Beads Testing

				INA219 (Ω-cm)	INA219 (Ω-cm)	INA219 (Ω-cm)	INA219 (Ω-cm)
	Total Salt (g)	GroPro (Ω-cm)		Porosity (*n*)	Texas Tech Box	Porosity (*n*)	AASHTO Resistivity Box
Test 1	7	505.05	Water Solution (ρ_w):	-	526.20	-	547.09
Test 1	7	505.05	Large Beads (ρ_a):	0.500	1323.75	0.477	1488.45
Test 1	7	505.05	Medium Beads (ρ_a):	0.383	1722.06	0.468	1486.71
Test 1	7	505.05	Small Beads (ρ_a):	0.365	1620.54	0.414	1570.65
Test 2	12	294.12	Water Solution (ρ_w):	-	325.25	-	333.79
Test 2	12	294.12	Large Beads (ρ_a):	0.488	799.83	0.497	852.05
Test 2	12	294.12	Medium Beads (ρ_a):	0.407	996.97	0.463	891.79
Test 2	12	294.12	Small Beads (ρ_a):	0.388	976.80	0.410	941.25
Test 3	17	200.80	Water Solution (ρ_w):	-	212.88	-	214.78
Test 3	17	200.80	Large Beads (ρ_a):	0.409	569.59	0.473	614.32
Test 3	17	200.80	Medium Beads (ρ_a):	0.314	772.02	0.416	713.85
Test 3	17	200.80	Small Beads (ρ_a):	0.375	738.64	0.385	739.34

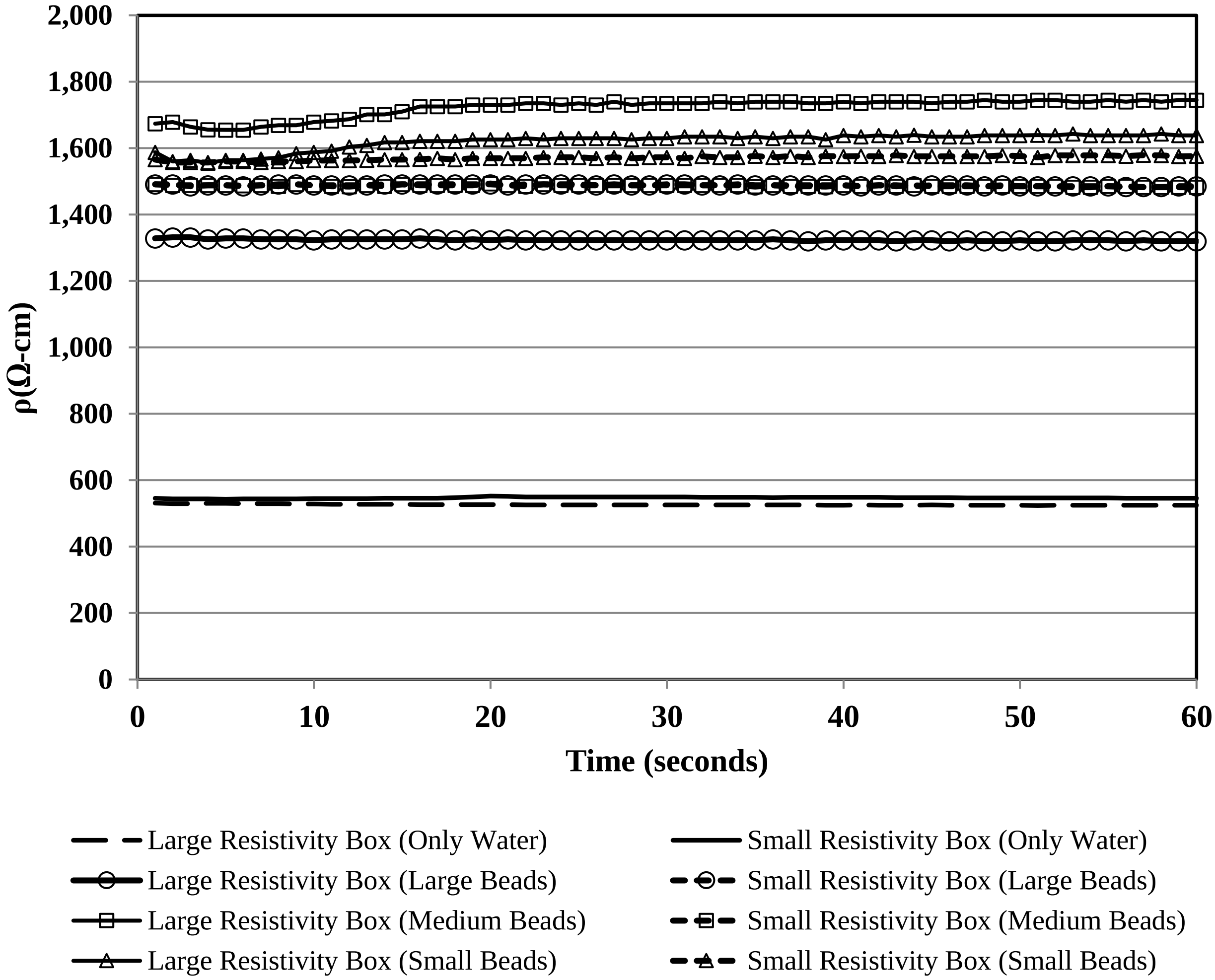


Figure 24: Test 1 Resistivity Measurements Using Texas Tech and AASHTO Resistivity Boxes

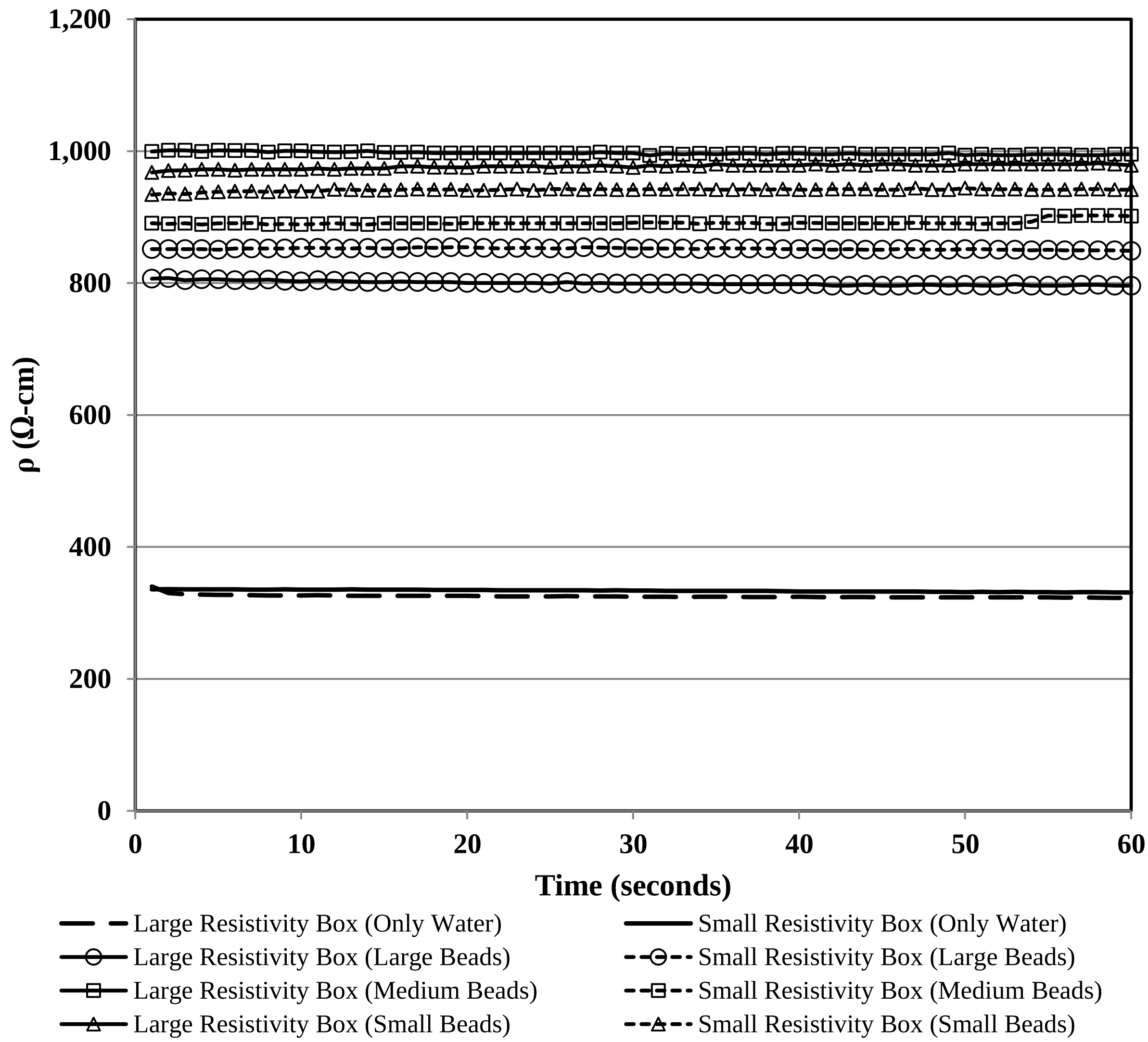


Figure 25: Test 2 on All Glass Beads using the Texas Tech and AASHTO Resistivity Boxes

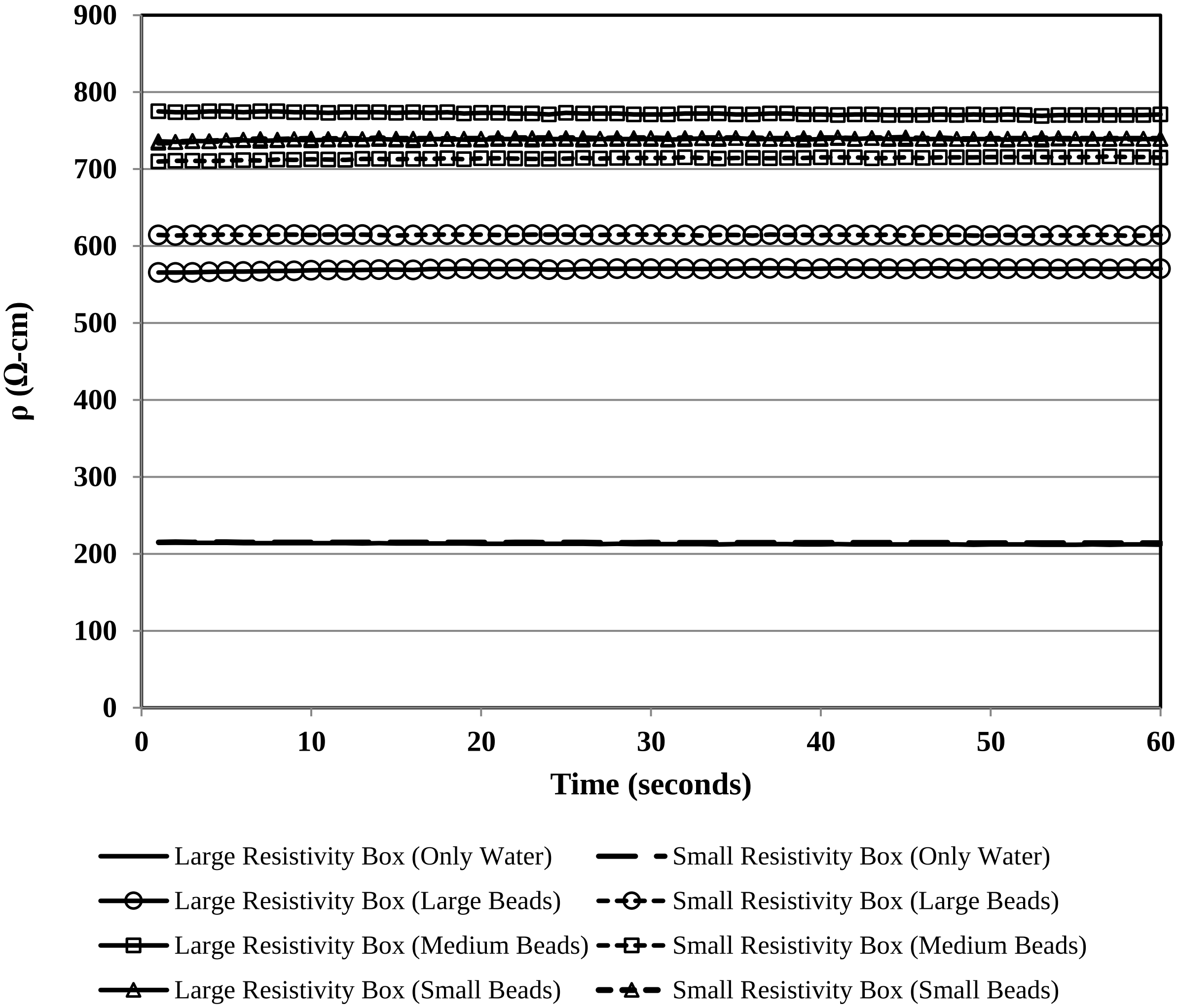


Figure 26: Resistivity Measurements using Texas Tech and AASHTO Resistivity Boxes: Test 3

Numerous observations were discovered when comparing the resistivity results obtained from all glass beads in each individual test. For one, the medium glass bead tests conducted using the Texas Tech Resistivity box measured the highest resistivity values compared to all other tests. Also, the ρ_w values measured with each test are always less than the ρ_a values. The water solution of a known concentration was always less than the concentration with inert material present. When comparing the ρ_w results from both the Texas Tech Resistivity Box and AASHTO Resistivity Box, the measurements obtained gave very similar values within a given test. It can be said that the ρ_w will be constant regardless of which resistance box is being used. The results between the GroPro Meter and INA219 expressed a wider margin of difference. The percent difference in water solution results were calculated from **Table 11** and are presented in **Table 12**. Between the two resistivity boxes, the percent difference ranges from 0.89% to 3.89%, but between the use of the GroPro Meter and INA219 Device, percent difference values ranged anywhere from 4.10% to 12.64%. The later value ranges are similar to the results seen when testing all resistivity devices, which are within reasonable value difference between each device. The percent difference between both resistivity boxes mathematically justifies the conclusion that a water solution of the same concentration will produce very similar resistivity values, regardless of box size.

Table 12: Percent Differences between Resistivity Boxes Used and Measuring Devices

Test 1	Texas Tech Resistivity Box and AASHTO Standard Resistivity Box	3.89%
Test 1	GroPro and INA219 (Texas Tech Resistivity Box)	4.10%
Test 1	GroPro and INA219 (AASHTO Resistivity Box)	7.99%
Test 2	Texas Tech Resistivity Box and AASHTO Standard Resistivity Box	2.59%
Test 2	GroPro and INA219 (Texas Tech Resistivity Box)	10.05%
Test 2	GroPro and INA219 (AASHTO Resistivity Box)	12.64%
Test 3	Texas Tech Resistivity Box and AASHTO Standard Resistivity Box	0.89%
Test 3	GroPro and INA219 (Texas Tech Resistivity Box)	5.84%
Test 3	GroPro and INA219 (AASHTO Resistivity Box)	6.73%

The largest particle-size glass bead gave the lowest ρ_a reading amongst all other bead tests. All large glass beads produced the lowest resistivity values, with the exception of the large glass beads used with the AASHTO Resistivity Box in Test 1. The AASHTO Resistivity Box (also known as the test standard AASHTO T 288-12 Soil Resistivity Box) cannot accommodate a representative sample of the larger glass bead size; the glass beads would either not completely fill-up the AASHTO Resistivity Box, or the glass beads would protrude above the top of the resistivity box. The outcome of this circumstance observed substantiates the fact that test standards enacted by national organizations like AASHTO cannot be used for certain electrochemical properties of coarser aggregate backfill materials.

Archie's empirical law was used to express a relationship between ρ_a and ρ_w for glass beads. The results calculated for use with Archie's empirical law are shown in **Table 13**. The logarithmic forms of porosity (*n*) and ρ_w/ρ_a ratio for every glass bead test was calculated and used to create a graph. This graph utilizes the logarithmic form of *n* and ρ_w/ρ_a to create an equation whose slope gives the value for the material-dependent empirical exponent (*m*), which Archie termed the cementation index because *m* increases with cementation. Essentially, the relationship between ρ_a and ρ_w is determined by evaluating the porosity of a given material with regard to cementation characteristics.

Each individual glass bead size was plotted for *m* calculations, and is shown in **Figure 27**. For the large beads, the associated *m* value is equal to 1.28; for the medium beads, the *m* value is equal to 1.11; the small beads gave an *m* value equal to 1.20. The greatest contribution to the varieties in *m* values is due to the porosity of each glass bead test. The large glass beads gave the highest *n* values in every test series and, except for the results obtained from the Texas Tech Box in Test 3, the small beads gave the lowest values of *n*. It is reasonable to assess that the large beads had the lowest resistivity values measured as compared with the two other glass beads. Several *m* values of different consolidated and non-consolidated media have been published and are tabulated in Friedman (2005). For spherical glass beads Friedman (2005) states that the corresponding *m* value is equal to 1.20 for porosity ranges between 0.33 and 0.37. The porosity ranges calculated in this research were not within the range suggested by Friedman (2005), but the resulting *m* values obtained correspond well within the value of 1.20. The small glass beads produced the same number of 1.20 as suggest by Friedman (2005), and had porosity values closest to the range of 0.33 and 0.37. This observation follows closely to that of other published research dealing with this subject matter, which strengthens the accuracy of the results obtained in this research.

Table 13: Archie's Empirical Law Parameter Calculations for All Glass Beads

		Porosity (n)	Log(n)	ρ_w/ρ_a	$\log(\rho_w/\rho_a)$
Test 1	Texas Tech Box with Water and Large Beads	0.500	0.30135	0.39751	0.40065
Test 1	Texas Tech Box with Water and Medium Beads	0.383	0.41645	0.30557	0.51489
Test 1	Texas Tech Box with Water and Small Beads	0.365	0.43761	0.32471	0.48851
Test 1	AASHTO Box with Water and Large Beads	0.477	0.32188	0.36755	0.43468
Test 1	AASHTO Box with Water and Medium Beads	0.468	0.32990	0.36799	0.43417
Test 1	AASHTO Box with Water and Small Beads	0.414	0.38291	0.34832	0.45802
Test 2	Texas Tech Box with Water and Large Beads	0.488	0.31141	0.40665	0.39077
Test 2	Texas Tech Box with Water and Medium Beads	0.407	0.39059	0.32624	0.48646
Test 2	Texas Tech Box with Water and Small Beads	0.388	0.41168	0.33298	0.47758
Test 2	AASHTO Box with Water and Large Beads	0.497	0.30373	0.39175	0.40699
Test 2	AASHTO Box with Water and Medium Beads	0.463	0.33396	0.37429	0.42679
Test 2	AASHTO Box with Water and Small Beads	0.410	0.38750	0.35462	0.45023
Test 3	Texas Tech Box with Water and Large Beads	0.409	0.38782	0.37374	0.42743
Test 3	Texas Tech Box with Water and Medium Beads	0.314	0.50268	0.27574	0.55950
Test 3	Texas Tech Box with Water and Small Beads	0.375	0.42616	0.28820	0.54030
Test 3	AASHTO Box with Water and Large Beads	0.473	0.32547	0.34963	0.45639
Test 3	AASHTO Box with Water and Medium Beads	0.416	0.38139	0.30088	0.52160
Test 3	AASHTO Box with Water and Small Beads	0.385	0.41500	0.29051	0.53684

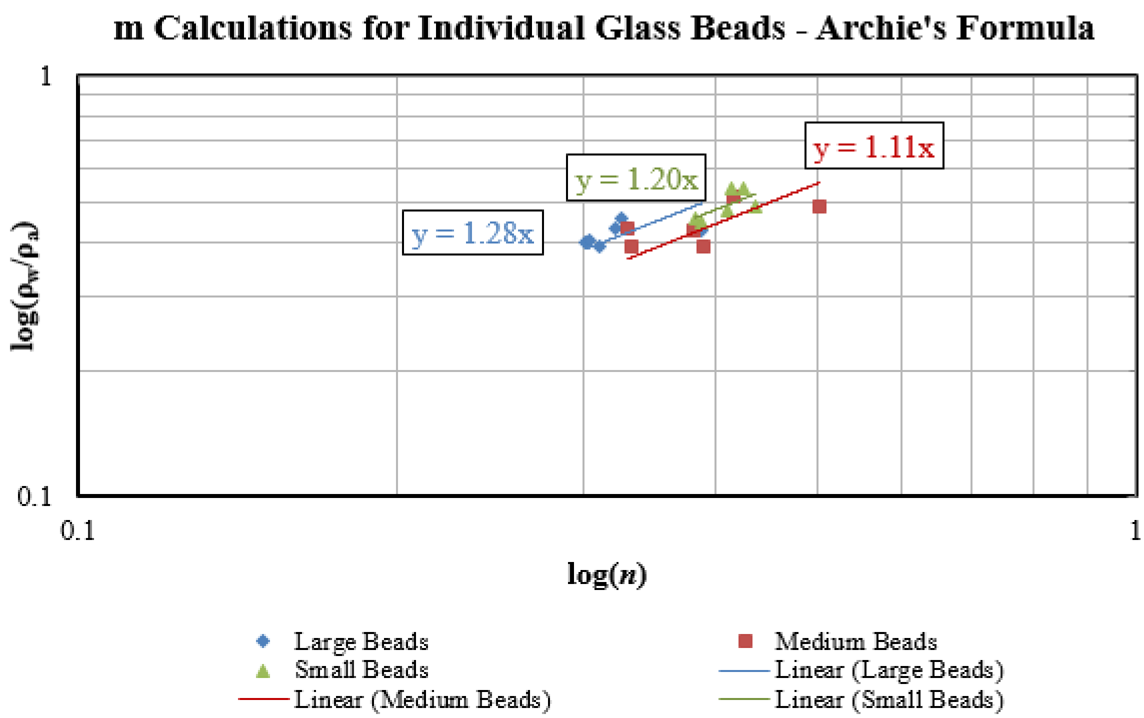


Figure 27: *m* Calculations for Each Glass Bead Size Resistivity Test Series

A corresponding *m* value was also established to represent the entire glass bead experiment and is shown in **Figure 28**. The slope presented in this equation shows a representative *m* value equal to 1.23. This value represents the overall *m* value for glass beads testing and can be used as the *m* value for any prediction of ρ_a or ρ_w using Archie's formula. To check if the overall *m* value of 1.23 would accurately predict either a ρ_a or ρ_w value, calculations were conducted using data collected from the three glass bead tests. A ρ_a value was calculated using *m* equal to 1.23 and the measured ρ_w and *n* values from each specific glass bead test. The predicted results were then plotted against the actual measured ρ_a value for each test. This graph is shown in **Figure 29**. The equation obtained from the graph shows the slope from the two ρ_a values is almost equal to one. A slope equal to one justifies that the predicted ρ_a value for each test is equal to the corresponding ρ_a value measured. Because of this, the *m* value of 1.23 accurately represents the material-dependent empirical exponent for glass beads.

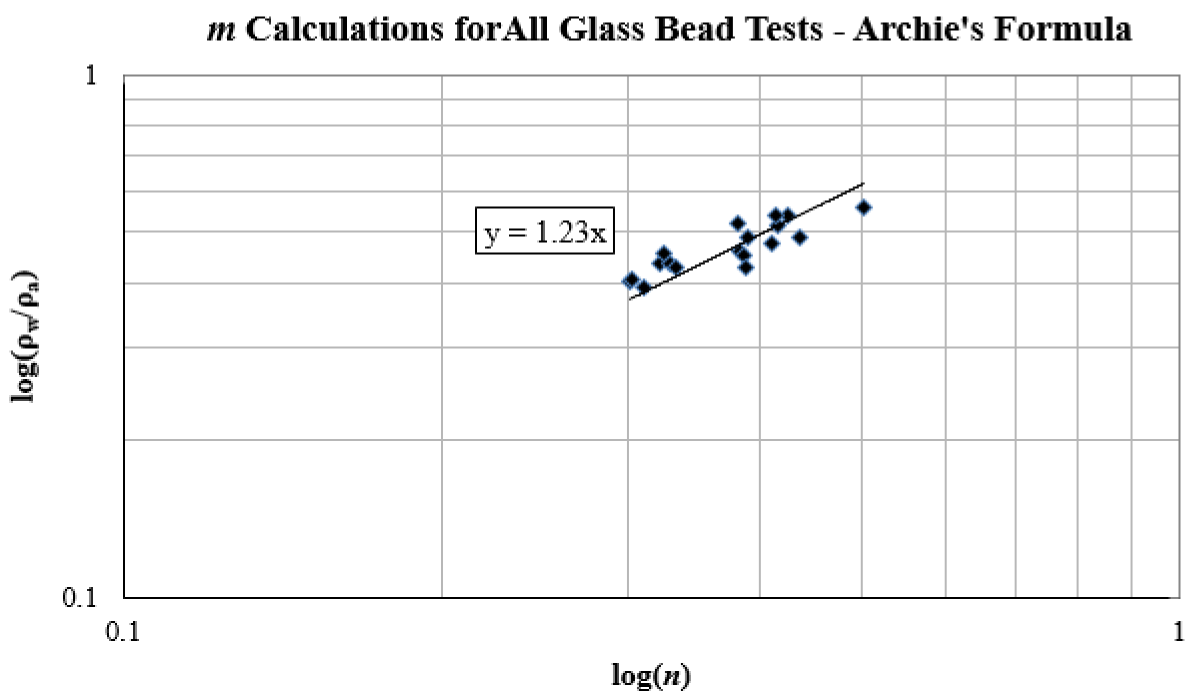


Figure 28: ***m*** **Calculation for All Glass Bead Size Resistivity Tests**

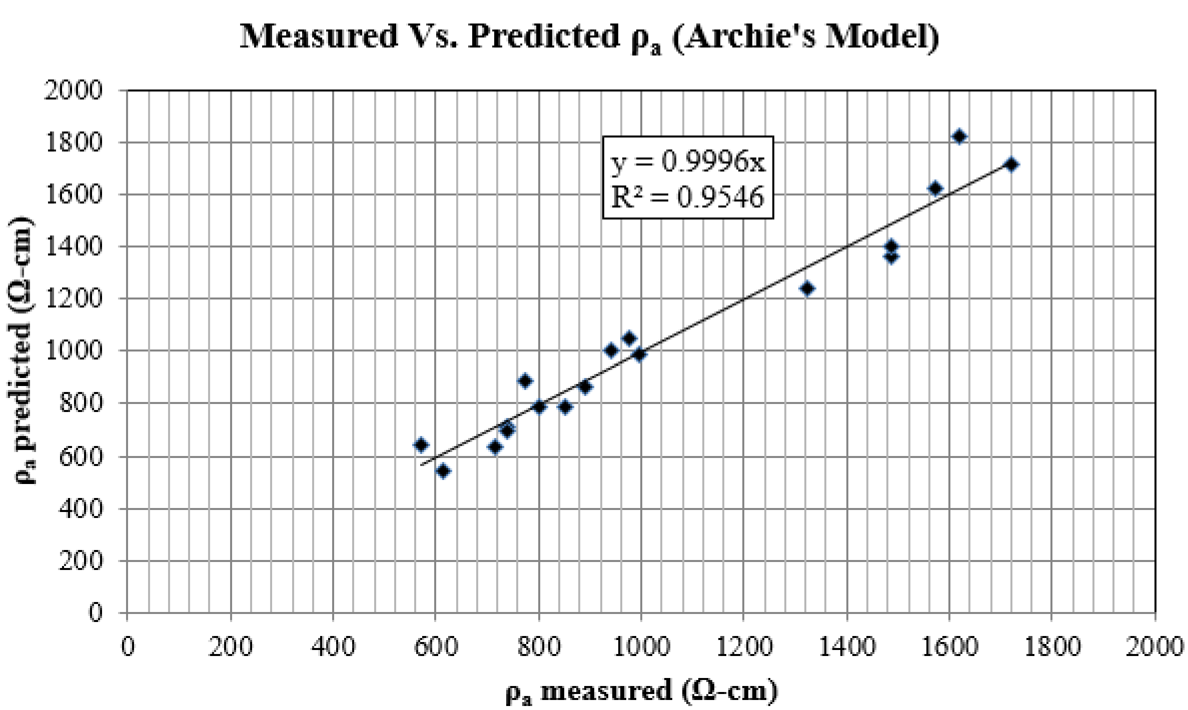


Figure 29: Comparisons between Measured and Predicted ρ_a using ***m*** **= 1.23**

Maxwell's formula was also used to express a relationship between ρ_a and ρ_w. Using only the *n* value from each glass bead test, a graph was plotted which compared *n* to the ρ_w/ρ_a ratio. This graph is shown in Figure 30. ρ_a values were predicted using the *n* and ρ_w values from each glass beads test and were plotted against the actual ρ_a values that were measured for each test. The resulting graph is shown in Figure 31. The accuracy of results using the Maxwell's Model is less than that of results found using Archie's empirical law, but Maxwell's formula does approximate the ρ_a and ρ_w values within a 95% accuracy rate. The reason Maxwell's model does not present more accurate results because the only variable that affects the ρ_a and ρ_w values is porosity. The over-simplified approach limits the accuracy of predicting the measured resistivity. However, Maxwell's formula does follow the same relationship described in Archie's empirical law, which suggests without knowing anything other than the porosity of a given sample, for a homogeneous material composed of similar-sized solid spheres one can easily create a relationship between ρ_a and ρ_w.

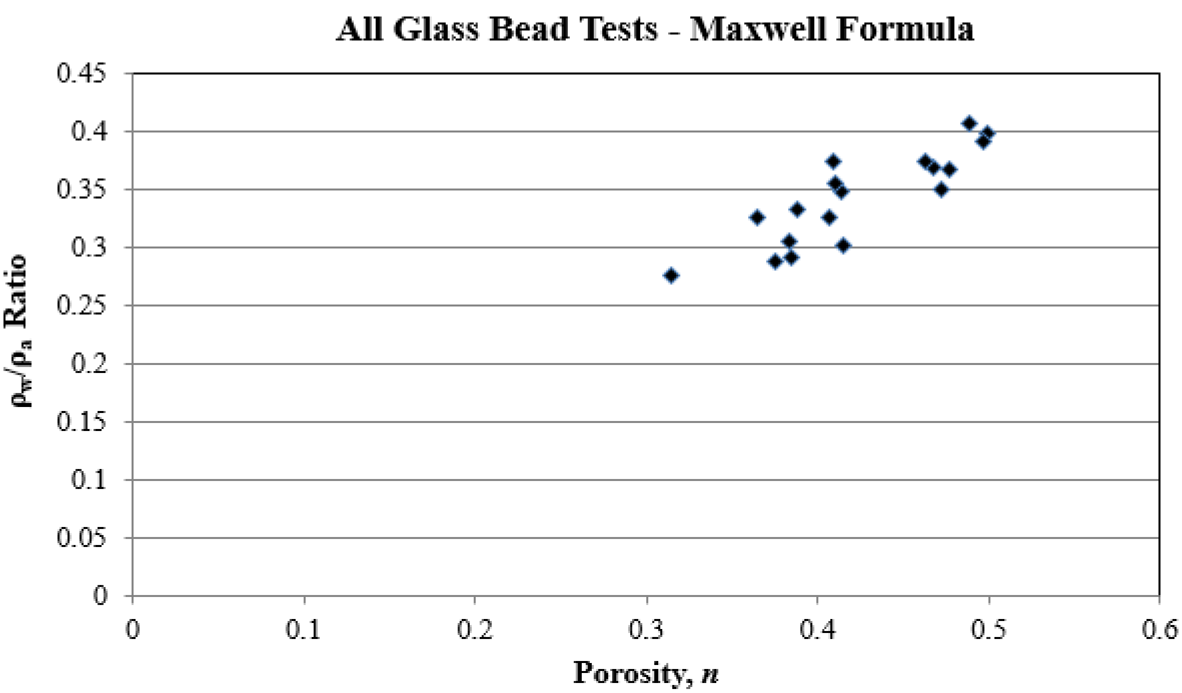


Figure 30: ρ_a and ρ_w comparisons using Maxwell's Formula

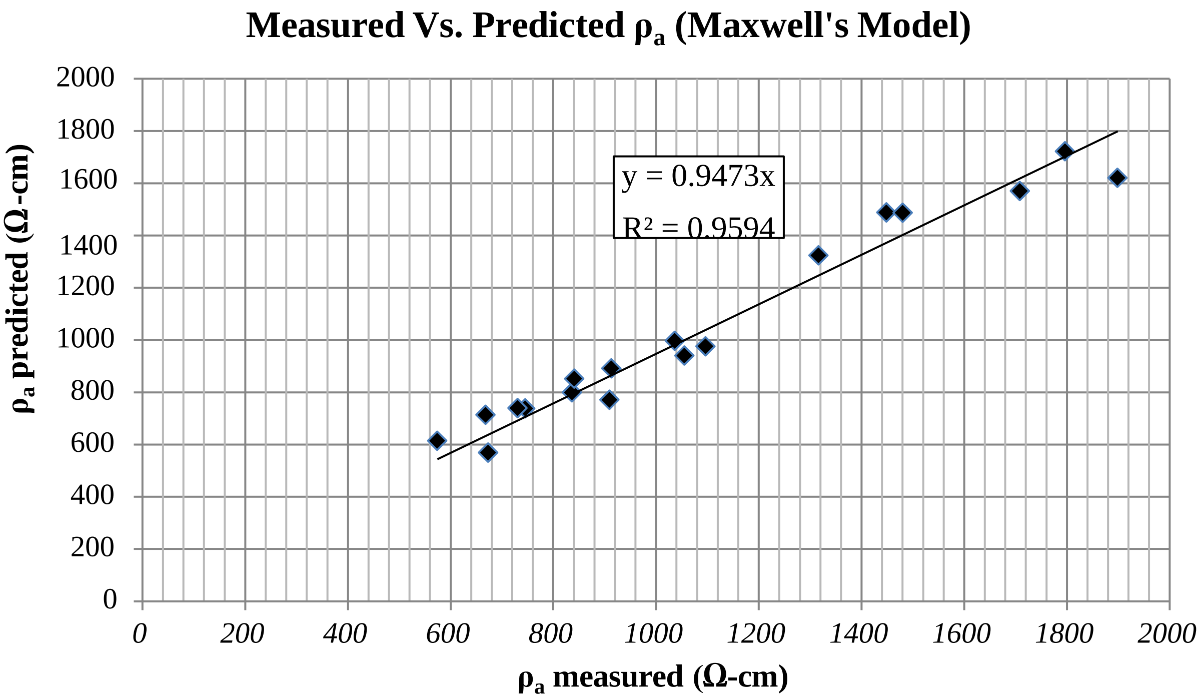


Figure 31: Comparisons between Measured and Predicted ρ_a using Maxwell's Model

4.4 Soil Backfill Material Resistivity Results and Data Analysis

With the knowledge gathered from resistivity testing on glass bead materials in mind, results obtained from soil backfill material resistivity tests were plotted and analyzed for similar characteristics to establish a relationship between ρa and ρw. Tables 14, 15, and 16 show the summary of results obtained for the three source materials in both AASHTO No. 57 and AASHTO Standard Gradations.

Table 14: Summary of Resistivity Results for Vulcan Material

	AASHTO No. 57	AASHTO No. 57	AASHTO No. 57	AASHTO No. 57	AASHTO Standard Gradation	AASHTO Standard Gradation	AASHTO Standard Gradation	AASHTO Standard Gradation	AASHTO Standard Gradation	AASHTO Standard Gradation
	ρa (Ω-cm)	ρw (Ω-cm)	ρw (Ω-cm)		ρa (Ω-cm)	ρ'w (Ω-cm)	ρ'w (Ω-cm)	ρw (Ω-cm)	ρw (Ω-cm)	
	Texas Tech Box	Miller Box			AASHTO Box	Miller Box				
	INA219	INA219	GroPro	Porosity (n)	INA219	INA219	GroPro	INA219	GroPro	Porosity (n)
Test 1	14898	4230	3704	0.424	4662	2557	3704	1007	1459	0.336
Test 2	15029	4320	3704	0.428	6049	3618	3704	1509	1544	0.597
Test 3	16093	4992	3846	0.439	5225	5246	5263	1641	1647	0.276

Table 15: Summary of Resistivity Results for Sandmill Material

	AASHTO No. 57	AASHTO No. 57	AASHTO No. 57	AASHTO No. 57	AASHTO Standard Gradation	AASHTO Standard Gradation	AASHTO Standard Gradation	AASHTO Standard Gradation	AASHTO Standard Gradation	AASHTO Standard Gradation
	ρa (Ω-cm)	ρw (Ω-cm)	ρw (Ω-cm)		ρa (Ω-cm)	ρ'w (Ω-cm)	ρ'w (Ω-cm)	ρw (Ω-cm)	ρw (Ω-cm)	
	Texas Tech Box	Mill			AASHTO Box	Miller Box				
	INA219	INA219	GroPro	Porosity (n)	INA219	INA219	GroPro	INA219	GroPro	Porosity (n)
Test 1	14519	3556	3125	0.456	1981	3374	2222	1459	961	0.479
Test 2	15541	3670	3226	0.454	2030	3084	2000	1700	1103	0.686
Test 3	-	-	-	-	2133	3304	3333	1646	1660	0.602

Table 16: Summary of Resistivity Results for RE Janes Material

	AASHTO No. 57	AASHTO No. 57	AASHTO No. 57	AASHTO No. 57	AASHTO Standard Gradation	AASHTO Standard Gradation	AASHTO Standard Gradation	AASHTO Standard Gradation	AASHTO Standard Gradation	AASHTO Standard Gradation
	ρa (Ω-cm)	ρw (Ω-cm)	ρw (Ω-cm)		ρa (Ω-cm)	ρ'w (Ω-cm)	ρ'w (Ω-cm)	ρw (Ω-cm)	ρw (Ω-cm)	
	Texas Tech Box	Mill			AASHTO Box	Miller Box				
	INA219	INA219	GroPro	Porosity (n)	INA219	INA219	GroPro	INA219	GroPro	Porosity (n)
Test 1	16098	6084	5556	0.433	12778	9833	10000	3692	3755	0.395
Test 2	13921	5564	5556	0.432	13505	11012	14286	4201	5450	0.414
Test 3	-	-	-	-	13969	7708	12500	2399	3890	0.289
Test 4	-	-	-	-	13903	10003	14286	4364	6232	0.537

Every resistivity test conducted on soil backfill material produced a ρ_a and ρ_w graph from data collected using the INA219 device for an allotted amount of time explained in Chapter 3. For the most part, the ρ_a versus time (T) graphs showed a trend of decreasing ρ_a values as time elapsed until the values would eventually steady to a minimum ρ_a value. Characteristics such as these look like **Figures 32**, **33**, and **34**. To establish a representative ρ_a value, an average of all ρ_a values was taken from the first time a minimum ρ_a value was measure until the end of the test. For example: in **Figure 32**, the first time a minimum ρ_a value was observed occurred at T equal to 690 minutes.

From that point on, all ρ_a values measured after the 690 minute mark were averaged together. This average ρ_a value was used as that material's representative ρ_a value. For **Figure 32**, that representative ρ_a value is equal to 14898 Ω-cm. This process was followed for all graphs showing this decreasing trend.

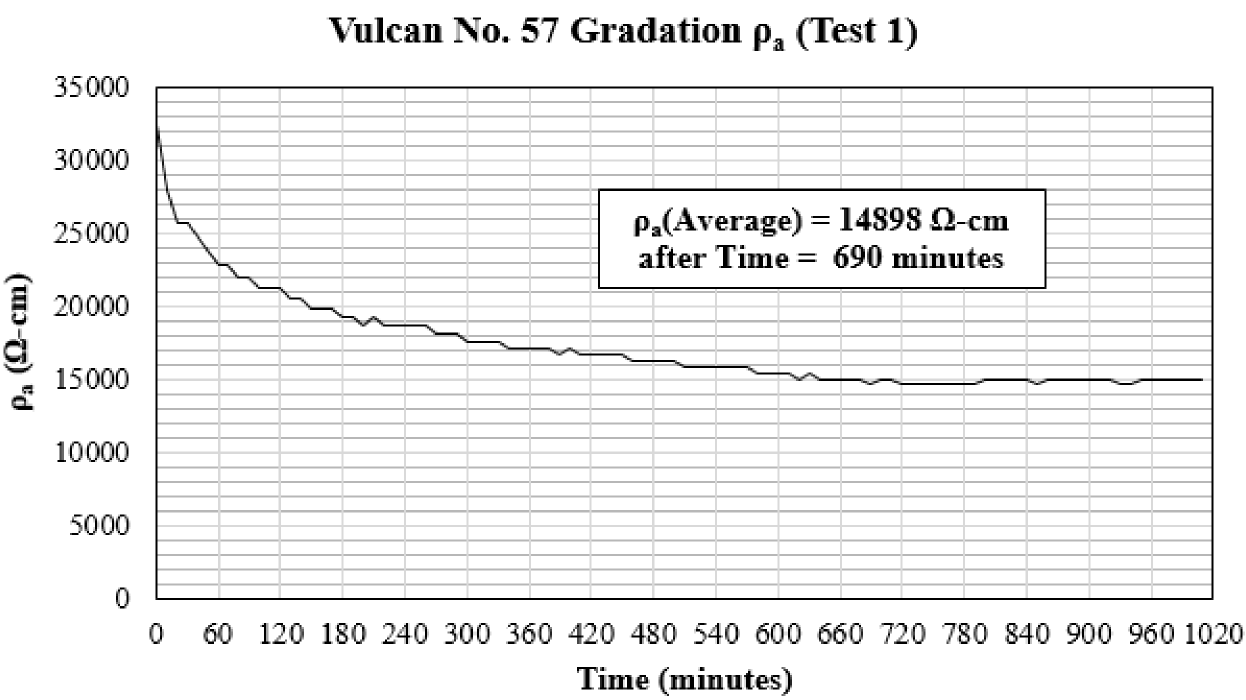


Figure 32: Vulcan No. 57 Gradation ρ_a for Test 1

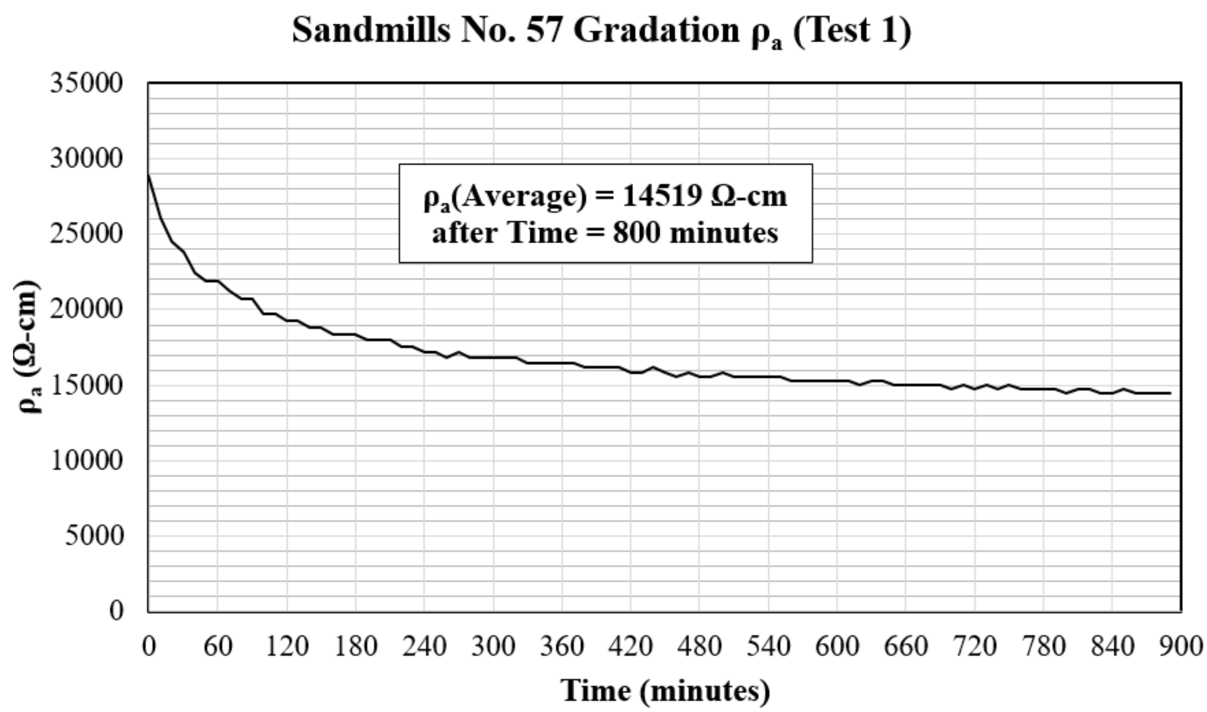


Figure 33: Sandmills No. 57 Gradation ρ_a for Test 1

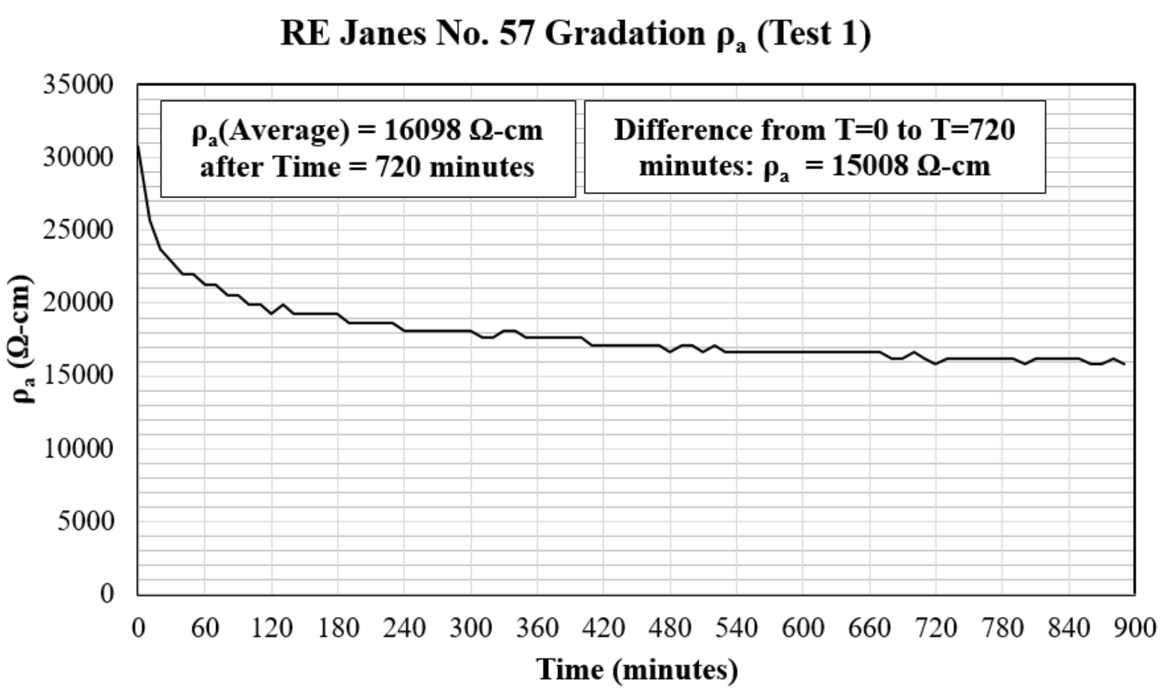


Figure 34: RE Janes No. 57 Gradation ρ_a for Test 1

Other ρ_a versus T graphs showed trends that would initially decrease at the beginning of the test, then would steady out at a minimum value, but would increase towards the end of the elapsed time of the test. Characteristics like these are shown in **Figures 35**, **36**, and **37**. To establish a representative ρ_a value for this type of trend, an average was taken from the first indicated minimum ρ_a value until the ρ_a values started to increase again. For example: in **Figure 35**, ρ_a values initially decreased as the time elapsed until around 60 minutes where a minimum value was observed. From there, all ρ_a values measured from the 60 minute mark were used to calculate an average ρ_a value until around T equal to 510 minutes, where ρ_a values started to increase rapidly. The average ρ_a value between these two times was calculated to equal 5225 Ω-cm. This value was selected to represent the ρ_a value for Vulcan Standard Gradation Test 3. This process was carefully followed for all tests exhibiting this same trend.

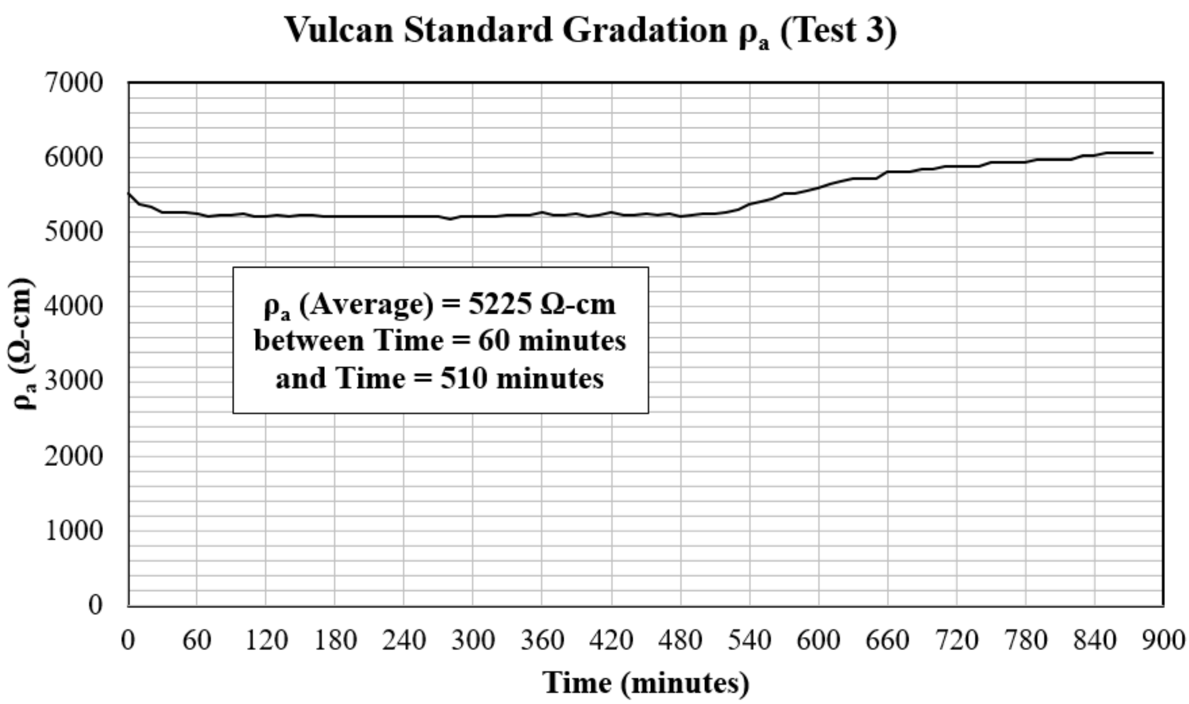


Figure 35: Vulcan Standard Gradation ρ_a for Test 3

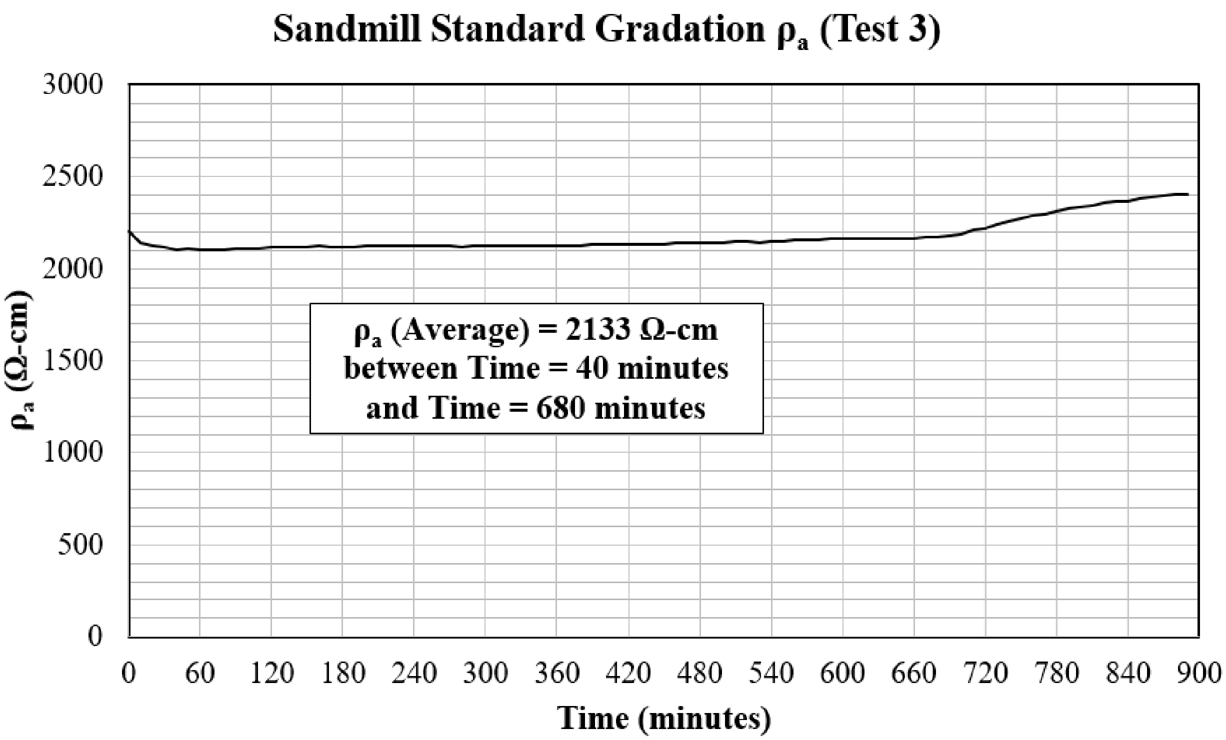


Figure 36: Sandmill Standard Gradation ρ_a for Test 3

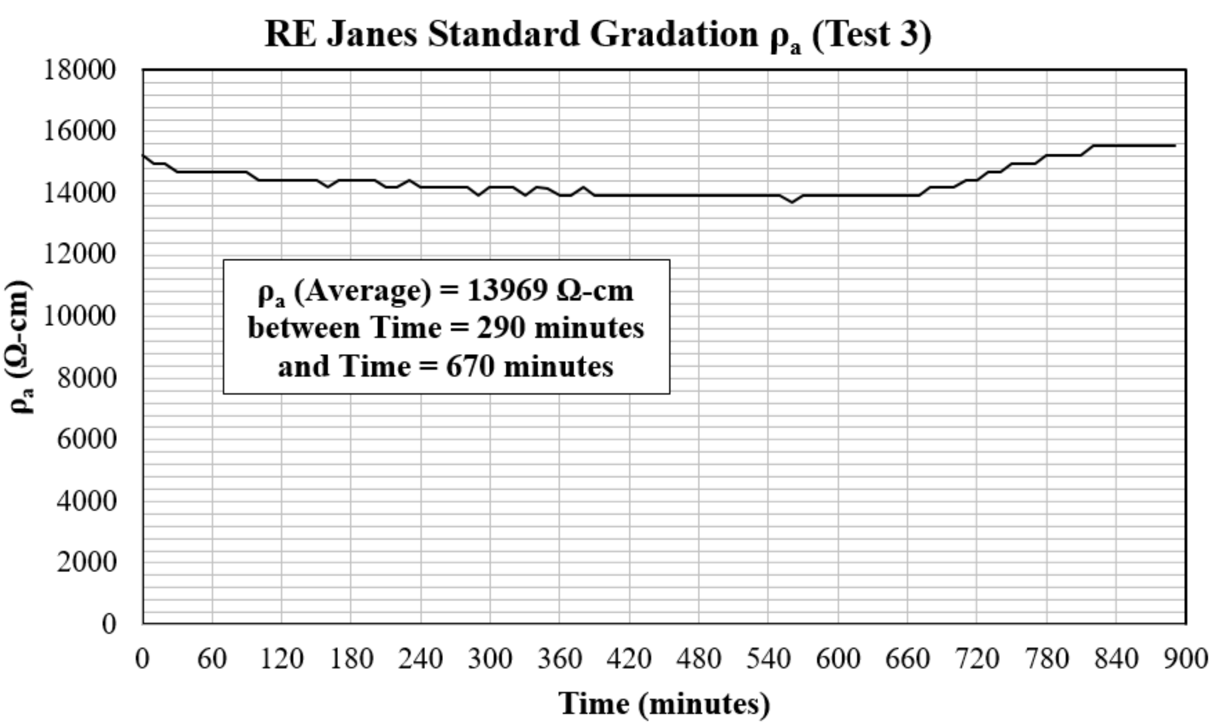


Figure 37: RE Janes Standard Gradation ρ_a for Test 3

Representative ρ_w values for AASHTO No. 57 gradation tests using Vulcan material were generated by taking the average of all ρ_w values measured for the entire test. All ρ_w graphs for the Vulcan No. 57 gradation tests provided ρ_w values well within range of each other and did not require any special process for ρ_w determination. A sample graph for determining ρ_w from AASHTO No. 57 gradation tests for Vulcan material is shown in **Figure 38** .

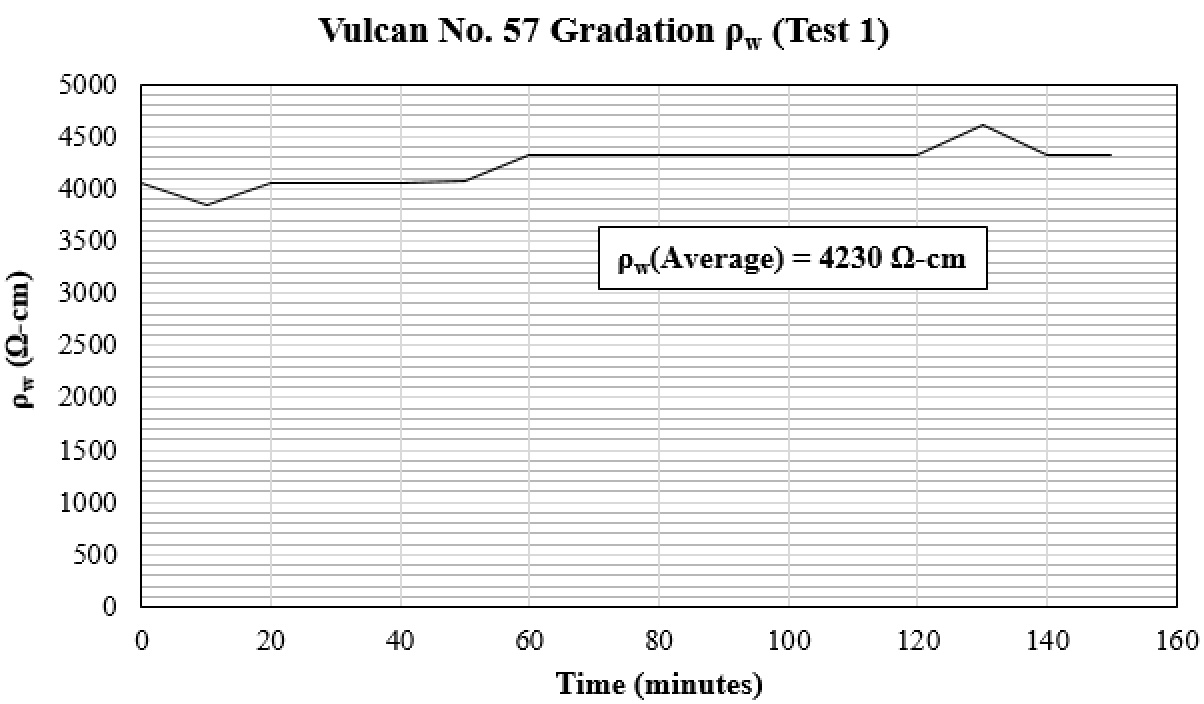


Figure 38: Vulcan No. 57 Gradation ρ_w for Test 1

RE Janes material using the AASHTO No. 57 gradation produces graphs that would have ρ_w values that would increase at random time intervals and then decrease to a minimum ρ_w value. The representative ρ_w value for RE Janes material was established by taking the average ρ_w values from the first time a minimum ρ_w value was observed until the end of the elapsed time. **Figure 39** shows an example graph where the representative ρ_w value was obtained by averaging ρ_w values collected after T equal to 720 minutes. The resulting ρ_w value of 6084 Ω-cm was used to represent that given test for the RE Janes material. This process was followed for both of the AASHTO No. 57 gradation tests using

RE Janes material

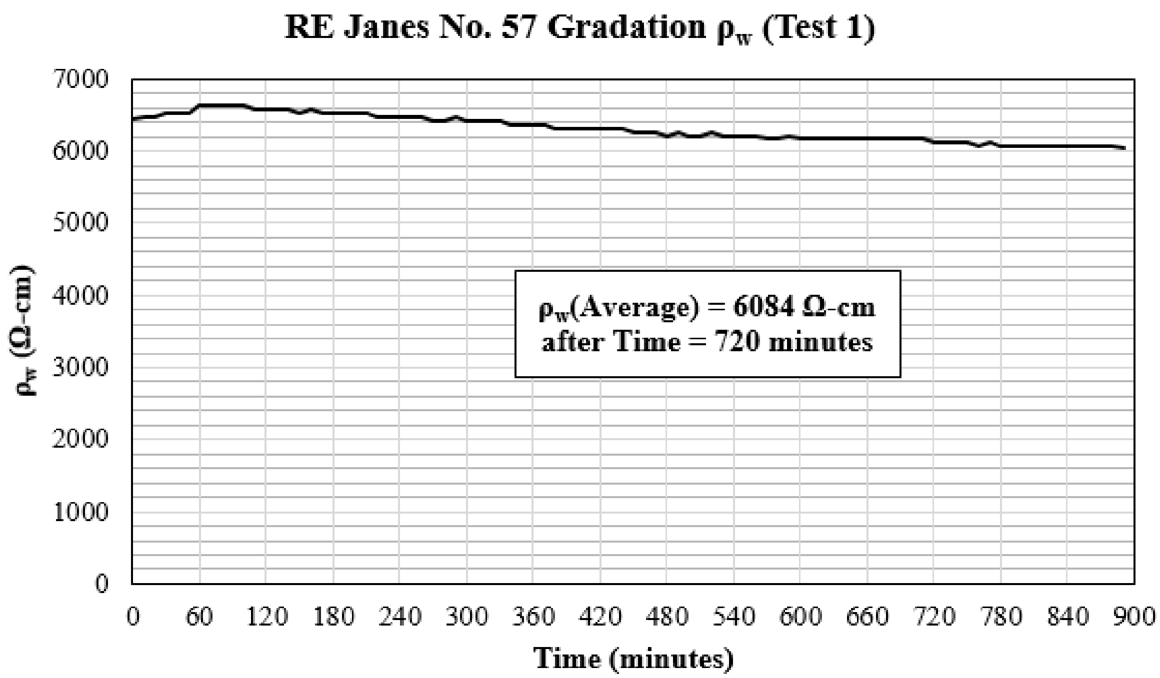


Figure 39: RE Janes No. 57 Gradation ρ_w for Test 1

All individual ρ_w and ρ_a graphs for each source material and gradation are shown in **Appendix B**. For AASHTO Standard gradation tests, a representative ρ_w value had to be calculated using characteristics described in Kohlrausch's law for equivalent conductivity of an electrolyte at infinite dilution and the measured ρ'_w values obtained through experimentation. A specific test was conducted that measured ρ_w values of several dilution ratios with each source material. These soil-to-water dilution ratio tests were used to generate an equation that could be used to convert the ρ_w values measured in the AASHTO Standard Gradation tests for the three source materials. The data collected for each of the three source material soil-to-water dilution ratio tests is shown in **Tables 17**, **18**, and **19**.

Table 17: Soil:Water Dilution Ratio Results and Calculations for Vulcan Material

	1:2	1:1	1:0.5	1:0.25
% Water in mix	66.66%	50.00%	33.33%	20.00%
Gropro (mS)	0.13	0.17	0.31	0.45
Gropro (ohm-cm)	7692.31	5882.35	3225.81	2222.22
Concentration (c)	0.50	1.00	2.00	4.00
Conductivity (K)	1.30E-04	1.70E-04	3.10E-04	4.50E-04
Λ_m = K/c	2.60E-04	1.70E-04	1.55E-04	1.13E-04
sqrt(c)	0.707	1.000	1.414	2.000

Table 18: Soil:Water Dilution Ratio Results and Calculations for Sandmill Material

	1:2	1:1	1:0.5	1:0.25
% Water in mix	66.66%	50.00%	33.33%	20.00%
GroPro (mS)	0.45	0.68	0.81	1.2
GroPro ρ (Ω-cm)	2222.22	1470.59	1234.57	833.33
Concentration (c)	0.50	1.00	2.00	4.00
Conductivity (K)	4.50E-04	6.80E-04	8.10E-04	1.20E-03
Λ_m = K/c	9.00E-04	6.80E-04	4.05E-04	3.00E-04
sqrt(c)	0.707	1.000	1.414	2.000

Table 19: Soil:Water Dilution Ratio Results and Calculations for RE Janes Material

	1:2	1:1.5	1:1	1:075	1:0.5	1:0.25
% Water in mix	66.66%	58.33%	50.00%	41.67%	33.33%	20.00%
GroPro (mS)	0.07	0.08	0.09	0.1	0.12	0.19
GroPro ρ (Ω-cm)	14285.71	12500.00	11111.11	10000.00	8333.33	5263.16
Concentration (c)	0.500	0.667	1.000	1.333	2.000	4
Conductivity (K)	7.00E-05	8.00E-05	9.00E-05	1.00E-04	1.20E-04	1.90E-04
Λ_m = K/c	1.40E-04	1.20E-04	9.00E-05	7.50E-05	6.00E-05	4.75E-05
sqrt(c)	0.707	0.816	1.000	1.155	1.414	2.000

The parameters of Λ_m and sqrt(c) found for each source material and were plotted against each other to create a graph. A power function trendline was then plotted for eachseries to generate an equation for that given material. **Figures 40**, **41**, and **42** shows each source material graph with corresponding equations.

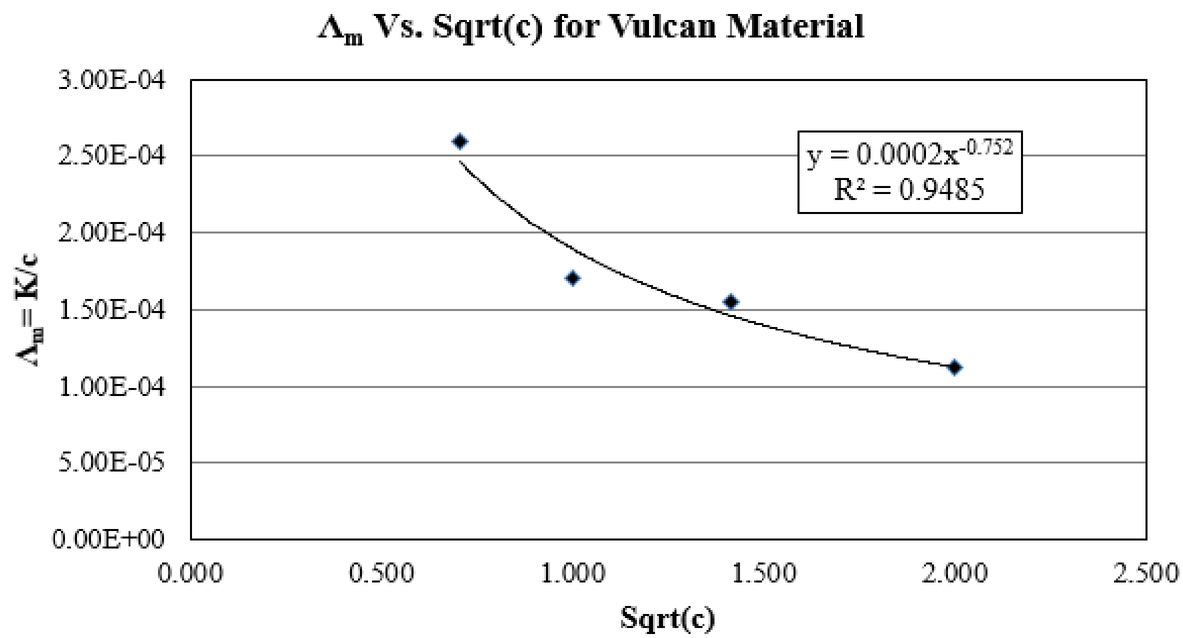


Figure 40: Λ_m versus Sqrt(c) Graph Calculations for Vulcan Material

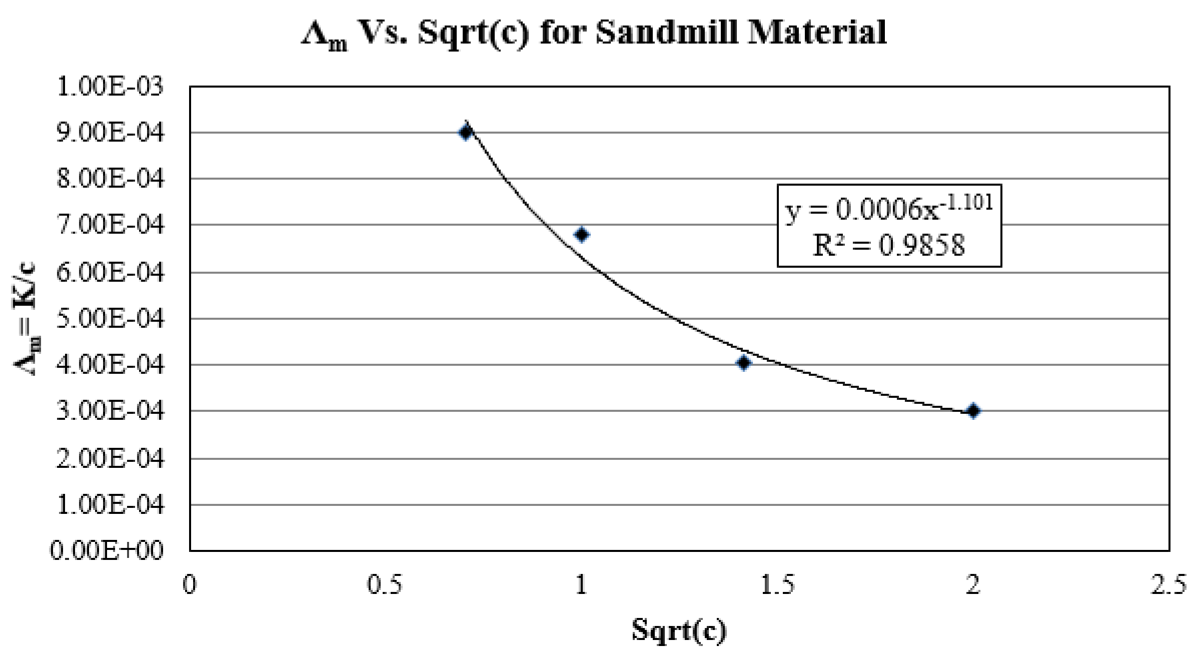


Figure 41: Λ_m versus Sqrt(c) Graph Calculations for Sandmill Material

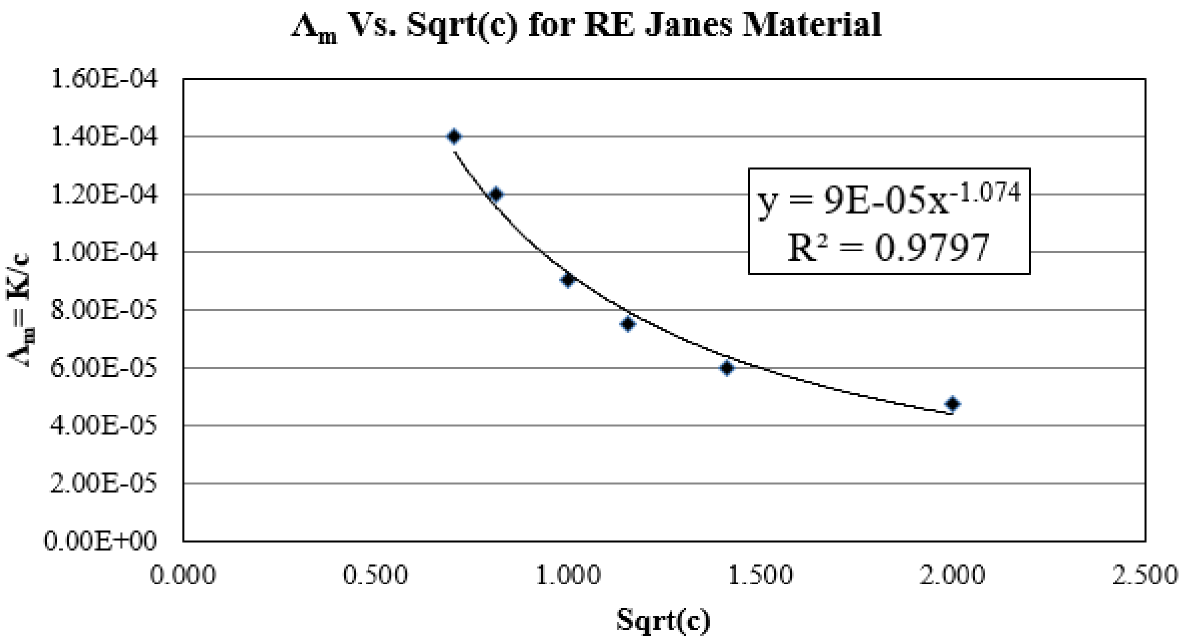


Figure 42: Λ_m versus Sqrt(c) Graph Calculations for RE Janes Material

The equations generated from each source material test was used to calculate corresponding ρ values for each of the source material's AASHTO Standard Gradation test concentrations (c). Using the known c-values from each test, a corresponding ρ value could be derived by using the equation generated from the graph to calculate a K/c value, which would then be multiplied by the known c to obtain the conductivity (K). The ρ value would then be calculated by taking the inverse of the K value. Each test ρ value was compared to a known ρ value using the appropriate soil-to-water ratio utilized for each AASHTO Standard Gradation test, shown in **Table 7**. The calculated ratio value for each test was multiplied by the measured ρ'_w value using the GroPro Meter and INA219 Device to obtain the representative ρ_w value for that given test, which are shown in the summary tables for each source material.

Results obtained for ρ_a values were compared between AASHTO No. 57 and AASHTO Standard gradations to analyze the vast difference between ρ_a values of a given source material. **Figures 43**, **44**, and **45** shows each material ρ_a results from tests conducted using both gradation types. The Sandmills material expressed the widest gap between the No. 57 and Standard Gradations, with an average No. 57 Gradation ρ_a equal to 15030 Ω-cm and an average Standard Gradation ρ_a equal to 2048 Ω-cm. For Vulcan material, the average No. 57 Gradation ρ_a value was equal to 15340 Ω-cm, and the Standard Gradation ρ_a value was equal to 5312 Ω-cm. RE Janes material gave similar ρ_a values between each gradation test. The average No. 57 Gradation ρ_a was equal to 15010 Ω-cm, and the average Standard Gradation was equal to 13539 Ω-cm. These results suggest that the amount of change between the two gradations varies between a given source material. For Vulcan and Sandmill materials, the average ρ_a value for the No. 57 Gradation can be anywhere from twice as large as the average Standard Gradation ρ_a value all the way to measurements that are seven-times as large as the average Standard Gradation ρ_a value. RE Janes Material suggests the average No. 57 Gradation ρ_a value is larger than the average Standard Gradation ρ_a value, but only slightly.

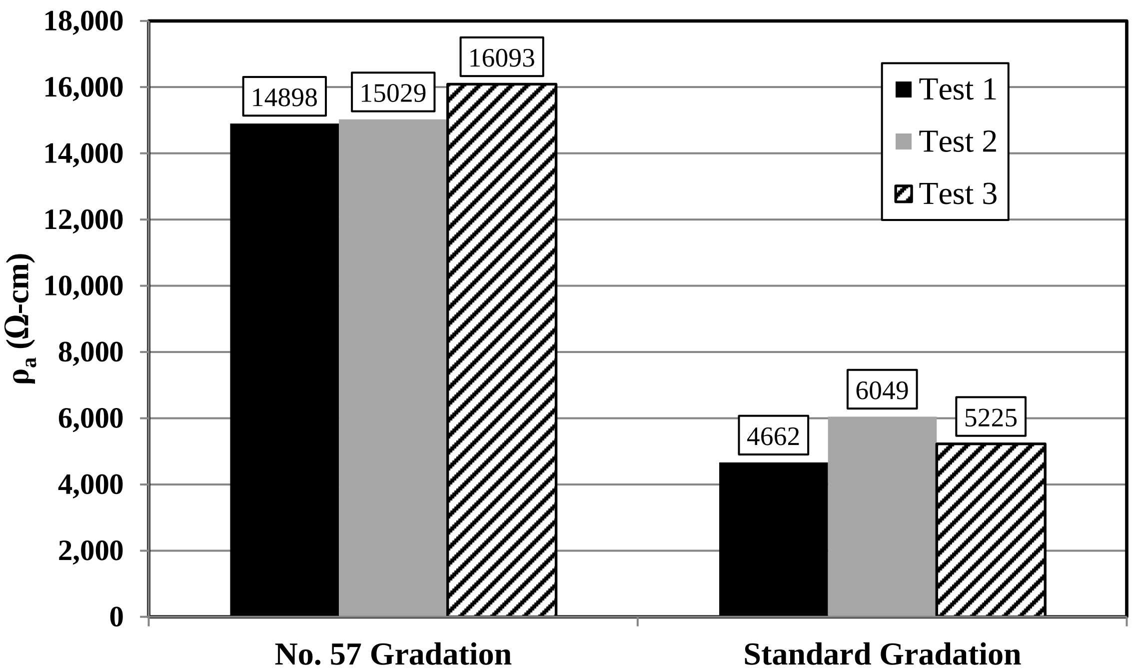


Figure 43: Comparing ρ_a Values for Vulcan Material between AASHTO No. 57 and AASHTO Standard Gradations

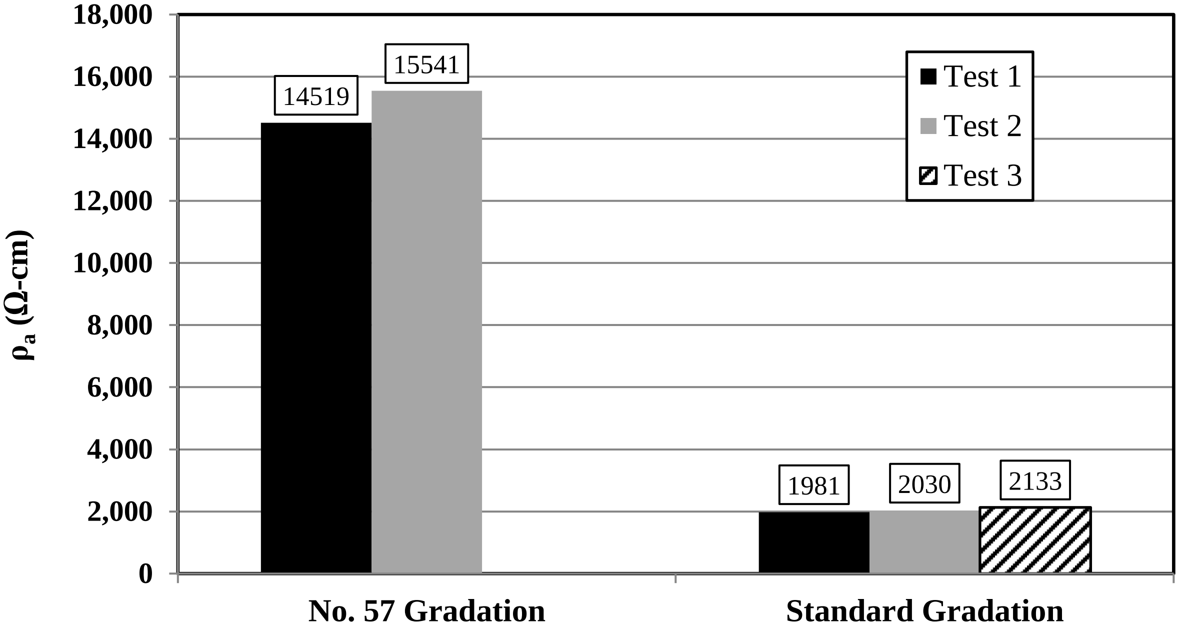


Figure 44: Comparing ρa Values for Sandmill Material between AASHTO No. 57 and AASHTO Standard Gradations

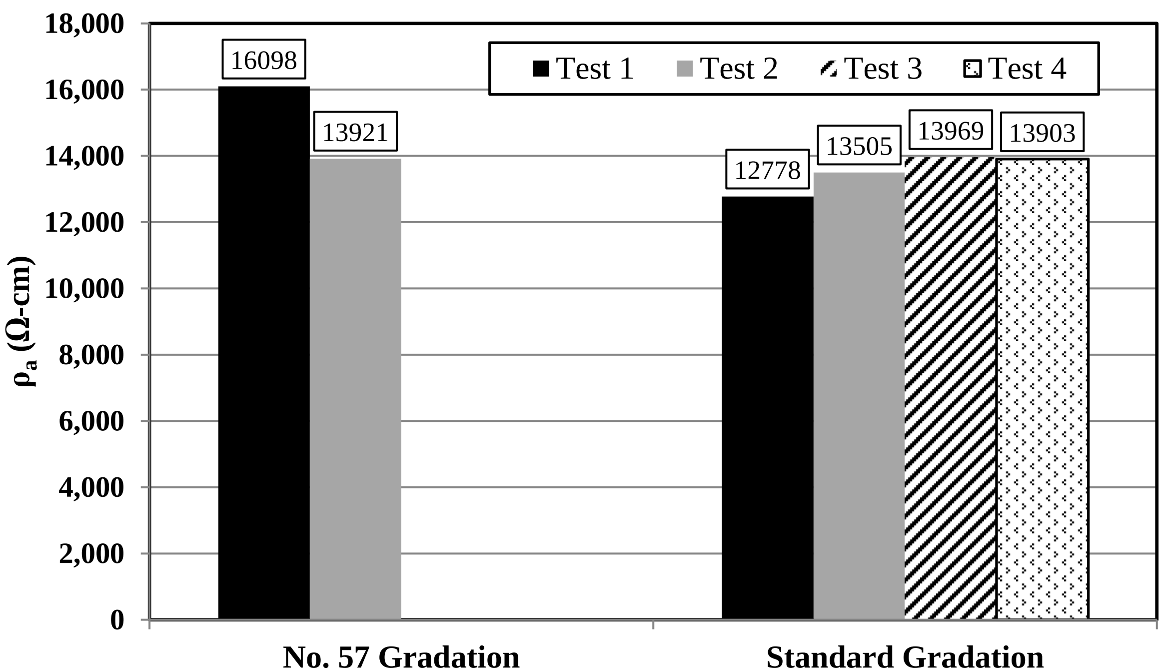


Figure 45: Comparing ρa Values for RE Janes Material between AASHTO No. 57 and AASHTO Standard Gradations

The ρ_w values obtained for the three source materials was collected and plotted against gradation. These graphs, shown in **Figures 46**, **47**, and **48**, express similar relationships seen with ρ_a comparisons. The average Vulcan Material ρ_w for the No. 57 Gradations, using both the GroPro Meter and INA219 Device, show values that are significantly higher than the average ρ_w values for the Standard Gradation tests using the GroPro Meter and INA219 Device. Although Sandmill material did not produce any INA219 Device results for No. 57 Gradation ρ_w, it can be inferred from the GroPro Meter ρ_w results that No. 57 Gradation results have higher ρ_w values than Standard Gradation results. Results obtained from RE Janes material show similar ρ_w values between the No. 57 and Standard Gradations using both the INA219 Device and GroPro Meter. The average No. 57 Gradation ρ_w values are higher than the average Standard Gradation ρ_w values. The results obtained for ρ_w can be concluded to follow the same trend observed for ρ_a comparisons – the amount of change between the two gradations varies between a given source material. Knowing the gradation of a given material is not sufficient to establish a clear connection between contributing effects on resistivity values.

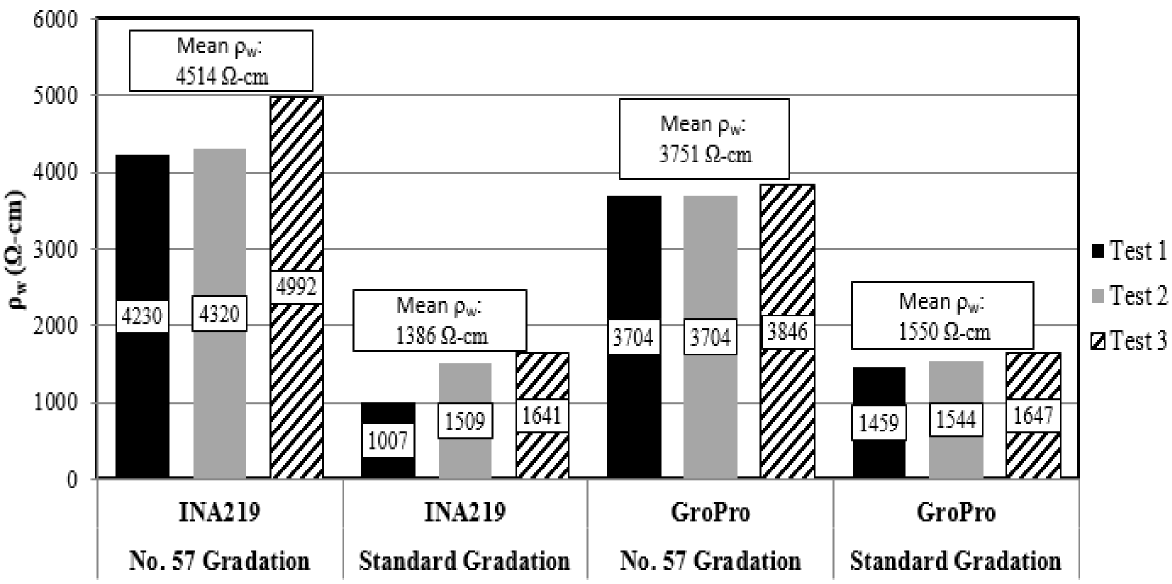


Figure 46: Comparing ρ_w Values for Vulcan Material between AASHTO No. 57 and AASHTO Standard Gradations

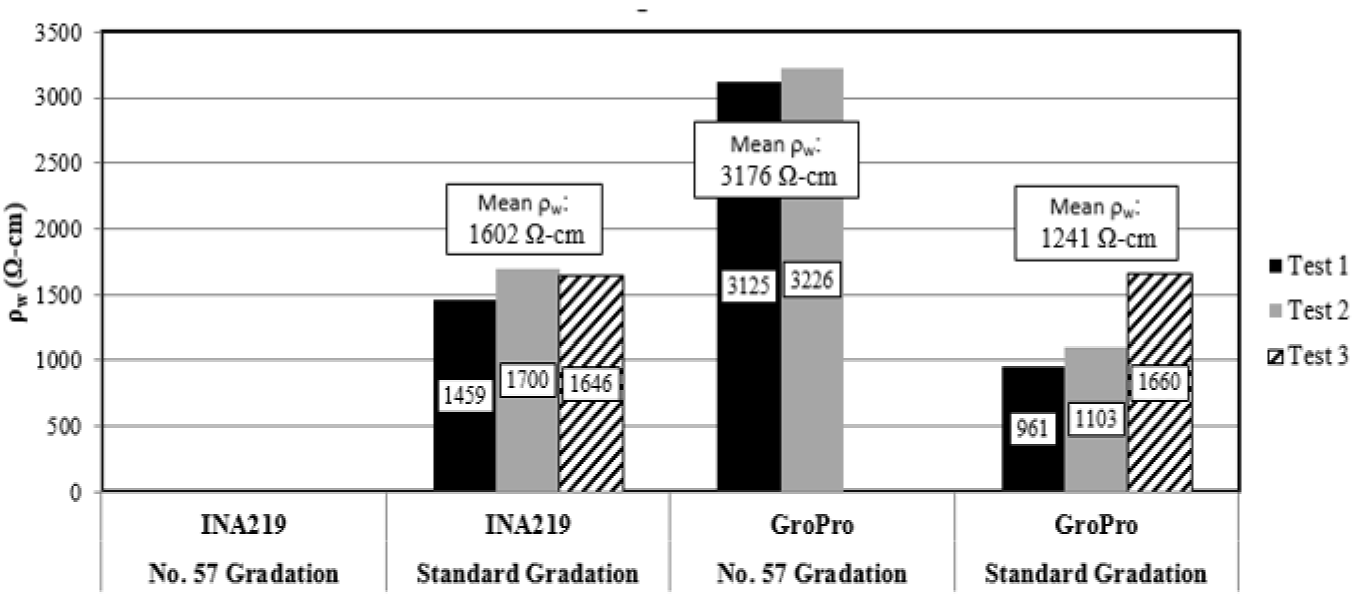


Figure 47: Comparing ρ_w Values for Sandmill Material between AASHTO No. 57 and AASHTO Standard Gradations

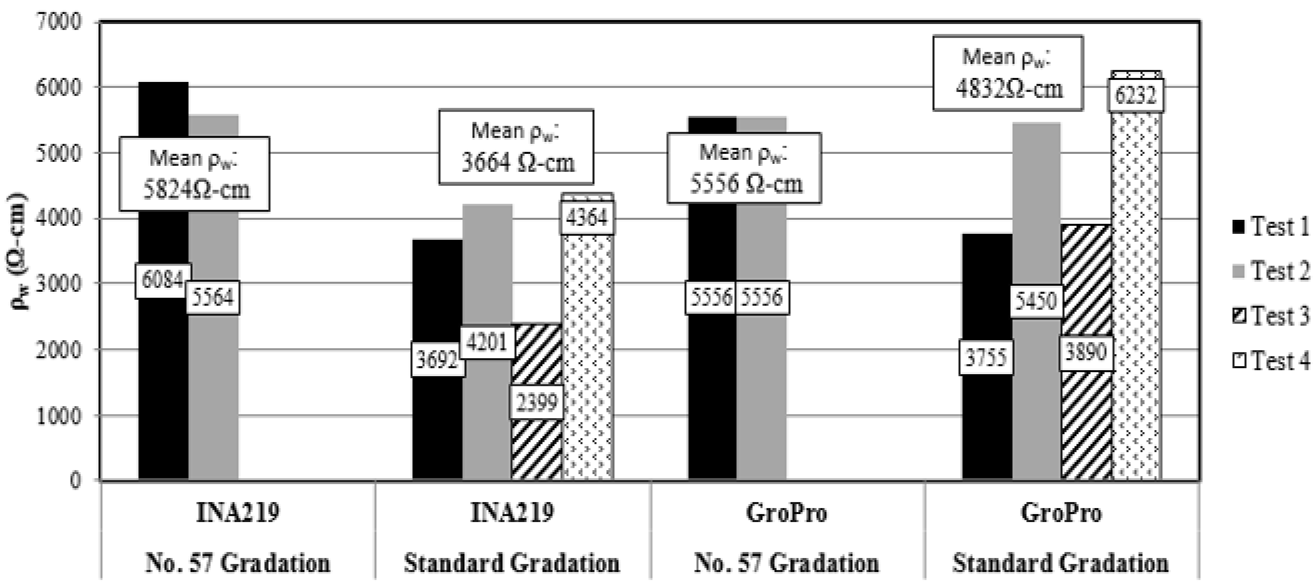


Figure 48: Comparing ρ_w Values for RE Janes Material between AASHTO No. 57 and AASHTO Standard Gradations

The parameter of porosity (*n*) was calculated for all soil backfill material tests. As seen with glass bead resistivity tests, the *n* of a given material can have adverse effects on the overall ρ_a and ρ_w values. *n* values for each source material resistivity test were calculated for data analysis purposes and are shown in **Table 20**. The overall *n* values for the No. 57 Gradation tests ranged from 0.424 to 0.456 while the *n* values for the Standard Gradation tests had a wider range of values, with a minimum *n* value of 0.276 and maximum *n* value of 0.686. **Figures 49**, **50**, and **51** show the *n* value comparisons for each source material in both the No. 57 and Standard Gradations. Within one soil backfill material test series, the *n* obtained from the No. 57 Gradation tests showed *n* values almost equal to each other, but the *n* obtained from the Standard Gradation tests varied widely.

Table 20: *n* Values for Vulcan, Sandmill, and RE Janes Material Tests

	No. 57 Gradation	Standard Gradation
	Porosity (n)	Porosity (n)
Vulcan Test 1	0.424	0.336
Vulcan Test 2	0.428	0.597
Vulcan Test 3	0.439	0.276
Sandmills Test 1	0.456	0.479
Sandmills Test 2	0.454	0.686
Sandmills Test 3	-	0.602
RE Janes Test 1	0.433	0.395
RE Janes Test 2	0.432	0.414
RE Janes Test 3	-	0.289
RE Janes Test 4	-	0.537

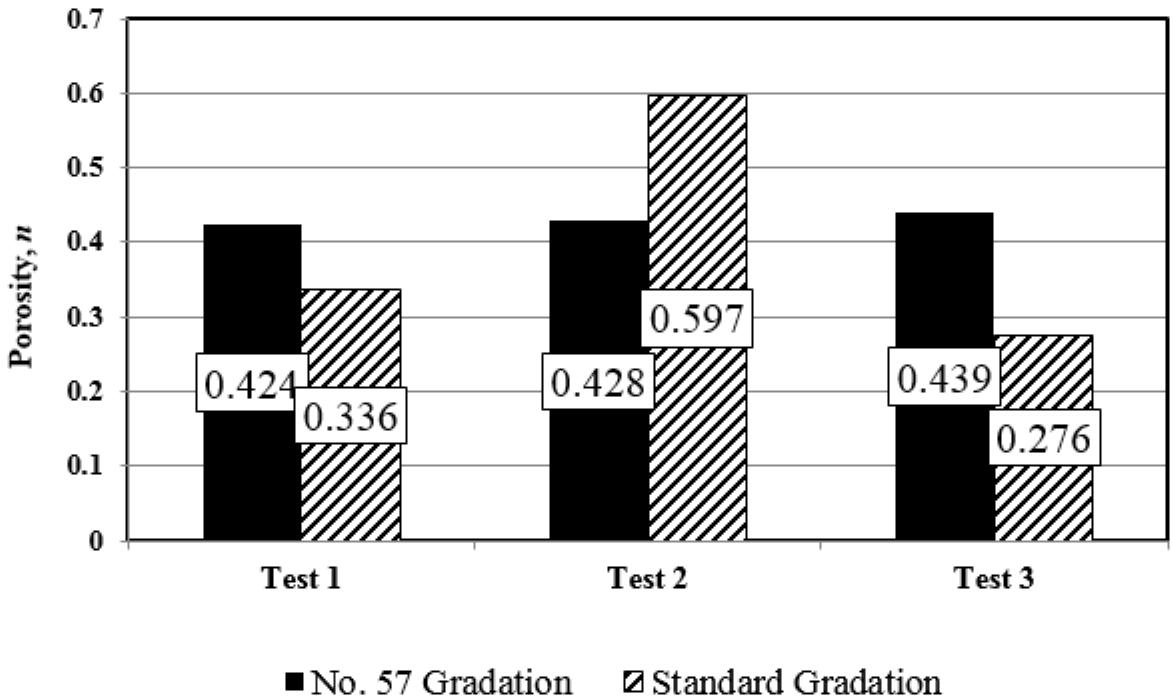


Figure 49: *n* comparisons for Vulcan Material

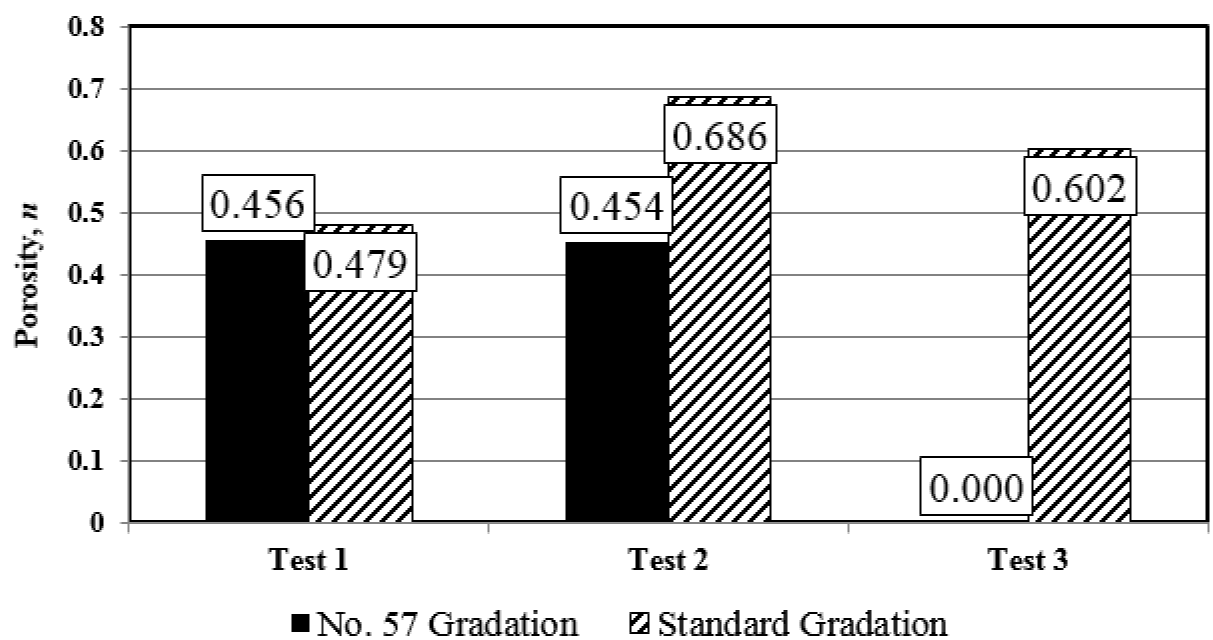


Figure 50: *n* comparisons for Sandmill Material

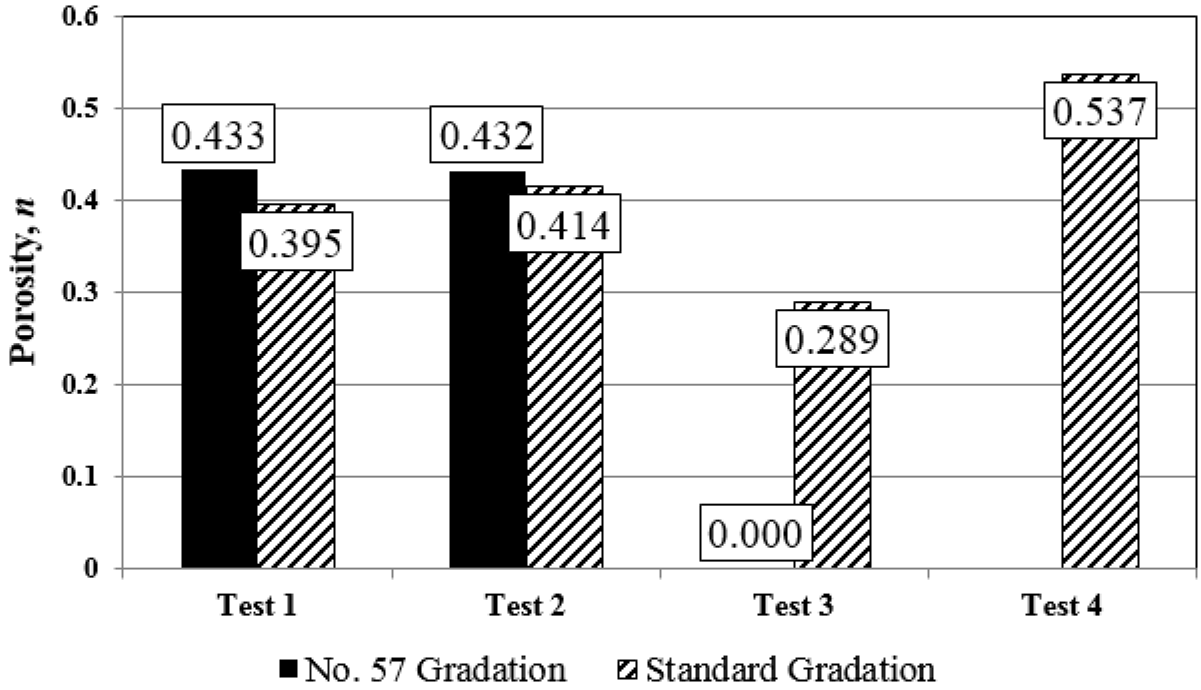


Figure 51: *n* comparisons for RE Janes Material

The percent differences within one gradation test series for each source material were calculated to show numerical comparisons between given gradations. These percent gradation calculations are shown in **Tables 21** and **22**. The percent difference calculated for all No. 57 Gradation tests are almost all under 1%, with the exception of Vulcan Material comparisons between Tests 1 and 3 and between Tests 2 and 3, which still has percent differences below 4%. Standard Gradation tests produced percent differences well above those seen with the No. 57 Gradations. For Vulcan Material, the percent difference ranged from 19.48% to as high as 73.54%. Sandmill material produced percent difference ranges between 13.09% and 35.41%. RE Janes material had one test with a percent difference less than 5%, but for the most part the percent difference ranged from 25.85% to as high as 60.01%. These wide arrays of *n* values for the Standard Gradation tests suggest that errors may have occurred when testing the source materials using the Standard gradation.

Table 21: Percent Difference Calculations for No. 57 Gradations

		Percent Difference (%)
Vulcan	Between Test 1 and Test 2	0.94%
Vulcan	Between Test 1 and Test 3	3.48%
Vulcan	Between Test 2 and Test 3	2.54%
Sandmills	Between Test 1 and Test 2	0.44%
RE Janes	Between Test 1 and Test 2	0.23%

Table 22: Percent Difference Calculations for Standard Gradations

Standard Gradation *n* Percent Differences		
		Percent Difference (%)
Vulcan	Between Test 1 and Test 2	56.07%
Vulcan	Between Test 1 and Test 3	19.48%
Vulcan	Between Test 2 and Test 3	73.54%
Sandmills	Between Test 1 and Test 2	35.41%
Sandmills	Between Test 1 and Test 3	22.58%
Sandmills	Between Test 2 and Test 3	13.09%
RE Janes	Between Test 1 and Test 2	4.67%
RE Janes	Between Test 1 and Test 3	31.00%
RE Janes	Between Test 2 and Test 3	35.54%
RE Janes	Between Test 1 and Test 4	30.42%
RE Janes	Between Test 2 and Test 4	25.85%
RE Janes	Between Test 3 and Test 4	60.01%

A conclusion can be drawn to say that between two samples of the same materials with the finer-aggregate gradations, the n values will not be the same. The No. 57 Gradation n values show comparable porosities which suggests that the materials used for resistivity testing were able to be replicated well enough. The Standard Gradation n results show wide variations which suggest a given test for a source material was not replicated from test to test. The backfill materials used for Standard Gradation resistivity tests may have not been properly created to match the target gradations set by AASHTO Standard material. Another reason the Standard Gradation n results were so different between two tests of the same backfill material could be that the full saturation of the fine aggregate was difficult to achieve for the entire 15 hours of resistivity data collection test.

A relationship between ρa and ρw was established using Archie's empirical law. Archie's empirical law utilizes n and ρw/ρa parameters to generate a graph that also produces an equation whose slope is equal to the m value. This m value is used within Archie's formula in correlation with n to produce a numerical ratio relationship between ρa and ρw. For the No. 57 Gradation tests using both the GroPro Meter and INA219 Device on the three source materials, n and ρw/ρa parameters calculations and results are presented in Table 23 and Table 24, respectively.

Table 23: *m* Calculations for No. 57 Gradation Tests using GroPro Meter

	ρ_a (Ω-cm)	ρ_w (Ω-cm)	Porosity, *n*	ρ_w/ρ_a	log10(ρ_w/ρ_a)	log10(*n*)	*m* using Archie's Formula
Vulcan Test 1	14898	3704	0.424	0.249	-0.604	-0.372	1.62
Vulcan Test 2	15029	3704	0.428	0.246	-0.608	-0.369	1.65
Vulcan Test 3	16093	3846	0.439	0.239	-0.622	-0.357	1.74
Sandmills Test 1	14519	3125	0.456	0.215	-0.667	-0.341	1.95
Sandmills Test 2	15541	3226	0.454	0.208	-0.683	-0.342	1.99
RE Janes Test 1	16098	5556	0.433	0.345	-0.462	-0.364	1.27
RE Janes Test 2	13921	5556	0.432	0.399	-0.399	-0.364	1.10

Table 24: *m* Calculations for No. 57 Gradation Tests using INA219 Device

	ρ_a (Ω-cm)	ρ_w (Ω-cm)	Porosity, *n*	ρ_w/ρ_a	log10(ρ_w/ρ_a)	log10(*n*)	*m* using Archie's Formula
Vulcan Test 1	14898	4230	0.424	0.284	-0.547	-0.372	1.47
Vulcan Test 2	15029	4320	0.428	0.287	-0.541	-0.369	1.47
Vulcan Test 3	16093	4992	0.439	0.310	-0.508	-0.357	1.42
Sandmills Test 1	14519	3556	0.456	0.245	-0.611	-0.341	1.79
Sandmills Test 2	15541	3670	0.454	0.236	-0.627	-0.342	1.83
RE Janes Test 1	16098	6084	0.433	0.378	-0.423	-0.364	1.16
RE Janes Test 2	13921	5564	0.432	0.400	-0.398	-0.364	1.09

Archie's Formula – Equation (2) – was used to calculate an associated m value for each resistivity test. The m values calculated for the No. 57 Gradation tests show ranges of m from 1.10 to 1.99 (for data collected using the GroPro Meter), and 1.09 to 1.83 (for data collected using the INA219 Device). Within each source material test series, the m values are very similar. This relation supports previous conclusions stating No. 57 gradation resistivity tests were replicated in a similar fashion as to allow for similar results.

Archie's formula was also applied to Standard Gradation resistivity tests for all three source materials. The results calculated from measured values obtained using the GroPro Meter and INA219 Device are shown in Table 25 and Table 26. The resulting m values show wide variations within each source material tests. Resulting m values calculated for each source material ranged from values as low as 0.42 to values as high as2.69 (for INA219 Device results) and ranged from 0.49 to 2.65 (for GroPro Meter results). Although the *m* values obtained for Standard Gradation resistivity tests show a wider range than values obtained from No. 57 Gradation resistivity tests, when comparing the *m* values within one source material results, the values are not as widespread. The greatest discrepancy occurs for the Vulcan material Standard Gradation results, with a range of *m* values between 0.90 and 2.65 for the three tests using the GroPro Meter. This observation is alike other relationships observed through other Standard Gradation data analysis. Because the *n* values are not similar within a given test sample, the *m* values vary widely in similar characteristics. Like conclusions drawn from the glass beads resistivity tests, Archie's empirical law follows well for tests utilizing AASHTO No. 57 gradations. From Archie's formula, it should be clear that as the porosity increases, the ratio of ρ_w/ρ_a also increases with regard to the *m* value. However, the results for *m* calculations show that something else if effecting the relationship between ρ_w and ρ_a. Porosity has a large effect on the resistivity being measured for both ρ_w and ρ_a, but it is not the only controlling factor contributing to resistivity value effects.

Table 25: *m* Calculations for Standard Gradation Tests using GroPro Meter

	ρ_a (Ω-cm)	ρ_w (Ω-cm)	Porosity, *n*	ρ_w/ρ_a	log10(ρ_w/ρ_a)	log10(*n*)	*m* using Archie's Formula
Vulcan Test 1	4662	1459	0.336	0.313	-0.505	-0.474	1.06
Vulcan Test 2	6049	1544	0.597	0.255	-0.593	-0.224	2.65
Vulcan Test 3	5225	1647	0.276	0.315	-0.501	-0.559	0.90
Sandmills Test 1	1981	961	0.479	0.485	-0.314	-0.319	0.98
Sandmills Test 2	2030	1103	0.686	0.543	-0.265	-0.164	1.62
Sandmills Test 3	2133	1660	0.602	0.778	-0.109	-0.221	0.49
RE Janes Test 1	12778	3755	0.395	0.294	-0.532	-0.403	1.32
RE Janes Test 2	13505	5450	0.414	0.404	-0.394	-0.383	1.03
RE Janes Test 3	13969	3890	0.289	0.278	-0.555	-0.5389	1.03
RE Janes Test 4	13903	6232	0.537	0.448	-0.348	-0.270	1.29

Table 26: *m* Calculations for Standard Gradation Tests using INA219 Device

	ρ_a (Ω-cm)	ρ_w (Ω-cm)	Porosity, *n*	ρ_w/ρ_a	log10(ρ_w/ρ_a)	log10(*n*)	*m* using Archie's Formula
Vulcan Test 1	4662	1007	0.336	0.216	-0.666	-0.474	1.40
Vulcan Test 2	6049	1509	0.597	0.249	-0.603	-0.224	2.69
Vulcan Test 3	5225	1641	0.276	0.314	-0.503	-0.559	0.90
Sandmills Test 1	1981	1459	0.479	0.736	-0.133	-0.319	0.42
Sandmills Test 2	2030	1700	0.686	0.837	-0.077	-0.164	0.47
Sandmills Test 3	2133	1646	0.602	0.772	-0.113	-0.221	0.51
RE Janes Test 1	12778	3692	0.395	0.289	-0.539	-0.403	1.34
RE Janes Test 2	13505	4201	0.414	0.311	-0.507	-0.383	1.32
RE Janes Test 3	13969	2399	0.289	0.172	-0.765	-0.5389	1.42
RE Janes Test 4	13903	4364	0.537	0.314	-0.503	-0.270	1.86

The GroPro Meter uses a multi-parameter probe that not only measures the EC of a aqueous solution, but can also measure the Total Dissolved Solids (TDS). Total Dissolved Solids are the total amount of mobile charged ions, such as salts, metals, or minerals, within a given sample of water, expressed in units of parts per million (ppm), or milligrams per unit volume of water (mg/L).The GroPro Meter measures the TDS of an aqueous solution within two settings – a 500 ppm scale and a 700 ppm scale. The 700 ppm scale is based on measuring potassium chloride (KCl) content of a solution, and the 500 ppm scale is based on measuring the sodium chloride (NaCl) content of a solution. Because this report measures the NaCl content in water solutions, the GroPro was calibrated to the 500 ppm scale and used simultaneously with EC measurements for all resistivity tests conducted on soil backfill source materials. **Table 27** shows the TDS measurements obtained with the GroPro Meter for all soil backfill materials.

Table 27: Total Dissolved Solids (TDS) Measurements for All Soil Backfill Material Resistivity Tests

Vulcan No. 57 Gradation	Test 1	130
Vulcan No. 57 Gradation	Test 2	140
Vulcan No. 57 Gradation	Test 3	130
Vulcan Standard Gradation	Test 1	130
Vulcan Standard Gradation	Test 2	130
Vulcan Standard Gradation	Test 3	90
Sandmills No. 57 Gradation	Test 1	160
Sandmills No. 57 Gradation	Test 2	170
Sandmills Standard Gradation	Test 1	200
Sandmills Standard Gradation	Test 2	220
RE Janes No. 57 Gradation	Test 1	90
RE Janes No. 57 Gradation	Test 2	90
RE Janes Standard Gradation	Test 1	50
RE Janes Standard Gradation	Test 2	40

The TDS values were compared between each source material test to compare TDS results obtained for the same material. These graphs are shown in **Figures 52**, **53**, and **54**. The TDS values measured for the No. 57 Gradations Vulcan material tests were slightly higher than values obtained for the Standard Gradation tests for Vulcan material (except for Test 1, which had TDS values of 130 ppm for both the Standard and No. 57 Gradation test). For Sandmill material test, the Standard Gradation TDS values were higher than the TDS values of No. 57 Gradation tests. The opposite relation was observed for the RE Janes Material TDS results – the No. 57 Gradation TDS values were considerably higher than the TDS values for Standard Gradation tests.

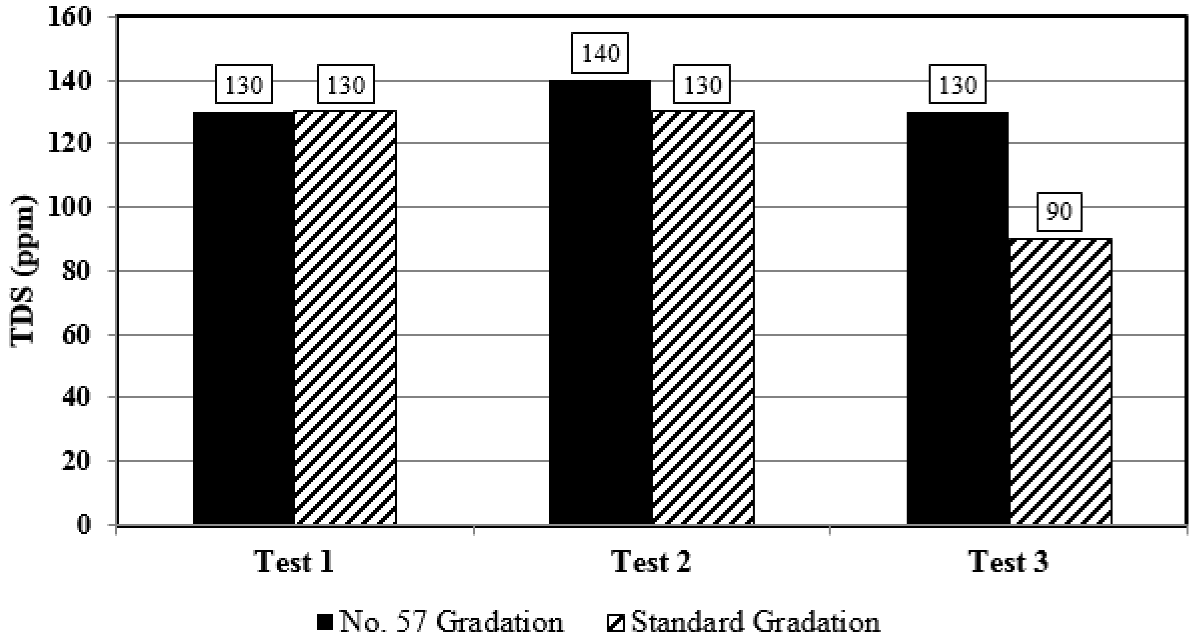


Figure 52: TDS Results for Vulcan Material Tests

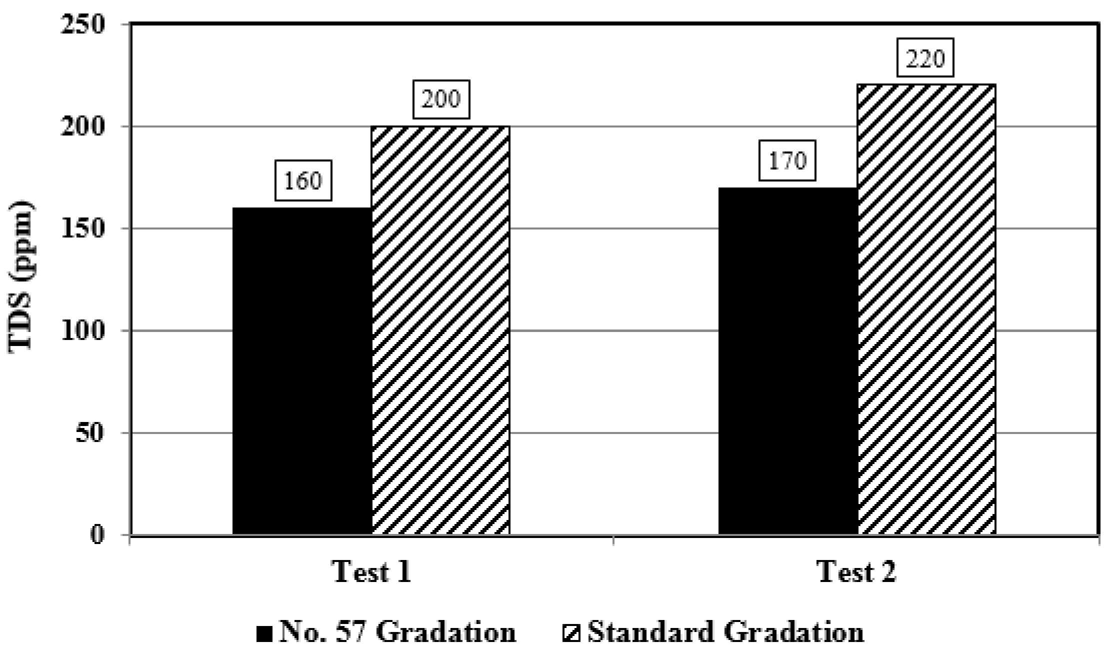


Figure 53: TDS Results for Sandmill Material Tests

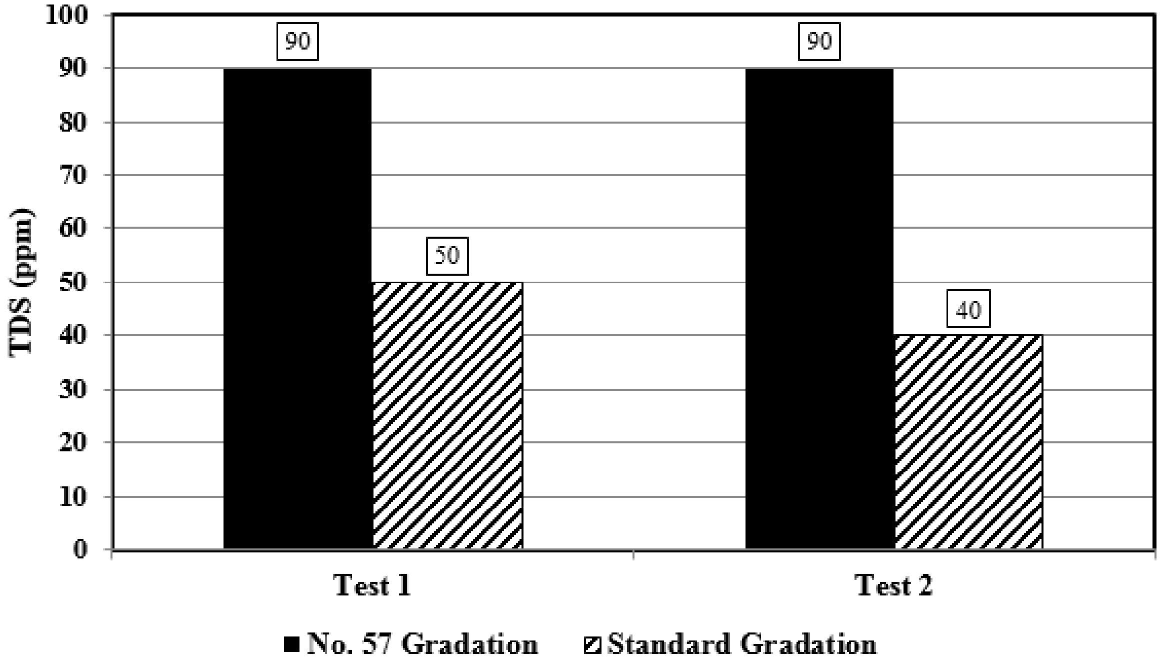


Figure 54: TDS Results for RE Janes Material Tests

TDS results from each set of gradation tests were compared to other material tests to try and see which material has the highest TDS values, and would therefore have the lowest ρ_w value. TDS comparisons for the first two tests of each source material using the Standard Gradation measurements are shown in **Figure 55**. TDS comparisons for the first two tests of each source material using the No. 57 Gradation measurements are shown in **Figure 56**. The Sandmill Material for both the Standard and No. 57 was observed to have the highest TDS values compared to the other two source materials. Vulcan Material tests were shown to have the next highest TDS values among the three source materials, which means RE Jane material has the lowest TDS values. The ρ_w values representing both the No. 57 and Standard Gradation tests for all three sources are compared to with the corresponding TDS values in **Table 28**. Because Sandmill material measured the highest TDS values, the corresponding ρ_w values should be lower than the other two source materials. As seen in **Table 28**, the ρ_w values representing the Sandmill material for both the No. 57 and Standard Gradation tests are the lowest compared to ρ_w values from the other two source materials. This follows successfully with the characteristics explained for TDS effects on ρ_w values. The RE Janes Material, which has the lowest TDS values compared with the other two source materials, has the highest ρ_w

values measured for both the No. 57 and Standard Gradation tests. These observations support the assumption that TDS directly affects the resistivity value; the higher the TDS value is, the more charged ions are present in an aqueous solution, the lower the ρ_w value will be.

Table 28: TDS and ρ_w Value Comparisons for All Soil Backfill Material Tests

			ρ_w (Ω-cm)
Vulcan No. 57 Gradation	Test 1	130	3704
Vulcan No. 57 Gradation	Test 2	140	3704
Vulcan No. 57 Gradation	Test 3	130	3846
Vulcan Standard Gradation	Test 1	130	1459
Vulcan Standard Gradation	Test 2	130	1544
Vulcan Standard Gradation	Test 3	90	1647
Sandmills No. 57 Gradation	Test 1	160	3125
Sandmills No. 57 Gradation	Test 2	170	3226
Sandmills Standard Gradation	Test 1	200	961
Sandmills Standard Gradation	Test 2	220	1103
RE Janes No. 57 Gradation	Test 1	90	5556
RE Janes No. 57 Gradation	Test 2	90	5556
RE Janes Standard Gradation	Test 1	50	3755
RE Janes Standard Gradation	Test 2	40	3890

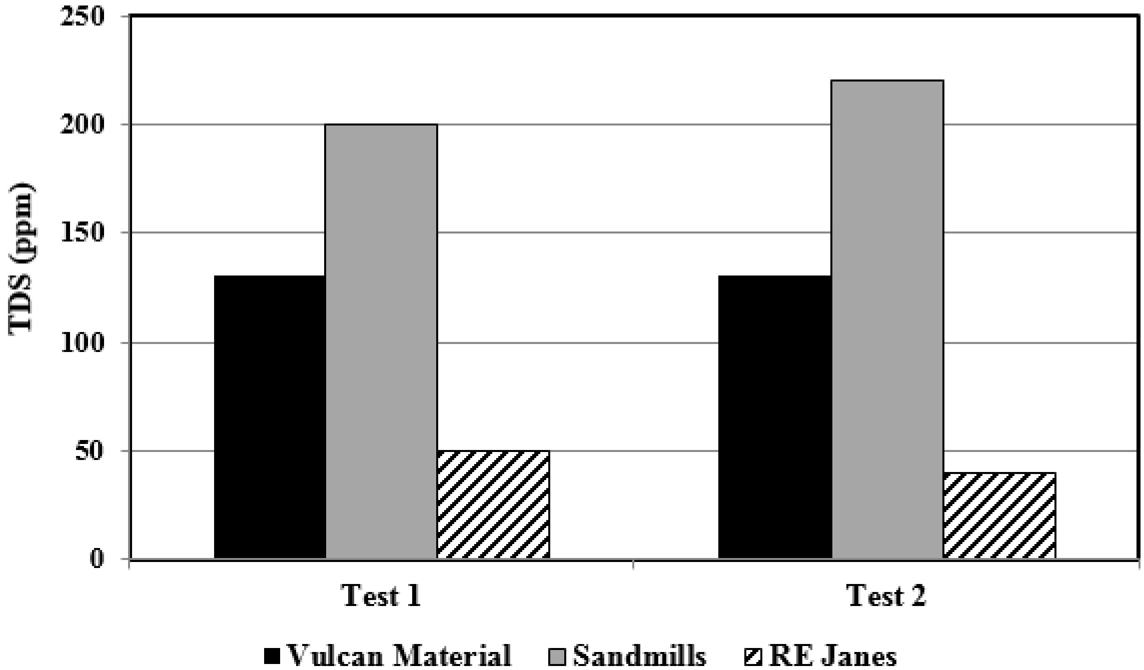


Figure 55: TDS Comparisons for Standard Gradation Test 1 and Test 2

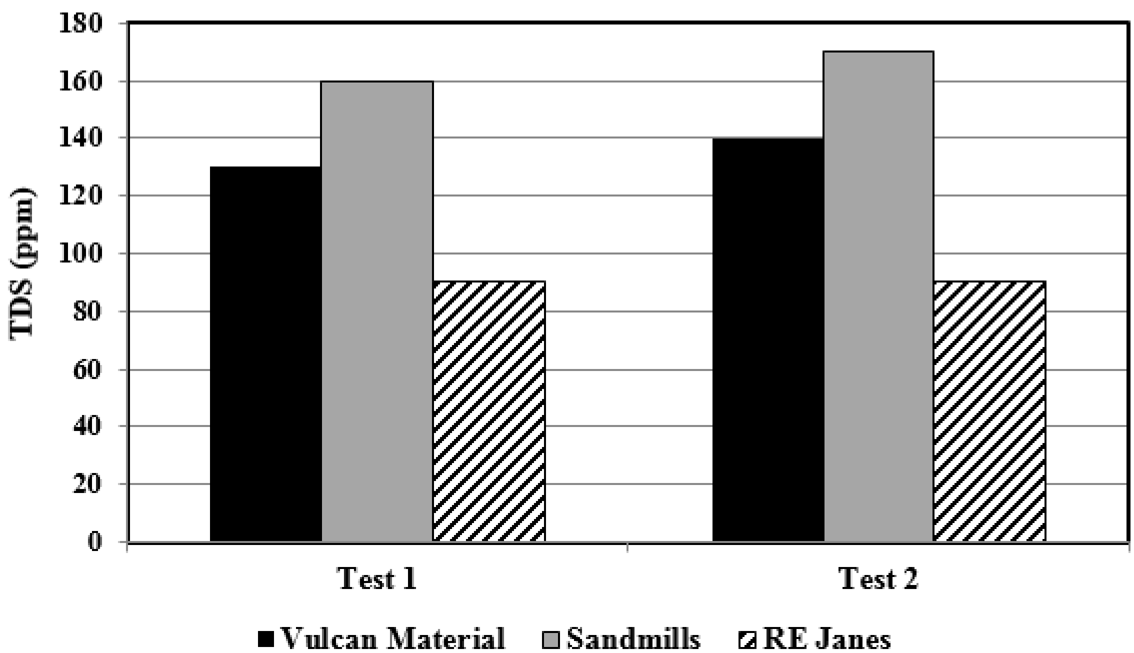


Figure 56: TDS Comparisons for No. 57 Gradation Test 1 and Test 2

Chapter 5 – Conclusions and Recommendations

5.1 General Overview

This report contains the results of a research study on the effects of particle gradation on granular soil resistivity. These effects were used to test an inert material and three different soil backfill materials with two different AASHTO gradation criteria for MSE retaining wall backfill selection purposes. Based on the results of this research, the following conclusions and recommendations were developed.

5.2 Conclusions

Water Solution Resistivity Testing

The INA219 Device, GroPro Meter, and Nilsson Meter were observed to produce consistent reliable resistivity measurements when compared between each device. The water solution resistivity test results using both the Texas Tech and AASHTO Resistivity Box show similar resistivity values for a given water solution with a certain NaCl concentration. Because of these resistivity tests conducted verified that all test systems produce reliable data, resistivity testing on the inert material and soil backfill material were conducted using the INA219 Device and GroPro Meter because the Nilsson Meter does not allow for continuous data collection and recording.

Glass Bead Resistivity Testing

The resistivity results obtained from the three differently sized glass beads showed numerous discoveries about the effect of particle size on the overall resistivity value. These discoveries include the particle size limitation observed when using the AASHTO Resistivity Box for coarse aggregates, the effect that pore-water solution resistivity (ρ_w) has on the bulk material resistivity (ρ_a), the secondary effect of porosity has on resistivity, the relation between ρ_w and ρ_a using models proposed by other researchers, and the validity in using these models for actual soil backfill material.

The AASHTO Resistivity Box used alongside AASHTO Standard Designation T 288-12 cannot accommodate a representative sample of coarse material. The resistivity results obtained using the Large Beads with the AASHTO Resistivity Box did not correlate with resistivity results obtained using the two other glass bead sizes. This observed limitation creates problems for future resistivity testing on soil backfill material with coarser aggregate gradations. Bases on these results, it was decided that the AASHTO Resistivity box would be used for resistivity measurements for the AASHTO Standard Gradation materials and the Texas Tech Resistivity box would be used for the AASHTO No. 57 Gradation material resistivity tests.

For water solutions with the same water-to-salt concentration, the ρ_w values measured with each test are always less than the corresponding ρ_a values. These ρ_w value results were observed to be similar regardless of box size, and only the physical characteristics of the inert glass beads caused a significant different between the ρ_w and ρ_a values. When observing the ρ_a value results between the three glass beads it was observed that even though the Large Beads produced the smallest ρ_a value, the results measured between the Small and Medium Beads did not follow any pattern for ρ_a values; one bead size will give a larger ρ_a value than the other bead for one test, but will measure a smaller ρ_a value in another test. From these observations, it was concluded that porosity plays some part in determining the overall resistivity value measured.

Archie's empirical law was used to establish a relationship between ρ_w and ρ_a. The resulting material-dependent empirical exponent (*m*) was compared with other spherical glass bead research using Archie's formula and the results were observed to be consistent in value. The representative *m* values used with Archie's formula to predict ρ_a values from known ρ_w value were accurate when compared with the measured ρ_a values. It was concluded from this newfound relationship between ρ_w and ρ_a that ρ_a for inert material can be calculated by simply measuring the ρ_w. These conclusions were then ready to be assessed using actual soil backfill material.

Maxwell's formula was also used to establish a relationship between ρ_w and ρ_a. The results calculated from *n* values and ρ_w/ρ_a parameters using the Maxwell formula successfully show another way for calculating ρ_a or ρ_w, but results were not as accurate when using known ρ_w and *n* values to predict a ρ_a value. Since Maxwell's formula is known to over-simplify approach limits for predicting the measured resistivity, only Archie's empirical law would be used for soil backfill material analysis.

Soil Backfill Material Resistivity Testing

Several conclusions were gathered throughout soil backfill material resistivity testing. These include the validity of AASHTO Standard T 288-12 with regards to the elapsed time necessary to obtain a minimum resistivity value, the accuracy associated with representative ρ_w values calculated from the measured ρ'_w using principles established in Kohlrausch's law, comparisons between ρ_a and ρ_w values obtained using the two different material gradations and the three different source materials, the effects of porosity on resistivity values, the relationship between ρ_a and ρ_w using Archie's empirical law, and using TDS to better understand the differences obtained in all soil backfill resistivity tests.

The graphs created from each individual resistivity test conducted for the three source materials and two separate gradation types indicate that the minimum resistivity of a given sample does not always occur after an elapsed time of 15 hours. AASHTO Standard Designation T 288-12 states that the minimum resistivity of a soil sample should be measured after the soil sample is saturated in water for a total of 15 hours. The data collected for each soil backfill material resistivity test using the INA219 Device produced graphs that show several different trends for resistivity of a given sample. For No. 57 Gradation test graphs, the resistivity values would drastically decrease from the time the test started to the time of minimum resistivity. The minimum value observed for several tests occurred before the 15 hour time mark, which suggests that AASHTO standards for measuring a minimum resistivity value are too conservative. The Standard Gradation graphs show no clear trend between the resistivity at a given time; the resistivity of a test material would sometimes increase initially before decreasing to a minimum resistivity value, other times the resistivity value would spike towards the 15-hour time mark. The sporadic nature of resistivity was concluded to warrant a continuous data collection recording method for all resistivity measurements.

Kohlrausch's law for equivalent conductivity of an electrolyte at infinite dilution concentrations was used to convert measured ρ'_w values into a representative ρ_w value. The resulting ρ_w values for all Standard Gradation tests were compared with ρ_w values measured for the No. 57 Gradation tests and were concluded to follow the same trend observed for ρ_a comparisons: the amount of change between the two gradations varies between a given source material. From these observations it was concluded that knowing the gradation of a given material is not sufficient to establish a clear connection between contributing effects on resistivity values.

The *n* results for every soil backfill material resistivity tests were analyzed and compared to try and see if porosity has any adverse effects on the overall ρ_a and ρ_w values. The results obtained for the No. 57 Gradations showed very similar *n* values when compared with other *n* values of the same source material. These same *n* values for No.57 Gradation tests was concluded to mean that a given source material gradation was able to be replicated. The Standard Gradation *n* values showed large variations between the source materials, which suggests that the materials may not have been properly prepared to the correct target gradations established by AASHTO. It was concluded that porosities for Standard Gradation materials are not replicable, which causes scrutiny when comparing *n* values and corresponding resistivity effects.

The results obtained from Archie's empirical law calculations showed *m* values to be similar for the same source material using No. 57 Gradation. It can be inferred that because the *m* values were similar for all No. 57 Gradation tests, Archie's formula establishes a viable relationship between ρ_a and ρ_w and should therefore be used as a means of calculation either ρ_a or ρ_w for coarse-grained materials. The resulting *m* values obtained from Standard Gradation tests were concluded that because the porosity values for the Standard Gradation tests were vastly different, Archie's empirical law could not successfully establish a relationship between ρ_a and ρ_w. Overall, the porosity of a soil sample affects the associated resistivity value in a way that makes porosity a vital parameter when measuring resistivity.

Of all the parameters measured to understand key effects on resistivity, the TDS values show the most promising means of affecting resistivity values. Since TDS represents the amount of mobile charged ions within a solution, the conclusion can be made that higher TDS values mean more charged ions are present in a solution, which causes the solution to be more conductive. This increase in conductivity causes an inverse

effect on resistivity, which means that as TDS values increase, the ρ_w should decrease.

With these characteristics in mind, the following conclusions can be made about the three source material TDS results. For Vulcan Material TDS results, the ρ_w values for Test 1 should be similar to each other because the TDS values for both the No. 57 and Standard Gradation test were equal to 130 ppm. The representative ρ_w values obtained using the GroPro Meter for the No. 57 and Standard Gradation from **Table 14** are equal to 3704 Ω-cm and 1459 Ω-cm, respectively. The two ρ_w values between the two gradations are drastically different. Several reasons were attributed to the significant difference observed between the two gradation ρ_w results. For one, the representative ρ_w value for Standard Gradation was converted from an equation formed by graphing several dilution ratios of the Vulcan material. The representative ρ_w value may be incorrect for the Standard Gradation Material test. Another observation seen in **Table 14** shows that the ρ'_w value measured for the Vulcan Material Test 1 is equal to 3704 Ω-cm, which is the exact same value measured for ρ_w in Vulcan Material No. 57 Gradation Test 1. The two ρ_w values being the same seemed purely coincidental until TDS measurements were compared showing that the two gradation tests were measured to have the same TDS value.

5.3 Recommendations

Based on the research conducted in this report, it is recommended that Archie's empirical law be used to establish a connection between ρ_w and ρ_a. The relationship between ρ_w and ρ_a allows for an alternative means of measuring resistivity of coarse aggregate soil backfill material used for MSE retaining wall project. Now that a connection has been established between the two resistivity properties, it is recommended that future work be implemented to try and correlate the ρ_w and ρ_a values obtained using Archie's formula with that of actual in-situ resistivity values.

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Appendix A

Glass Bead Resistivity Tests

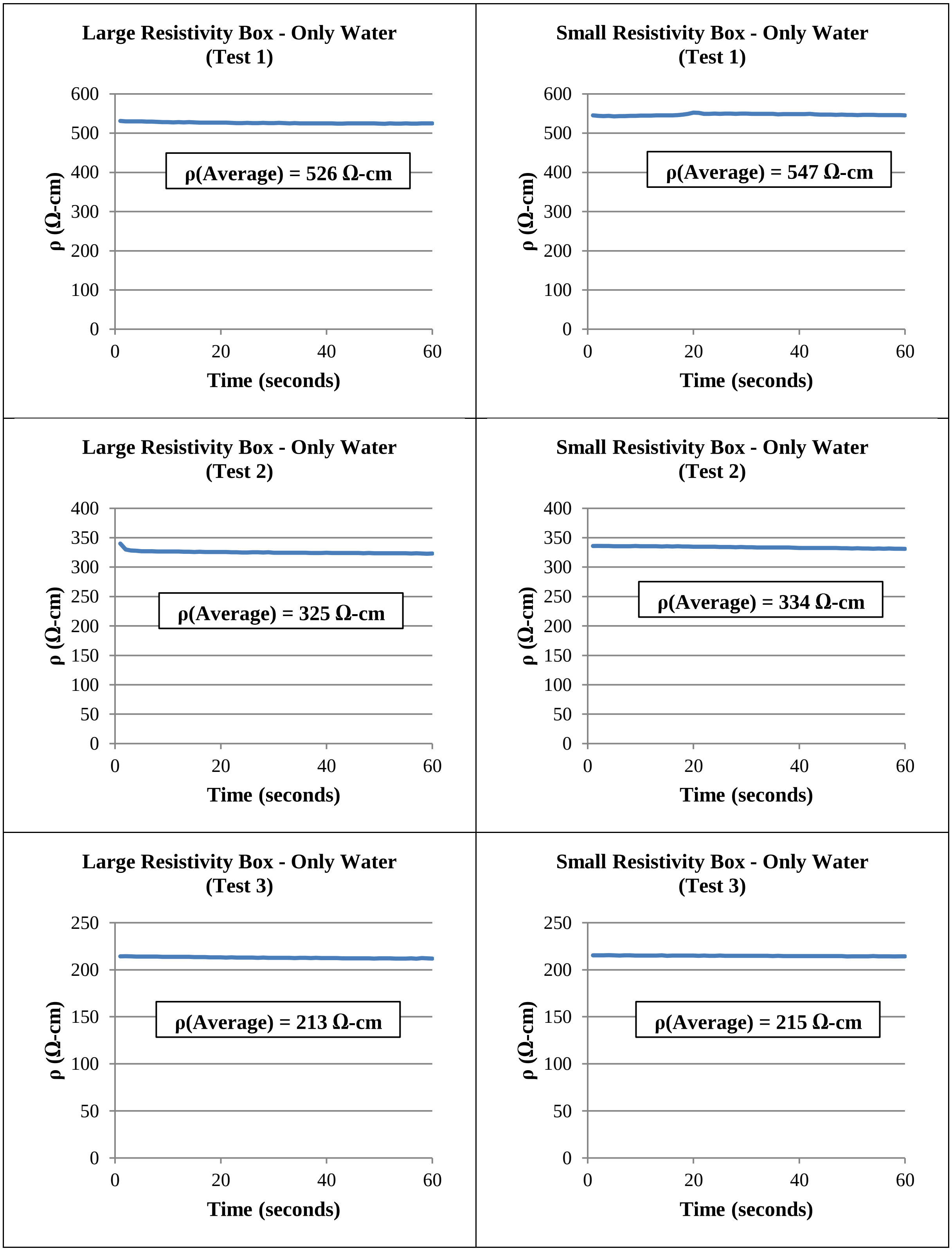

Figure A.1: Glass Beads Resistivity Testing on Water Solution

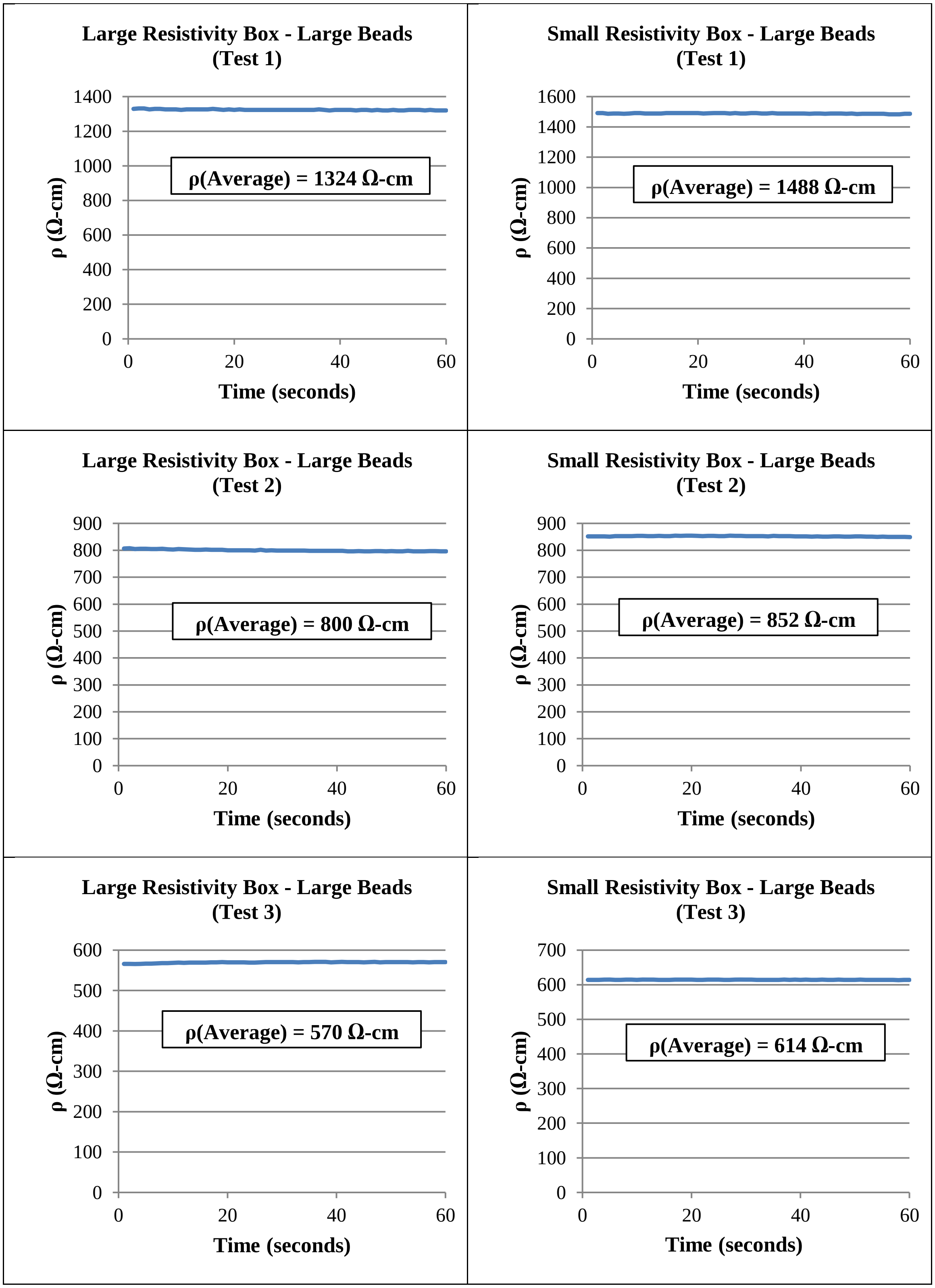

Figure A.2: Glass Beads Resistivity Testing on Large Beads

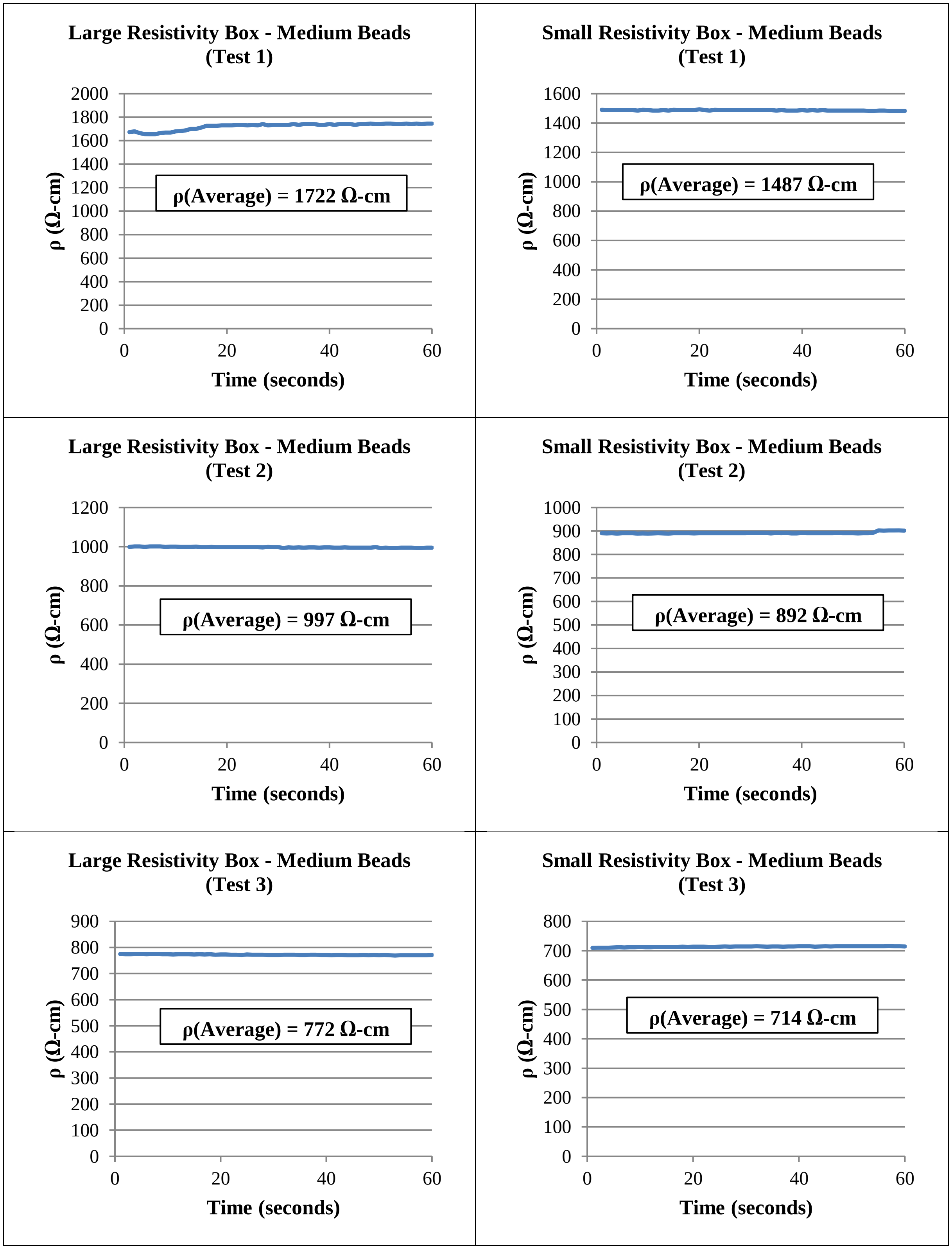

Figure A.3: Glass Beads Resistivity Testing on Medium Beads

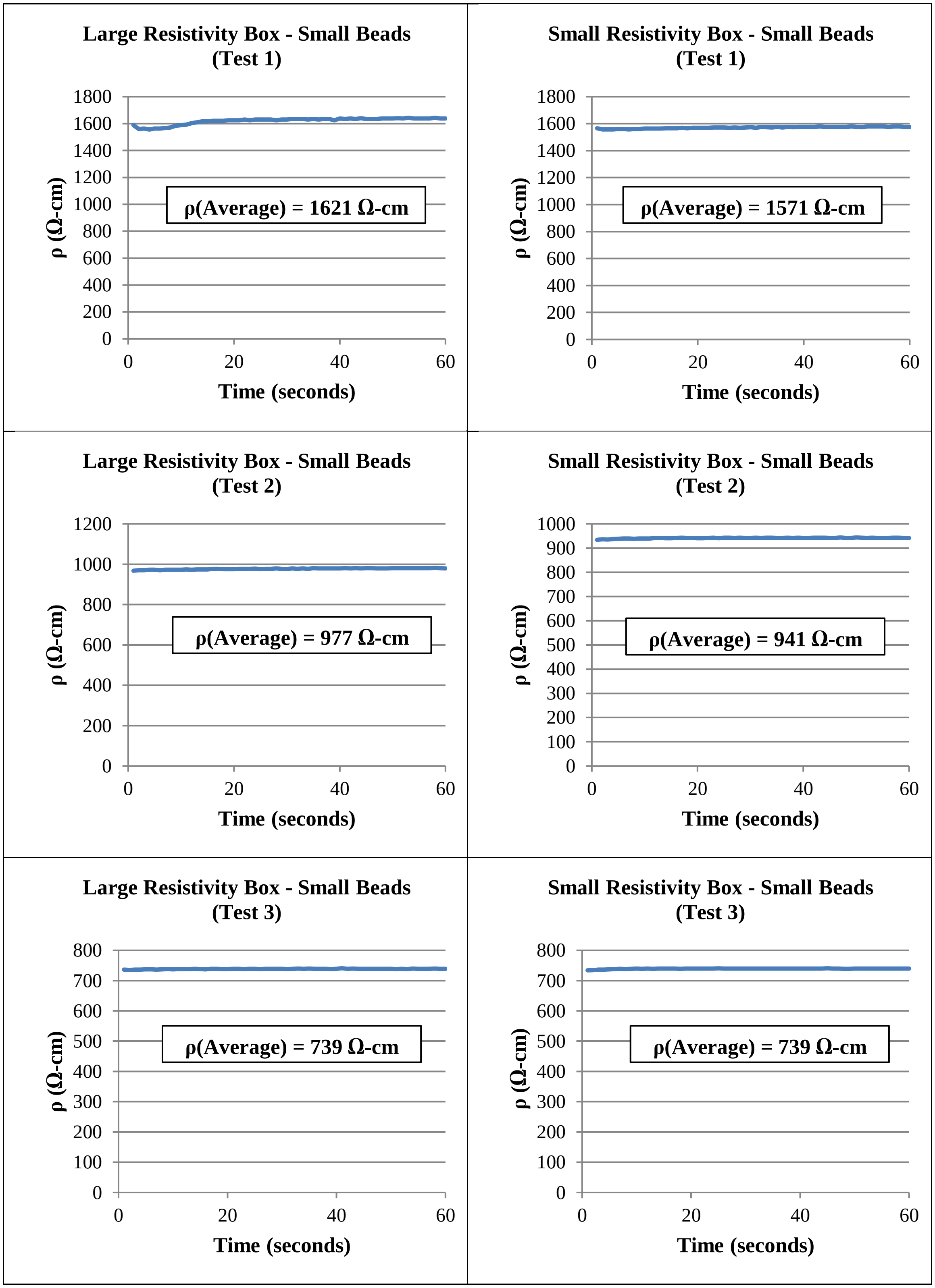

Figure A.4: Glass Beads Resistivity Testing on Small Beads

Appendix B

Soil Backfill Material Resistivity Tests

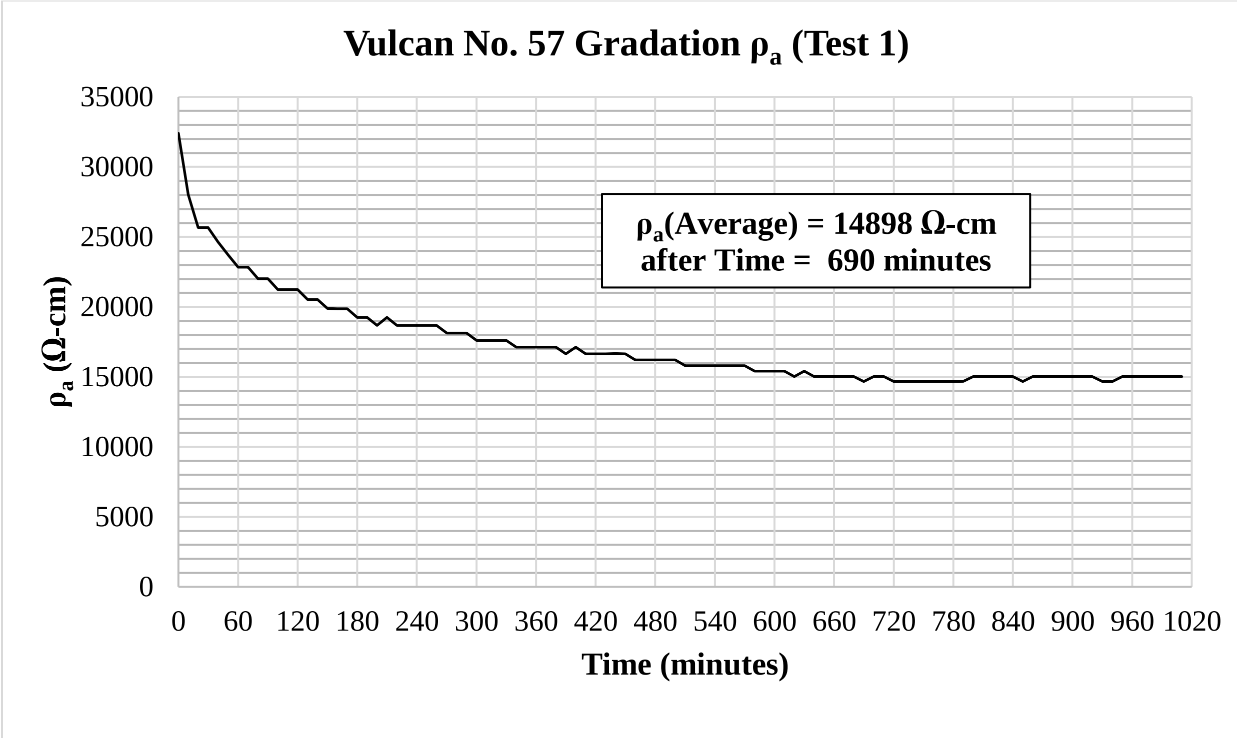

Figure A.5: Vulcan No. 57 Gradation ρ_a for Test 1

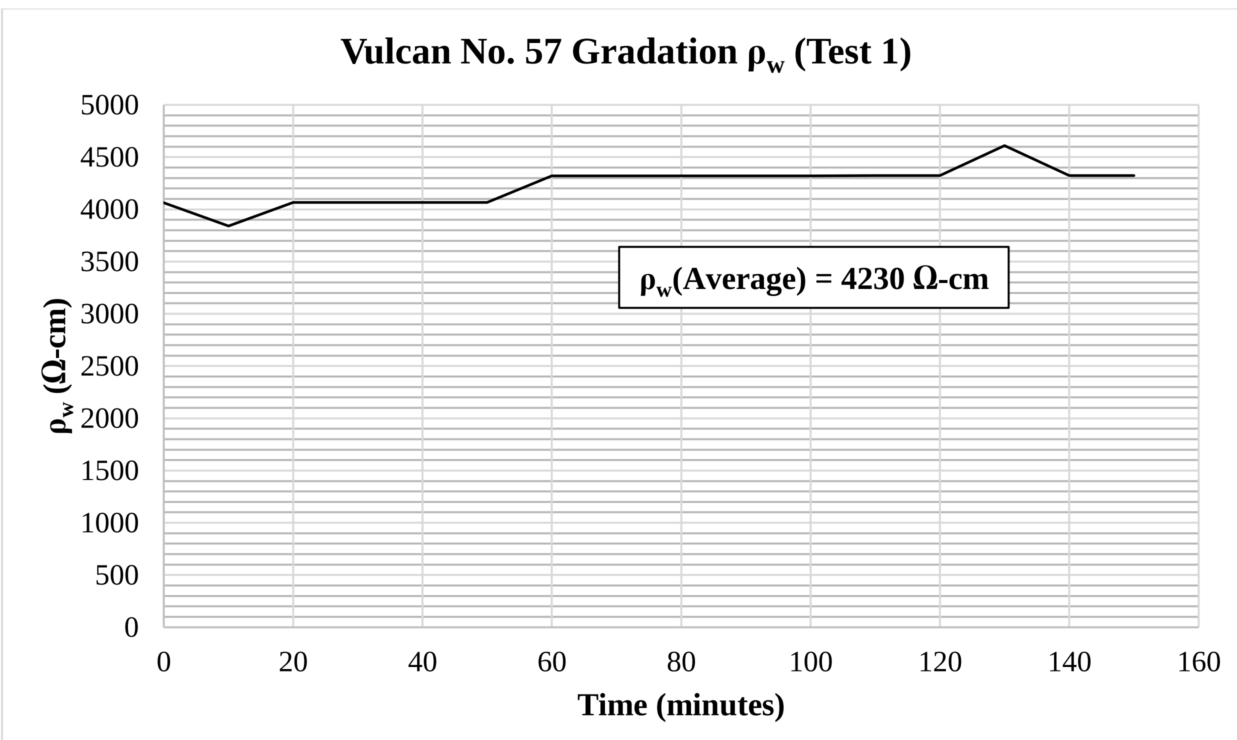

Figure A.6: Vulcan No. 57 Gradation ρ_w for Test 1

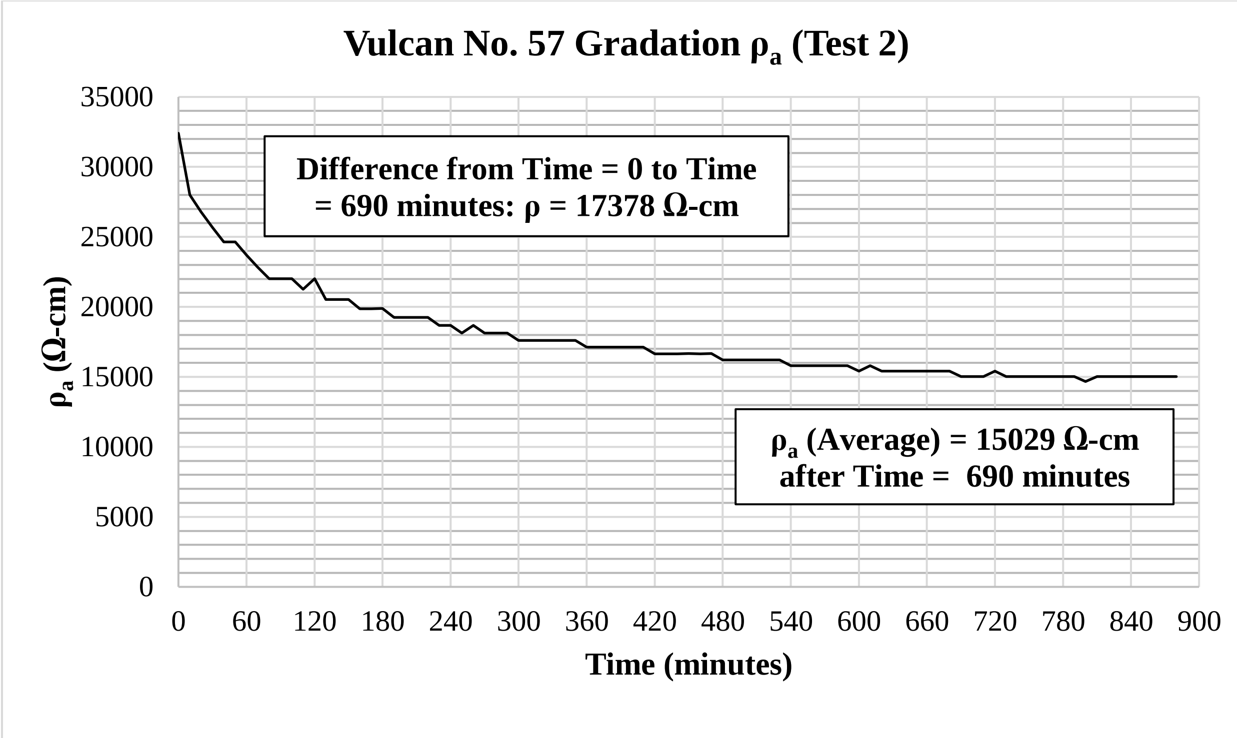

Figure A.7: Vulcan No. 57 Gradation ρ_a for Test 2

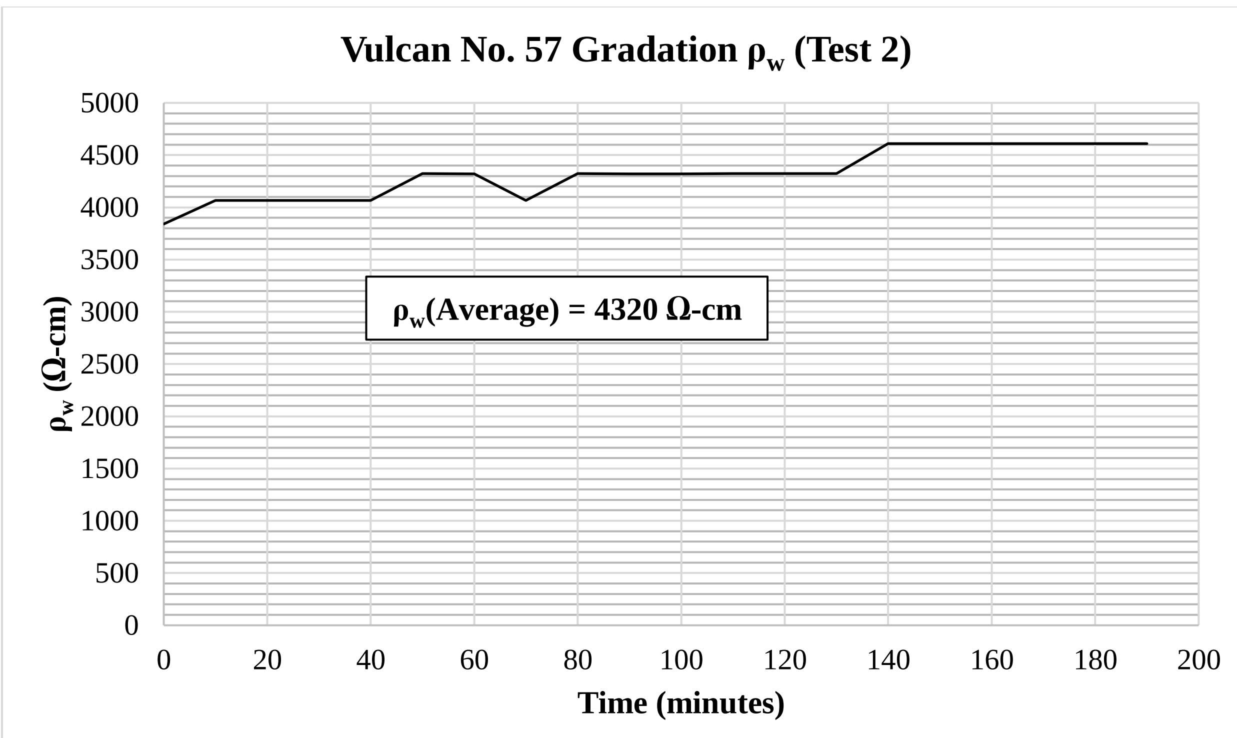

Figure A.8: Vulcan No. 57 Gradation ρ_w for Test 2

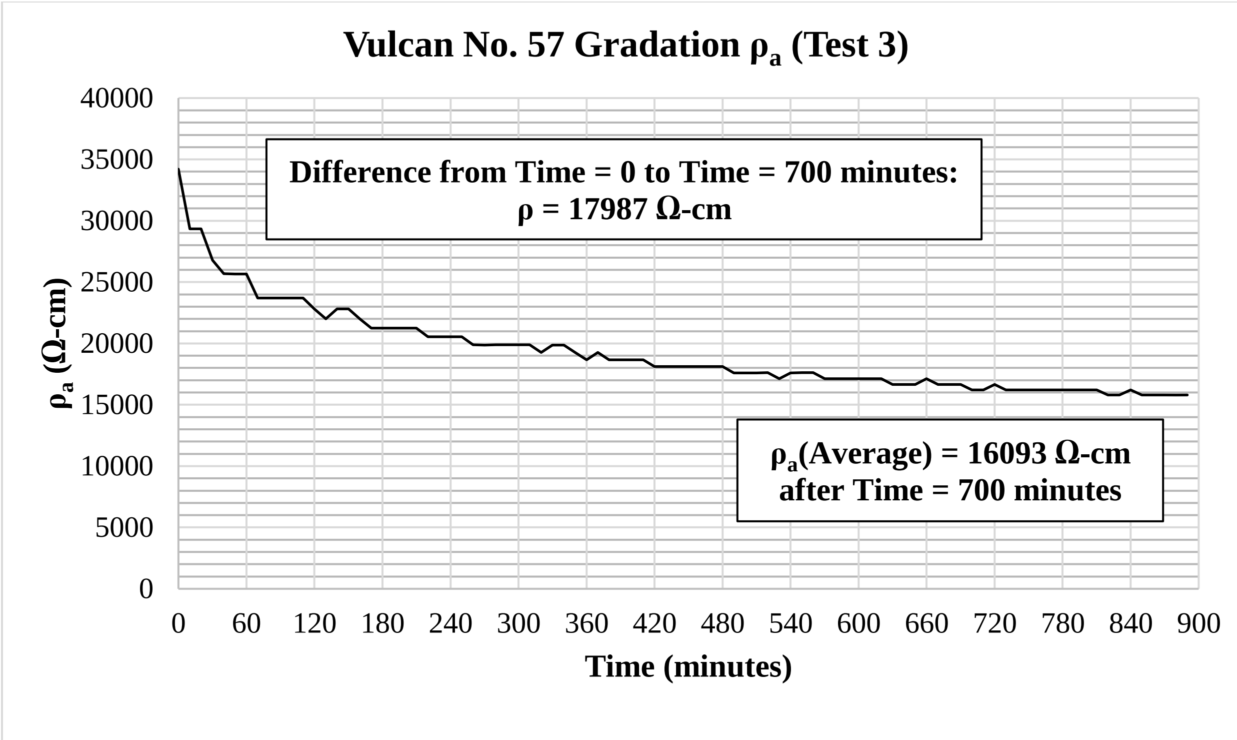

Figure A.9: Vulcan No. 57 Gradation ρ_a for Test 3

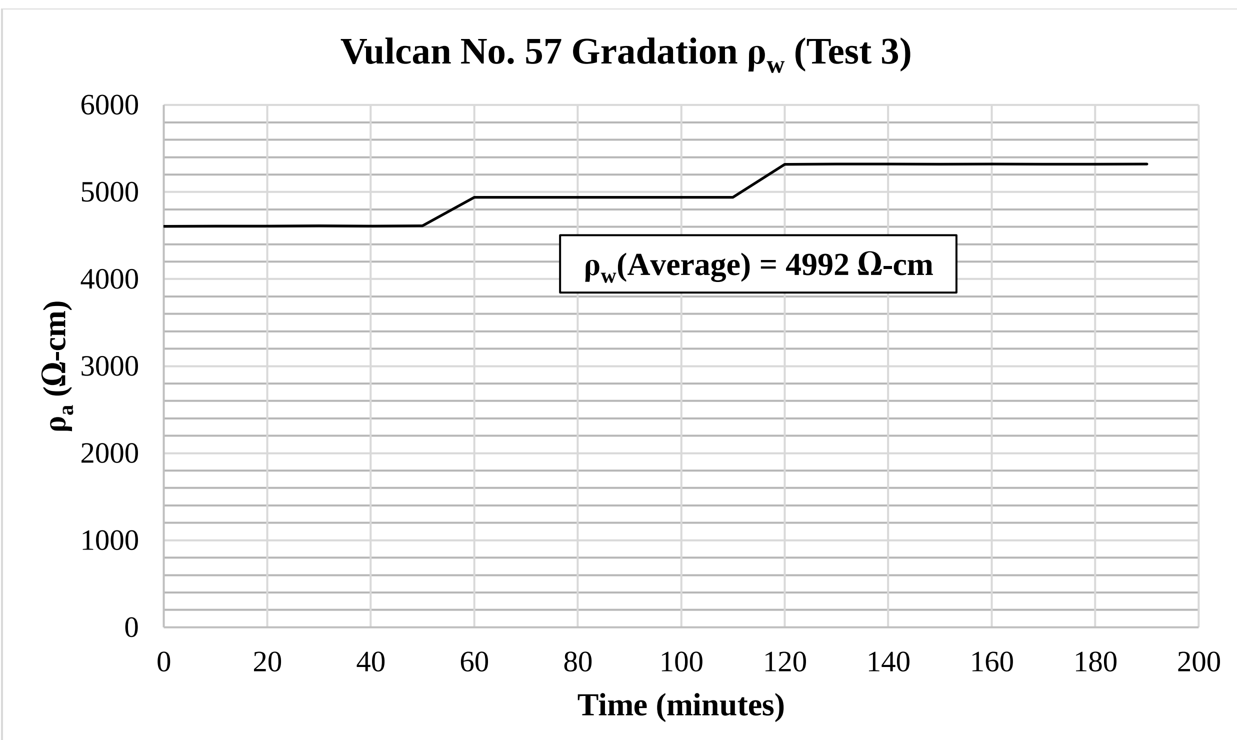

Figure A.10: Vulcan No. 57 Gradation ρ_w for Test 3

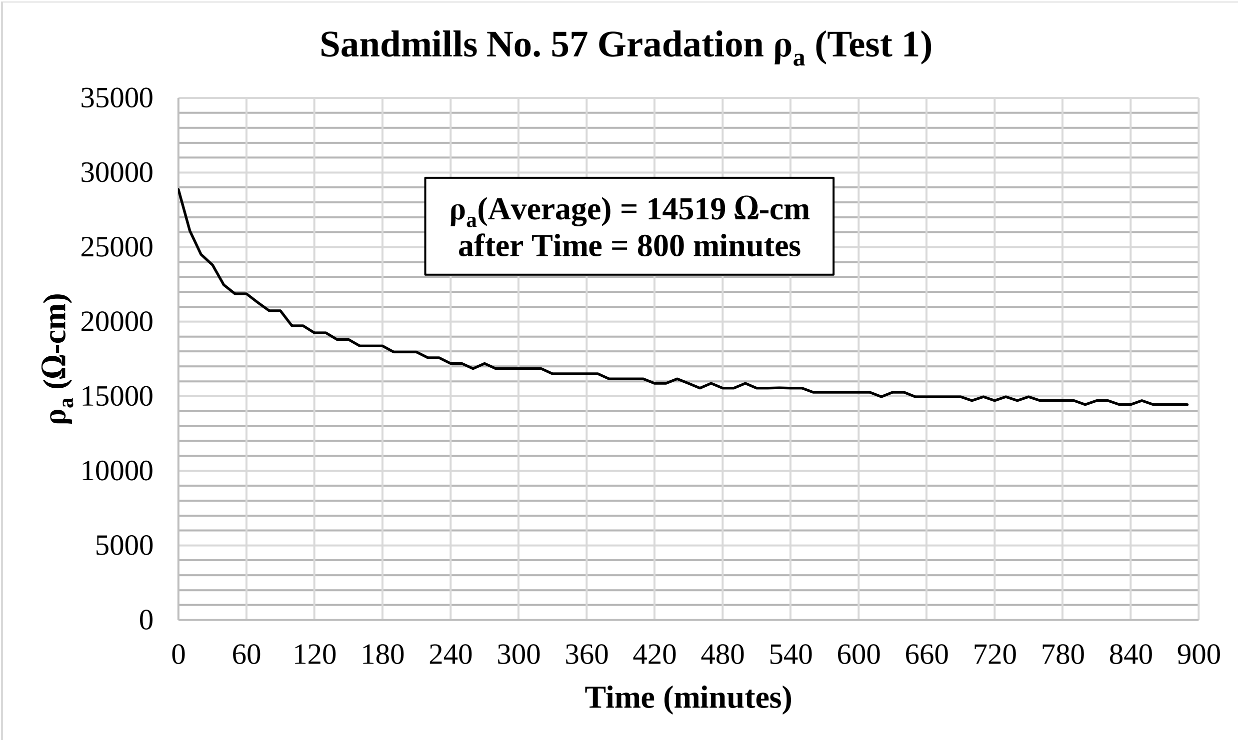

Figure A.11: Sandmills No. 57 Gradation ρ_a for Test 1

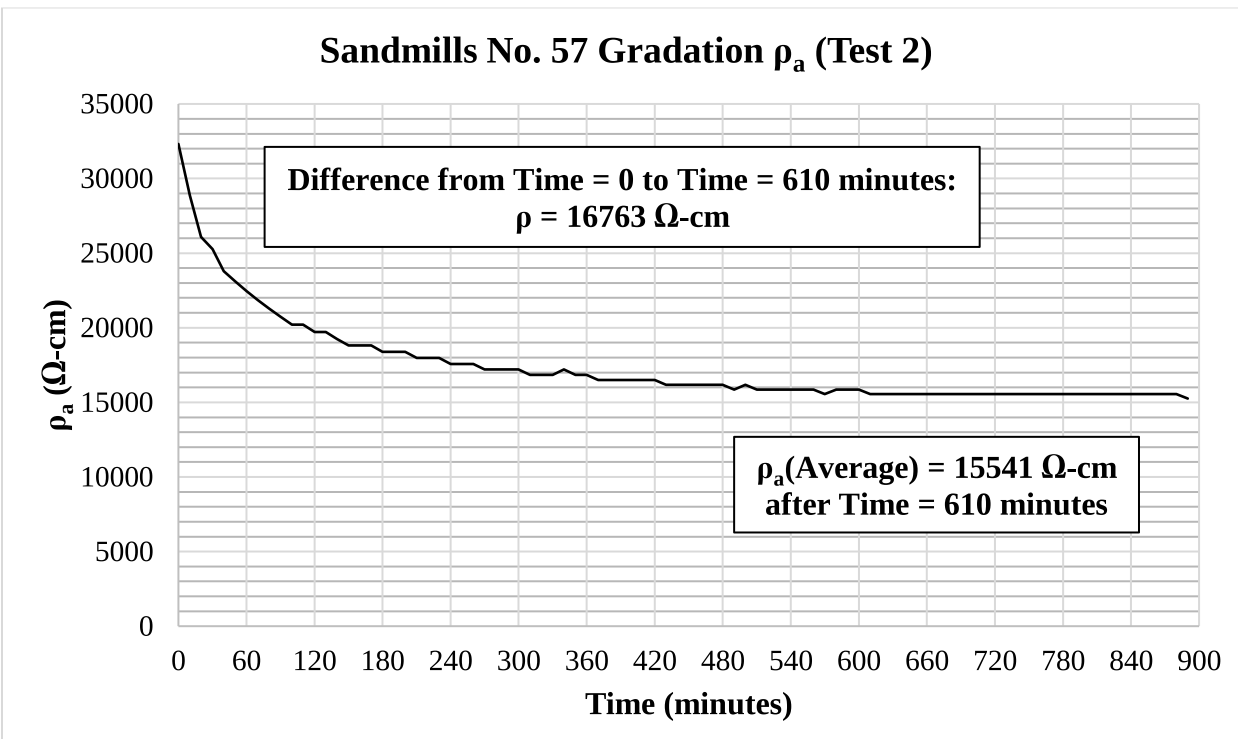

Figure A.12: Sandmills No. 57 Gradation ρ_a for Test 2

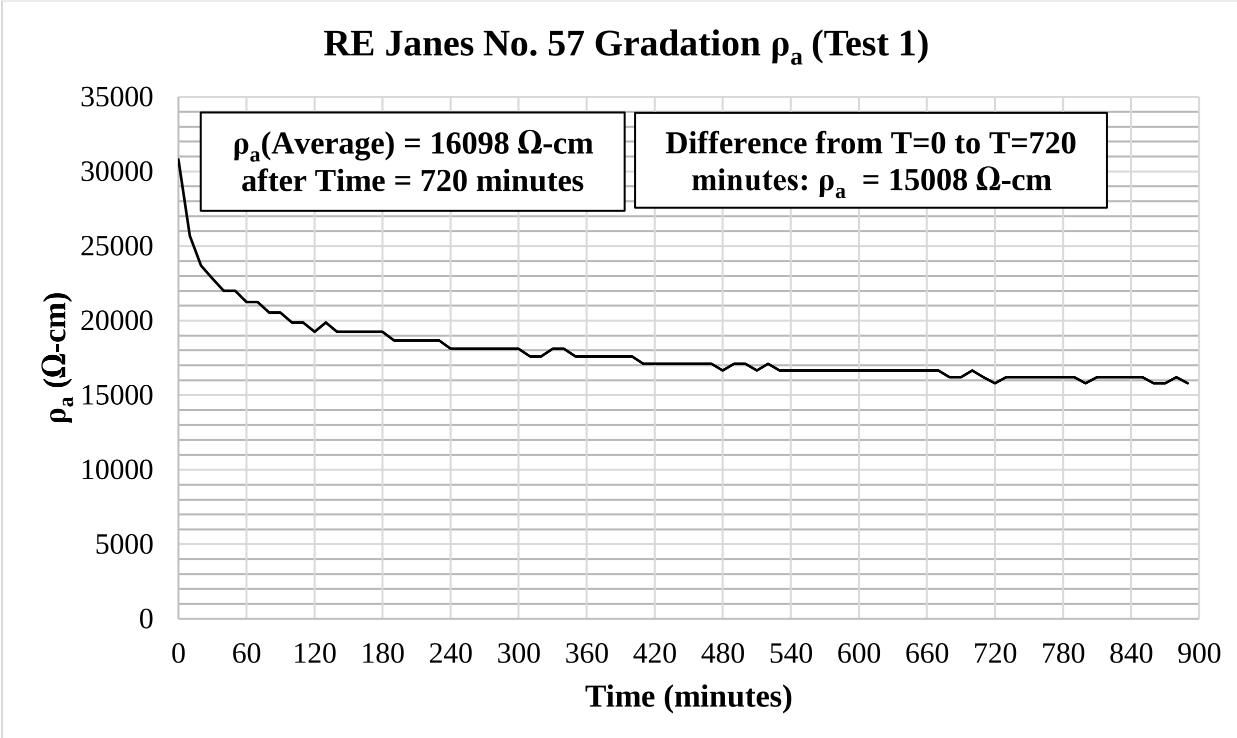

Figure A.13: RE Janes No. 57 Gradation ρ_a for Test 1

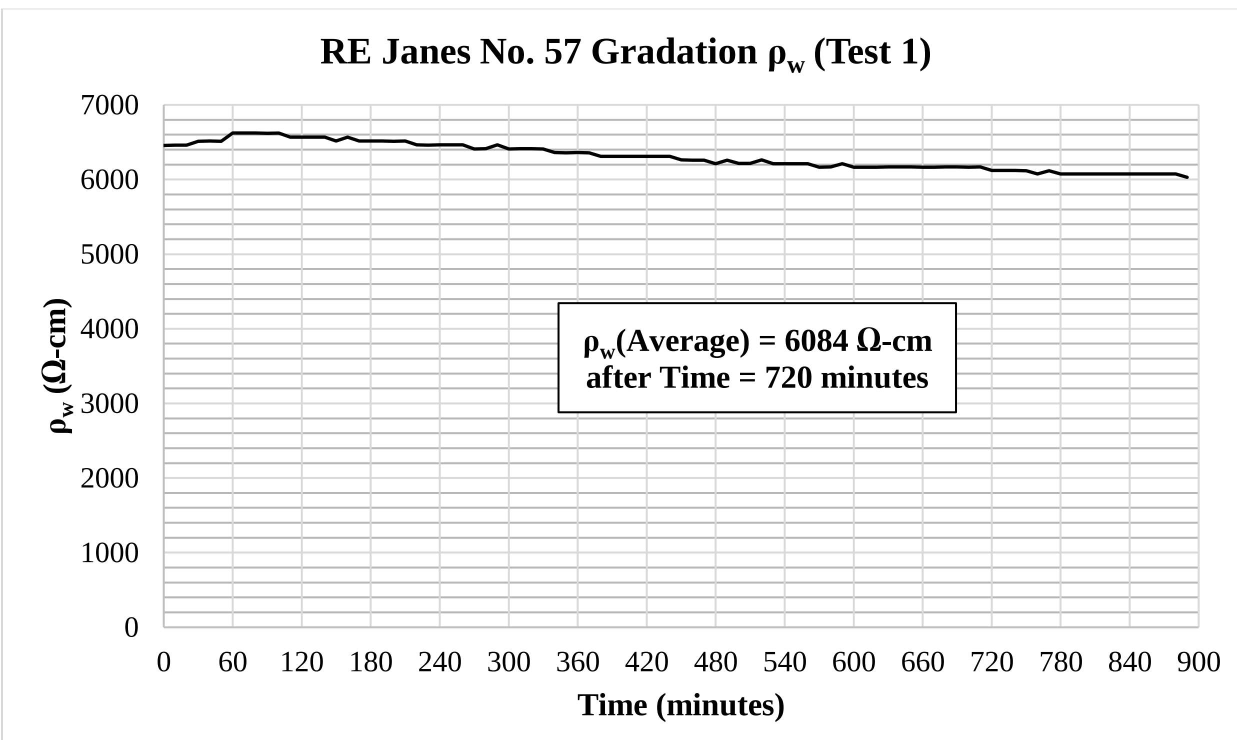

Figure A.14: RE Janes No. 57 Gradation ρ_w for Test 1

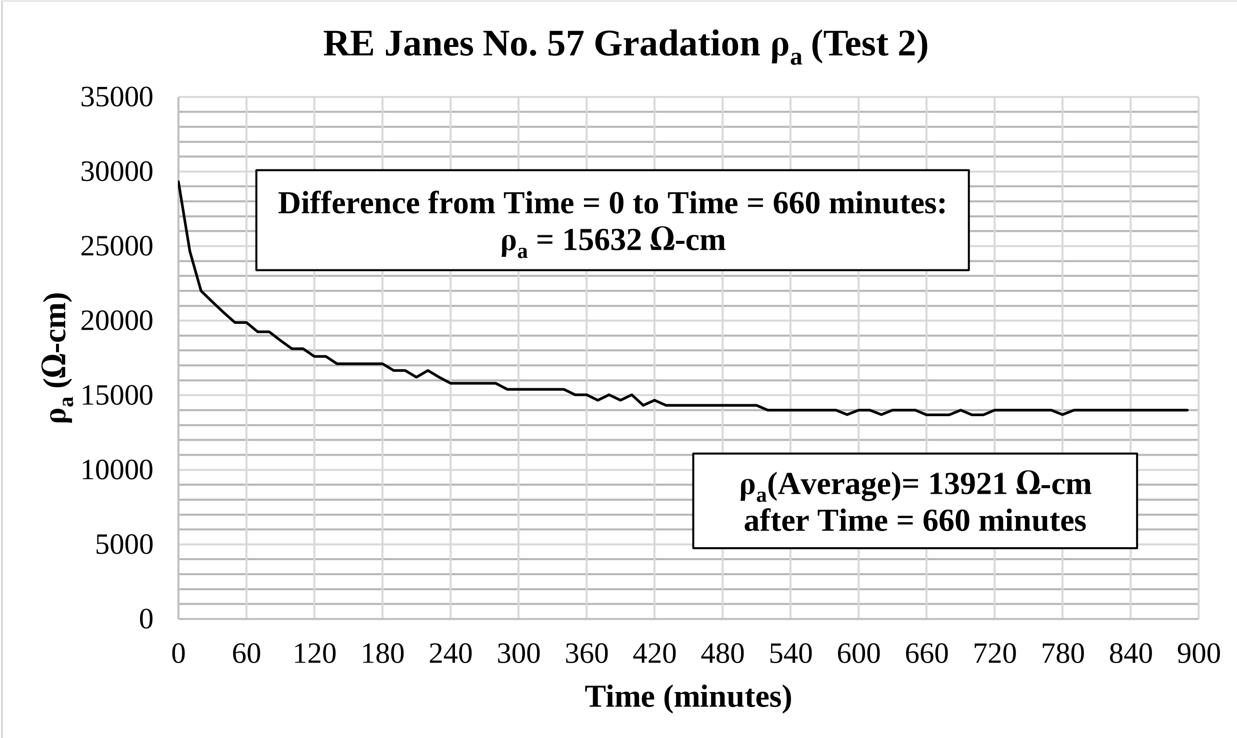

Figure A.15: RE Janes No. 57 Gradation ρ_a for Test 2

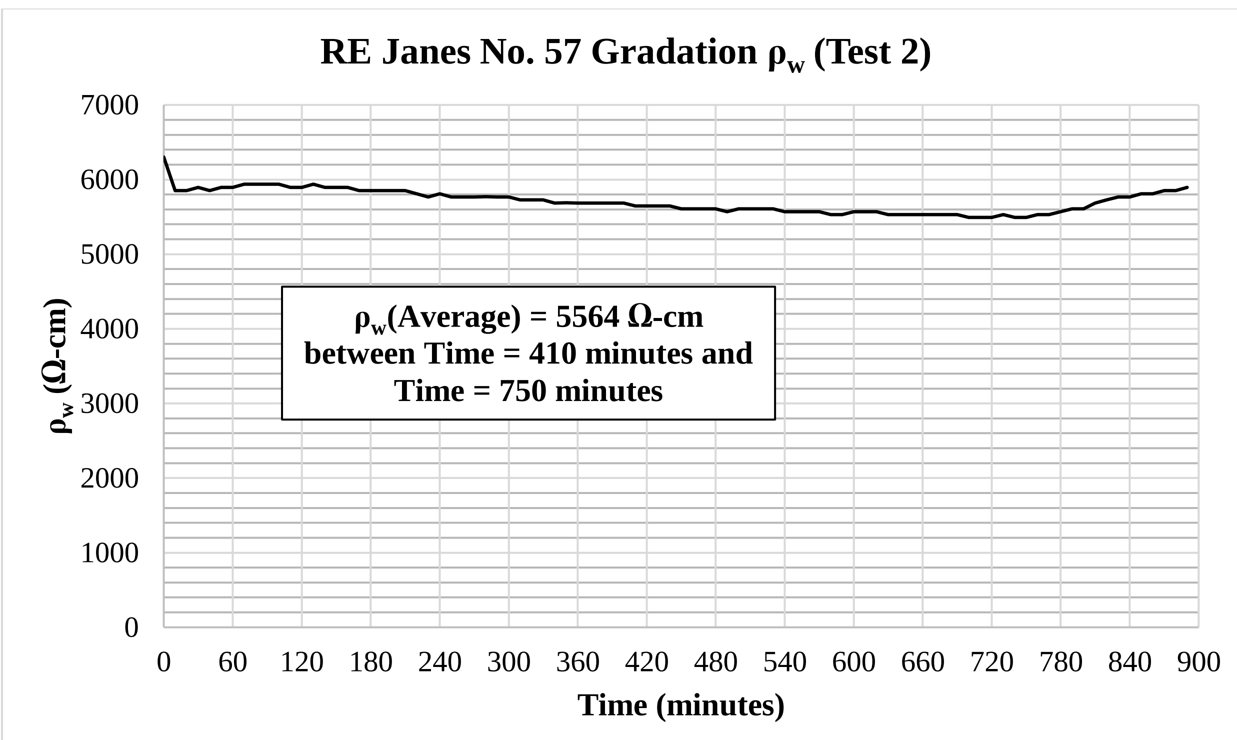

Figure A.16: RE Janes No. 57 Gradation ρ_w for Test 2

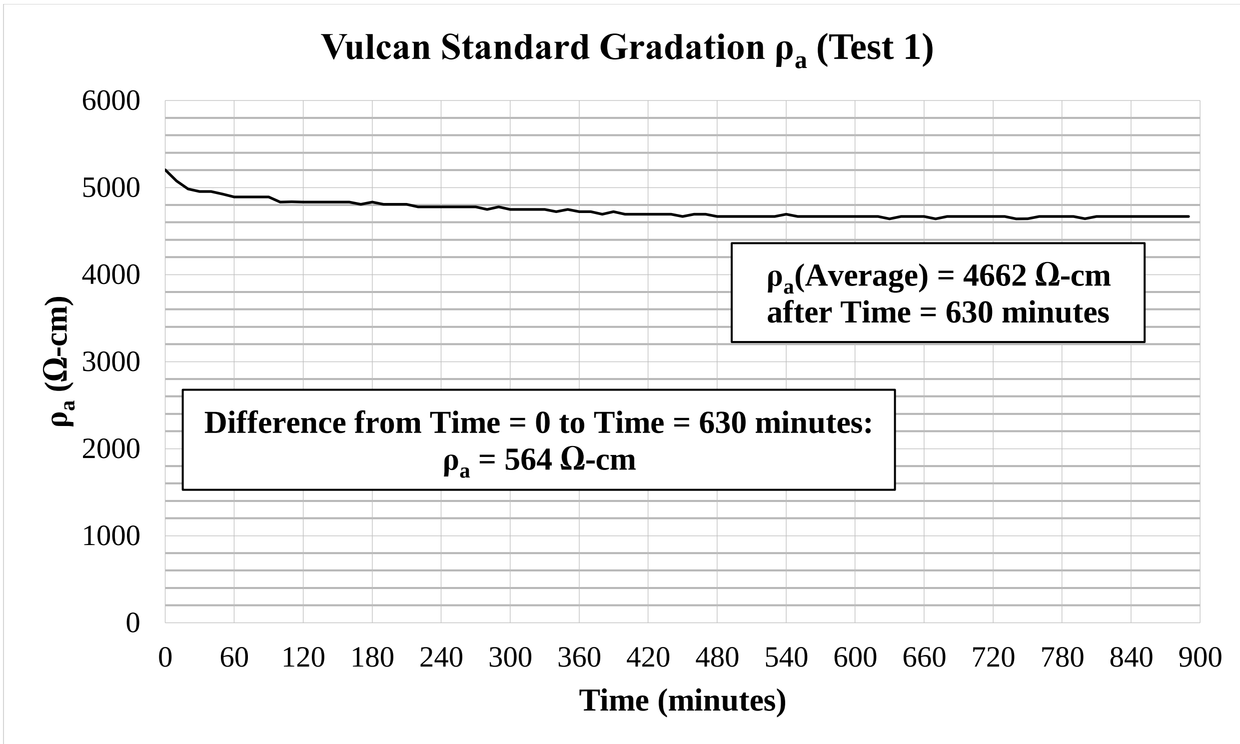

Figure A.17: Vulcan Standard Gradation ρ_a for Test 1

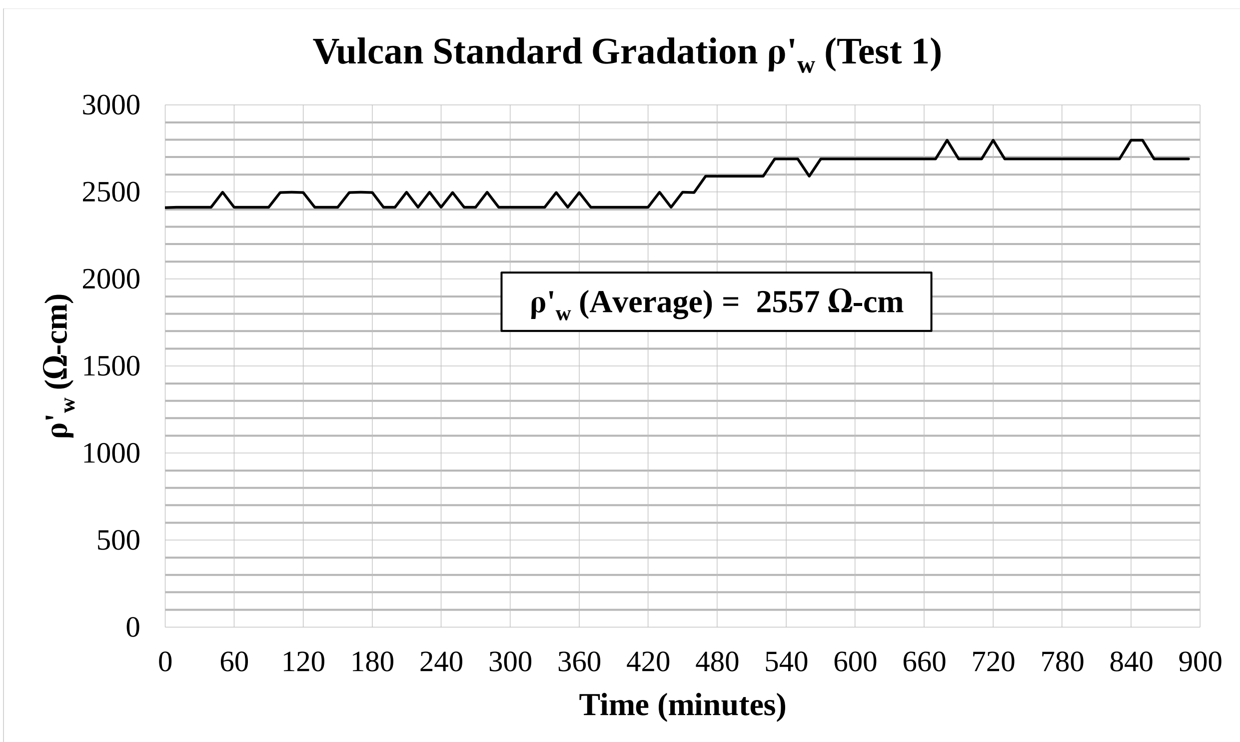

Figure A.18: Vulcan Standard Gradation ρ'_w for Test 1

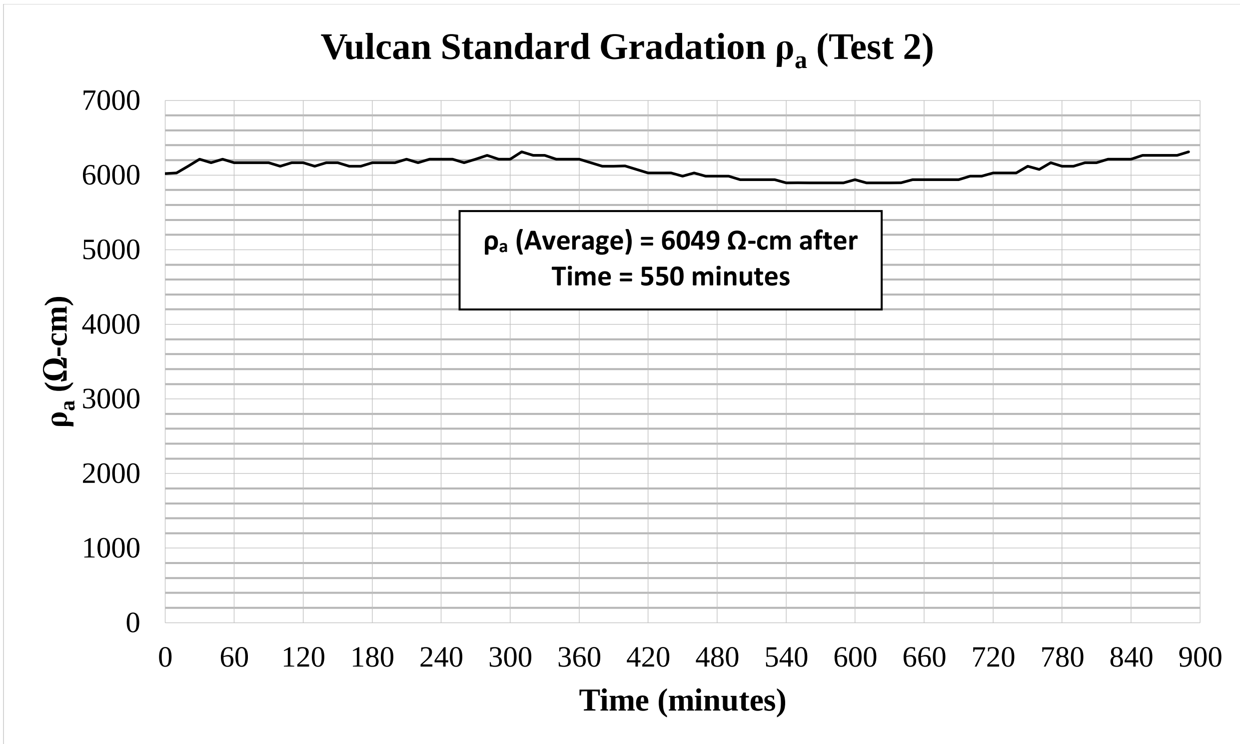

Figure A.19: Vulcan Standard Gradation ρ_a for Test 2

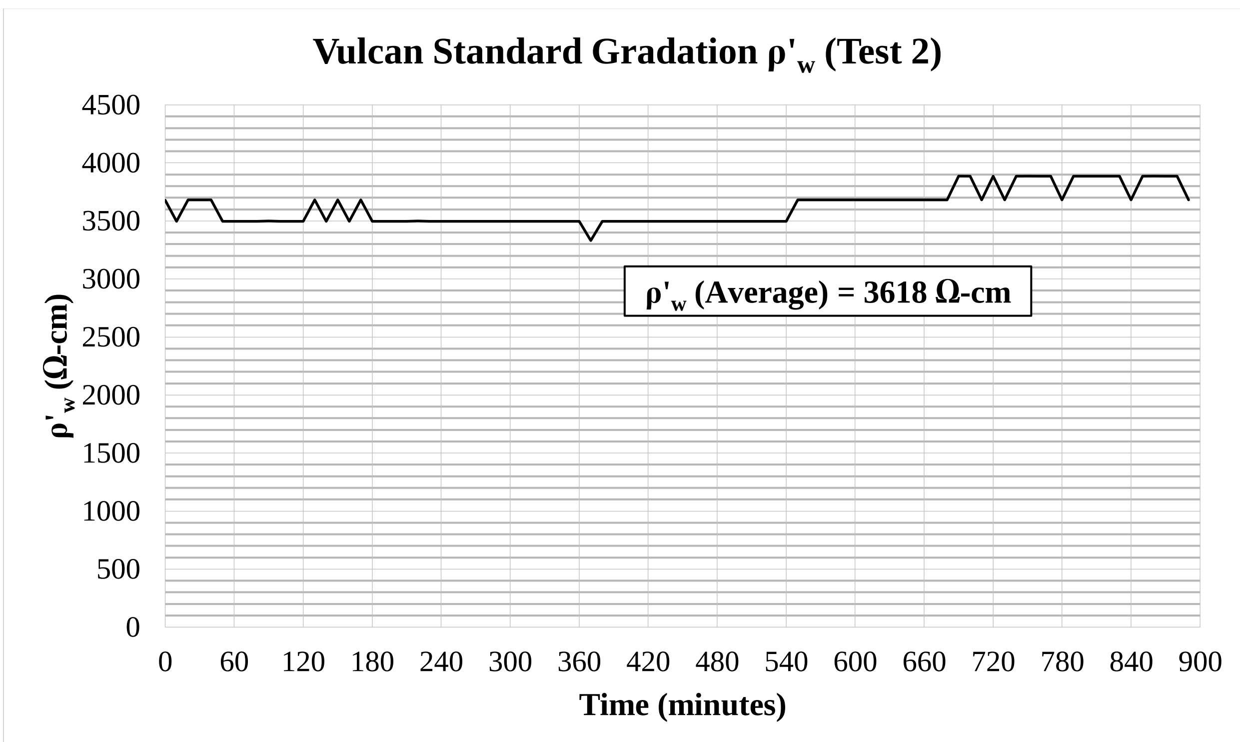

Figure A.20: Vulcan Standard Gradation ρ'_w for Test 2

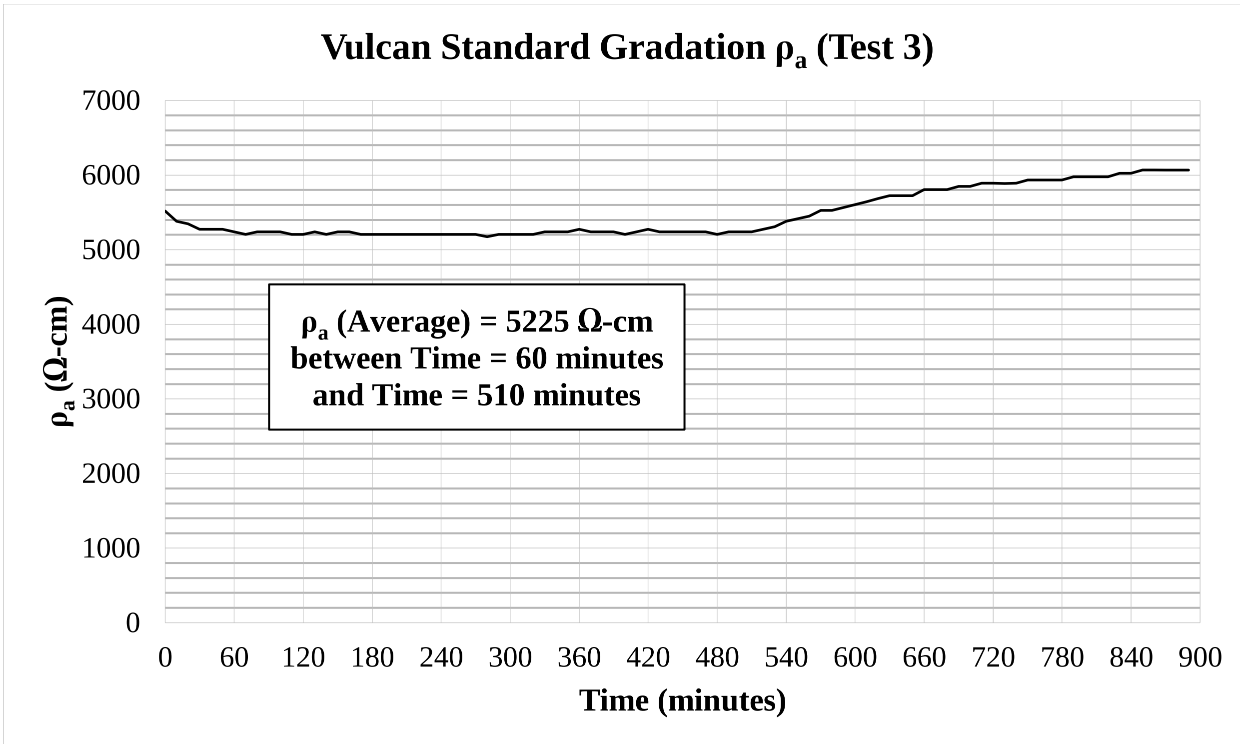

Figure A.21: Vulcan Standard Gradation ρ_a for Test 3

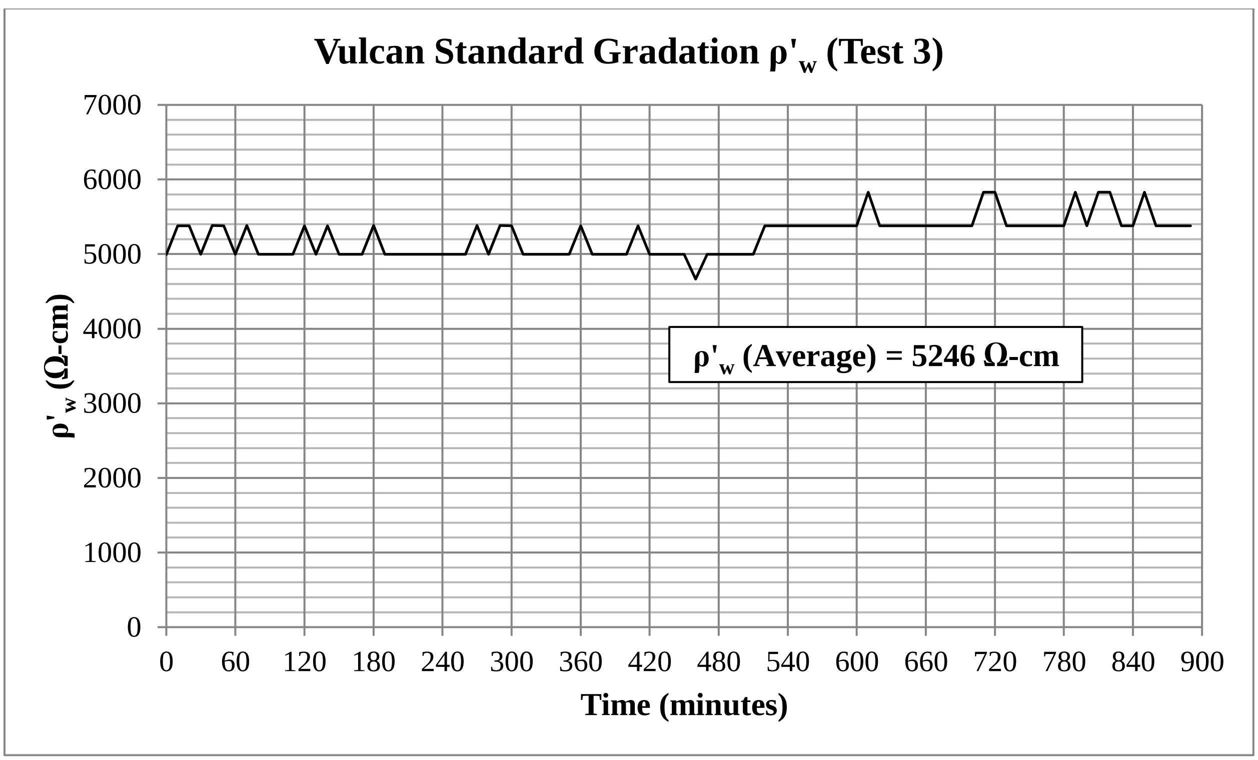

Figure A.22: Vulcan Standard Gradation ρ'_w for Test 3

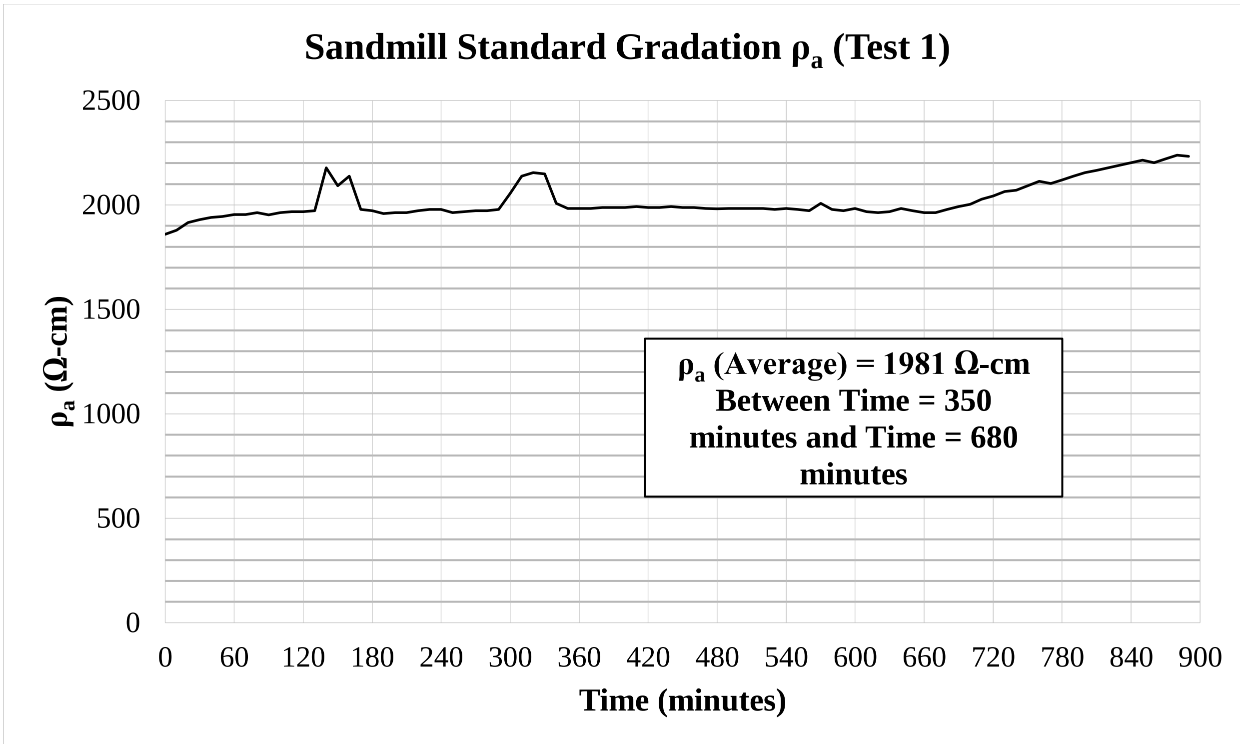

Figure A.23: Sandmill Standard Gradation ρ_a for Test 1

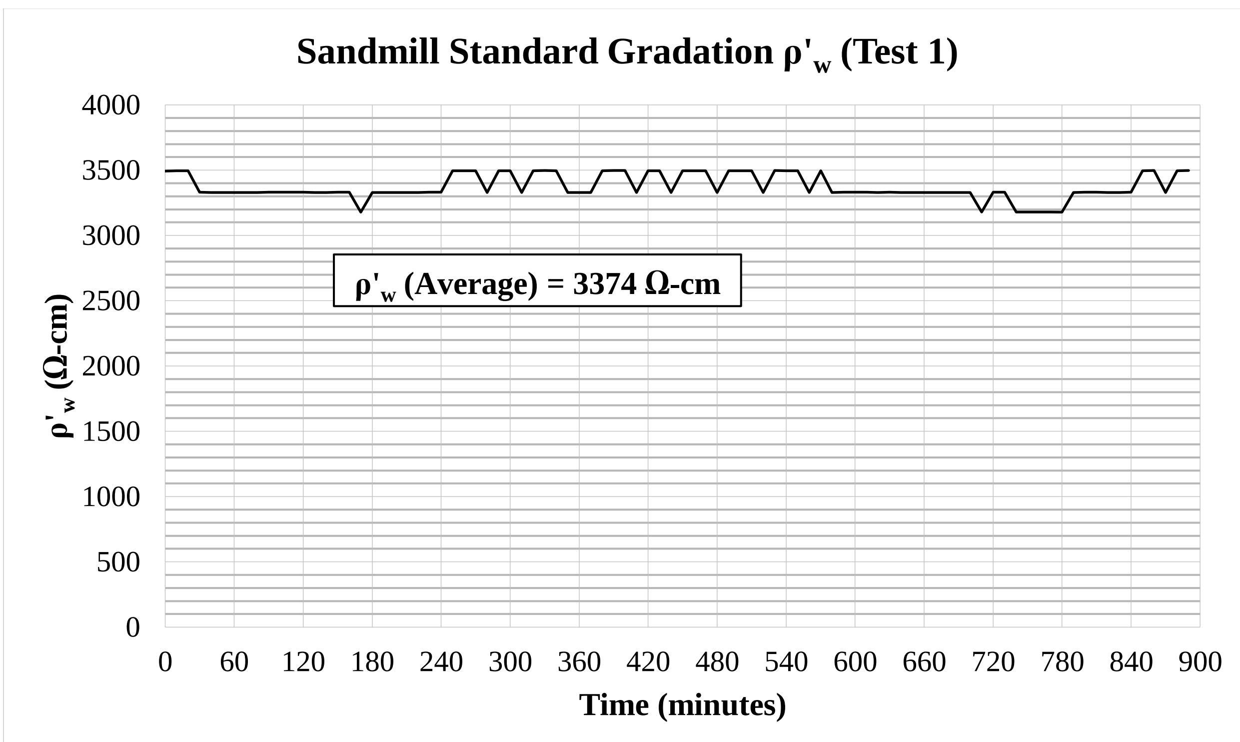

Figure A.24: Sandmill Standard Gradation ρ'_w for Test 1

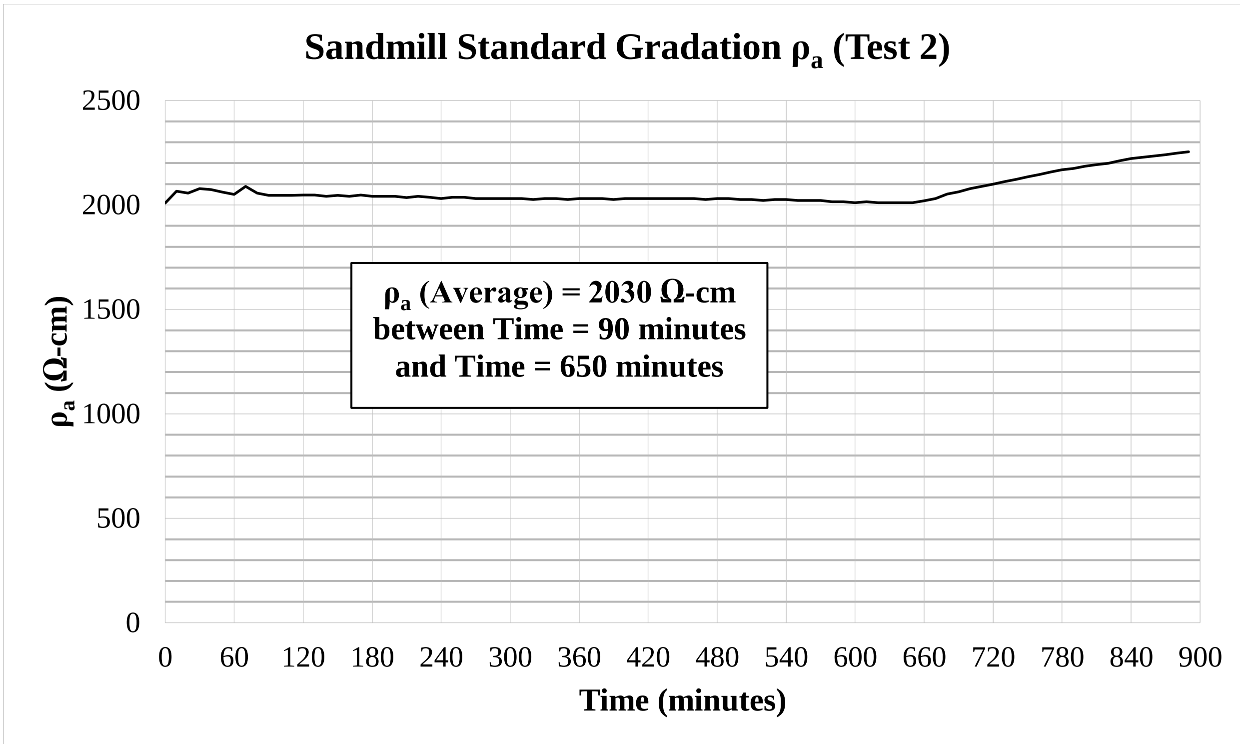

Figure A.25: Sandmill Standard Gradation ρ_a for Test 2

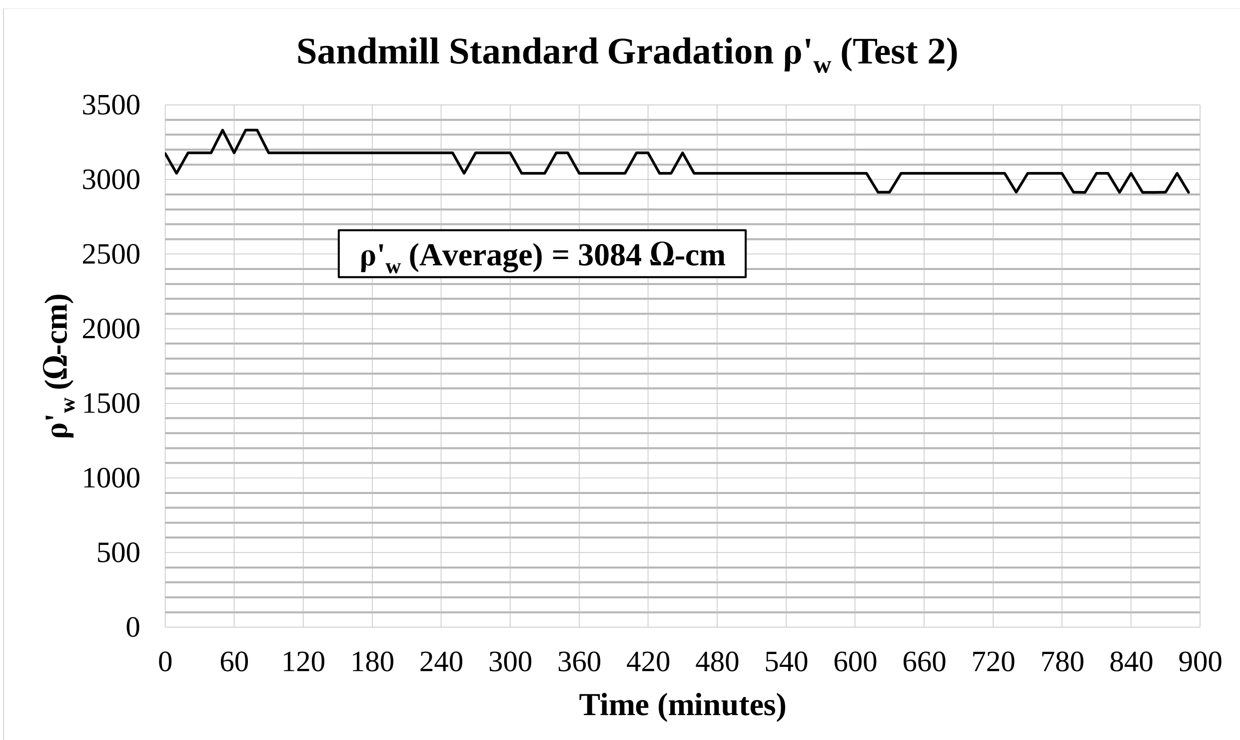

Figure A.26: Sandmill Standard Gradation ρ'_w for Test 2

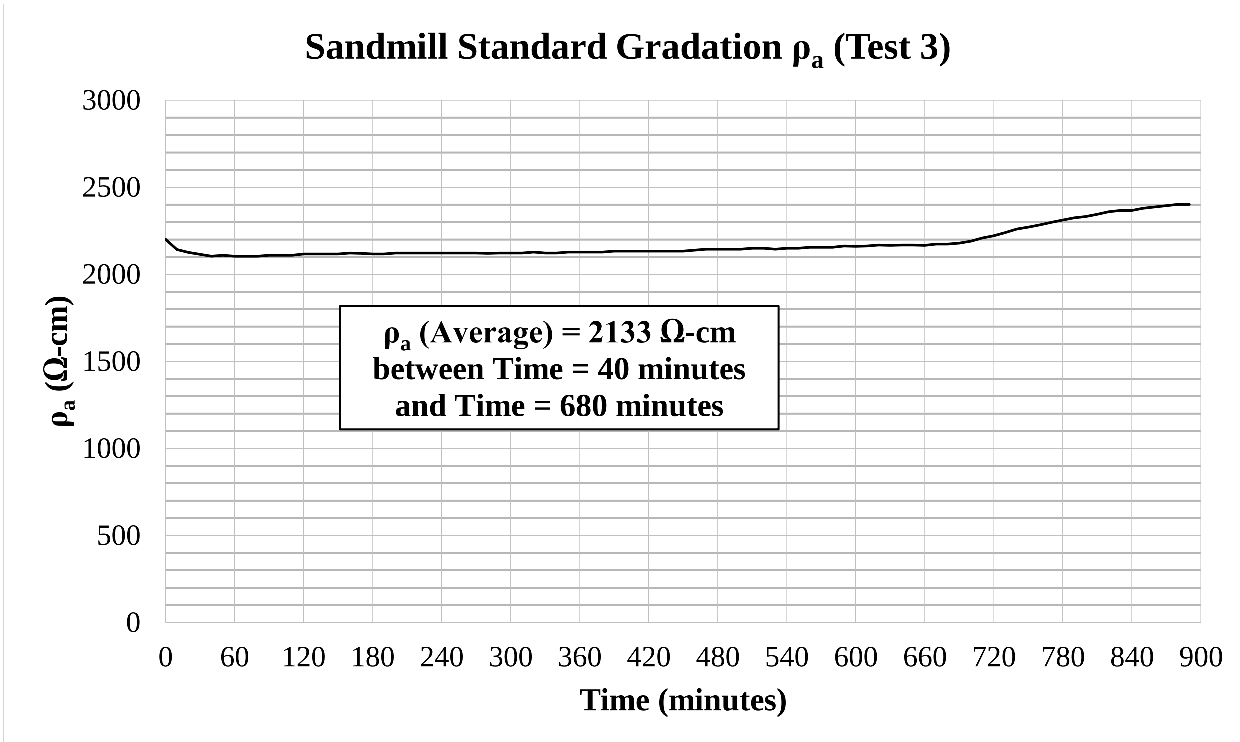

Figure A.27: Sandmill Standard Gradation ρ_a for Test 3

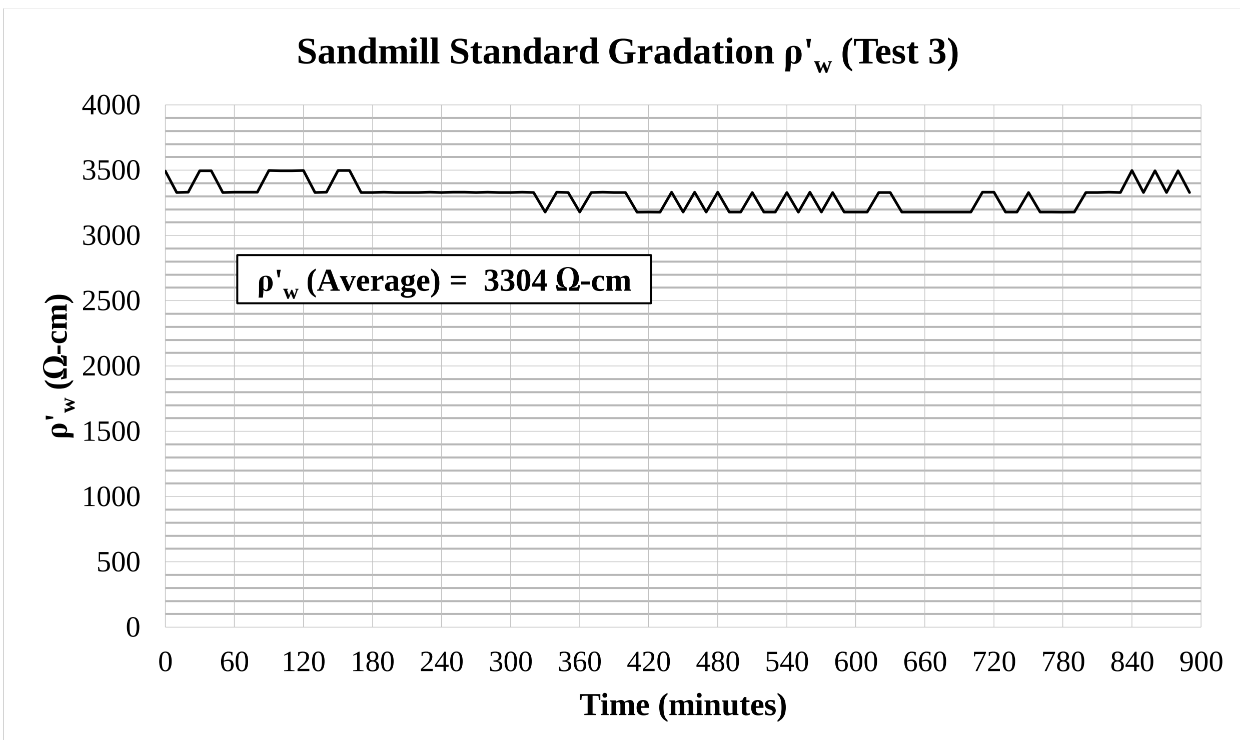

Figure A.28: Sandmill Standard Gradation ρ'_w for Test 3

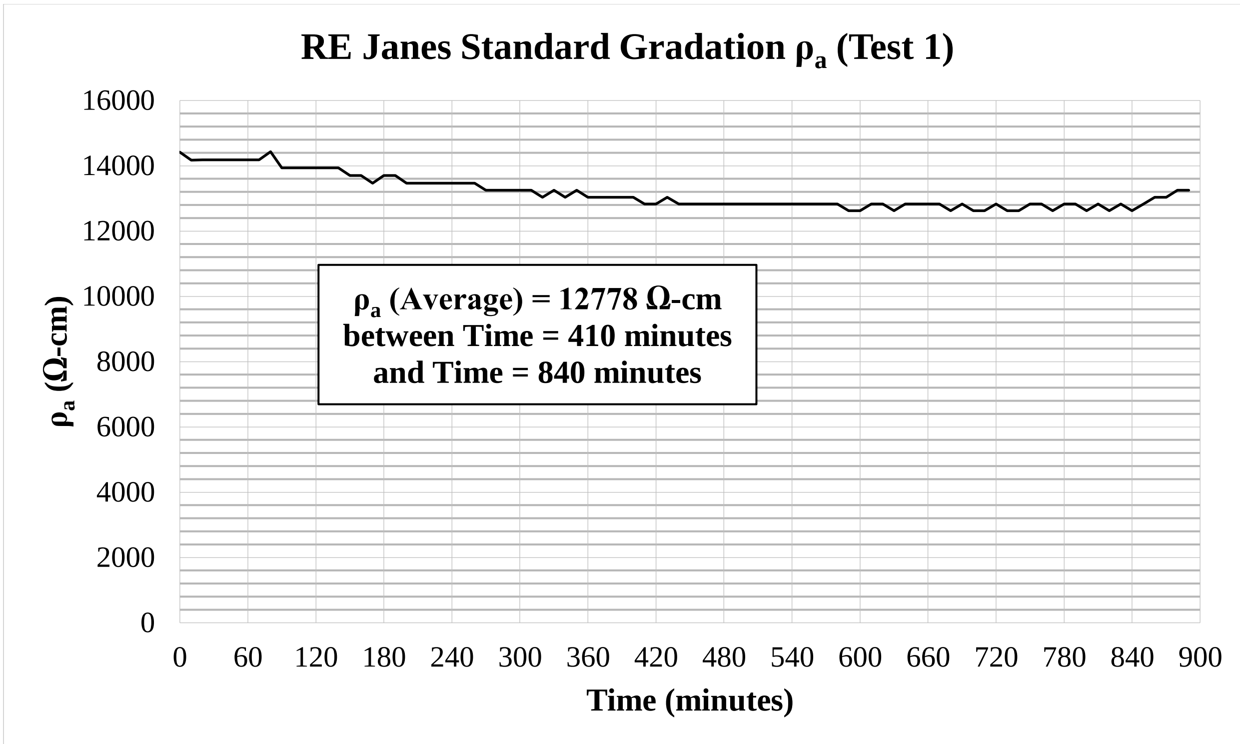

Figure A.29: RE Janes Standard Gradation ρ_a for Test 1

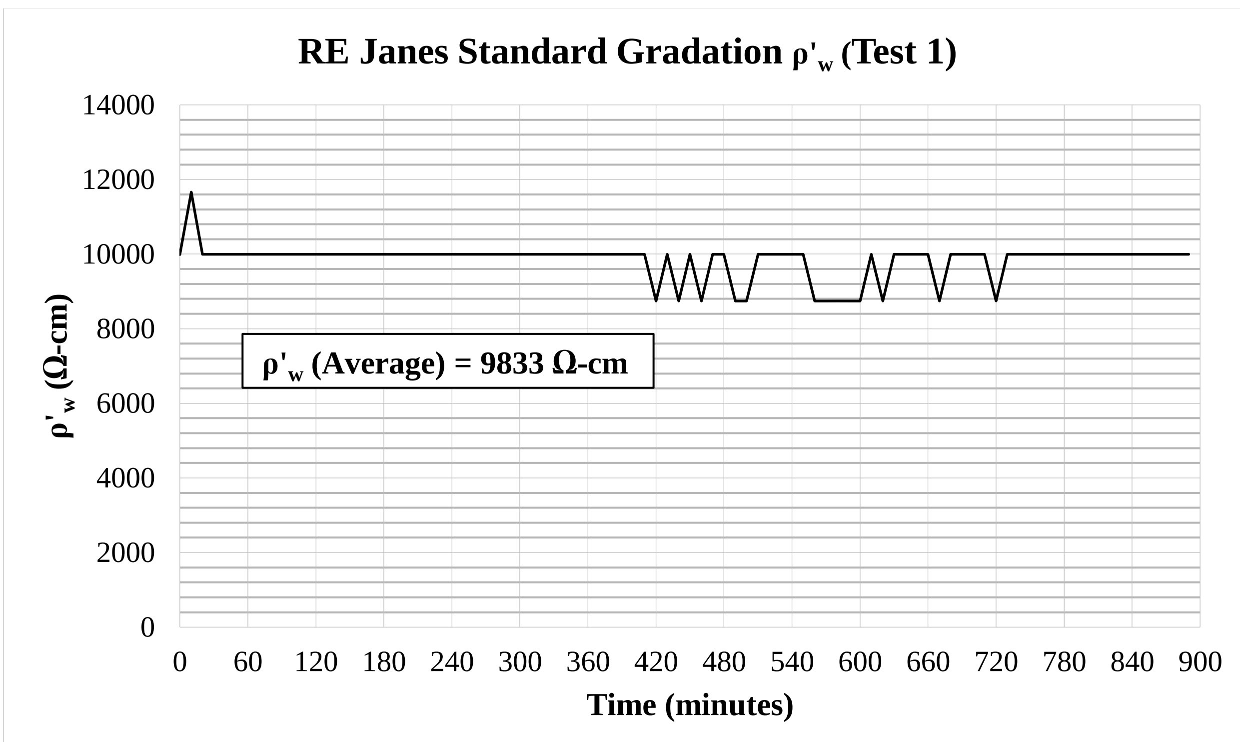

Figure A.30: RE Janes Standard Gradation ρ'_w for Test 1

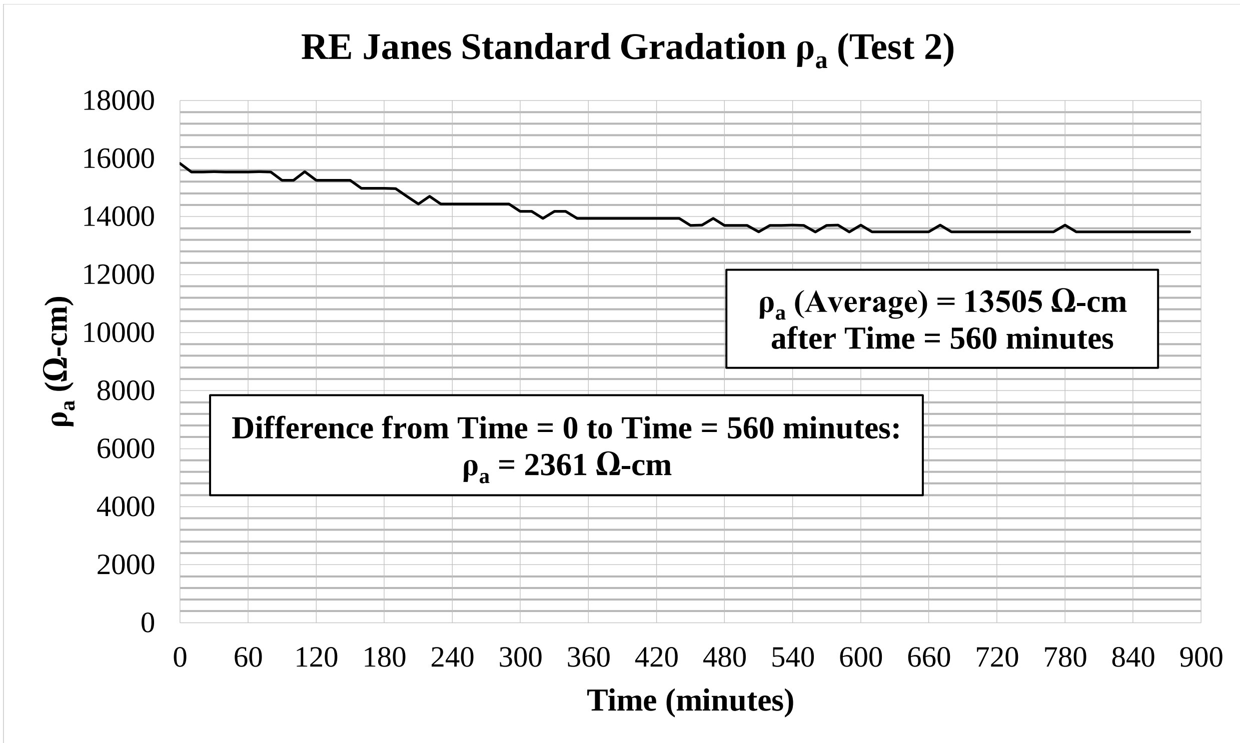

Figure A.31: RE Janes Standard Gradation ρ_a for Test 2

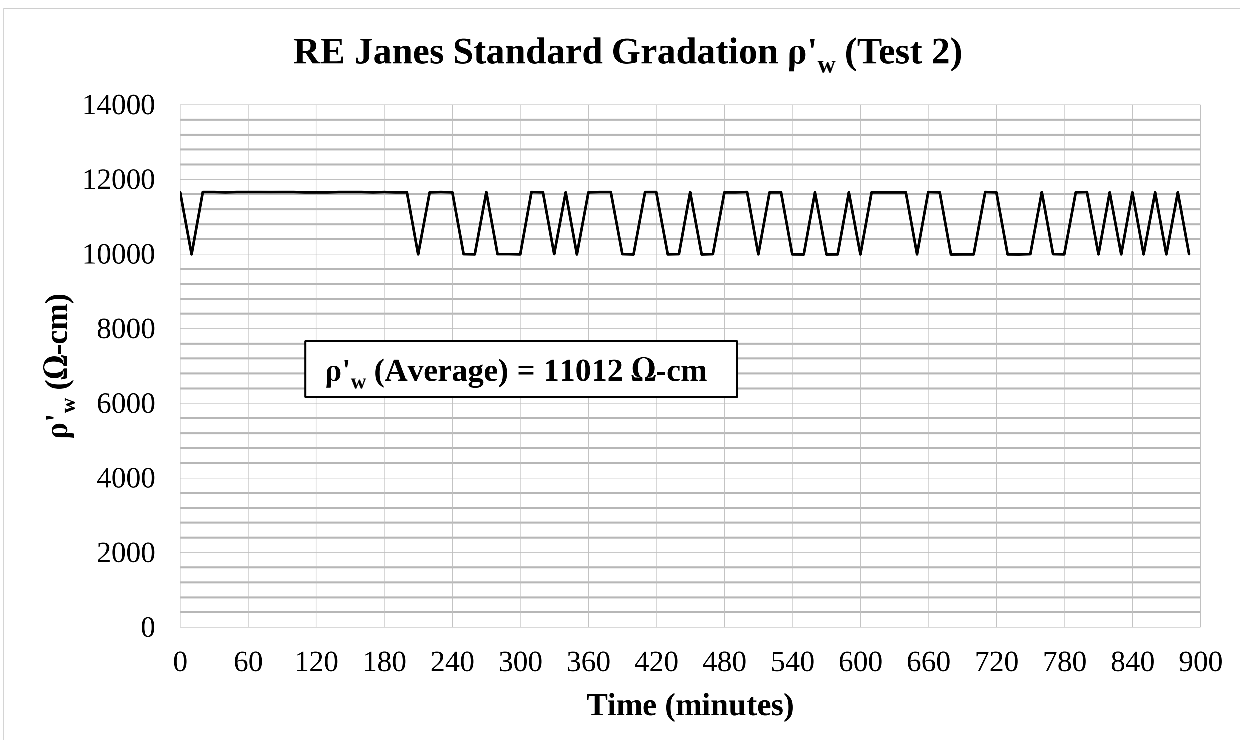

Figure A.32: RE Janes Standard Gradation ρ'_w for Test 2

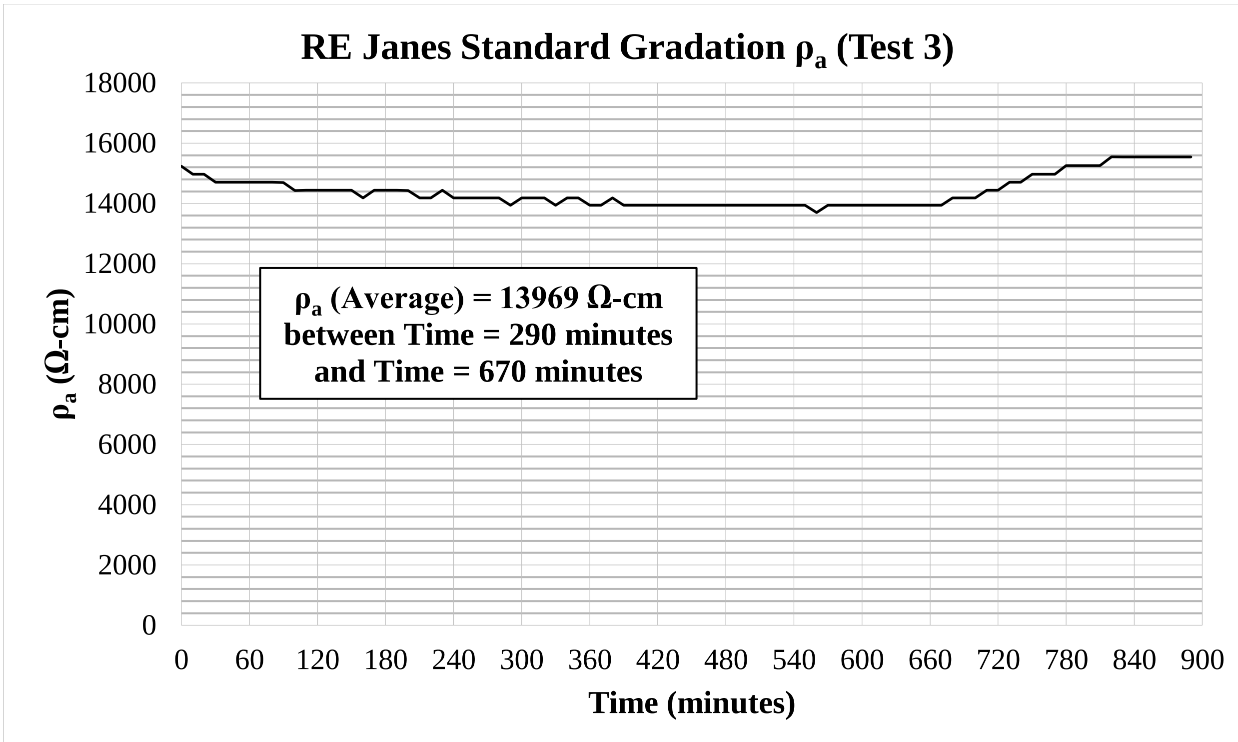

Figure A.33: RE Janes Standard Gradation ρ_a for Test 3

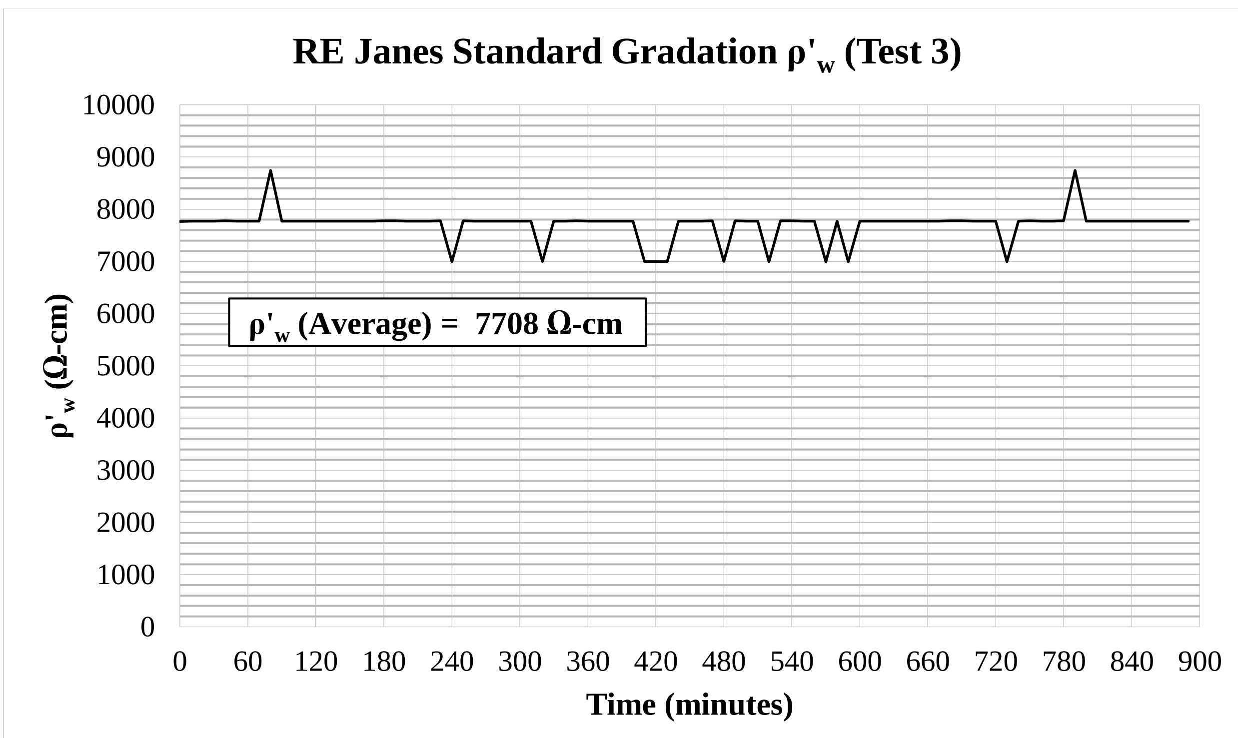

Figure A.34: RE Janes Standard Gradation ρ'_w for Test 3

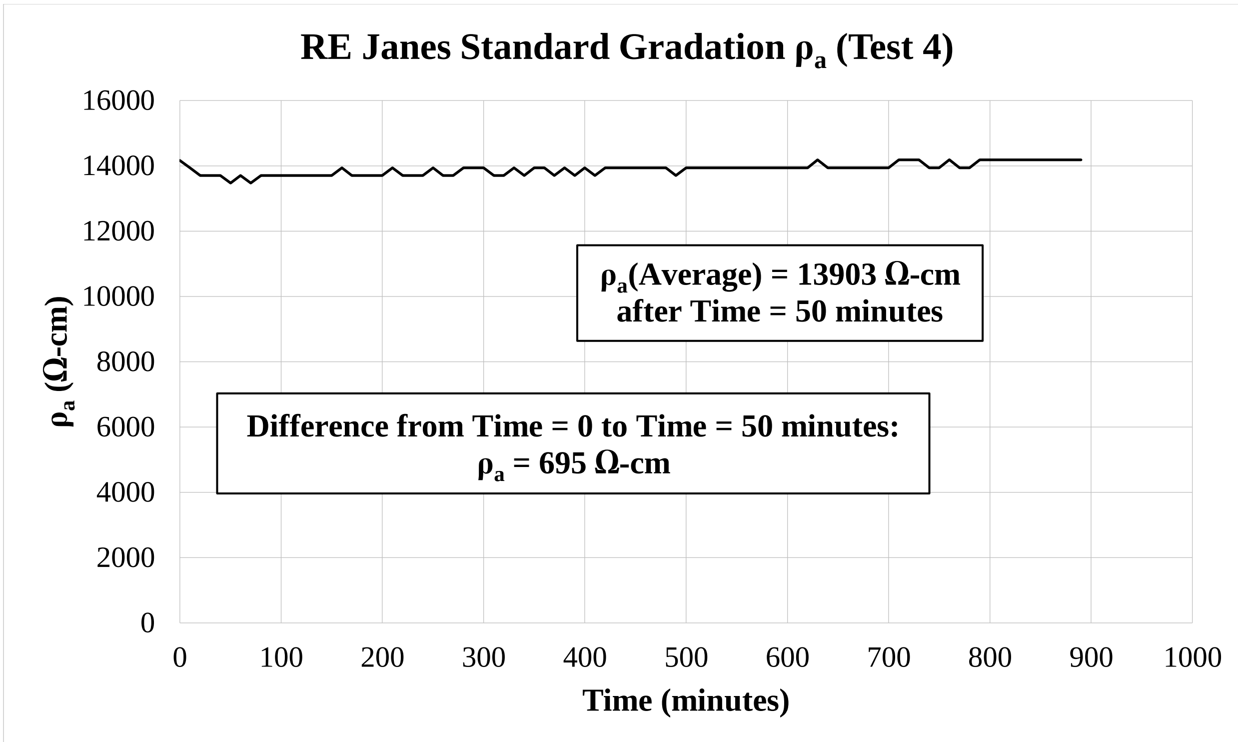

Figure A.35: RE Janes Standard Gradation ρ_a for Test 4

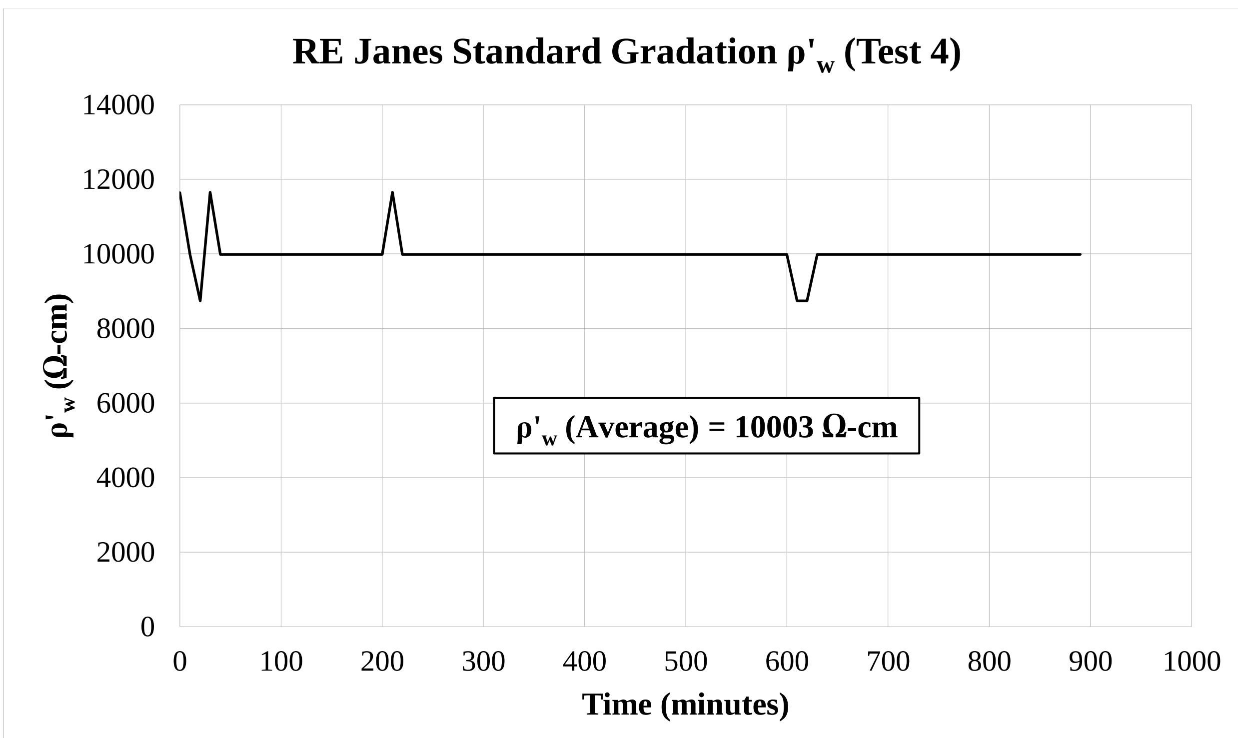

Figure A.36: RE Janes Standard Gradation ρ'_w for Test 4