INVESTIGATING RESISTIVITY TESTING AS A METHOD FOR QUALITY CONTROL OF CONCRETE MIXTURES

By

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INVESTIGATING RESISTIVITY TESTING AS A METHOD FOR QUALITY CONTROL OF CONCRETE MIXTURES

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Title of Study: INVESTIGATING RESISTIVITY TESTING AS A METHOD FOR QUALITY CONTROL OF CONCRETE MIXTURES

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Abstract:

Concrete is a composite material. It is a mixture of cement, sand, rocks and water. It is the second largest consumable product in the world. Unfortunately, many of the concrete structures before completing the designed service life experience premature deterioration and failure. In-service, the foreign components in the form of fluids (e.g., chlorides or sulfates) or gas (e.g., carbon dioxide) ingress into the porous cementitious matrix causing various durability issues and corrosion of rebar in cases of reinforced concrete. The electrical resistivity is a rapid and low-cost method to evaluate the ionic movement in concrete. The surface resistivity method is becoming popular as a quality control test to determine the durability issues due to the movement of chloride or sulfate ions, and as a corrosion indicator. In this study, the important, influential parameters that effects the surface resistivity measurements were investigated to verify and add to the research completed in the past, which includes the effect of curing method and temperature, ambient temperature, w/cm, fly ash content and sources, paste fraction, and aggregate type and size. Also, the comparative study was completed to determine the relationship of surface resistivity with transport mechanisms such as sorptivity, total absorption, and compressive strength with the change in influential parameters explained above. Furthermore, a comparative study was conducted on statistical techniques, multiple regression, decision tree, and neural networks to define a simple and best suitable model to predict resistivity and to develop a quality control criteria to determine the important concrete mixture parameters, w/cm and fly ash content, but this study didn’t fulfill the desired goal of the study. Another study was performed by using statistical analysis, Levene’s test, ANOVA, Welch’s test and Tukey’s test to develop a quality control method which successfully determines the presence of fly ash content and potential w/cm of the concrete mixture. The efficacy of statistical criteria was evaluated with various concrete mixtures with similar and different material sources. The development of novel quality control criterion to verify the key concrete mixture parameters, w/cm and fly ash content would help to minimize the durability issues, repair and rehabilitation cost, and an increase in service life of the concrete structure.

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CHAPTER 1

INTRODUCTION

1.1 Background

The hydrated paste matrix of concrete is porous in nature. The material consists of solid and liquid phases. The solid phase is mainly composed of crystallized hydrated calcium silicates and other minor crystalline products. The liquid phase is generally saturated with various ions (e.g., Ca^{2+}, OH^{-}, K^{+}, Na^{+}, and SO_4^{2+} ions). With age (i.e., maturity) the cementitious matrix changes, it gains density and strength as solid-solution interactions continue [1]. In-service, external agents may enter the porous medium and alter its delicate balance. Foreign components in the form of an aqueous solution (e.g., chlorides or sulfates) or gas (e.g., carbon dioxide) ingress into the porous cementitious matrix causing various material durability issues and corrosion of rebar in cases of reinforced concrete. Here, ionic movement through the partially or completely saturated pore system is, in part, responsible for the detrimental effects. The mechanisms that involve ion transport are capillary action, diffusion, migration in electrical field and permeation due to the pressure gradient, to name a few [2]. Field structures are often subjected to combinations of these transport mechanisms, which makes it difficult to single out the ongoing process. The problem is that the standard methods for measuring these principles are considered time-consuming, variable and impractical. Still, it is well known that resistance against ionic or fluid penetration is the best defense mechanism for concrete against durability issues. Therefore, there is a need for finding an economical and rapid nondestructive method for measuring these processes [3].

The four-point Wenner probe resistivity method was initially developed by Wenner in early 1900 to measure the resistivity of soils to indicate their permeability characteristics. Over a period of a century, the resistivity testing revolutionized and gained popularity as a non-destructive surface method due to rapid, low cost, and user-friendly characteristics that indicate the ability of concrete to conduct current. Based on past investigations and continuous efforts by researchers and scholars lead to the development of AASHTO TP 95 “*Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration”* [4].

The surface resistivity method is used an as a quality control test to determine the durability issues due to movement of chloride or sulfate ions. The correlation between resistivity and chloride ion penetrability is accepted and implemented worldwide [5-7].

The resistivity of concrete is inversely proportional to corrosion after the depassivation of reinforcement. The resistivity method can be used as corrosion indicator to determine the risk of corrosion of steel in the period of initiation and propagation. The high resistivity of concrete shows a low risk of corrosion, as well as the rate of corrosion [8,9]. The past studies have shown correlations between resistivity and corrosion [10,11].

It can also be used to differentiate between the concrete mixtures based on their mixture proportions. The past studies have shown that the surface resistivity method can differentiate concrete mixtures with various w/cm and cementitious material replacement (6,9-10). When w/c ratio is low, higher resistivity is noted at an early age. The specimens with higher w/c ratio showed lower resistivity at an early age and higher resistivity at very later age [12-13].

As previously stated, resistivity is known to be sensitive to variations in the concrete mixture which is deemed as a limitation of the non-destructive method [14]. However, this distinctive feature could be utilized as an advantage. The question is: how sensitive is the method to mixture variations? Thus, warranting an investigation on the potential of resistivity testing in assessing key mixture design parameters critical for durability performance of concrete mixtures, translating into the development of a new quality control and compliance criteria for concrete mixture approval and compliance in addition to currently used test methods and specifications. This would allow infrastructure owners and stakeholders to produce high quality and durable concrete.

1.2 Scope

The purpose of this study is to investigate the potential of resistivity testing as a mean for mixture quality control and compliance in addition to current DOT specifications, which would help DOT's to produce high quality and durable concrete. The systematic approach is developed using the surface resistivity method to evaluate the compliance of fabricated concrete mixture design with that of the approved mixture design by determining two key parameters, water-to-cementitious material ratio (w/cm) and secondary cementitious material (class-C fly ash). The feasibility of the method will be evaluated for two mixture design classes commonly used for construction of pavement and bridge deck in Oklahoma. In order to achieve the main goal of the study, the first objective is to perform an experimental parametric investigation to model time-resistivity behavior of typical ODOT Class A and Class AA concrete mixtures. This objective is achieved by understanding and analyzing the influencing parameters on resistivity measurements. The second objective is to perform an experimental comparative investigation of influential transport mechanism and properties on durability and strength of concrete. It will help to understand the relationship of resistivity with an ionic transport mechanism and strength for varying parameters in concrete mixtures. The third objective is to establish a time-dependent resistivity model for quality control of concrete mixtures to identify the water-to-cement ratio and cementitious materials present in the mixture, and the final objective is to evaluate the efficacy of quality control criteria and its application to compliance control of mixture design. It will evaluate the reliability and practicality of the developed quality control criteria.

The dissertation document consists of eleven chapters. The introduction to this research study is presented in the first chapter of the dissertation.

- In the second chapter, the information regarding concrete mixtures produced and standards followed are presented for each study.
- The third chapter presents the study that broadens the investigation done previously on the use of aggregate types and sizes on resistivity testing. The interest of this study is to acknowledge previous findings and to increase the knowledge of the influence of materials variance on resistivity testing, which could help in firming the concept of using the surface resistivity testing as a quality control method.
- In fourth chapter, a preliminary study on effect of chemical admixtures on surface resistivity was conducted. The effect of addition of mid-range water reducer and air entrainer on surface resistivity of concrete is compared to the resistivity of concrete without chemical admixtures. In addition, the influence of 10% and 20% fly ash replacement in the presence of water-reducer and air entrainer on surface resistivity is also determined.
- In the fifth chapter, the study investigates the influence of sample conditioning, curing method and curing temperature, on resistivity measurements. It evaluates whether variations of curing temperature within ASTM specified limits have a significant effect on the surface resistivity measurement along with ASTM acceptable means of saturation (moist curing and immersion curing).

- The sixth chapter presents the study to evaluate the consistency in the reproduction of concrete mixtures from a producer by using surface resistivity testing. A comparative study is completed by performing statistical analysis on resistivity measurements to evaluate the consistency of concrete mixtures produced by 8 different producers

- The seventh chapter is focused on analyzing the relationship of surface resistivity method with sorptivity, percentage absorption and compressive strength of concrete by varying the concrete parameters, such as w/cm, fly ash content, fly ash source, aggregate type and size and paste fraction and the addition of chemical admixtures. The examples describe that each of these parameters has an influence on transport properties and strength of concrete.

- The eighth chapter explains the significance of electrical resistivity method as a quality control indicator, for not only durability issues due to movement of chloride or sulfate ions and as a corrosion indicator, but it can also be used to differentiate between the concrete mixtures based on their mixture proportions. This specific quality of resistivity testing could be helpful to develop models to predict the resistivity value of a concrete mixture and the development of resistivity prediction intervals to identify the mixture parameters.

- The ninth chapter presents an approach to develop a simple quality control method to determine the potential fly ash content and w/cm of the placed concrete mixture. The statistical analyses are performed on surface resistivity data by using Levene’s test, ANOVA and Tukey’s test, and with 95% confidence intervals, the possible fly ash content in the concrete could be determined after 3 days of immersion curing. The potential w/cm of the concrete mixtures containing fly ash, or no fly ash content could be identified by using the mean resistivity value at testing day. The statistical criteria offer a simple tool to control the quality of concrete in compliance with approved mixture design that could benefit the future production of concrete.

- The tenth chapter focuses on the study to investigate the potential of resistivity testing in assessing the key mixture design parameters critical for durability performance of concrete mixtures of varying mixture design and material source. The objective is to establish and validate a method based on resistivity method to identify the water-to-cement ratio of a given mixture and class-C fly ash as a supplementary cementitious material. This will aid in the development of a new quality control and compliance criteria for concrete mixture approval and compliance in addition to currently used test methods and specifications. This would allow infrastructure owners and stakeholders to produce high quality and durable concrete in future.
- Lastly, in the eleventh chapter, the conclusions of the studies explained in various chapters are summarized and concluded, along with the recommendations for future scope of the study.

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CHAPTER 2

EXPERIMENTAL DESIGN

In order to accomplish the objectives of the research, an experimental program was organized, which include the materials handling and testing, concrete mixing, demolding and curing, and, lastly, the experimental procedures followed in accordance with standards. The activities performed to complete research tasks are presented in this chapter.

2.1 Materials

The materials required to make concrete mixtures were brought from various sites in Oklahoma. The materials were stocked outside and inside the laboratory, cleaned, and tested as per requirements before mixing the concrete. The details for each material used are given in following sections.

2.1.1 Cement

In all the concrete mixtures, Type-I (ASTM C 150) Central Plains Portland cement was used. Few concrete mixtures were also prepared using Type-I/II Buzzi cement for comparison. The cement bags received were stocked inside the Bert Cooper Engineering Lab at a clean and dry place. The chemical composition of cements is shown in Table 2.1.

Table 2.1 Chemical Compositions of Cement Sources

Chemical Composition	Cement (% by weight)	
	Central Plains	Buzzi Unicem
MgO	1.9	1.86
CaO	62.9	64.25
SO_3	3.3	2.63
SiO_2	19.4	20.56
Al_2O_3	5.1	4.41
Fe_2O_3	3.4	3.28

2.1.2 Fly Ash

The concrete mixtures prepared with the replacement of Class-C fly ash (ASTM C 618) content were obtained from Red Rock, Headwaters Hugo, Ray Nixon and Muskogee. In order to establish the baseline criteria, and develop the guidelines for quality control, class-C fly ash from Red Rock was used as a secondary cementitious material. Other fly ash sources were used for the comparative analysis and validation of established criteria. The fly ash received from the various sources were sealed in 5-gallon buckets and stocked inside the Bert Cooper Engineering Lab. The chemical compositions of fly ash sources are shown in Table 2.2.

Table 2.2 Chemical Compositions of Fly Ash Sources

Chemical Composition	Class-C Fly Ash (% by weight)			
	Red Rock	Muskogee	Ray Nixon	Headwaters, Hugo
K_2O	0.58	0.41	0.46	0.39
MgO	5.55	7.46	5.87	6.70
CaO	23.12	29.74	24.41	25.84
SO_3	1.27	1.89	1.07	1.91
Na_2O	1.78	1.82	1.73	1.78

SiO_2	38.71	32.88	36.27	36.20
Al_2O_3	18.82	18.37	19.17	17.85
Fe_2O_3	5.88	5.58	6.28	5.61

2.1.3 Coarse Aggregates

The concrete mixtures were prepared with various types and sizes of concrete aggregates as per ASTM C 33 [1]. The aggregates were obtained from Richard Spur Limestone (#56, #57 and #67), Coleman Dolomite (#57), and Roosevelt Granite (#56). All the mixtures were made with aggregates received from Richard Spur source, aggregates from other sources were used for the comparison. The coarse aggregates were stocked outside the Bert Cooper Engineering Lab. The aggregates were tested for sieve analysis (ASTM C136), dry rodded unit weight (ASTM C29), specific gravity and absorption (ASTM C127) for the purpose of quality control and mixture design. The chemical compositions of coarse aggregates are shown in Table 2.3.

Table 2.3 Chemical Compositions of Coarse Aggregate Sources

Chemicals	Coarse Aggregates (% by weight)		
	Richard Spur Limestone	Coleman Dolomite	Roosevelt Granite
Ca	35.93	20.67	7.24
CaO	50.27	28.92	10.13
$CaCO_3$	89.73	51.62	18.08
Mg	1.02	9.74	1.07
MgO	1.69	16.15	1.77
$MgCO_3$	3.54	33.77	3.71
Fe_2O_3	0.25	0.85	4.07
Al_2O_3	0.6	2.08	16.91
Si	3.38	4.03	24.3
SiO_2	7.24	8.63	51.99
S	-	-	-
SO_3	-	-	-

Sodium Oxide	-	-	0.422
Titanium Dioxide	-	-	0.16
Potassium Oxide	-	-	0.316

2.1.4 Fine Aggregates

In all the concrete mixtures, natural sand from Dover quarry meeting the specifications of ASTM C 33 [1] was used. The sand was stocked outside the Bert Cooper Engineering Lab. The fine aggregates were tested for sieve analysis (ASTM C136), specific gravity and absorption (ASTM C128) to meet up to the standards.

2.1.5 Water

The portable water used in all concrete mixtures was provided by Stillwater Municipal Water System. The annual water quality reports for 2015 and 2016 are presented in Appendix-F.

2.1.6 Chemical Admixtures

For comparative analysis, the concrete mixtures were prepared with the addition of chemical admixtures. The air-entraining admixture (AE) (ASTM C 233), MasterAir AE 90 from BASF, and mid-range water reducer (WR) (ASTM C 494), MasterPolyheed 1020 from BASF were used in the concrete mixtures.

2.2 Concrete Mixtures

A total of 159 concrete mixtures were prepared for this research study in Civil Engineering Laboratory and Bert Cooper Engineering Laboratory at Oklahoma State University. For each concrete batch, slump, unit weight, and pressure air meter tests were performed to maintain the quality of concrete mixtures. The cylindrical concrete samples (Ø100 mm x 200 mm approx.)

were prepared (ASTM C 192) to perform the experiments from each concrete mixture. Detailed mixture designs are provided in Appendix-A. The details of the concrete mixtures produced are as follows:

- Seven concrete mixtures were prepared to have 0.45 w/cm, fly ash content (10%, 15%, 20% and 25%) with the addition of AE. In these concrete mixtures, crushed Limestone (#57), natural sand, type-I Portland cement and class-C fly ash from Red Rock were used.
- Eleven concrete mixtures were made, having w/cm (0.40, 0.45, 0.50, 0.55 and 0.60), fly ash content (0% and 20%) with and without adding AE. In these concrete mixtures, crushed Limestone (#57), natural sand, type-I Portland cement and class-C fly ash from Red Rock were used.
- Thirty concrete mixtures were prepared for parametric investigation to model time-resistivity behavior, having w/cm (0.40, 0.45, 0.50, 0.55 and 0.60) and fly ash content (0%, 5%, 10%, 15%, 20% and 25%). In these concrete mixtures, crushed Limestone (#56), natural sand, type-I Portland cement and class-C fly ash from Red Rock were used.
- Six concrete mixtures were made, having w/cm (0.40, 0.45 and 0.50) and fly ash content (10% and 20%). In these concrete mixtures, crushed Limestone (#56), natural sand, type-I Portland cement and class-C fly ash sourced from Headwaters, Hugo were used.
- Thirty concrete mixtures were prepared, having w/cm (0.40, 0.45, 0.50, 0.55 and 0.60) and fly ash content (0%, 5%, 10%, 15%, 20% and 25%) with the addition of AE and WR. In these concrete mixtures, crushed Limestone (#56), natural sand, type-I Portland cement and class-C fly ash from Red Rock were used.
- Six concrete mixtures were made with w/cm (0.40, 0.45 and 0.50) and fly ash content (10% and 20%). In these concrete mixtures, crushed Limestone (#56), natural sand, Type-I/II cement sourced from Buzzi, and class-C fly ash from Red Rock were used.

- Thirty concrete mixtures were prepared, having (0.40, 0.45 and 0.50) and fly ash content (0%, 10% and 20%) with paste fractions of 24%, 27%, 30% and 33%. These concrete mixtures were produced with crushed Limestone (#56), natural sand, type-I Portland cement, and class-C fly ash from Red Rock were used.
- Nine concrete mixtures were made with crushed Limestone (#67) coarse aggregate sourced from Richard Spur, natural sand, type-I Portland cement, and class-C fly ash from Red Rock, having (0.40, 0.45 and 0.50) and fly ash content (0%, 10%, and 20%).
- Six concrete mixtures were made with Muskogee class-C fly ash source, crushed Limestone (#56), natural sand, type-I Portland cement, having (0.40, 0.45 and 0.50) and fly ash content (10%, and 20%).
- Six concrete mixtures were made with Ray Nixon class-C fly ash source, crushed Limestone (#56), natural sand, type-I Portland cement, having (0.40, 0.45 and 0.50) and fly ash content (10%, and 20%).
- Nine concrete mixtures were made with Dolomite (#56) coarse aggregate sourced from Coleman, natural sand, type-I Portland cement and class-C fly ash from Red Rock, having (0.40, 0.45 and 0.50) and fly ash content (0%, 10%, and 20%).
- Nine concrete mixtures were made with Granite (#57) coarse aggregate sourced from Roosevelt, natural sand, type-I Portland cement and class-C fly ash from Red Rock, having (0.40, 0.45 and 0.50) and fly ash content (0%, 10%, and 20%).

2.3 Demolding and Marking

All the concrete samples were demolded after 24 hours of casting. After demolding, each concrete sample was marked with a specific identification number (ID), which represents the mixture design of concrete sample. The nomenclature is shown in Table 2.4.

Table 2.4 Nomenclature of Sample ID

W/C	%FA	Agg. #	Admixtures	Cement Supplier	Fly Ash Supplier	Aggregate Supplier
40 (0.40)	00 (0%)	56	0 (no admixtures)	1 (Central Plains Cement Company)	0 (No Fly Ash)	1 Limestone
45 (0.45)	05 (5%)	57	1 (air-entrainer only)	2 (Buzzi Unicem)	1 (Red Rock)	2 Dolomite
50 (0.50)	10 (10%)	67	2 (Water-reducer only)		2 (Headwaters)	3 Granite
55 (0.55)	15 (15%)		3 (air-entrainer and Water-reducer)		3 (Muskogee)	
60 (0.60)	20 (20%)				4 (Ray Nixon)	

An example is shown in Figure 2.1. In this figure, the ID “50-20-56-0-1-4” represents, 50(0.50 w/cm) – 20 (% Fly ash) – 56 (aggregate size) – 0 (No chemical admixtures) – 1 (Limestone aggregate) – 4 (Ray Nixon fly ash).

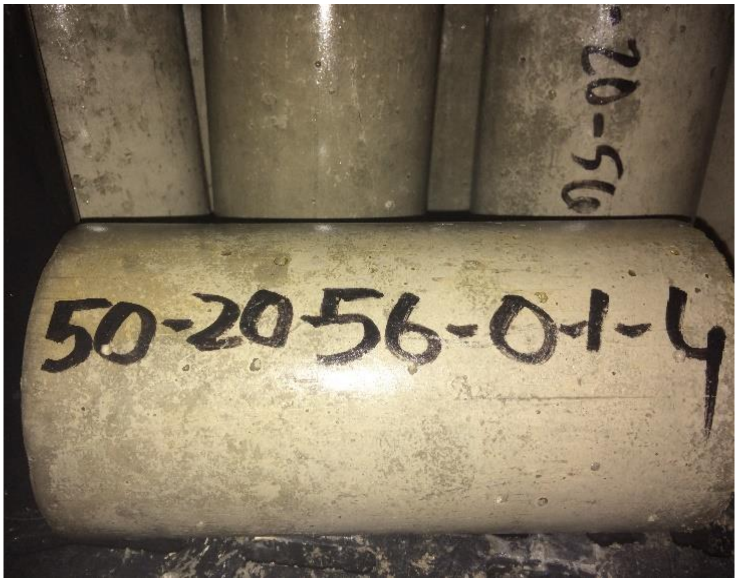


Fig. 2.1 Example of sample ID

2.4 Curing Methods

The concrete samples were cured according to ASTM C511 *"Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes."* All the concrete samples were cured in saturated limewater tank with one expectation; to study the effects of curing and temperature, both limewater storage tanks maintained at two different temperatures and 100% moist curing were conducted.

2.4.1 Limewater Tanks

All the concrete samples were cured in saturated limewater tank storage maintained at 23±2 °C temperature, as shown in Figure 2.2. A study was completed to determine the effect of variation in temperature, the second saturated limewater tank was set up at a controlled temperature of 25 °C by precision tank heater, as shown in Figure 2.3.

Fig. 2.2 Limewater tank at 23°C temperature

Fig. 2.3 Precision tank heater

2.4.2 Moist Room

Some concrete samples were cured in 100% moist room at a controlled temperature of 23±2 °C, as shown in Figure 2.4.

Fig. 2.3 100% moist room at 23±2°C temperature

2.5 Testing Procedures

In this study, various testing procedures were performed according to their respective standards, which include surface resistivity test, compression test, sorptivity test, and percentage absorption test.

2.5.1 Surface Resistivity Test

The surface resistivity test is becoming a popular method to indicate the quality of concrete, not only due to its ability to access the permeability of concrete mixtures having their own rate of resistivity development due to variable w/cm and cementitious materials but also due to its rapid, user-friendly and low-cost procedure. The author found this method a simplest and easiest technique to determine the resistivity of concrete in a controlled environment. The surface resistivity testing was conducted by following AASHTO TP 95, *“Standard Test Method for Surface Resistivity of Concrete’s Ability to Resist Chloride Ion Penetration.”* A set of 6 concrete cylinders were prepared from each concrete mixture to perform resistivity testing, except few mixtures where a set of 3 concrete samples were made.

2.5.2 Compressive Strength Test

The strength of concrete is considered the most important property of concrete along with durability. Like resistivity, the strength of concrete is influenced by water-to-cement (w/cm) ratio, the degree of compaction and curing temperature. However, both methods evaluate concrete based on two different phenomena, pore solution, and aggregate paste bonding. The author wants to analyze the effect of variation in different parameters of concrete and their effect on the relationship between resistivity and compressive strength. The compression test was performed by adopting the ASTM C39/C39M – 17b *"Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens."* A set of 2 or 4 concrete cylinders were prepared from each concrete mixture to perform the compression test, 2 samples at day-28, and 2 samples at day-56, except few mixtures where a set of 3 concrete samples were made for testing at day-28.

2.5.3 Sorptivity Test

The rate of absorption (sorptivity) is one of the important transport mechanisms, which involves ion transport in concrete. This test was chosen for this study because it relates to the ingress of harmful ions (carbon, sulfates, and chlorides) from outside environment breaking into the first barrier (surface) of concrete through capillary action. Little study has been done in the past to determine the relationship between resistivity and sorptivity of concrete. Therefore a good scope of research interested the author for performing the sorptivity test. The sorptivity test was performed by following the ASTM C1585 – 13 *"Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes."*

2.5.4 Percentage Absorption Test

The total volume of water that can be absorbed by a concrete sample is useful information to relate with a the resistivity of the same concrete sample at a given age. In literature, no past studies have been found, which determines the relationship between percentage absorption and resistivity of concrete. Therefore, the author found this test very instructive to relate it with the resistivity of concrete. The percentage absorption test was conducted by adopting the ASTM C642 – 13 *"Standard Test Method for Density, Absorption, and Voids in Hardened Concrete."*

2.6 Research Schedule

The research schedule is spread over four years of research work. The research schedule for spring, summer and fall semesters from years 2013 to 2017 is shown in Table 2.5.

Table 2.5 Research Schedule

Research Design	2013	2014		2015			2016			2017			2018
	S/Su/F	S	F	S	Su	F	S	Su	F	S	Su	F	S
Exposure Regime Setup		▨	▨	▨		▨							
Preparation of Concrete Mixtures			▨	▨	▨	▨	▨	▨	▨	▨	▨		
Surface Resistivity Test				▨	▨	▨	▨	▨	▨	▨	▨		
Compression Test				▨	▨	▨	▨	▨	▨	▨	▨		
Percentage Absorption Test					▨	▨	▨	▨	▨	▨	▨		
Sorptivity Test					▨	▨	▨	▨	▨	▨	▨	▨	
Data Collection			▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	
Data Analysis						▨	▨	▨	▨	▨	▨	▨	
Modelling/ Statistical Criteria & Validation							▨	▨	▨	▨	▨	▨	
Dissertation and Submittal										▨	▨	▨	▨

CHAPTER 3

EFFECT OF AGGREGATE TYPE AND SIZE ON SURFACE RESISTIVITY TESTING

Preface

In this study, the author and undergrad research team, under the supervision of Dr. Julie Ann Hartell, prepare all the concrete mixtures with different sizes and types of aggregates at Bert Cooper Engineering Lab to determine the effect of the variation in aggregate properties on surface resistivity testing.

Abstract

Surface resistivity testing has gained popularity as a nondestructive test method to assess the physical and chemical characteristics of concrete. This may be due to the fact that it is sensitive to variations in material parameters, especially cementitious phases. This experimental investigation concentrates on the effects of coarse aggregate type and gradation to determine whether they may be contributing factors in the variability of the resistivity measurements for a given cementitious binder. A total of 21 concrete mixtures designed with various aggregate type (limestone, dolomite, and granite), gradation (#67, #57 and #56) and binders (0.4, 0.45, 0.5 w/c with Type I cement and class-C fly ash) were prepared and evaluated using surface resistivity testing. It was found that small changes in gradation may not necessarily influence the outcome of a resistivity test for a given mortar matrix. As for a change in aggregate type, there is minimal impact on the resistivity measurement for mixtures prepared with a type I cement binder; however, the addition of fly ash seems to have a significant impact. The change in resistivity gain in time varied for all three aggregate types. Here, aggregate-paste interaction had a role in either diminishing or increasing the resistivity value which may be consequential for concrete mixture classification with respect to ionic penetrability and misinterpretation of binder performance.

Author keywords: Surface resistivity; aggregate type; gradation; water-to-cement ratio; fly ash

3.1 Introduction

The four-point probe resistivity method was initially developed by Wenner in the early 1900s to measure the resistivity of soils to indicate their permeability characteristics. With time, resistivity testing has gained popularity in the concrete industry as a nondestructive surface method due to its rapid, low cost and simple procedure. It is a versatile test with many applications due to its sensitivity to chemical and physical properties of materials.

Surface resistivity has long been used to evaluate the performance of a concrete mixture with respect to its resistance to ionic movement. It has been used in the field to assess corrosion activity of reinforced concrete structures. Concrete resistivity is inversely related to corrosion potential after depassivation of reinforcement. The method can be used to determine the likelihood of ongoing steel corrosion during its initiation and propagation as the electrochemical process takes place. Moreover, it may provide an indication on whether a concrete may be susceptible to corrosion. Concrete with a low resistivity measurement could imply the threat of corrosion and likely to have a higher rate of corrosion than concrete of higher resistivity. (Bungey et al. 2006) This principle was utilized to develop a laboratory-based method to aid in qualifying mixtures based on their resistance to ionic movement or, in this case, chloride ion penetrability.

Corrosion performance and resistance to chloride ion penetration has traditionally been determined by performing the Rapid Chloride Permeability test (RCPT) (ASTM C 1202). In efforts to find another method which is simpler and less time consuming, it was found that the surface resistivity method suited the need as it correlates well with RCPT. This led to the development of a standardized procedure (AASHTO TP95) where resistance to ion penetrability classification equivalencies to that of RCPT are provided. (Kessler et al. 2005 and 2008; Layssi et al. 2015) With that, the development of the method expanded, and its versatility widen.

The ability of the method to detect changes in the microstructure of the cementitious matrix has also been of interest. Detection of crack initiation and monitoring of crack propagation may be possible using resistivity-based techniques due to the method's sensitivity to physical characteristics of pore structure where an increase in size facilitates ionic transport assuming presence of an electrolyte (Lastate et al. 2003; Layssi et al. 2015). Moreover, the method may be useful to locate areas of high moisture content or containing undesirable concentrations in detrimental agents due to the inherent property of conductivity of electrolytes (Polder 2000). Likewise, this concept may also be useful for determining the setting time of cement paste and concrete due to the nature of cement hydration and its physico-chemical changes in time. Again, the underlying principles of cement hydration, a continuously changing pore solution chemistry and pore refinement, can be applied towards monitoring or modeling the maturity of a concrete mixture with respect to curing temperature along with compressive strength prediction (Layssi et al. 2015; Bentz et al. 2014; Ramezanianpour et al. 2011; Xiao and Wei 2011; Ferreira and Jalali 2010). This non-exhaustive list grows with the development of the concepts of Formation Factor and cementitious phase modeling (Spragg et al. 2013; Samson et al. 2000). For each application exists a commonality where the method is used to better understand the performance of the cementitious matrix. The change in resistivity measurement is attributed to the changes in the cementitious matrix with respect to a concrete property. Here, the role of the aggregate portion and how it influences the measured resistivity is not necessarily taken into account. For every test method, there are factors influencing its accuracy and limitations to what the test method can actually measure with a certain degree of reliability. Hence, it is of importance to understand the contribution of other present materials and its composite effect on the measurement.

There is limited information available in literature on the effect of the aggregate fraction of a concrete mixture on resistivity testing. Limited studies have been conducted which investigates the influence of aggregate size, type and paste volume fraction of concrete mixtures for the resistivity test. It was observed that an increase in size and content of coarse aggregates would increase the resistivity of concrete due to an increase in aggregate volume and, consequently, a decrease in porous cement paste (Morris et al. 1996; Azarsa and Gupta 2017). Similarly, for a given aggregate gradation, an increase in paste fraction results in a decrease in resistivity (Sengul 2014; Azarsa and Gupta 2017). In addition, the type of aggregate, in terms of texture and shape, may also affect the resistivity of concrete. Concrete mixtures made with an angular aggregate measured higher resistivity compared to that containing a rounded aggregate. This may be attributed to differences in tortuosity and bonding of paste-aggregate interface (Morris et al. 1996; Sengul 2014). As for the type of aggregate, one study reported that the use of a granitic coarse aggregate in a concrete mixture containing a class-F fly ash resulted in higher resistivity measurements than that containing a limestone aggregate type at elevated curing temperatures (Liu and Moreno 2014). However, with standardization and widespread use of the method, expanding our understanding of influential concrete parameters which may have a significant effect on resistivity properties of concrete is of importance.

This experimental investigation concentrates on the effects of coarse aggregate type and gradation to determine whether they may be contributing factors in the variability of the resistivity measurements. Locality of aggregate material plays a significant role in variance of its properties, which could affect the properties of concrete and/or the outcome of a standard test.

The research outcomes could be helpful to understand this potential impact of using different types and gradation of aggregates on the resistivity of a mixture prepared with a given cementitious binder.

3.2 Experimental Procedure

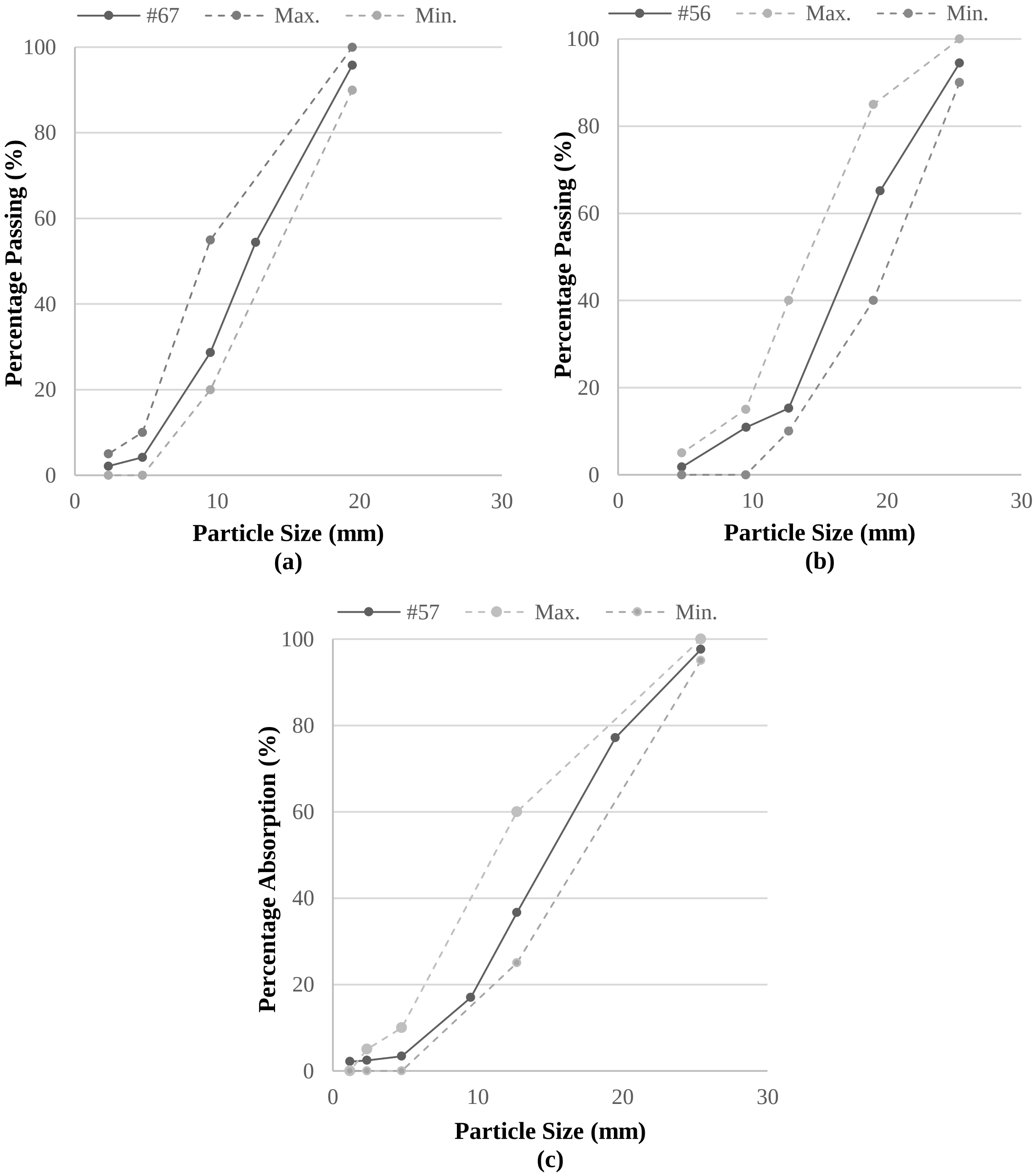
The experimental procedure was designed to investigate the influence of aggregate selection for concrete on surface resistivity testing. To that end, various concrete mixtures consisting of different aggregate types and gradation were prepared while maintaining the cementitious proportions constant.

3.2.1 Materials

First, the effect of coarse aggregate type on the resistivity behavior of concrete mixtures was investigated by preparing concrete mixtures with three different types of aggregates: limestone, dolomite, and granite. The chemical composition of the aggregate material is given in Table 3.1.

Table 3.1 Chemical Properties of Coarse Aggregates

Chemical Compounds	Limestone	Dolomite	Granite
		(% by weight)	
Ca	35.93	20.67	7.24
CaO	50.27	28.92	10.13
$CaCO_3$	89.73	51.62	18.08
Mg	1.02	9.74	1.07
MgO	1.69	16.15	1.77
$MgCO_3$	3.54	33.77	3.71
Fe_2O_3	0.25	0.85	4.07
Al_2O_3	0.6	2.08	16.91
Si	3.38	4.03	24.3
SiO_2	7.24	8.63	51.99
NaO	-	-	0.422
TiO2	-	-	0.16
K2O	-	-	0.316



(a)

(b)

(c)

Fig. 3.1(a,b,c) Sieve analysis of #67, #56 and #57 aggregate sizes

Next, the influence of aggregate gradation on surface resistivity behavior of concrete mixtures was analyzed by preparing specimens with gradations respecting #67, #57 and #56 classes as per ASTM C 33 *"Standard Specification for Concrete Aggregates"* (American Society of Testing and Materials). Crushed limestone coarse aggregates coming from the same quarry were used in the preparation of the mixtures. The percent passing gradations for each coarse aggregate material were determined in accordance with ASTM C 136 (Figure 3.1). The aggregate material was sampled directly from the aggregate stockpile used in the preparation of the mixtures. As for the fine aggregate proportion of the concrete mixture, the same natural sand, quartz, was used in the preparation of all samples to minimize any variability in results for this parametric investigation.

A type-I Portland cement as per ASTM C 150 *"Standard Specification for Portland Cement"* was used in the preparation of all concrete mixtures. Moreover, the interaction between supplementary cementitious material (SCM) addition such as fly ash and aggregate composition was investigated, as it may influence the resistivity measurement according to Liu et al. (2014). A class-C fly ash (ASTM C 618) locally available in the state of Oklahoma was used in the preparation of the concrete mixtures. The chemical compositions of the cement and fly ash are shown in Tables 3.2 and 3.3.

Table 3.2 Chemical Properties of Portland cement

Chemical composition (% by weight)					
MgO	CaO	SO_3	SiO_2	Al_2O_3	Fe_2O_3
1.9	62.9	3.3	19.4	5.1	3.4

Table 3.3 Chemical Composition of Class-C fly ash

Chemical composition (% by weight)							
K2O	MgO	CaO	SO_3	Na_2O	SiO_2	Al_2O_3	Fe_2O_3
0.58	5.55	23.12	1.27	1.78	38.71	18.82	5.88

3.2.2 Sample Preparation and Conditioning

Concrete mixtures (21) were prepared in a controlled laboratory environment following ASTM C192. Several mixture designs, which varied in the water-to-cement ratio (0.40, 0.45 and 0.50 w/cm) and class-C fly ash content (0% FA and 20% FA), were investigated in order to better understand the relative effect of coarse aggregate type on the resistivity properties of standard concrete mixtures. The concrete mixture proportions are presented in Table 3.4. The paste content ranged from 25.8% to 30.5%, and the fine-to-coarse aggregate ratio was kept 0.4 for all concrete mixtures.

Table 3.4 Mixture Design Details

	Mixture	w/cm	Fly Ash (%)	Water (kg/m^3)	Cement (kg/m^3)	Fly Ash (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Paste (%)
Limestone	1	0.40	0%	145.4	362.5	0	1097.6	714.9	27.8%
	2	0.40	20%	145.4	290.0	72.5	1097.6	714.9	27.8%
	3	0.45	0%	163.2	362.5	0	1097.6	714.9	29.2%
	4	0.45	20%	163.2	290.0	72.5	1097.6	714.9	29.2%
	5	0.50	0%	181.5	362.5	0	1097.6	714.9	30.5%
	6	0.50	20%	181.5	290.0	72.5	1097.6	714.9	30.5%
Dolomite	7	0.40	0%	145.4	362.5	0	1163.5	816.6	25.8%
	8	0.40	20%	181.5	290.0	72.5	1163.5	816.6	25.8%
	9	0.45	0%	145.4	362.5	0	1163.5	770.3	27.9%
	10	0.45	20%	181.5	290.0	72.5	1163.5	770.3	27.9%
	11	0.50	0%	145.4	362.5	0	1163.5	724.4	29.7%
	12	0.50	20%	181.5	290.0	72.5	1163.5	724.4	29.7%
Granite	13	0.40	0%	145.4	362.5	0	1145.5	861.1	26.1%
	14	0.40	20%	145.4	290.0	72.5	1145.5	861.1	26.1%
	15	0.45	0%	163.2	362.5	0	1145.5	814.8	27.6%
	16	0.45	20%	163.2	290.0	72.5	1145.5	814.8	27.6%
	17	0.50	0%	181.5	362.5	0	1145.5	766.4	29.4%
	18	0.50	20%	181.5	290.0	72.5	1145.5	766.4	29.4%
#56	19	0.45	20%	163.2	290.0	72.5	1097.6	714.9	29.2%
#57	20	0.45	20%	163.2	290.0	72.5	1097.6	714.9	29.2%
#67	21	0.45	20%	163.2	290.0	72.5	1156.8	800.92	27.0%

All material batching, concrete mixing, and casting procedures were carried out within a temperature-controlled laboratory to minimize variability in test measurements. Common material quality control was performed in accordance with relevant ASTM standardized procedures. The required number of cylindrical specimens (Ø100 mm x 200 mm cylinders) were sampled from a single batch to ensure reproducibility of test results. For the present study, six specimen replicates for each mixture type were prepared for a total of 126 specimens. They were prepared in three equal layers using rodding as the method of consolidation. Then, they were demolded after 24 hours of curing in their molds and placed in a temperature controlled limewater tank, ASTM C 511, for the duration of the test period.

3.2.3 Surface Resistivity Testing

The surface resistivity testing was performed on Ø100 mm x 200 mm cylindrical samples in accordance with the procedure described in AASHTO TP 95 *"Standard method of test for surface resistivity indication of concrete's ability to resist chloride ion penetration"* (American Association of State Highway and Transportation Officials, 2014). The four probes are placed on a concrete surface producing an adequate electrical contact. The external probes produce a pulse of alternating current traveling though the concrete medium; meanwhile, the inner two probes, attached to a voltmeter, amount the potential difference between the probes (American Concrete Institute, 2013).

The apparent resistivity value can be calculated from Equation 1. Where ρ is the apparent resistivity (ohm-cm), s is spacing between probes (cm), V is the measured voltage (volts), and I is the amplitude of alternating current (amps). For the apparatus used, the measured resistivity corresponds to the apparent resistivity of a Ø100 mm x 200 mm-cylindrical sample. The surface resistivity measurements were taken with a fixed probe spacing of 38 mm.

$$\rho = \frac{2\pi s V}{I} \tag{1}$$

On the first day of testing, which was immediately after demolding the samples, each sample was marked at four different points equally spaced at 90° of the transverse axis to ensure repetition of the resistivity measurements at the same location for the duration of the test period. Subsequent to taking the measurements, the cylinders were cured in limewater maintained at 23±2°C for the rest of the testing period. During this time, resistivity measurements were recorded on days 3 and 7 during the first week; then, weekly up to 56 days of curing. To ensure a moist test surface, the samples were lightly sprayed with tap water, and excess water was removed with a damp cloth by tapping the test surface. This also ensured removal of any salt accumulation on the test surface caused by saturated limewater curing. Moreover, the ambient temperature was kept within (AASHTO TP95) standard range of 20 °C and 25 °C, to minimize variability in the resistivity measurements (Polder et al. 2000, Gulrez and Hartell 2017).

3.3 Results and Discussions

The influence of aggregate type and gradation on the surface resistivity of concrete mixtures is determined via comparative analysis. The results of the experimental phase are presented in the form of surface resistivity versus timeline charts where variation from the mean is expressed as two standard deviations from the mean (95% confidence interval). Here, the resistivity behavior during the test period of 56 days is compared for similarities in resistivity gain and trends over time. Next, the comparative analysis was performed for data sets obtained at 7, 28 and 56 days, as those measurement days are commonly used in the industry to assess early-age, standard and long-term (respectively) properties of concrete. The data sets, composing of six cylinder replicates per mixture, were analyzed with an ANOVA followed by Tukey's test and Student t-test in order to determine whether a change in aggregate type (limestone, dolomite, granite) and a small variation in aggregate gradation (#56, #57, #67) alters the outcome of a surface resistivity test for concrete mixtures of similar binding phase. In the phase testing the effect of coarse aggregate type on surface resistivity testing, three water-to-cementitious materials ratio (0.4, 0.45 and 0.5 w/cm) are investigated along with two different binder compositions (100% type I Portland cement and an 80% cement and 20% class-C fly ash blend). As for the phase testing, only one water-to-cement ratio (0.45 w/cm) was investigated, as quantities of material for this study were limited. Results are presented in tabular format.

3.3.1 Effects of Various Aggregate Type on Surface Resistivity Testing

First, the results from mixtures made with Portland cement will be discussed. Figure 1 (a,b,c) demonstrate the time-resistivity curves of 0.40, 0.45, and 0.50 w/cm mixtures made with crushed limestone, dolomite and granite rock. Within the variability of the results, it can be seen that there is a similar trend in resistivity gain over time for specimens made with the three aggregate types. Between the three w/cm, there is no clear trend on whether an aggregate type results in a higher or lower resistivity value with respect to the other types. For the 0.40 w/cm mixtures, the mean values obtained for the limestone aggregate is continuously lower than the two other samples; however, the granite aggregate mixture records lower values for the 0.45 w/c and 0.50 w/c. Moreover, for the 0.50 w/cm mixtures, limestone recorded the highest values. However, variations in resistivity values through time (peaks and valleys) are noticeable for the granite and dolomite concrete curves, especially at 28- and 56-day test ages. These differences are attributed to slight variations in curing temperature and ambient temperature at the time of the test, which may be significant when outside allowable limits (Gulrez and Hartell 2017). This concept will be taken into account when assessing the null hypothesis on whether the aggregate type has no influence on the test outcome for similar binders.

For all test ages, there is a significant difference between sample means according to the returned p-values of ANOVA test for the 0.40 w/cm mixtures (Tables 3.5, 3.6, and 3.7). Conducting the post hoc tests, it seems that there is a significant difference between the resistivity readings of the limestone mixtures and that of both the granite and dolomite mixtures. Meanwhile, the results indicate differences between limestone and dolomite mixtures only at day-56. As for the granite aggregate mixture, the decrease in resistivity due to a decrease in ambient temperature at the time of test may have caused the change in behavior as that seen for the other test ages (Figure 3.2a). A percent difference between mixtures above approximately 10% yielded differences as the coefficients of variation remain below that recommended by the standard procedure (8.6%).

Table 3.5 Results of Statistical Analysis at Day-7 with 0% Fly Ash Content

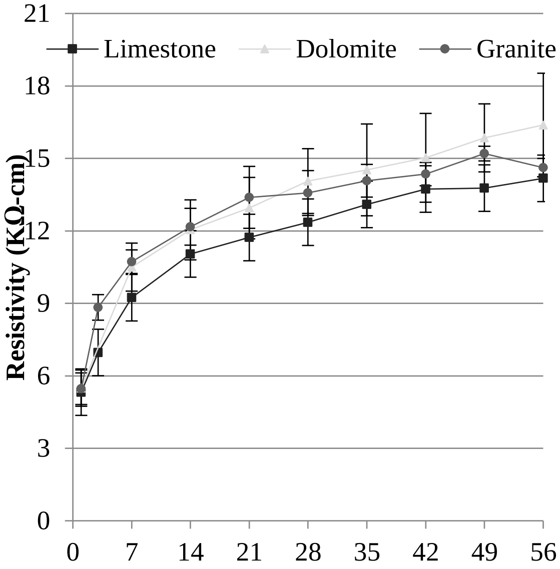
w/cm	Aggregate Type	Resistivity (KΩ-cm)			ANOVA	Comp.	Tukey's test	T-test	Diff. (%)
		Mean	Std. Dev.	COV (%)					
0.40	Limestone (L)	9.2	0.34	3.7	1 E-5	D/G	-	0.343	1.8
	Dolomite (D)	10.5	0.50	4.7		L/G	Sig. diff.	5.5 E-6	15.0
	Granite (G)	10.7	0.24	3.0		L/D	Sig. diff.	4 E-4	13.1
0.45	Limestone (L)	8.8	0.49	5.6	0.210	D/G	-	0.187	4.4
	Dolomite (D)	9.3	0.34	3.7		L/G		0.796	1.1
	Granite (G)	8.9	0.64	6.7		L/D		0.061	5.5
0.50	Limestone (L)	7.5	0.28	3.6	0.702	D/G	-	0.530	2.6
	Dolomite (D)	7.5	0.41	5.5		L/G		0.513	2.6
	Granite (G)	7.7	0.67	9.6		L/D		0.968	0.0

Table 3.6 Results of Statistical Analysis at Day-28 with 0% Fly Ash Content

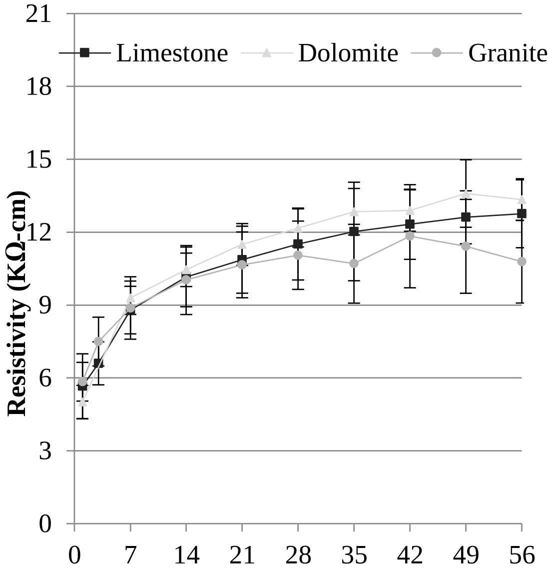
w/cm	Aggregate Type	Resistivity (KΩ-cm)			ANOVA	Comp.	Tukey's test	T-test	Diff. (%)
		Mean	Std. Dev.	COV (%)					
0.4	Limestone (L)	12.4	0.47	3.8	2.1 E-4	D/G	-	0.167	3.5
	Dolomite (D)	14.1	0.67	4.8		L/G	Sig. diff.	0.001	9.7
	Granite (G)	13.6	0.46	3.4		L/D	Sig. diff.	5 E-4	13.7
0.45	Limestone (L)	11.5	0.74	6.4	0.024	D/G	Sig. diff.	0.006	9.0
	Dolomite (D)	12.2	0.39	3.2		L/G	-	0.293	3.5
	Granite (G)	11.1	0.70	6.4		L/D	-	0.081	6.1
0.5	Limestone (L)	10.2	0.40	3.9	0.128	D/G	-	0.451	3.1
	Dolomite (D)	9.7	0.54	5.6		L/G		0.064	7.8
	Granite (G)	9.4	0.76	8.1		L/D		0.146	4.9

Table 3.7 Results of Statistical Analysis at Day-56 with 0% Fly Ash Content

w/cm	Aggregate Type	Resistivity (KΩ-cm)			ANOVA	Comp.	Tukey's test	T-test	Diff. (%)
		Mean	Std. Dev.	COV (%)					
0.4	Limestone (L)	14.2	0.55	3.9	0.016	D/G	-	0.048	11.0
	Dolomite (D)	16.4	1.07	6.5		L/G	-	0.230	2.8
	Granite (G)	14.6	0.19	1.3		L/D	Sig. diff.	0.004	15.5
0.45	Limestone (L)	12.8	0.70	5.5	0.013	D/G	Sig. diff.	0.009	18.8
	Dolomite (D)	13.3	0.43	3.2		L/G	Sig. diff.	0.008	15.6
	Granite (G)	10.8	0.85	7.9		L/D	-	0.106	3.9
0.5	Limestone (L)	11.2	0.28	2.5	0.165	D/G	-	0.383	5.8
	Dolomite (D)	10.4	0.32	3.1		L/G		0.149	12.5
	Granite (G)	9.8	1.12	11.4		L/D		0.006	7.1



(a)



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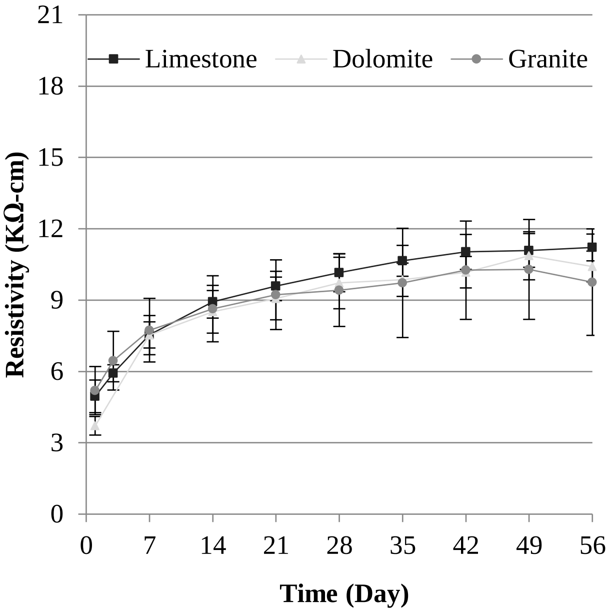
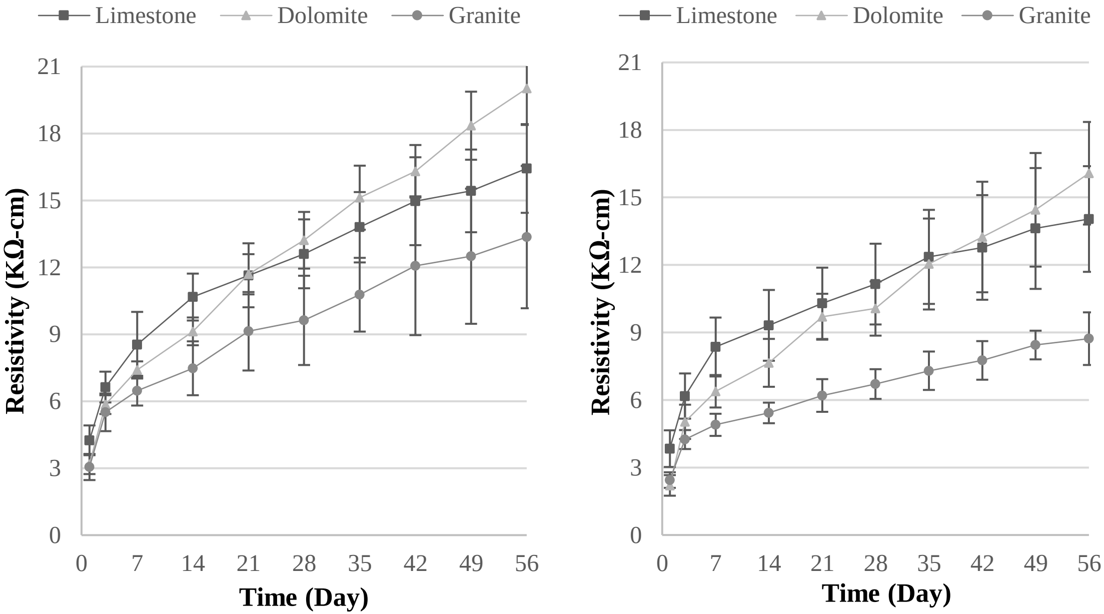


(c)

Fig. 3.2 Time-resistivity behavior of 0% fly ash concrete mixtures (a) 0.40 w/cm (b) 0.45 w/cm (c) 0.50 w/cm with varying aggregate type

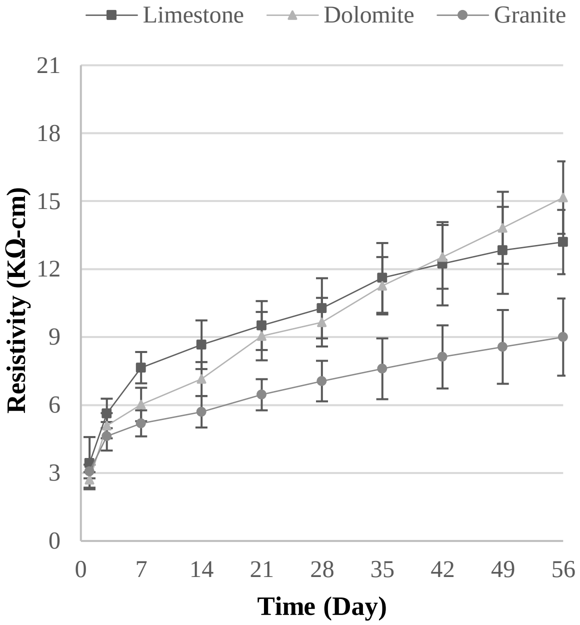
A similar trend is noticeable for 0.45 w/c mixtures (Figure 3.2b), at the age of day-7, there is no significant difference found between the means of the samples, but with an increase in age, a significant difference is obtained in results from ANOVA test performed at days 28 and 56. This shows that in the beginning (7 days), the comparative samples attain the same resistive property, and then it disperses with an increase in age. This may be due to the influence of aggregate properties. Post analysis demonstrates a difference between dolomite and granite samples at test ages of 28 and 56 days with a mean difference up to 18% approximately and coefficients of variation within the allowable range. It seems like the difference in mean resistivity for the different aggregate types increases with concrete age, which might be due to the influence of aggregate properties on paste medium. However, the effects of temperature at time of test, espacially at 56 days may have also played an influential role in the differences observed.

The temperature effect was not as predominant for the 0.50 w/c mixtures. This may have contributed to no observable differences between all of the aggregate types at the three different test ages (Figure 3.2c). As such, it would seem that the change in aggregate type (limestone, dolomite, granite) did not affect the outcome of the resisitivity test for a portland cement concrete mixture. Conversely, the addition of fly ash to the cementitous blend seemed to have a different outcome.



(a)

(b)



(c)

Fig. 3.3 Time-resistivity behavior of 20% fly ash concrete mixtures (a) 0.40 w/cm (b) 0.45 w/cm (c) 0.50 w/cm with varying aggregate type

The same study was repeated to evaluate whether a change in binder chemistry would yield similar results as that observed for the ordinary portland cement mixtures. The same mixtures were prepared but with a 20% cement replacement with a class-C fly ash. Figure 3.3 (a,b,c) displays the time-resistivity curves of mixtures prepared with limestone, dolomite and granite aggregates having 0.40, 0.45 and 050 w/cm. Opposing to that observed for the Portland cement mixtures, the resistivity profiles for each of the concrete mixtures prepared with a different aggregate. In addition, these mixtures had a similar trend for all three w/cm investigated. The figures show that the limestone samples gain higher resistivity compared to that of dolomite and granite samples at an early age. However, the mixtures containing a dolomite aggregate attain a higher resistivity value due to a higher rate in resistivity gain over time. This behavior is not observed for the concrete prepared with the granite aggregate; they maintained a lower resistivity profile than that of dolomite and limestone concrete samples.

Table 3.8 Results of Statistical Analysis at Day-7 with 20% Fly Ash Content

w/cm	Aggregate Type	Resistivity (KΩ-cm)			ANOVA	Comp.	Tukey's test	T-test	Diff. (%)
		Mean	Std. Dev.	COV (%)					
0.40	Limestone (L)	8.5	0.73	8.6	9 E-5	D/G	Sig. diff.	0.002	12.9
	Dolomite (D)	7.4	0.19	2.6		L/G	Sig. diff.	9 E-5	26.6
	Granite (G)	6.5	0.33	5.1		L/D	Sig. diff.	0.011	13.8
0.45	Limestone (L)	8.4	0.65	7.8	5 E-9	D/G	Sig. diff.	8 E-5	26.5
	Dolomite (D)	6.4	0.36	5.6		L/G	Sig. diff.	3 E-6	52.6
	Granite (G)	4.9	0.25	5.0		L/D	Sig. diff.	7 E-5	27.0
0.50	Limestone (L)	7.7	0.35	4.5	8 E-8	D/G	Sig. diff.	0.001	14.2
	Dolomite (D)	6.0	0.37	6.1		L/G	Sig. diff.	1 E-7	38.8
	Granite (G)	5.2	0.29	5.5		L/D	Sig. diff.	1 E-5	24.8

Table 3.9 Results of Statistical Analysis at Day-28 with 20% Fly Ash content

w/cm	Aggregate Type	Resistivity (KΩ-cm)			ANOVA	Comp.	Tukey's test	T-test	Diff. (%)
		Mean	Std. Dev.	COV (%)					
0.4	Limestone (L)	12.6	0.80	6.1	3 E-6	D/G	Sig. diff.	2 E-5	27.3
	Dolomite (D)	13.2	0.60	4.8		L/G	Sig. diff.	2 E-4	23.8
	Granite (G)	9.6	1.00	10.4		L/D	-	0.167	4.8
0.45	Limestone (L)	11.2	0.90	8	1 E-8	D/G	Sig. diff.	3 E-7	33.7
	Dolomite (D)	10.1	0.60	6		L/G	Sig. diff.	2 E-5	40.2
	Granite (G)	6.7	0.30	4.9		L/D	Sig. diff.	0.033	9.8
0.5	Limestone (L)	10.3	0.70	6.5	1 E-7	D/G	Sig. diff.	4 E-6	26.8
	Dolomite (D)	9.7	0.50	5.6		L/G	Sig. diff.	2 E-6	31.1
	Granite (G)	7.1	0.40	6.3		L/D	-	0.109	5.8

Table 3.10 Results of Statistical Analysis at Day-56 with 20% Fly Ash content

w/cm	Aggregate Type	Resistivity (KΩ-cm)			ANOVA	Comp.	Tukey's test	T-test	Diff. (%)
		Mean	Std. Dev.	COV (%)					
0.4	Limestone (L)	16.4	0.99	6	0.002	D/G	Sig. diff.	0.003	33.0
	Dolomite (D)	20	0.82	4.1		L/G	Sig. diff.	0.008	18.3
	Granite (G)	13.4	1.59	11.9		L/D	Sig. diff.	0.001	22.0
0.45	Limestone (L)	14	1.20	8.4	3 E-4	D/G	Sig. diff.	6 E-4	46.0
	Dolomite (D)	16.1	1.10	7.1		L/G	Sig. diff.	2 E-4	37.9
	Granite (G)	8.7	0.60	6.7		L/D	Sig. diff.	0.043	15.0
0.5	Limestone (L)	13.2	0.70	5.4	0.003	D/G	Sig. diff.	8 E-4	40.8
	Dolomite (D)	15.2	0.80	5.3		L/G	Sig. diff.	1 E-4	31.8
	Granite (G)	9	0.90	9.5		L/D	Sig. diff.	0.007	15.2

The comparative analysis of the three aggregate type mixtures is shown in Tables 3.8, 3.9 and 3.10. The results demonstrate that there is a significant difference in resistivity measurements observed based on the ANOVA test between the three aggregates types at days 7, 28 and 56. For concrete prepared with a blend of 20% class-C fly ash and 80% Type I Portland cement, a change in aggregate type may change the outcome of the resistivity test. Likewise, the results of Tukey's test and t-test show significant differences between mean resistivity values for mixtures made with limestone, dolomite, and granite aggregates. Except for the test age of 28-days, the recorded percent difference in mean values between the mixtures containing limestone and dolomite aggregate are 4.8%, 9.8% and 5.8% for the 0.40 w/cm, 0.45 w/cm and 0.50 w/cm respectively making them marginally significant to insignificant. This is due to the crossing of both curves near that test ages. Based on the profile trends and comparative analysis at 7- and 56-days, the aggregate type may have an effect on the development of resistivity properties over time.

Based on the observed results and limited literature on the interaction of aggregate type and cementitious phase on electrical properties, it is difficult to comment on the contribution of each element of the concrete mixture and their role on conductivity properties without further investigation. With the development of this test method and intended applications such as evaluating the durability of a concrete mixture and its susceptibility to initiating steel corrosion, it is important to understand its limitations. In this case, the concrete mixtures prepared with a granite aggregate and a class-C fly ash would be classified as a high risk to chloride ion penetration even at a 0.40 w/cm. However, a mixture containing no fly ash and a granite aggregate would be deemed moderate to chloride ion penetration. Further research into this behavior is necessary to understand the phenomena.

3.3.2 Effects of Various Aggregate Size on Surface Resistivity Testing

The effect of aggregate size and gradation on resistivity testing was evaluated using #67, #56 and #57 sizes of crushed limestone aggregates in concrete mixtures. It has been investigated in the past that the increase in the size of aggregates cause an increase in resistivity of concrete. Similarly, a decrease in size of aggregates causes a decrease in resistivity measurements possibly due to the increase in surface area and formation of more interfacial transition zones (ITZ) (Azarsa and Gupta, 2017). It is known that the ITZ zones are more permeable than the rest of the porous structure. The smaller size aggregates have a larger surface area to interact with mortar, which results in the creation of more ITZ zones that might influence in lower resistivity of concrete samples. However, if larger maximum size aggregates are used in concrete mixtures, the aggregates have less surface area compared to smaller size aggregates and less ITZ zones will be created that may influence in higher resistivity. The large size of aggregates provides increased resistance due to low porosity compared to porous cement medium. Therefore, the size of aggregates and its gradation may have an influence on the outcome of a resistivity test for a given mortar matrix.

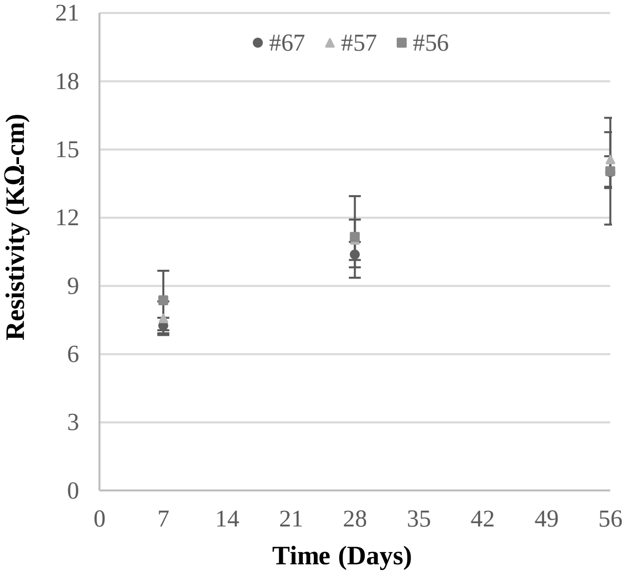


Fig. 3.4 Influence of aggregate sizes on resistivity measurements 20% FA

Table 3.11 Results of Statistical Analysis at Day-7

w/cm	Aggregate	Resistivity (KΩ-cm)			ANOVA	Comp.	Tukey's test	T-test	Diff. (%)
	Limestone	Mean	Std. Dev.	COV (%)					
0.45-20%	56	8.4	0.65	7.8	4.4 E-3	57/56	-	0.103	9.5
	57	7.6	0.37	4.9		56/67	Sig. diff.	0.008	15.1
	67	7.3	0.17	2.4		57/67	-	0.106	4.1

Table 3.12 Results of Statistical Analysis at Day-28

w/cm	Aggregate	Resistivity (KΩ-cm)			ANOVA	Comp.	Tukey's test	T-test	Diff. (%)
	Limestone	Mean	Std. Dev.	COV (%)					
0.45-20%	56	11.2	0.90	8.0	0.125	57/56	-	0.834	1.8
	57	11.0	0.44	4.0		56/67	-	0.028	7.7
	67	10.4	0.28	2.7		57/67	-	0.190	5.8

Table 3.13 Results of Statistical Analysis at Day-56

w/cm	Aggregate	Resistivity (KΩ-cm)			ANOVA	Comp.	Tukey's test	T-test	Diff. (%)
	Limestone	Mean	Std. Dev.	COV (%)					
0.45-20%	56	14.0	1.17	8.3	0.205	57/56	-	0.655	4.3
	57	14.6	0.60	4.1		56/67	-	0.236	0.0
	67	14.0	0.35	2.5		57/67	-	0.298	4.3

In Figure 3.4, the results of surface resistivity testing on concrete specimens made with 0.45 w/cm and cement replacement with 20% fly ash at days 7, 28 and 56 are shown. The data points of three aggregate sizes are close, and standard deviation bars (95% confidence interval) are overlapping with each other. The statistical analysis of #67, #56 and #57 mixtures are shown in Tables 3.11, 3.12 and 3.13. A significant difference is identified between the three aggregate sizes samples from ANOVA test at day 7, whereas, there is no significant difference found among the aggregate sizes samples at the age of 28 and 56 days. Further analysis shows that there is a significant difference in resistivity between #56 and #67 aggregate samples. The low coefficient of variation obtained for the #67 aggregate mixture (2.6%) may have contributed the rejection of the null hypothesis; still, the percent difference of 15.1% is considerable high leading to the results observed. Therefore, it may be that an early developmental age and the effect of ITZ permeable zones due to the difference in aggregates gradation, #56 and #67, may be an influential factor; however, at a later stage in cement hydration, a small variance in aggregate size and gradation does not seem to change the outcome of a resistivity test for a given mortar matrix. Still, the sampling type is limited for this preliminary study and further investigation is necessary to ascertain the behavior for other w/cm and cement blends.

3.4 Conclusion

Surface resistivity testing is becoming a popular method to evaluate the quality and durability of placed concrete. Due to the composite nature of concrete, a variety of materials is available on the market, which could affect the properties of concrete and/or the outcome of a standard test. Complementary to previous investigations, the findings of this study could be helpful to understand the impact of using different types and gradation of aggregates on the resistivity of a mixture with the same cementitious binder.

Preliminary findings demonstrate a potential marginal difference to no difference between the mixtures prepared with limestone, dolomite and granite aggregate and ordinary Portland cement binder. The trends were similar for their development in resistivity over time. However, this was not the case for the same mixture designs with 20% cement replacement with a class-C fly ash. The resistivity behavior in time for the samples changed in comparison to that of the samples containing no fly ash and varied by aggregate type. In this case, the aggregate type may influence the outcome of a test leading to differences in result interpretation in accordance with AASHTO TP95. As for the size and gradation of aggregates, small changes in aggregate gradation may not influence the outcome of a resistivity test for a given mortar matrix. However, the sample types studied herein are limited and conclusions are based on materials investigated only. As information is limited on the observed phenomena, further investigation is required to better understand the impact of aggregates on concrete resistivity properties.

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CHAPTER 4

EFFECT OF WATER-REDUCER AND AIR-ENTRAINER ON SURFACE RESISTIVITY TESTING

Preface

In this study, the author and undergrad research team, under the supervision of Dr. Julie Ann Hartell, prepared all the concrete mixtures with the addition of water-reducer and air-entrainer to determine the effect of these chemical admixtures on resistivity compared to the similar mixtures not added with chemical admixtures. In addition, the influence of 20% fly ash replacement in the presence of water-reducer and air entrainer on surface resistivity was also investigated.

Abstract

Surface resistivity technique is achieving popularity as a quality control test, due to its sensitivity to variation in material parameters in concrete mixtures. This study is a contribution to the research work previously done to determine the effect of addition of chemical admixtures (water-reducer and air entrainer) on surface resistivity testing. It was concluded that the addition of water reducer and air entrainment admixtures did not affect the resistivity measurements unless fly ash content was added in the concrete mixtures.

Author keywords: Surface resistivity; Aggregate; Paste volume; Water reducer; Air entrainment; Fly ash

4.1 Introduction

In early 1900s, Wenner developed four-probe resistivity method. With time resistivity testing has gained popularity as a non-destructive surface method due to rapid, low cost and ease of conducting resistivity measurements that indicate the ability of concrete to conduct current. Based on past investigations and continuous efforts by researchers and scholars lead to the development of AASHTO TP 95 "*Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration"* (American Association of State Highway and Transportation Officials, 2014) [1]. While ASTM (American Society of Testing and Materials) Committee C09 is in the process of developing a standard procedure for evaluating the surface electrical resistivity of concrete [2]. In recent years, the surface resistivity testing became a popular method in the construction industry for the quality control and durability assessment of concrete. Also, some state agencies have adopted, and several state and federal agencies have shown interest in including surface resistivity as a quality control test in their quality assurance regulations.

In the past, several studies have been conducted on various applications of resistivity to evaluate certain durability characteristics of concrete. The evaluation of concrete resistance to chloride penetration in concrete can be determined by surface resistivity method. The surface resistivity test proved to be a better option than Rapid Chloride Permeability (RCP). Therefore, the permeability ranges provided in RCP test standard were revised with the addition of surface resistivity limits [2-4]. In addition, the method to determine the setting time of concrete was developed by using the concept of electrical resistivity. The microstructure of concrete changes with time as the concrete hardens due to the process of hydration. The concrete becomes dense, pore space decreases and discontinuity occurs in capillary pore system, results in an increase in resistivity [5]. The research for predicting the setting time of cement paste and concrete has been done by Bentz et al. by using electrical resistivity method [2].

Likewise, several researchers observed and investigated various factors that could affect the surface resistivity measurements. The increase or decrease in temperature could influence the resistivity of concrete. An increase in temperature will cause an increase in the mobility of ions in pore solution. The variances in temperature may also influence the solution's ionic concentration. The resistivity of the solution will change with temperature due to changes in ionic mobility and ion-solid interaction in the cement paste, for a given pore solution [6-8]. It was stated that the change in temperature to 1 °C could change the resistivity from 3% to 5% [2,9-10]. A correction factor of 0.33 KΩ-cm/°C was also suggested for variation in temperature [11-12]. Further, the electrical resistivity variate with a change in moisture content of concrete specimen. The condition of moisture content changes the ion mobility in the porous structure, thus resulting in a change in resistivity measurements because electrical current is carried by ion flowing through the pore solution in concrete [13-14]. It was reported that the decrease in moisture content by 20% could increase the resistivity measurements by an average of 6 times, and the resistivity measurements could increase by 50% when the specimen is tested in the air-dry state [15]. Moreover, the effect of curing condition on resistivity test was also reported in the literature. According to AASHTO TP 95 [1], a factor of 1.1 should be applied to resistivity values of samples cured in saturated limewater storage to become equivalent to the resistivity of samples cured in moist rooms. An average difference of 9.7% in resistivity measurements between concrete samples cured in saturated limewater versus concrete samples cured in a moist room was also reported [3]. Likewise, the electrical resistivity is also affected by the geometry of specimen.

The measured resistivity value based on a ratio of cross-sectional area to length of the specimen can be factorized by applying a factor to compensate for specimen geometry [16].

Moreover, some material parameters also have an impact on resistivity measurements such as aggregate size and type, addition of admixtures, and paste volume in concrete mixtures. These important parameters were investigated and reported in the past. The researchers have observed that the increase in size and content of aggregates increases the resistivity of concrete due to increase in denser aggregate volume and decrease in porous cement paste. The type of aggregate in terms of texture and shape also affect the resistivity of concrete, concrete made with rough surface showed higher resistivity compared to concrete prepared with round surface aggregates, which might be because of difference in tortuosity and bonding between paste and aggregate surface [15-16]. Likewise, by adding chemical admixtures in concrete mixtures like water reducer or air entertainer showed the negligible effect on resistivity measurements within the age of 2 days [8,17]. However, a little is known about the addition of chemical admixtures with material variability and its influence on surface resistivity measurements; there is a lot of room available to investigate the effect of chemical admixtures on resistivity testing.

This study focuses on expanding the investigation done previously on the use of chemical admixtures on resistivity testing. The interest of this study is to acknowledge the previous findings and to increase the knowledge of the influence of admixtures on resistivity testing, which could help in firming the concept of using the surface resistivity testing as a quality control method.

4.2 Experimental Design

4.2.1 Materials

Various concrete mixtures were prepared in the laboratory to analyze the effect of addition of water-reducer (WR) and air-entrainer (AE) on surface resistivity testing. The change in resistivity by adding chemical admixtures is compared to the concrete samples made with similar mixture design without addition of chemical admixtures. Six replicates of Ø100 mm x 200 mm cylinders were produced from each concrete mixture. The Limestone (#56) aggregates and Type-I Portland cement with natural sand were used for all concrete mixtures. Few mixtures were replaced with 20% class-C fly ash. The chemical compositions of cement and fly ash used in the concrete mixtures are shown in Table 4.1.

Table 4.1 Chemical Properties of Portland Cement and Fly ash

Chemical Composition of Portland Cement (% of weight)					
MgO	CaO	SO_3	SiO_2	Al_2O_3	Fe_2O_3
1.9	62.9	3.3	19.4	5.1	3.4

Chemical Composition of Class-C Fly Ash (% of weight)							
K_2O	MgO	CaO	SO_3	Na_2O	SiO_2	Al_2O_3	Fe_2O_3
0.58	5.55	23.12	1.27	1.78	38.71	18.82	5.88

The concrete mixtures were also prepared with the addition of mid-range water reducer (WR) and air entraining (AE) admixtures. The concrete mixtures prepared for this study are summarized in Table 4.2.

Table 4.2 Summary of Concrete Mixtures

	Mixture	w/cm	Fly Ash (%)	Water (kg/m^3)	Cement (kg/m^3)	Fly Ash (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Paste (%)
No Chemical Admixture	1	0.4	0%	145.4	362.5	0	1097.6	714.9	27.8%
	2	0.4	10%	145.4	326.3	36.2	1097.6	714.9	27.8%
	3	0.4	20%	145.4	290	72.5	1097.6	714.9	27.8%
	4	0.45	0%	163.2	362.5	0	1097.6	714.9	29.2%
	5	0.45	10%	163.2	326.3	36.2	1097.6	714.9	29.2%
	6	0.45	20%	163.2	290	72.5	1097.6	714.9	29.2%
	7	0.5	0%	181.5	362.5	0	1097.6	714.9	30.5%
	8	0.5	10%	181.5	326.3	36.2	1097.6	714.9	30.5%
	9	0.5	20%	181.5	290	72.5	1097.6	714.9	30.5%
WR & AE	10	0.4	0%	145.4	362.5	0	1097.6	714.9	27.8%
	11	0.4	10%	145.4	326.3	36.2	1097.6	714.9	27.8%
	12	0.4	20%	145.4	290	72.5	1097.6	714.9	27.8%
	13	0.45	0%	163.2	362.5	0	1097.6	714.9	29.2%
	14	0.45	10%	163.2	326.3	36.2	1097.6	714.9	29.2%
	15	0.45	20%	163.2	290	72.5	1097.6	714.9	29.2%
	16	0.5	0%	181.5	362.5	0	1097.6	714.9	30.5%
	17	0.5	10%	181.5	326.3	36.2	1097.6	714.9	30.5%
	18	0.5	20%	181.5	290	72.5	1097.6	714.9	30.5%

4.2.2 Surface Resistivity Testing

The surface resistivity testing was performed on Ø100 mm x 200 mm cylindrical samples in accordance with AASHTO TP 95 *"Standard method of test for surface resistivity indication of concrete's ability to resist chloride ion penetration"* [1]. The surface resistivity measurements were taken with a fixed probe spacing of 38 mm, as shown in Figure 4.1. To ensure the moist testing surface, the samples were lightly sprayed with tap water, and to remove excess water or any salt accumulation the testing surface was tapped with a paper towel before taking the measurements. Each sample was marked at four different points equally distant at 90° of the transverse axis to ensure repetition of the resistivity measurements at the same location for the duration of the test period, after demolding the cylinders. Subsequently, the resistivity measurements were taken at day-1, and the cylinders were placed for curing in a temperature-controlled limewater storage maintained at 25 °C for rest of the testing period. During this time, resistivity measurements were recorded on days 3 and 7 during the first week and then weekly up to 56 days. The results of surface resistivity testing reported in the following section represent the average value of six-cylinder replicates. During resistivity testing, the ambient temperature was kept within standard limits (AASHTO TP95) of 20°C to 25°C.

The illustration of surface resistivity and test principle is shown in Figures 4.1. The four probes are placed on the concrete surface and the adequate contact electrically established. The external probes produce a pulse of alternating current into the concrete medium; meanwhile, the inner two probes attached to a voltmeter measure the potential difference between the probes [18]. The apparent resistivity value can be calculated from Equation 4.1. The measured resistivity corresponds to the apparent resistivity of a Ø100 mm x 200 mm-cylindrical sample.

$$\rho = \frac{2\pi sV}{I} \tag{4.1}$$

Where ρ is the apparent resistivity (ohm-cm), s is spacing between probes (cm), V is the measured voltage (volts), and I is the amplitude of alternating current (amps).

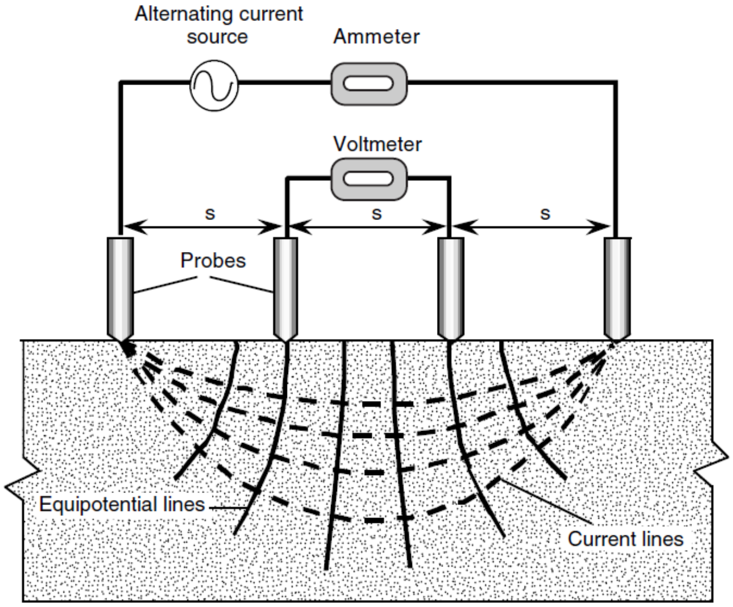


Fig. 4.1 Surface resistivity test setup (adopted ACI 228-2R)

4.3 Research Study

This research study was conducted to determine the effect of addition of chemical admixtures in concrete on surface resistivity testing along. This study could help to verify the results of previous studies and learn something new on resistivity testing which was not discussed in literature before.

4.3.1 Addition of Admixtures

To determine the effect of chemical admixtures on resistivity testing, mid-range WR and AE was used in the concrete mixtures. Eighteen concrete mixtures were prepared with 0.40, 0.45 and 0.50 w/cm having 0%, 10%, and 20% fly ash content. The specimens from nine concrete mixtures containing WR and AE were compared with similar nine concrete mixtures specimens made without adding chemical admixtures. The paste content of concrete mixtures ranges from 27% to 30% and the fine-to-coarse aggregate ratio was kept 0.40.

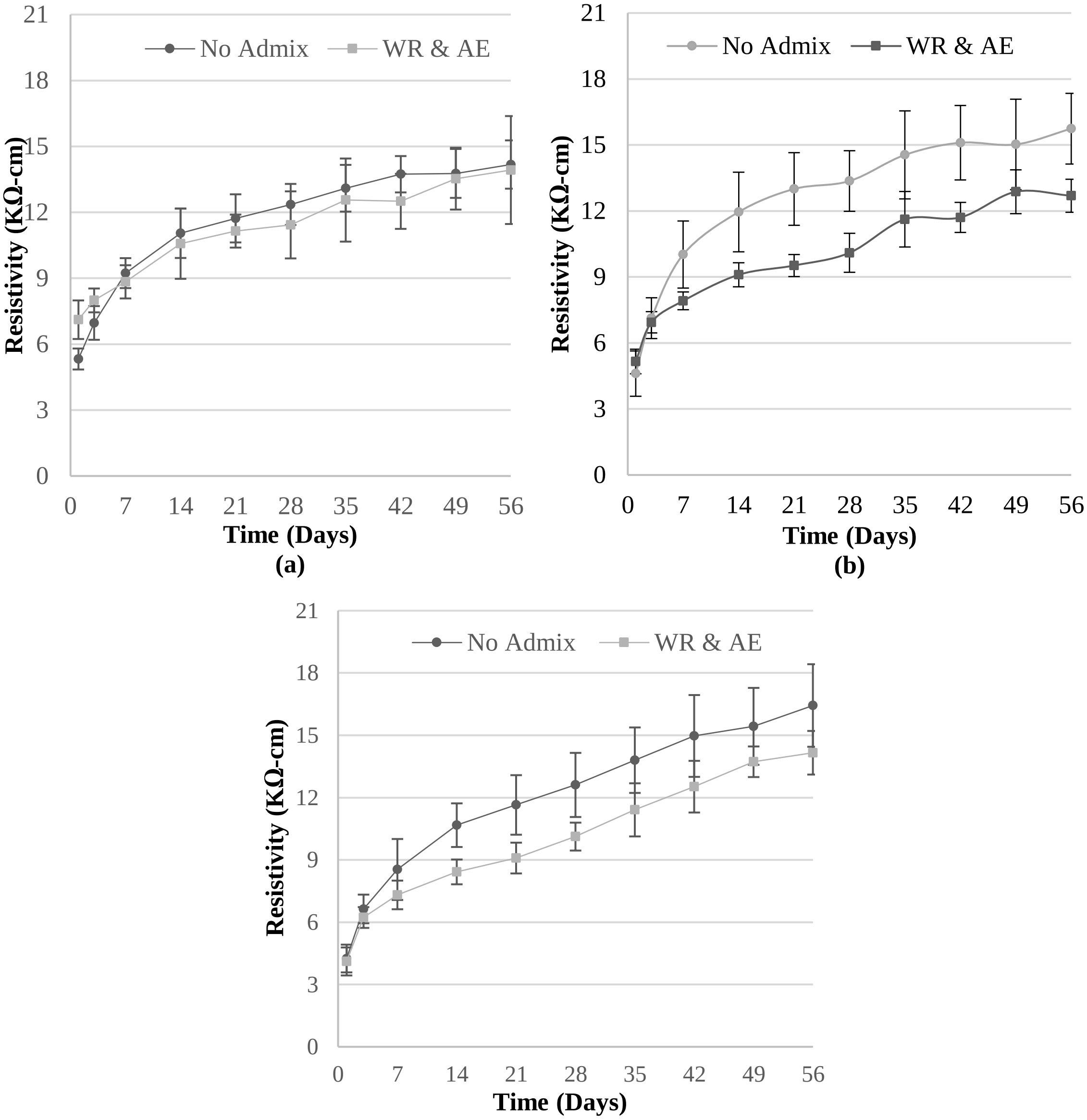
4.4 Results and Discussions

4.4.1 Water Reducer and Air Entrainment

The effect of mid-range WR and AE on surface resistivity testing was investigated by preparing specimens from 0.40, 0.45, and 0.50 w/cm concrete mixtures with and without replacement of fly ash material (0%, 10%, and 20%). The time-resistivity behavior of the concrete mixtures, without addition of WR and AE, and with addition of WR and AE having 0%, 10% and 20% fly ash content is shown in Figure 4.2(a,b,c) for 0.40 w/cm, Figure 4.3(a,b,c) for 0.45 w/cm and Figure 4.4(a,b,c) for 0.50 w/cm. The statistical analyses are shown in Tables 4.3, 4.4, and 4.5.

The t-test was conducted to compare the resistivity values between no chemical admixture added concrete mixtures, and WR & AE added concrete mixtures. The t-test results for 0.40 w/cm with

0% fly ash mixtures showed a significant difference in resistivity values between no admixture and WR & AE concrete mixtures. In Figure 4.2(a), variation in WR & AE samples resistivity can be observed, which might happen due to change in curing temperature outside the ASTM C 511 specified limits [19]. The t-test results of 10% and 20% fly ash mixtures showed a significant decrease in resistivity values of WR & AE mixtures. The effect of WR & AE in concrete mixtures with 10% and 20% fly ash content in it can be seen in Figures 4.2(b,c). In Table 4.4, the results of t-test have shown no significant difference in resistivity values for 0.45 w/cm and 0% fly ash content concrete mixtures as shown in Figure 4.3(a), which verify the findings from Castro [7]. It might be because of the mediums of WR and AE, which may not have any resistance against electric current. A similar result obtained for 0.50 w/cm and 0% fly ash mixtures, presented in Table 4.5 and shown in Figure 4.4(a). The t-test performed on 0.45 w/cm with 10% fly ash content showed significant different among the mixtures with and without WR & AE, whereas, no significant difference in resistivity is determined for 20% fly ash content concrete mixture, which is contrary to the results obtained for 0.40 w/cm and 20% fly ash concrete mixtures. It is probably due to variation in resistivity measurements due to change in curing temperature outside the limits [19]. For 0.50 w/cm with 10% and 20% concrete mixtures, there is a significant decrease in resistivity found from t-test, presented in Table 4.5. The variation in resistivity curve due to change in curing temperature after 28 days can be noted in Figure 4.4(c).



(a)

(b)

(c)

Fig. 4.2 Effect of admixtures on time-resistivity behavior of 0.40 w/cm concrete mixtures (a) 0% FA (b) 10% FA (c) 20% FA

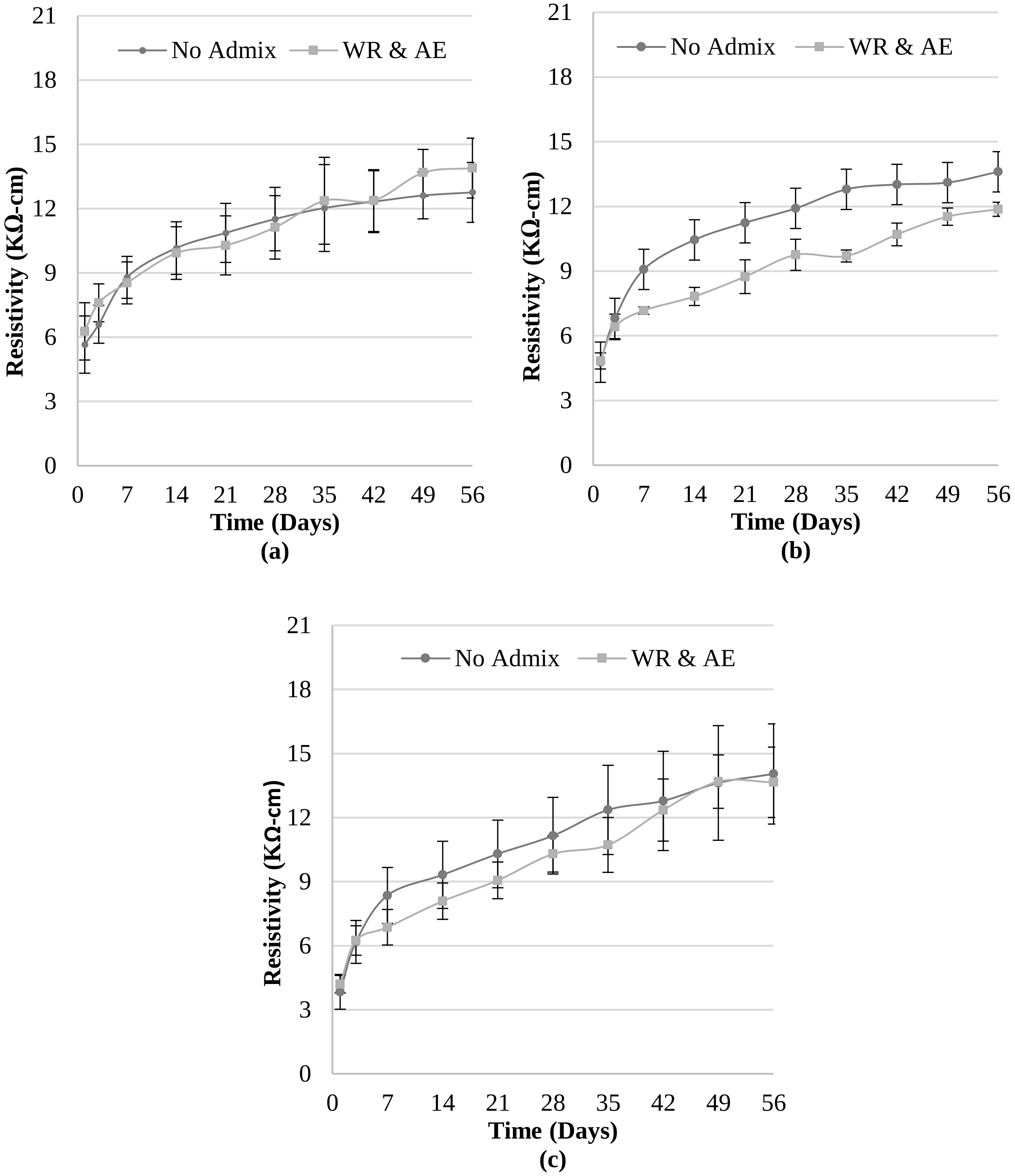
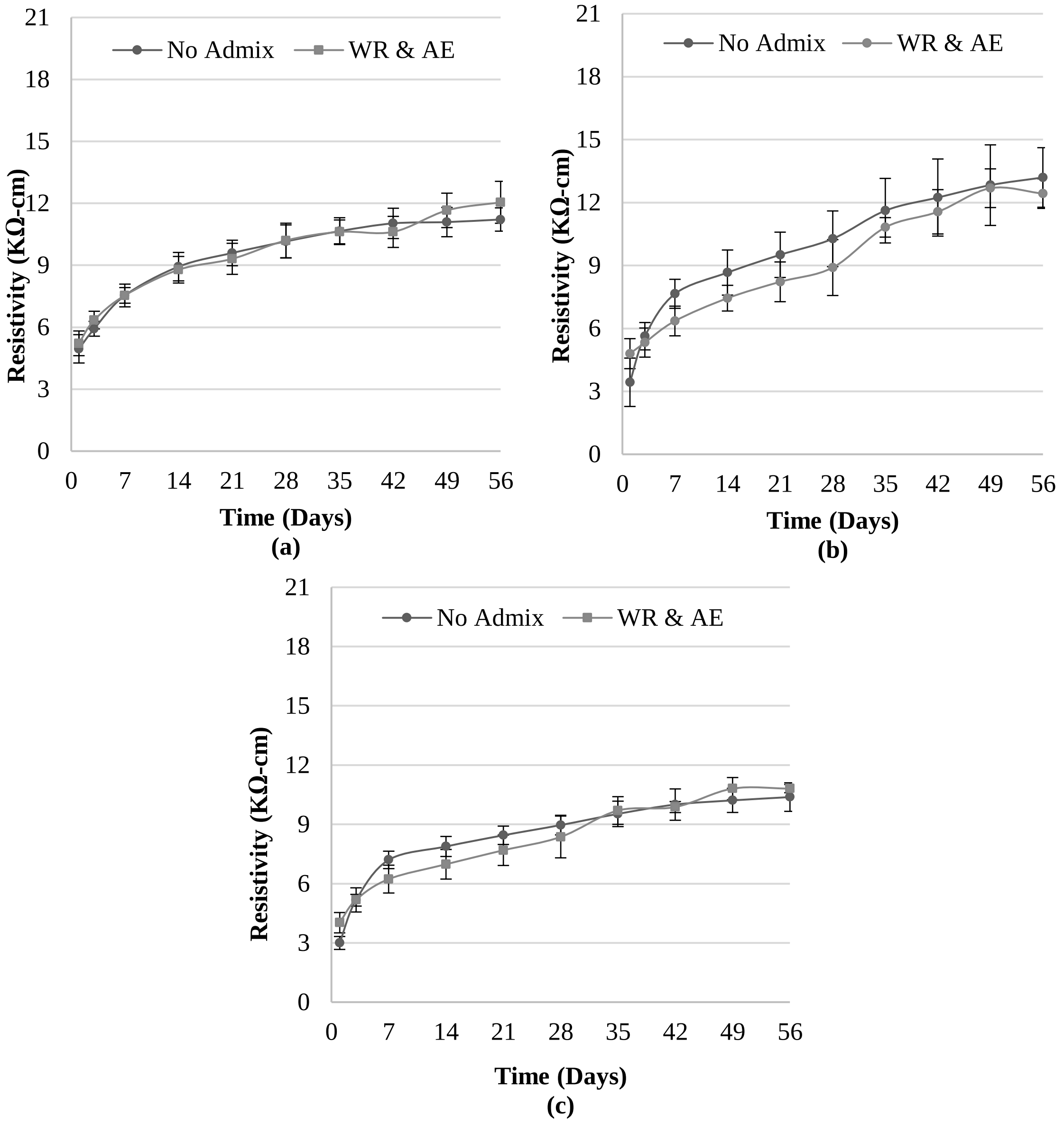


Fig. 4.3 Effect of admixtures on time-resistivity behavior of 0.45 w/cm concrete mixtures (a) 0% FA (b) 10% FA (c) 20% FA



(a) (b) (c)

Fig. 4.4 Effect of admixtures on time-resistivity behavior of 0.50 w/cm concrete mixtures (a) 0% FA (b) 10% FA (c) 20% FA

Table 4.3 Results of Statistical Analysis of 0.40 w/cm mixtures

FA%	Mixture	Resistivity (KΩ-cm)			Student t-test
	0.4 w/cm	Mean	Std. Dev.	COV (%)	p-val/p-val
0%	No Admix	12.4	0.47	0.9	0.03
	WR & AE	11.4	0.76	1.5	
10%	No Admix	13.4	0.69	5.2	2 E-6
	WR & AE	10.1	0.44	4.4	
20%	No Admix	12.6	0.77	6.1	3 E-5
	WR & AE	10.1	0.34	3.3	

Table 4.4 Results of Statistical Analysis of 0.45 w/cm mixtures

FA%	Mixture	Resistivity (KΩ-cm)			Student t-test
	0.45 w/cm	Mean	Std. Dev.	COV (%)	p-val/p-val
0%	No Admix WR & AE	11.5 11.1	0.74 0.61	6.4 5.5	0.346
10%	No Admix WR & AE	11.9 9.8	0.69 0.36	5.8 3.7	4.7 E-5
20%	No Admix WR & AE	11.2 10.3	0.90 0.42	8.0 4.1	0.06

Table 4.5 Results of Statistical Analysis of 0.50 w/cm mixtures

FA%	Mixture	Resistivity (KΩ-cm)			Student t-test
	0.50 w/cm	Mean	Std. Dev.	COV (%)	p-val/p-val
0%	No Admix WR & AE	10.2 10.2	0.40 0.42	3.9 4.1	0.85
10%	No Admix WR & AE	9.0 8.4	0.25 0.53	2.8 6.3	0.031
20%	No Admix WR & AE	10.3 8.9	0.66 0.67	6.5 7.5	0.005

The mean resistivity values at day-28 were compared between the 0%, 10% and 20% fly ash concrete mixtures made with and without the addition of WR and AE. The results show that the resistivity at day 28, for specimens made with no fly ash content may not significantly influence the resistivity measurement irrespective of addition of WR & AE. But when fly ash is replaced with 10% and 20% cement content, a significant influence in resistivity measurement was observed with the addition of admixtures, WR and AE. The addition of WR and AE may limit the involvement of fly ash in the hydration process, which results in a decrease in resistivity, and the difference remained consistent up to 56 days of testing. Therefore, it is concluded from the results that the addition of WR and AE in the presence of fly ash content may be considered for achieving a required level of durability of concrete.

4.5 Conclusions

The surface resistivity testing is becoming a popular method to evaluate the quality of concrete. Concrete is a composite material. The availability of various types of materials in the market could affect the properties of concrete. The findings of this study could be helpful to understand the change and impact of using chemical admixtures on the resistivity of concrete in support of previous investigations.

The addition of WR and AE in a concrete mixture is a common practice to attain the desired properties of concrete. It was concluded from the study that the addition of WR and AE in a concrete mixture having no fly ash content does not affect the resistivity measurements. Whereas, in the presence of fly ash content, adding WR and AE could be the reason for lower resistivity values. However, these conclusions are based on preliminary results and further investigations are recommended in this research area.

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CHAPTER 5

EFFECT OF CURING CONDITION AND TEMPERATURE ON SURFACE RESISTIVITY MEASUREMENTS

Preface

In this study, the effect of curing condition and temperature on surface resistivity testing was observed on concrete samples. The four different concrete mixtures were prepared and cured under three curing conditions. The experimental work is performed by author and undergrad research team at Civil Engineering Lab under the supervision of Dr. Julie Ann Hartell. This chapter is reviewed and published at 26th ASNT proceedings. Further, studies were carried out on the effect of curing method on resistivity testing and the results were presented at ACI Convention held in Fall 2017. These results and discussions are presented in the supplementary section of this chapter.

Abstract

The durability of concrete is widely recognized to be controlled by the ingress of detrimental agents. Here, preventing penetration of water, oxygen, carbon dioxide along with minimizing ionic migration within the material is key to maximize material performance and longevity. Recently, investigations have demonstrated that electrical methods such as surface resistivity are accurate means for assessing the quality of a concrete mixture based on its performance in resisting ionic flow. However, there are many factors which may influence the accuracy of the measured values due to the test principle itself and the inherent variability of concrete materials. This study investigates the influence of sample conditioning, curing method and curing temperature, on resistivity measurement. It evaluates whether variations of curing temperature within ASTM specified limits have a significant effect on the surface resistivity measurement along with ASTM acceptable means of saturation (moist curing and immersion curing).

Keywords: concrete, curing, temperature, surface resistivity

5.1 Introduction

The structure of concrete's hydrated paste matrix is porous in nature. The material consists of a solid phase and a liquid phase. The solid phase is mainly composed of crystallized hydrated calcium silicates and other minor crystalline products. Its liquid phase is generally saturated with various ions (e.g. Ca^{2+}, OH^{-}, K^{+}, Na^{+} and SO_4^{2+} ions). With age (i.e. maturity) the cementitious matrix changes; it gains density and strength as solid-solution interactions continue [1]. In-service, external agents may enter the porous medium and alter its delicate balance. Foreign components in the form of fluids (e.g. chlorides or sulfates) or gas (e.g. carbon dioxide) ingress into the porous cementitious matrix causing various durability issues and corrosion of rebar in cases of reinforced concrete. Here, ionic movement through the partially or completely saturated pore system is, in part, responsible for the detrimental effects. There are many mechanisms that involve ion transport: capillary action, diffusion, migration in electrical field and permeation due to pressure gradient to name a few [2]. Field structures are often subjected to combinations of these transport mechanisms which makes it difficult to single out the ongoing process. The problem is that the standard methods for measuring these principles are considered to be time-consuming, variable and impractical. Still, it is well known that resistance against ionic or fluid penetration is the best defense mechanism for concrete against durability issues. Therefore, there is a need for finding alternative methods for measuring these processes [3].

The physical and chemical nature of concrete makes it particularly sensitive to electrical conductivity. Recently, investigations have demonstrated that non-destructive electrical methods such as the surface resistivity and bulk resistivity methods are cost-effective and accurate means of assessing the quality of a concrete mixture based on its performance in resisting ionic flow [4-6]. Efforts lead to the development of AASHTO TP 95: *Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration* [7].

Since many studies demonstrated that resistivity measurements are mainly influenced by the microstructure of concrete, pore solution conductivity, saturation condition and temperature of concrete [6, 8-9]. However, it is unclear whether the different curing regimens recommended in the ASTM C511-13, *Standard Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes* [10], may influence the accuracy of the measured resistivity values due to the test principle itself and the inherent variability of concrete materials.

The curing of concrete is an important process in the making of Portland cement concrete; it is responsible for the development of mechanical and durability properties. ASTM C511-13, specify two types of curing regimes: complete immersion in a lime-saturated water tank or storage in a moist environment. In both cases, the specified curing temperature is 23.0 °C ± 2.0 °C. Deviations from this range may impact the cementitious reaction kinetics; in turn, altering the expected mechanical or physical properties of the material at a given age. For example, if the curing temperature is increased by 22 °C (from 23 °C to 45 °C), it may result in an increase in porosity, chloride ion diffusion coefficient, and moisture permeability. An increase in curing temperature accelerates the reaction kinetics, which may impact the morphology of the calcium silicate hydrate phase [11, 12]. It may also promote leaching of other hydration products and alkali ions found in the pore solution, both impacting the microstructure of concrete [6,13]. Moreover, immersion curing may also promote leaching of calcium hydroxide or other solute ions due to a chemical imbalance between curing solution (ideally saturated with lime) and pore solution [10]. Therefore, the curing temperature and type may influence the cementitious microstructure and the pore solution chemistry which are two important parameters affecting the material's electrical properties resistivity value [8]. This was reflected in a study where Kessler et al. observed an average of 9.7% difference between concrete samples cured in saturated limewater versus concrete samples cured in a moist room. The latter curing method is recording the higher resistivity values [4].

Moreover, a change in temperature at the time of test may also impact the measurement due to the relationship between solution conductivity and temperature. An increase in temperature will cause an increase in the mobility of ions in a solution. Also, temperature variances may also influence a solution's ionic concentration. As such, the temperature coefficient can be expressed as the rate at which a solution's resistivity decreases with an increase in temperature. It is generally expressed as a percentage of resistivity for a one-degree temperature change (ex: % / °C). Different solutions have different temperature coefficients; it varies with the type and concentration of ions present in the solution. For example, a variation in temperature of 0.1 °C will cause a change in conductivity of 0.55% for pure water. This demonstrates how temperature may vary the outcome of a measurement if not well controlled or not accounted in result interpretation. In the context of concrete, for a given pore solution, the resistivity of the solution will change with temperature due to changes in ionic mobility and ion-solid interaction in the cement paste [6, 14-15]. Therefore, for different temperature ranges, the change in resistivity number does not necessarily mean that the concrete and its cementitious matrix has changed for the better or worst. This is an important fact to consider when comparing measurements to a set range which has been established at a given temperature. Spragg et al. 2013 reported that a relatively narrow range in temperature (e.g., ±2 °C) should be specified at the time of test since ion mobility increases with temperature. Another study suggested a 3 %/°C and 5 %/°C temperature coefficient for moist concrete and for dry concrete respectively [9, 16].

This study investigates the influence of sample conditioning, curing method and curing temperature, on resistivity measurement. It evaluates whether variations of curing temperature within ASTM specified limits have a significant effect on the surface resistivity measurement along with ASTM acceptable means of saturation (moist curing and immersion curing).

5.2 Experimental Procedure

5.2.1 Materials

For this study, a total of four concrete mixtures (0.45 water-to-cement ratio) of varying fly ash percent replacement (10%, 15%, 20% and 25%) were investigated. The concrete mixtures were prepared with a # 57 crushed limestone concrete aggregate and a natural sand for the fine aggregate proportion. A type-I cement and a Class-C fly ash manufactured in Oklahoma were used. The chemical compositions of the cement and fly ash are given in Table 5.1 and Table 5.2. An air-entraining admixture was also added to the mixtures. Mixture proportions are presented in Table 5.3.

Table 5.1 Chemical Composition of Portland Cement

Chemical Composition (% by weight)					
MgO	CaO	SO_3	SiO_2	Al_2O_3	Fe_2O_3
1.9	62.9	3.3	19.4	5.1	3.4

Table 5.2 Chemical Composition of Fly Ash

Chemical Composition (% by weight)							
K_2O	MgO	CaO	SO_3	Na_2O	SiO_2	Al_2O_3	Fe_2O_3
0.58	5.55	23.12	1.27	1.78	38.71	18.82	5.88

Table 5.3 Mixture Design Details

Mixture	w/cm	Fly Ash (%)	Water (kg/m^3)	Cement (kg/m^3)	Fly Ash (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Air Entrainer (ml/kg)	Paste (%)
1	0.45	10%	163.2	326.2	36.2	1088.7	709.0	0.7	29.7
2	0.45	15%	163.2	308.1	54.4	1088.7	709.0	0.7	29.7
3	0.45	20%	163.2	290.0	72.5	1088.7	709.0	0.8	29.7
4	0.45	25%	163.2	271.9	90.6	1088.7	709.0	0.8	29.7

Materials were batched and mixed in a temperature-controlled environment and samples were cast respecting standard methods of preparing concrete samples in a laboratory environment (ASTM C 192) [17]. In order to carry out the testing regimen, approximately 24 cylinders (Ø100 mm x 200 mm) per concrete batch were prepared and demolded after 24 hours.

5.2.2 Curing Conditions and Temperatures

After demolding, the samples were placed in their respective curing environment for the 56-day test duration:

- moist curing room maintained within ASTM limits 23.0 °C ± 2.0 °C (denoted as Moist)
- limewater tank maintained within ASTM limits 23.0 °C ± 2.0 °C (denoted as Tank-1)
- limewater tank maintained at 25.0 °C ± 2.0 °C (denoted as Tank-2)

The temperature of each curing condition was monitored on a daily basis using a digital thermocouple thermometer and measurement were also taken at the time of resistivity testing. Each curing condition was observed for variation in temperature during the test period. The average curing temperatures were determined after 56 days for each curing condition. For moist curing the average temperature was 23.3 °C, limewater tank-1 was 23.5 °C, and tank-2 was 25.1°C. Variations in temperature within ASTM specified limits was observed for limewater tank-1; the curing temperature crossed the maximum limit during the testing days 23, 25 and 56.

5.2.3 Experimental Procedure

Resistivity methods were initially used in geotechnical areas to measure the resistivity of soils to provide an indication of their permeability characteristics. The four-point Wenner probe was originally developed for that purpose by Wenner in the early 1900's. It has now gained popularity as a non-destructive surface method to measure the ability of concrete to conduct current. As seen in Figure 5.1, the four probes are electrically connected to a concrete surface through adequate contact, and the outer probes produce a small alternating current. Meanwhile, the inner two probes connected to a voltmeter measure the response to current flow [18]. The apparent resistivity value is determined from Equation 5.1. The apparent resistance value obtained can be factorized to compensate for specimen geometry by simply applying a factor based on a ratio of sample cross-sectional area to length [19]. The values presented herein are not factorized; therefore, they correspond to the apparent resistivity of an Ø100 mm x 200 mm cylindrical sample.

$$\rho = \frac{2\pi sV}{I} \tag{5.1}$$

Where,

ρ: apparent resistivity (ohm-cm)

S: spacing between probes (cm)

V: measured voltage (volts)

I: amplitude of alternating current (amps)

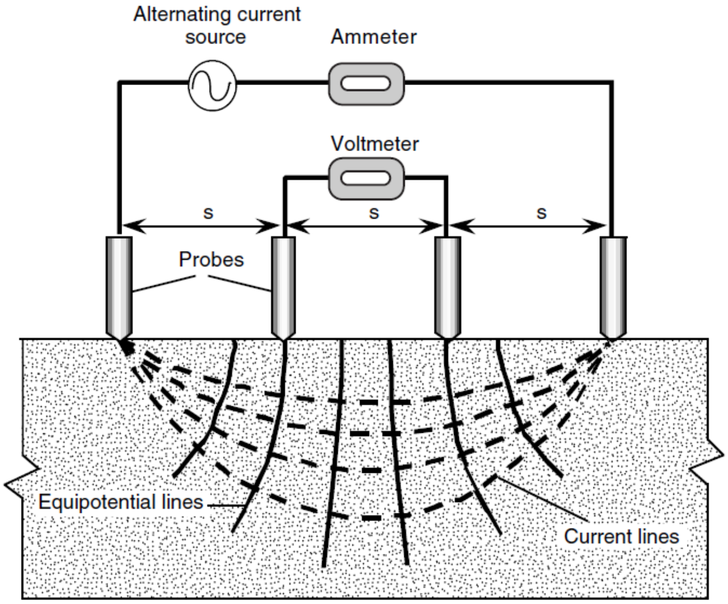
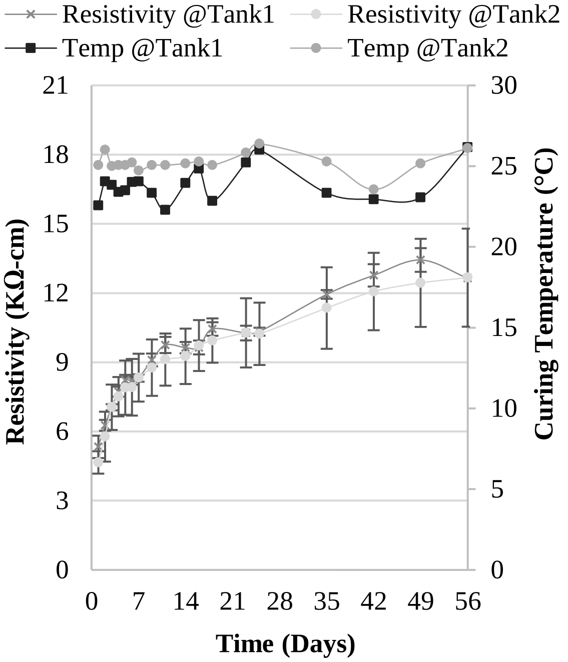


Fig. 5.1 Test principle of surface resistivity using four-point Wenner Probe apparatus. [19]

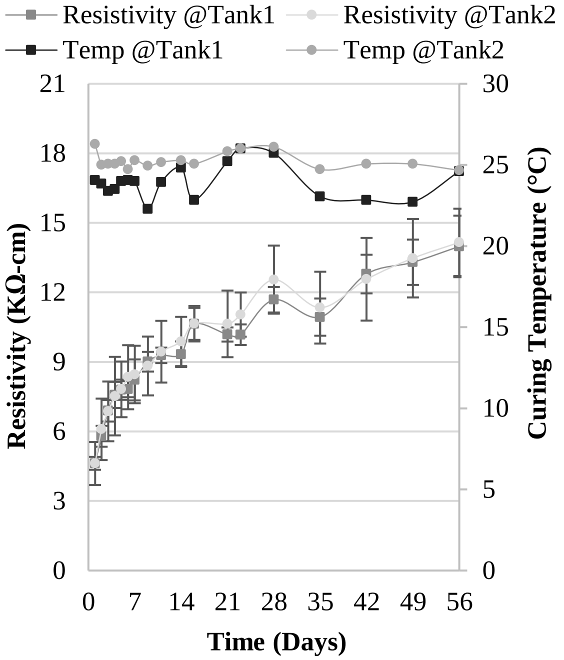
The surface resistivity test was performed using a resistivity meter with a probe spacing of 38 mm. The test was performed in accordance with the AASHTO TP 95 standard, *Standard Test Method for Surface Resistivity of Concrete's Ability to Resist Chloride Ion Penetration* [16]. First, each cylinder was carefully marked to ensure repetition of the non-destructive reading at the same test location on the cylinder. Resistivity measurements were taken on day-1 (after cylinder demolding) and daily for the first seven days of curing. Then, readings were taken bi-weekly up to 28 days of curing followed by weekly reading up to 56 days of curing. Adequate surface preparation prior to each resistivity measurement is necessary to minimize replicate variability. Cylinders removed from the saturated limewater tanks were lightly sprayed with tap water to remove any accumulated salts on the test surface. Test surfaces were kept moist (not wet) while conducting the test.   Resistivity values presented in the results section represent the calculated average resistivity value for a set of three cylinders replicates.

5.3 Results and Discussions

5.3.1 Effect of Curing Temperature for Immersion Limewater Curing



(a)



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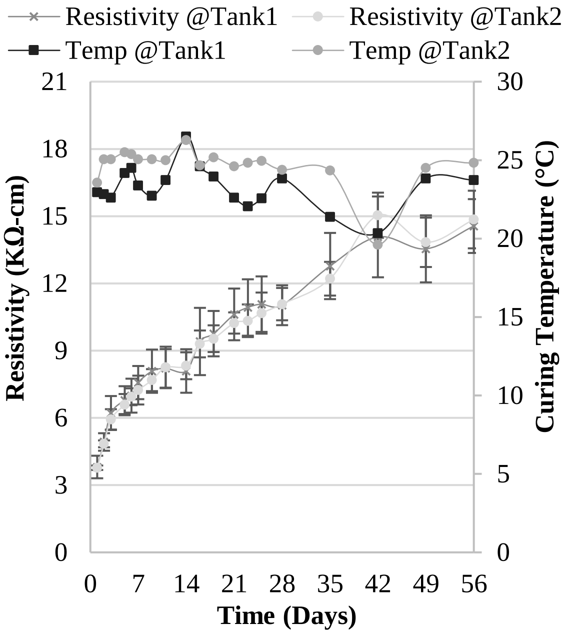

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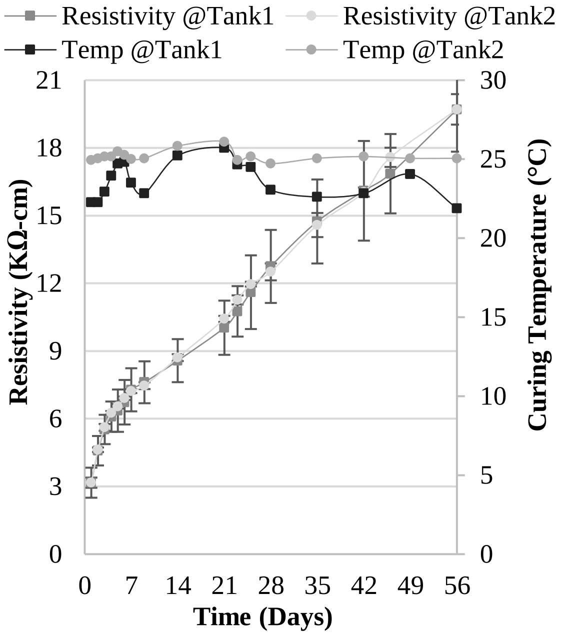


(d)

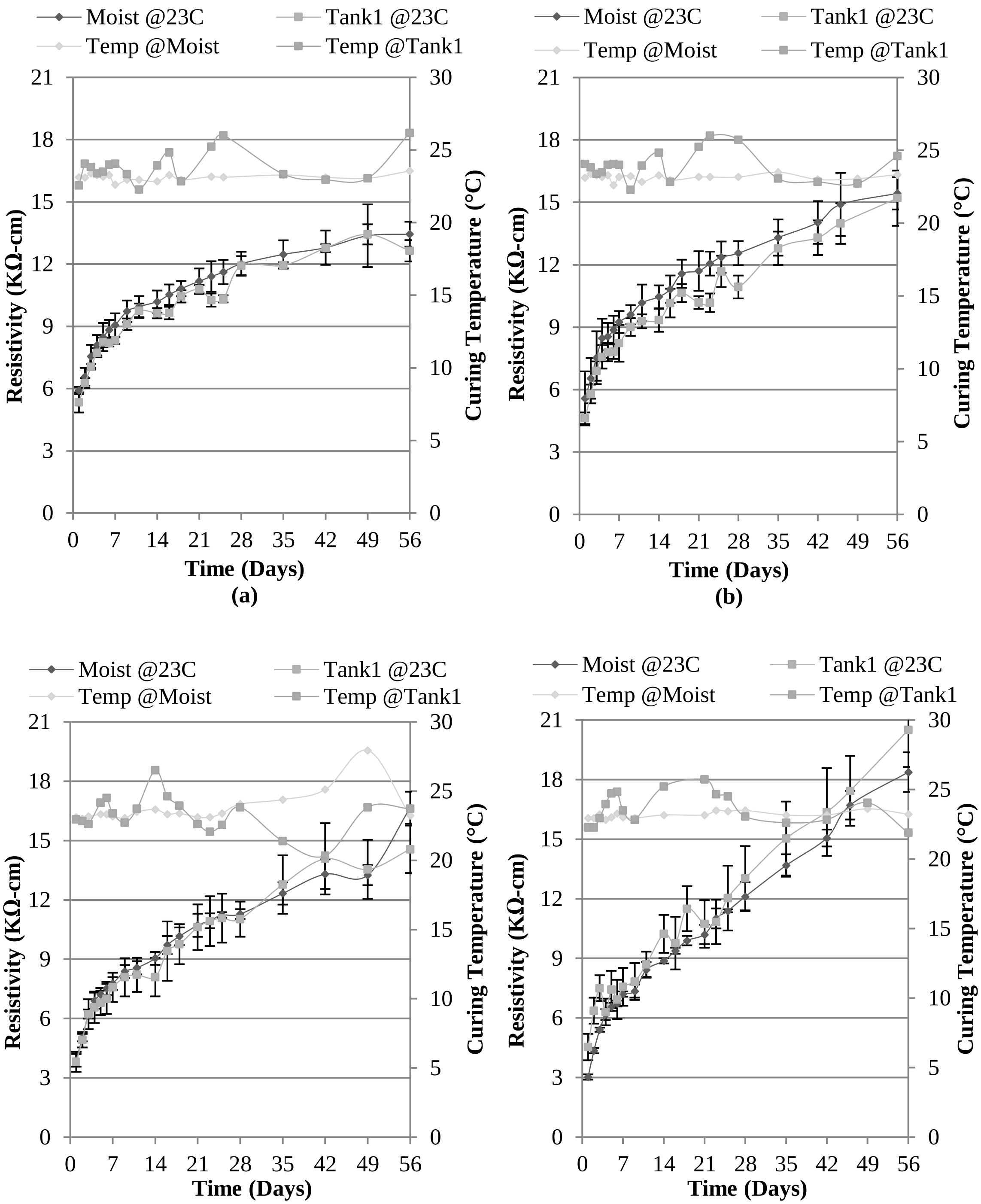
Fig. 5.2 Effect of curing temperature on resistivity behaviors of 0.45 w/c with varying fly ash (a) 10%, (b) 15%, (c) 20% & (d) 25% concrete mixtures added with air admixture.

Figure 5.2 demonstrates the recorded apparent resistivity over time profiles for all four mixture types in addition to the recorded temperature of the curing medium, the limewater curing tanks 1 and 2. The vertical error bar added to the point result represents two standard deviations (2s) from the sample mean calculated from the readings of the three cylinder replicates.

First, it can be seen that the temperature profile for tank-2 is more uniform than tank-1. Still, fluctuations in temperature for tank-1 are within the specified ASTM temperature range, and tank-2 is bordering the upper boundary limit of the ASTM range as desired. Overall, the 2.0 °C difference in temperature is maintained throughout the test period. Results demonstrate that there are no significant differences in resistivity reading between curing temperatures over the test period. Therefore, a positive difference in 2.0 °C from the recommended curing temperature 23.0 °C does not seem to appreciably change the gain in resistivity over time regardless of the mixture ingredients.

5.3.2 Effect of Curing Type - Moist and Immersion Curing

It was reported by Kessler at al. [4] that there was on average a 9.7% difference between both curing regimens which lead to the adoption of moist curing only as the accepted means for sample condition for the Florida Departement of Transportation (DOT) test method [4, 20]. Meanwhile, other state agencies, such as Kansas DOT, the method includes a stipulation rather than opting for a specific curing regimen; the measured value must be multiplied by a factor of 1.1 for samples cured in limewater tanks. Therefore, for this study both curing types were compared to determine the necessity of this factor. Figure 5.3 demonstrates the recorded apparent resistivity over time profiles for all four mixture types in addition to the recorded temperature profiles for each curing medium (the moist curing room and the limewater curing tank-1). Again, the vertical error bar added to the point result represents two standard deviations (2s) from the sample mean derived from the readings of three-cylinder replicates.



(a)

(b)

(c)

(d)

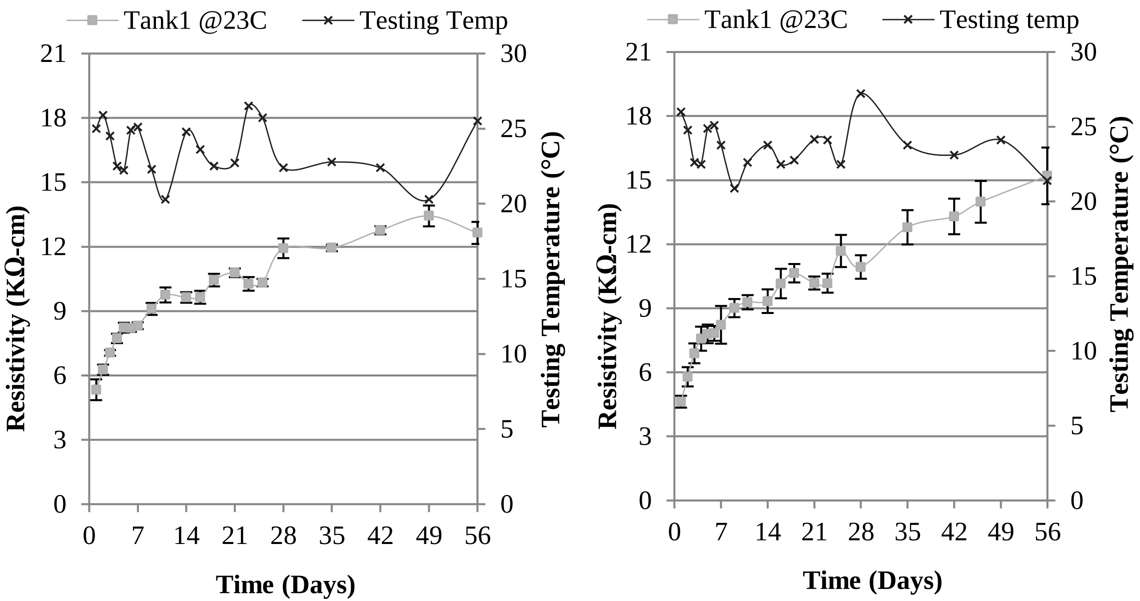
Fig. 5.3 Effect of curing type on resistivity behaviors of 0.45 w/c with varying fly ash (a) 10%, (b) 15%, (c) 20% & (d) 25% concrete mixtures added with air admixture.

As seen in Figures 5.3a and 5.3b, the resistivity profile for the immersion curing is lower than that of moist curing. This trend is in accordance with past investigations [4] for both mixture type. For the sample containing 10% fly ash (Figure 5.3a), the average percent change is 5.5%. As for the sample containing 15% fly ash (figure 5.3b), the percent change is 9.1%. As seen in Figure 4.3c, the resistivity values are similar for both curing conditions until 28 days of curing. The resistivity values for tank-1 samples are 3.8% higher than that of moist cured samples. This trend continues for the 25% fly ash replacement mixture (Figure 5.3d), where samples curing in tank-1 recorded higher resistivity values than samples undergone moist curing. On average, the values are 5.3% greater for immersion limewater curing. This behavior is opposite than that observed for the first mixture. Therefore, the observable trend for these mixtures does not justify the application of a factor (1.1) to increase the value of a measurement if immersion curing was the selected mean of sample conditioning. Further investigations are necessary to confirm the validity of the factor.

Moreover, there is no significant difference found between both curing regimens. The average results, at a given sample age, fall within two standard deviations of each other except for a few points presenting evident fluctuations in the profile. These do not seem to be attributed to curing temperature fluctuation. This warrants a closer look at the effects of temperature at the time of test where a difference in 2.0 °C may significantly affect the result.

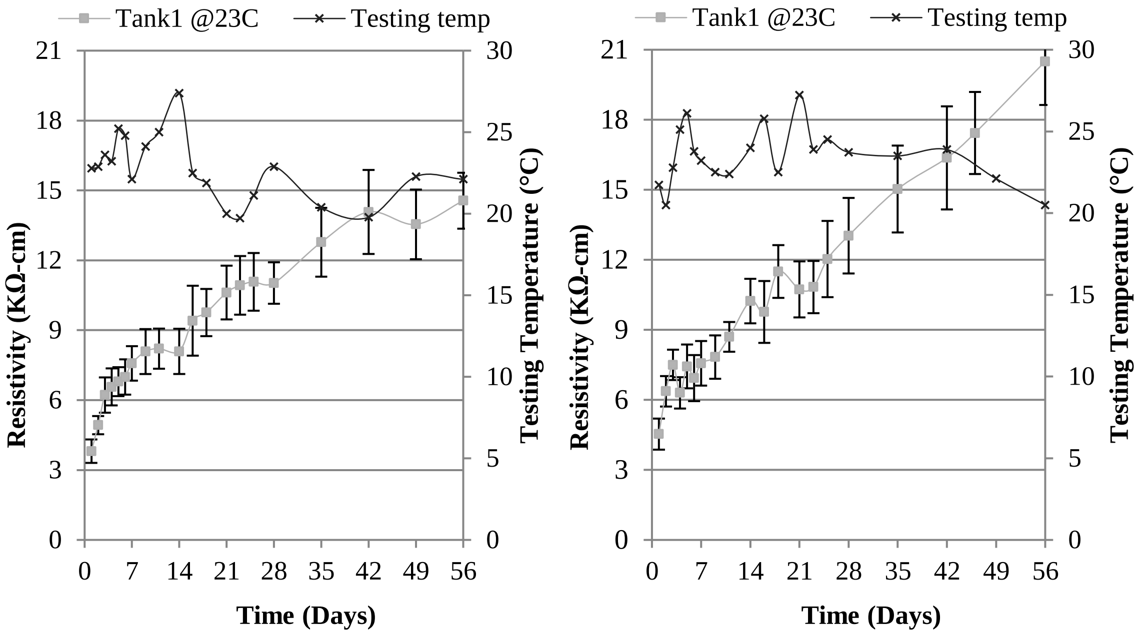
5.3.3 Effect of Ambient Temperature at Time of Test

In order to evaluate the noticed variability in the resistivity profiles, Tank-1 demonstrating several peaks and valleys in the curve will be utilized and compared with its corresponding temperature profile a time of the test (Figure 5.4). The observable variation of the resistivity value seems to coincide better with the variation of the temperature at the time of testing rather than curing temperature. The increase in temperature at the time of testing resulted in a decrease in the resistivity values and vice versa, which confirms the findings of previous studies [12, 13]. However, the application of a temperature coefficient, 3 %/°C in the case of moist concrete does not seem to account for the fluctuations. The reported temperature coefficient was suggested in the case of mixtures containing Portland cement only. Here, the presence of a supplementary cementitious material such as fly ash alters the pore solution chemistry changing the relationship between solution conductivity and temperature. Specifying an ambient room temperature at the time of testing would help in the reduction of result variability and increase the accuracy of the measurement. Further research is necessary to understand the influence of temperature on the electrical conductivity concrete to develop appropriate temperature coefficient criteria, which may be dependent or independent of the concrete mixture design.



(a)

(b)



(c) (d)

Fig. 5.4 Effect of ambient temperature on resistivity behaviors of 0.45 w/c with varying fly ash (a) 10%, (b) 15%, (c) 20% & (d) 25% concrete mixtures added with air admixture.

5.4 Conclusions

Surface resistivity is a simple non-destructive utilitarian method, which has gained popularity in the concrete industry. However, simple test parameters such as temperature inhibit its widespread use as a concrete quality control method. The results of this preliminary study on the effects of curing condition and temperature at the time of test demonstrate the temperature sensitivity. However, this study did not corroborate the application of a factor (1.1) to increase the apparent resistivity of a sample cured in limewater tank in order to match the apparent resistivity of a sample cured in a moist room. Also, temperature fluctuations within ASTM range during limewater tank curing did not seem to significantly affect the results of a test on a given day within the evaluated curing regimen of 56 days. However, fluctuations in the ambient room temperature did seem to impact the resistivity measurement. It was also noticed that saturated limewater curing yielded higher resistivity values for concrete samples having higher fly ash contents compared to their companions cured in a 100% moist curing room after 28 days. These parameters will be further investigated within the scope of the research project to potentially increase the reliability of the resistivity method for quality control of concrete mixtures.

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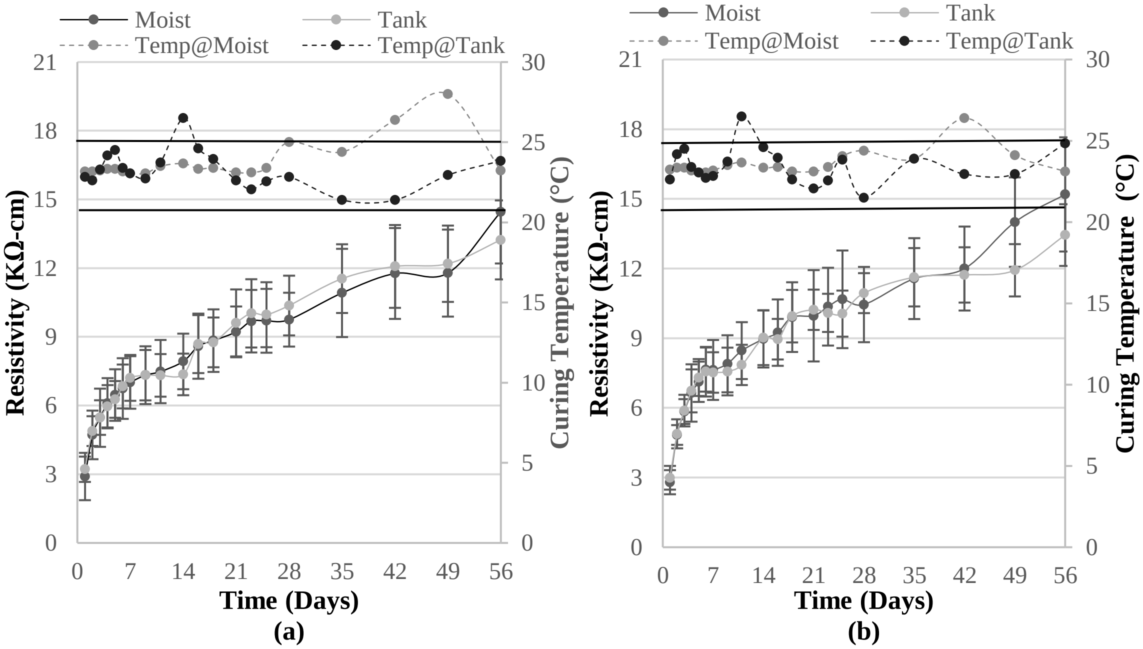
5.5 Supplementary Section

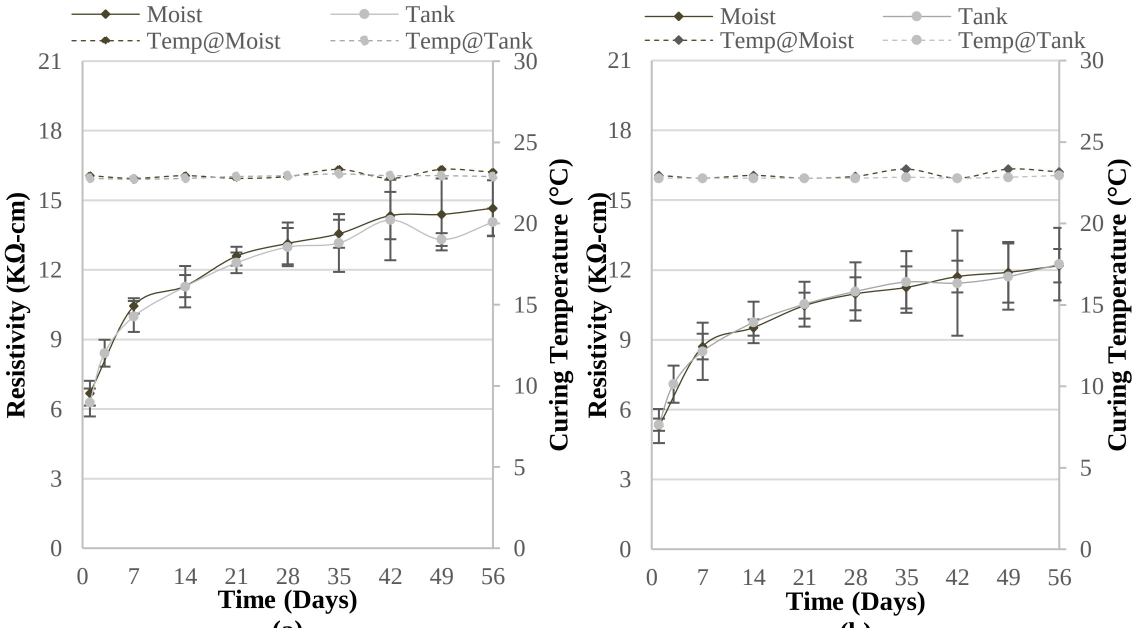
This section consists of results and discussions of further studies conducted on the effect of curing method on resistivity testing. In Figure 4.5(a,b), the two comparisons of time-resistivity curves for samples cured in 100% moist room and saturated limewater tank along with curing temperature profiles for concrete mixtures having 0.45 w/cm with 10% and 20% are shown.



(a) (b)

Fig. 5.5(a,b) Effect of curing temperature on resistivity measurements of 0.45 w/c with 20% fly ash content.

In Figures 5.5(a) and (b), the variation in curing temperature outside the specified limits (ASTM C 511) of curing temperature can be observed from curing temperature profiles. The resistivity curves are almost overlapping each other except to the testing days when curing temperature has crossed the curing limits of 21 °C and 25 °C. The resistivity curves do not show 10% lower resistivity of samples cured in limewater tank compared to the resistivity of samples cured in 100% moist room. Therefore, increasing the resistivity of samples cured in limewater tank by 10% (AASHTO TP95) to make them comparable to the resistivity of samples cured in the moist room may result in overestimation of resistivity results of limewater-cured samples. In addition, the variation in temperatures of curing regimes within the ASTM temperature limits could be observed in Figure 4.5. It is a well-known fact that the resistivity measurements are sensitive to temperature variation, whereas, the results have shown that the variation of curing temperature within the ASTM specified curing temperature limits (ASTM C 511) does not affect the resistivity results significantly.



(a) (b)

Fig. 5.6(a,b) Effect of curing temperature on resistivity measurements of (a) 0.40 w/cm and (b) 0.45 w/cm concrete mixtures with no fly ash content.

In Figures 5.6 (a) and (b), the comparison of time-resistivity curves of 0.40 w/cm and 0.45 w/cm concrete mixtures for 100% moist room and saturated limewater tank-curing regimes are shown. The difference of 10% resistivity between the limewater tank and moist room cured samples were not found for both mixtures. Therefore, apparently, there is no effect of curing method on hydration process and development of the porous structure of concrete specimens. Further, the curing temperature profiles were consistent during the testing period. As a result there is no sign of change in resistivity due to variation in curing temperature in Figures 5.6(a) and 5.6(b). However, in Figure 5.6(a), the variation in resistivity at day 49 could be noted, and it may be the result of a change in ambient temperature at the time of testing.

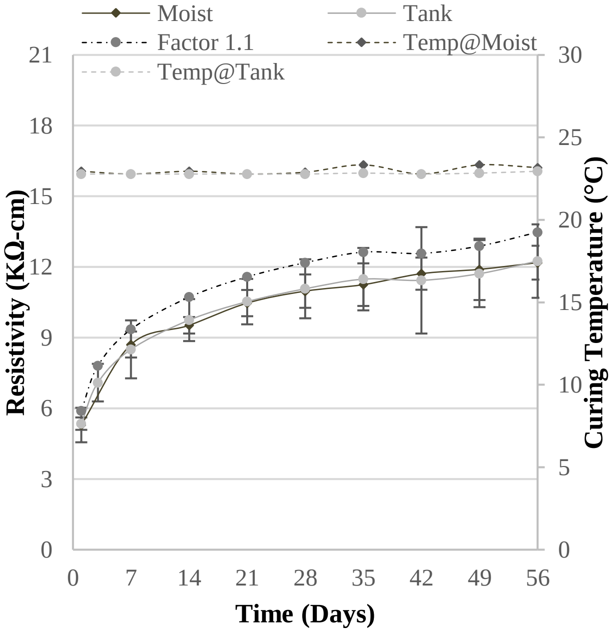


Fig. 5.7 Application of factor 1.1 to the resistivity of samples cured in limewater tank of 0.45 w/cm concrete mixture.

In Figure 5.7, the comparison of time resistivity curves of 0.45 w/cm concrete mixtures were shown. Both the resistivity curves do not show a difference of 10% resistivity due to curing method over the period of 56 days. The factor of 1.1 was applied to the resistivity values of the samples cured in limewater tank as recommended by AASHTO TP95 standard procedure, which increases the resistivity values of limewater tank samples as shown in the figure above. At day

28, the original measured resistivity value was 11.1 KΩ-cm, which became 12.2 KΩ-cm after applying the multiplication factor of 1.1. The previous resistivity measurement of 11.1 KΩ-cm indicates that the concrete samples fall under the high chloride-ion penetrability level according to 28-day permeability classifications, ASTM 1202-12 (RCP limits) and AASHTO TP95-11 limits, and after multiplication of factor 1.1, the resistivity of concrete samples increased to 12.2 KΩ-cm, which fall in moderate chloride-ion penetrability level. Therefore, it can be concluded that there could be an overestimation of resistivity values with the application of factor 1.1 recommended in AASHTO TP95, and it may not be applicable to limewater cured samples.

CHAPTER 6

EVALUATING THE CONSISTENCY OF CONCRETE MIXTURES PRODUCED IN THE FIELD BY COMPARATIVE ANALYSIS OF SURFACE RESISTIVITY MEASUREMENTS

Preface

In this study, the consistency of concrete samples was evaluated by using surface resistivity method. The concrete samples produced by 8 different concrete manufactures in Oklahoma were received at Bert Cooper Engineering Lab at the age of 7, 14 and 21 days. The concrete mixtures with similar mixture design produced by a concrete manufacturer were comparatively analyzed by using time-resistivity curves and statistical methods. The experimental work is completed by Abhishek Reguri, and the statistical analysis is performed by the author.

Abstract

The consistency of concrete mixtures can be evaluated by using surface resistivity method to assure the quality of concrete for future production. In this way, the concrete producers could be emphasized to maintain a better-quality control of concrete production according to approved mixture design. The preliminary results show that most of the approved concrete producers remained unsuccessful to maintain consistency in concrete reproduction. It was determined

through the comparative study of mean surface resistivity values and statistical analysis of 28-day resistivity measurements between the concrete mixtures having similar mixture design that some concrete producers were successful in maintaining the consistency in concrete manufacturing. Therefore, it is essential to develop a quality control criterion to determine the consistency in concrete production even the concrete mixtures in the fresh state have passed the quality control tests. This study could help to develop a tool for evaluating the quality of concrete along with compressive strength. In addition, the procedure could also be used to develop a long-term credential rating for concrete producers, which could provide assistance in technical evaluation of a concrete producer.

Keywords: Surface resistivity; Water-to-cement ratio; Fly ash; Paste fraction; ANOVA; T-test.

6.1 Introduction

The importance of quality control or compliance testing of concrete cannot be ignored during construction. To maintain the consistency in concrete batches during construction is a challenge. The Oklahoma Department of Transportation (ODOT) has implemented quality assurance tests for fresh and hardened concrete to ensure its compliance with established mixture design specifications. However, recurring durability issues like cracking, spalling, surface scaling, and corrosion are still problematic and compromise the intended service and economic performance of the built infrastructure. Therefore, it is an immense requirement to develop a quality assurance criterion to evaluate the consistency of concrete mixtures manufactured by concrete producers.

There are several approved concrete producers by ODOT providing concrete at various construction projects at different residencies in Oklahoma. All the concrete manufacturers follow ODOT specifications for producing concrete material with mixture design acceptance as shown in Table 6.1 (ODOT specifications) followed by quality assurance tests in fresh and hardened state. But, there is no method which can evaluate the consistency of concrete batches produced multiple times by a single producer along with strength test during the construction project. By introducing a simple method which can track the inconsistency between concrete batches in hardened state along with strength test can help to improve the quality of new concrete production in future.

Table 6.1 ODOT Specifications for Mixture Design Acceptance

Class of Concrete	Minimum Cememt Content, lb/yd3 [kg/m3]	Air Content, %	Water/Cement Ratio, lb/lb [kg/kg]	Slump, in [mm]	Minimum 28-day Compressive Strength, psi [MPa]
AA	564 [335]	6.5±1.5	0.25 - 0.44	2±1 [50±25]	4,000 [27.6]
A	517 [307]	6±1.5	0.25 - 0.48	2±1 [50±25]	3,000 [20.7]

In the early 1900s, Wenner learned to measure the resistivity of soils by inventing four-point Wenner probe resistivity method to investigate the permeability characteristics [1]. The resistivity testing method became popular in civil engineers due to low cost and easy to conduct measurements that indicate the characteristics of concrete to resist the flow of current. In the past, researchers studied the resistive property to investigate the durability indicators explicitly the transport properties to predict and assess the durability of concrete [2]. The continuous efforts by researchers and scholars lead to the development of AASHTO TP 95 "*Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration"* [3]. While, ASTM Committee C09 is in the process of developing a standard procedure for evaluating the surface electrical resistivity of concrete. The procedural parameters, which influence the resistivity measurements, such as surface condition, surface to probe contact, the degree of saturation and temperature [4] could be controlled to evaluate the material properties of concrete mixtures precisely. Therefore, in the controlled testing environment, the change in material properties of concrete can be investigated by using surface resistivity method.

The studies conducted in the past concluded that the resistivity measurements are influenced by the microstructure, conductivity of pore solution, degree of saturation of concrete specimen, and temperature [4-5]. Moreover, some material parameters also have an impact on resistivity measurements such as water-to-cement (w/cm) ratio, secondary cementitious materials, aggregate size and type, addition of admixtures, and paste volume in concrete mixtures. The effect of all these parameters was investigated and reported in the past. The researchers have found that the resistivity measurements are sensitive to change in w/cm of the concrete mixture as well as percentage replacement of cement content with secondary cementitious materials [6-7]. The variation in resistivity is due to the change in the chemical behavior of concrete materials, which influence the hydration process. It was also determined that the increase in size and content of aggregates in a concrete mixture increases the resistivity of concrete due to increase in denser aggregate volume and decrease in porous cement paste. The type of aggregate in terms of texture and shape also affect the resistivity of concrete. The concrete made with rough surface showed higher resistivity compared to concrete prepared with round surface aggregates, which might be because of difference in tortuosity and bonding between paste and aggregate surface [8-9]. Likewise, by adding chemical admixtures in concrete mixtures like water reducer or air entrainment showed the negligible effect on resistivity measurements within the age of 2 days. In addition, the increase in paste volume from 27% to 33% resulted in significant decrease resistivity under 2 days' time [10-11]. Therefore, by considering the parameters such as w/cm, cement, secondary cementitious material content, aggregate size and paste fraction, the surface resistivity method can be used as a tool to determine the consistency in concrete mixtures repeatedly manufactured by a concrete producer.

The focus of this study is to evaluate the consistency in the reproduction of concrete mixtures from a producer by using surface resistivity test. A comparative study is completed by performing statistical analysis on resistivity measurements to evaluate the consistency of concrete mixtures with similar mixture design made by various concrete producers for construction projects across the state. This investigation could help to assure the quality of concrete manufactured in the future and to develop a credible rating of concrete producers.

6.2 Experimental Design

In this study, the concrete producers are evaluated for maintaining consistency in concrete production of concrete mixtures with repeatable mixture design. The concrete mixtures were categorized with respect to their manufacturers, based on their mixture design having similar w/cm, fly ash content and paste fraction. A set of three concrete samples received from each concrete mixture was tested for surface resistivity measurements. The comparative study was performed to evaluate the consistency of concrete mixtures by comparing time-resistivity curves developed from mean resistivity values at each testing day and applying the analysis of variance, ANOVA, followed by Tukey's and Student's t-test on 28-day resistivity measurements. The details of field samples and experimental procedures followed are explained in the following sections.

6.2.1 Field Samples

The field samples of 40 concrete mixtures were received from 15 different residencies in Oklahoma, provided by ODOT (Oklahoma Department of Transportation). These concrete mixtures were produced by 8 concrete producers for various construction projects across the state. The composition of concrete mixtures with respective concrete producer is shown in Table 6.2. In the table, the information regarding number of concrete mixtures with similar mixture design produced by each concrete producer for various residencies are given. The mixture design includes the information on cement type, w/cm, percentage replacement with fly ash content, paste volume and admixtures used for making concrete mixtures.

Table 6.2 Concrete Mixtures Information

Concrete Producers	Residency	No. of Mixtures	Mixture Design				
			Cement	w/cm	Fly Ash	Paste Vol.	Admixture*
Producer-1	AD	6	Type-I	0.44	20%	28%	WR
	W/A/O	5	Type-I/II	0.44	20%	24%	WR
	AD/C/S	8	Type-I/II	0.38	20%	25%	WR
	A/S	3	Type-I/II	0.38	0%	25%	WR
Producer-2	T/S/AL	4	Type-IL(10)	0.38	20%	20%	AE
Producer-3	P/C	3	Type-I/II	0.42	15%	23%	WR & AE
Producer-4	AN	3	Type-I/II	0.44	20%	28%	WR & AE
Producer-5	S	2	Type-I/II	0.44	20%	24%	WR & AE
Producer-6	B	2	Type-II	0.41	20%	24%	AE
Producer-7	E	2	Type-I/II	0.41	20%	27%	WR & AE
Producer-8	G	2	Type-I/II	0.44	0%	28%	WR & AE

*WR: Water reducer, AE: Air entrainer

The concrete samples were prepared in the field by various producers across the state with approved materials and mixture design. As shown in Table 6.2, producer 1 has made 22 concrete mixtures comprising four different mixture designs for 6 different residencies. Producer 2 delivered 4 concrete mixtures to 3 residencies with similar mixture design. Producer 3 prepared 3 mixtures for two residencies and producer 4 prepared 3 mixtures for a single residency. Likewise, producers 5,6,7 and 8, each made 2 concrete mixtures for a residency with similar mixture design. The Type I, I/II or IL(10) cements were used in the concrete mixtures with replacement of 0%,15% and 20% fly ash content. The w/cm used in the mixtures ranges from 0.38 to 0.44, and the paste fraction was limited between 20% to 28%. All the concrete mixtures were added with chemical admixtures; water-reducer or air-entrainer or both.

Field samples from each concrete mixture consists of three (Ø100 x 200 mm) concrete cylinders, which represents a concrete mixture design of Class AA & A, concrete (ODOT specifications). Each concrete mixture was provided with the mixture design sheet submitted by the manufacturer and approved by ODOT specifying the w/cm, fly ash content, aggregate source, and paste fraction. The design specifications for Class AA & A concrete implemented by ODOT are shown in Table 6.1. All the concrete mixtures are required to fulfil the quality standards in fresh and hardened state, as specified in Table 6.1. The sample sets were received within the first week of production, demolded, marked and measured; and, cured in a 100% moist room at 23±2 ºC temperature in accordance with ASTM C 511.

6.2.2 Surface Resistivity Testing

The surface resistivity testing was performed on Ø100 mm x 200 mm cylindrical samples in accordance with AASHTO TP 95 *"Standard method of test for surface resistivity indication of concrete's ability to resist chloride ion penetration"* [3]. The surface resistivity measurements were taken with a fixed probe spacing of 38 mm, as shown in Figure 6.1. The samples were lightly sprayed with tap water to ensure the moist testing surface. The excess water was removed from the testing surface by tapping with a paper towel before taking the measurements. Each sample was marked at four different points equally distant at 90° of the transverse axis to ensure repetition of the resistivity measurements at the same location for the duration of the test period.

Resistivity measurements were taken after one day of curing and at a sample age of 7 days based on the date of concrete production provided by ODOT. Next, weekly measurements were taken up to 56 days. The results of surface resistivity testing reported in the following section represent the average value of three-cylinder replicates. During resistivity testing, the ambient temperature was kept within (AASHTO TP95) standard range of 20 °C and 25 °C, to minimize variability in the resistivity measurements [13,14].

The illustration of surface resistivity and test principle is shown in Figures 6.1 and 6.2. The four probes are placed on the concrete surface and the adequate contact electrically established. The external probes produce a pulse of alternating current into the concrete medium; meanwhile, the inner two probes attached to a voltmeter measure the potential difference between the probes

[12]. The apparent resistivity value can be calculated from Equation 6.1. The measured resistivity corresponds to the apparent resistivity of a Ø100 mm x 200 mm-cylindrical sample.

$$\rho = \frac{2\pi s V}{I} \tag{6.1}$$

Where ρ is the apparent resistivity (ohm-cm), *s* is spacing between probes (cm), V is the measured voltage (volts), and I is the amplitude of alternating current (amps).

Fig. 6.1 Illustration of surface resistivity

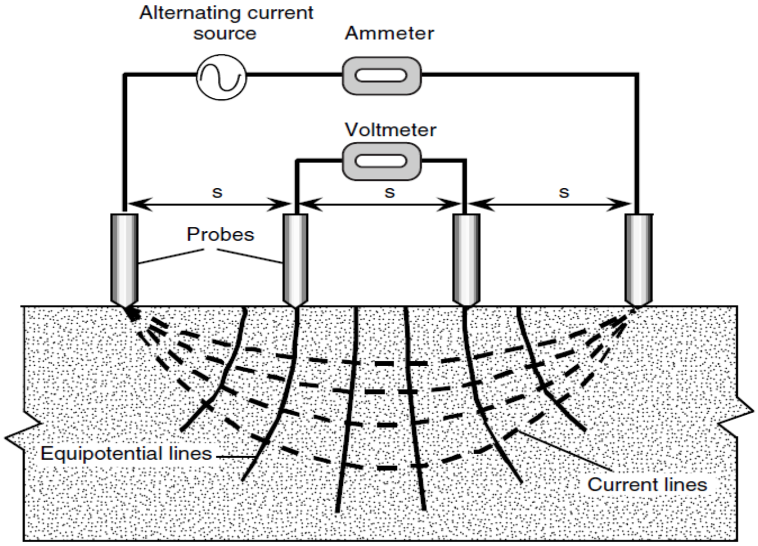


Fig. 6.2 Surface resistivity test setup (adopted ACI 228-2R)

6.3 Results and Discussions

The consistency between concrete mixtures with similar mixture design is investigated via comparative analysis. The surface resistivity versus timeline charts were developed with the results obtained from experimental period of 56 days, where variation from the mean is expressed as two standard deviations from the mean (95% confidence interval). Further, comparative analysis was performed at 28 days using analysis of variance ANOVA, followed by Tukey's test and Student's t-test for examining the difference between data sets. The analyses were executed at the age of 28 days because this age is commonly used in the industry to perform quality assurance tests in hardened concrete. The statistical comparative analysis of resistivity measurements at the age of 28 days will help to analyze the quality of concrete by determining the consistency of concrete mixtures made by a concrete producer.

6.3.1 Concrete Producer-1

The concrete producer-1 manufactured 22 concrete mixtures in total with four different mixture designs for 6 residencies (Table 6.2). A first, the concrete producer-1 produced 6 concrete mixtures of 0.44 w/cm with replacement of 20% fly ash content and paste fraction of 28% for a residency at different times. Mixture-1 samples were received at the age of 14 days, mixtures 2 and 3 were received at day 21, whereas, mixtures 4,5 and 6 were received at day-7.
As shown in Figure 6.3, the mean resistivity values are plotted against time (days). It can be seen from the figure that there is no similarity in rate of increase in resistivity between the mixtures 1,2 and 3. Also, the mixtures 1,2 and 3 attains higher resistivity compared to the mixtures 4,5 and 6. All the 6 mixtures, produced for the same residency with one mixture design, no compatibility between the mixtures for resistivity testing is found, whereas, all the mixtures have passed the quality control tests and approved. However, out of 6 mixtures, the mixtures 4,5 and 6 show consistency in the production. According to 28-day permeability classifications [5,7], only

mixture 2 touched the moderate chloride ion penetrability (CIP) boundary, whereas, all other mixtures remain under low ion penetrability level at the age of 28 days.

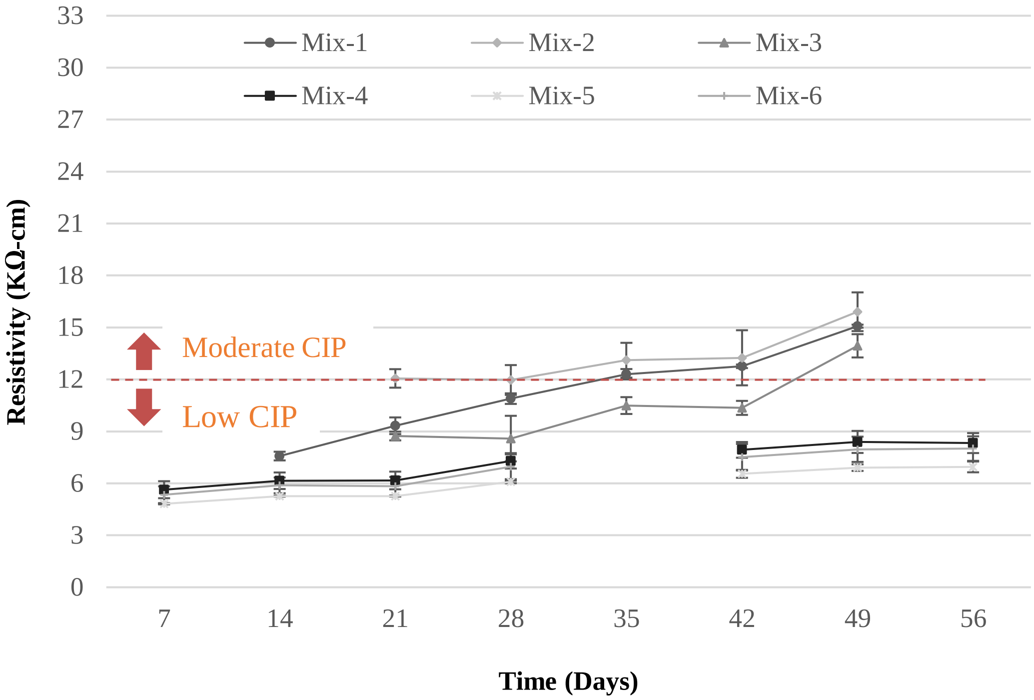


Fig. 6.3 Concrete mixtures manufactured by concrete producer-1

Table 6.3 Statistical Analysis of Concrete Resistivity from Producer-1

	Mixtures	Resistivity (KΩ-cm)			ANOVA	Comp.	Tukey's Test	T-test
		Mean	Std. Dev.	COV (%)	p-value			
Concrete Producer-1	Mix-1	10.9	0.15	1.0	8.2 E-10	M1/M2	Sig. diff.	0.015
						M1/M3	Sig. diff.	0.004
						M2/M3	Sig. diff.	0.002
	Mix-2	12.0	0.43	4.0		M4/M1	Sig. diff.	5.4 E-5
						M4/M2	Sig. diff.	7.6 E-5
	Mix-3	8.6	0.66	8.0		M4/M3	Sig. diff.	0.033
						M5/M1	Sig. diff.	1.6 E-4
						M5/M2	Sig. diff.	1.7 E-3
	Mix-4	7.3	0.22	3.0		M5/M3	Sig. diff.	0.003
						M5/M4	Sig. diff.	7.3 E-4
	Mix-5	6.1	0.04	1.0		M6/M1	Sig. diff.	7.4 E-4
						M6/M2	Sig. diff.	1.3 E-4
						M6/M3	Sig. diff.	0.031
	Mix-6	7.0	0.36	5.0		M6/M4	-	0.234
						M6/M5	-	0.050

The statistical analysis is performed at 28-day resistivity data shown in Table 6.3. The maximum COV achieved is 8%. The results of ANOVA showed that the null hypothesis is rejected and there is a significant difference between the resistivity measurements between the mixtures, followed by Tukey's test and Students t-test, which shows significant difference in resistivity measurements between the mixtures. Meanwhile, t-test show no significant difference between mixture 6 and mixtures 4 and 5. The reason for significant difference in returned p-value could be the deficiency in quality control of concrete materials or ineffective implementation of mixture design, which results in lack of consistency in the reproduction of same concrete mixture design. However, it was noted that the source of coarse aggregates for mixtures 1, 2, and 3 are different from mixtures 4, 5, and 6. The source of aggregates could be influential to resistivity of concrete mixtures. Therefore, it is concluded that the concrete producer-1 may remain unsuccessful in maintaining the consistency in concrete mixtures and change in the source of aggregates could influence the resistivity of concrete. Further, it is recommended to investigate the influence of aggregate source on surface resistivity testing.

The concrete producer-1 manufactured 5 concrete mixtures of 0.44 w/cm with 20% fly ash content and 24% paste fraction to three residencies (Table 6.2). These concrete mixtures are referred from mix-6 to mix-11. Figure 6.4 represents the time-resistivity curves of the mixtures. The samples of mixtures 7 and 9 were received on day 7, whereas, samples of mixtures 6,8,10 and 11 were received on day 14. The figure shows the resistivity of concrete mixtures having similar mixture design is increasing contrarily to each other and no compatibility is found between the mixtures throughout the testing period. From the figure, the resistivity of mixtures 8 and 10 are coinciding with each other, whereas mixtures 7 and 9 are gaining resistivity at the same rate. But, there is no uniformity in 5 concrete mixtures found from resistivity testing approved with the same mixture design. Also, the mixtures 8 and 10 have entered into moderate chloride ion penetrability level out of 5 mixtures. The mixtures 7,9 and 11 were at a high risk of chloride ion penetrability according to 28-day permeability classifications [5,7].

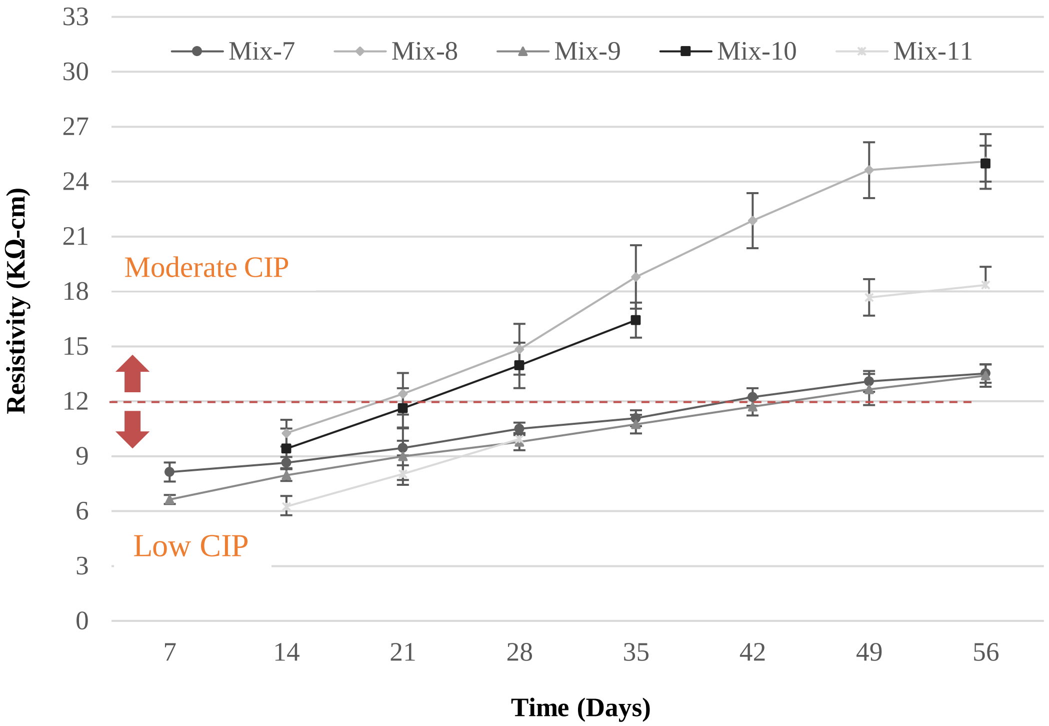


Fig. 6.4 Concrete mixtures manufactured by concrete producer-1

Table 6.4 Statistical Analysis of Concrete Resistivity from Producer-1

	Mixtures	Resistivity (KΩ-cm)			ANOVA	Comp.	Tukey's Test	T-test
		Mean	Std. Dev.	COV (%)	p-value			
Concrete Producer-1	Mix-7	10.5	0.17	2.0	8.8 E-8	M7/M8	Sig. diff.	4.6 E-4
						M7/M9	Sig. diff.	0.012
	Mix-8	14.8	0.69	5.0		M8/M9	Sig. diff.	2.7 E-4
						M10/M7	Sig. diff.	0.007
	Mix-9	9.8	0.23	2.0		M10/M8	-	0.176
						M10/M9	Sig. diff.	3.9 E-4
	Mix-10	14.0	0.62	4.0		M11/M7	Sig. diff.	0.016
						M11/M8	Sig. diff.	0.005
	Mix-11	9.9	0.16	2.0		M11/M9	-	0.357
						M11/M10	Sig. diff.	4.1 E-4

The results of statistical analysis are shown in Table 6.4. The p-value of AVOVA reflects the null hypothesis is rejected and there is a significant difference among the resistivity data of the mixtures, where the COV within the concrete mixtures ranges from 2% to 5%. Similar results are noted from Tukey's test and t-test, except the mixtures 8 and 10, and mixtures 9 and 11 show no significant difference in resistivity values. There was no difference noted between the materials source used to prepare the concrete mixtures. Therefore, it is concluded that concrete producer-1 has not been able to maintain the consistency in reproducing concrete mixtures at different times. The reason could be poor quality control and ineffective implementation of mixture design during production.

The concrete mixtures having 0.38 w/cm, 20% fly ash content, and 25% paste fraction were manufactured 8 times by concrete producer-1 and delivered to three residencies. These 8 concrete mixtures were labelled from mix-12 to mix-19. In Figure 6.5, the resistivity verses timeline plots are shown. The time-resistivity curve of mixture-12 is very different from other mixtures, whereas, mixtures 13 to 19 attains approximately same rate of increase in resistivity. According to 28-day ion permeability classifications [5,7], all the mixtures falls in low chloride ion permeability level except mixture 12, which achieved mean resistivity >12 KΩ-cm at day-28.

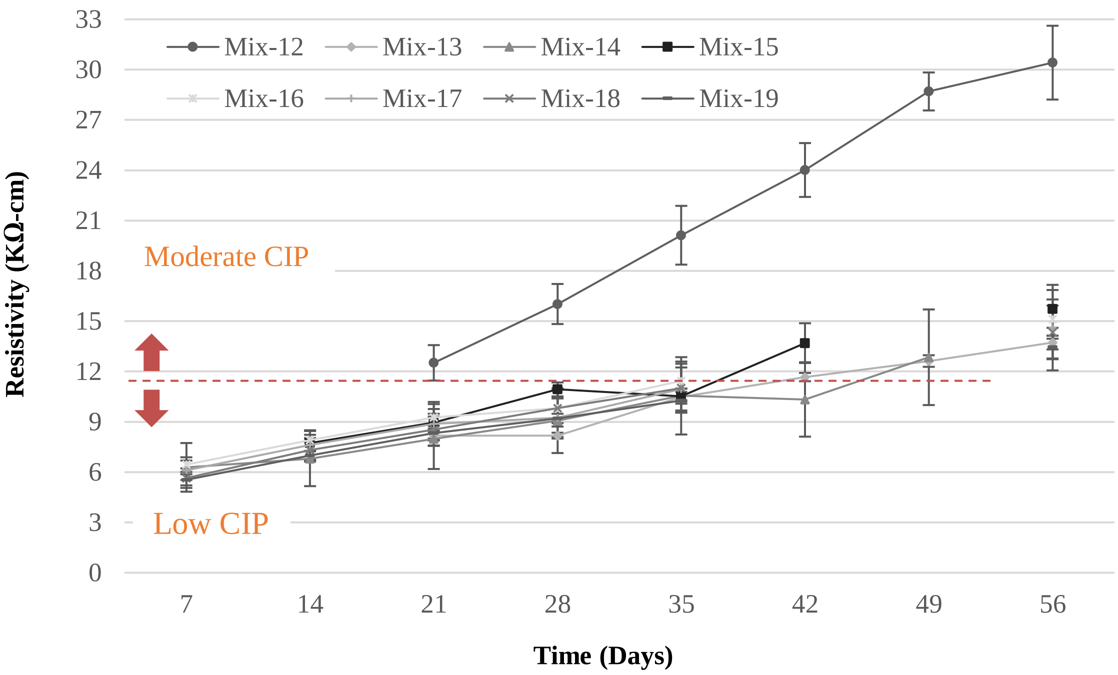


Fig. 6.5 Concrete mixtures manufactured by concrete producer-1

Table 6.5 Statistical Analysis of Concrete Resistivity from Producer-1

	Mixtures	Resistivity (KΩ-cm)			ANOVA	Comp.	Tukey's Test	T-test
		Mean	Std. Dev.	COV (%)	p-value			
Concrete Producer-1						M12/M13	Sig. diff.	0.002
	Mix-12	16.0	0.60	4.0		M12/M14	Sig. diff.	4.4 E-4
						M13/M14	-	0.250
						M15/M12	Sig. diff.	1.5 E-4
	Mix-13	8.2	0.09	1.0		M15/M13	Sig. diff.	3.0 E-5
						M15/M14	Sig. diff.	0.031
						M16/M12	Sig. diff.	4.4 E-4
	Mix-14	9.1	0.96	11.0		M16/M13	Sig. diff.	0.010
						M16/M14	-	0.276
						M16/M15	Sig. diff.	0.008
						M17/M12	Sig. diff.	1.4 E-4
	Mix-15	10.9	0.21	2.0		M17/M13	Sig. diff.	0.032
						M17/M14	-	0.794
					9.6 E-11	M17/M15	Sig. diff.	0.009
						M17/M16	-	0.218
	Mix-16	9.8	0.33	3.0		M18/M12	Sig. diff.	2.0 E-4
						M18/M13	Sig. diff.	0.007
						M18/M14	-	0.322
	Mix-17	9.3	0.57	6.0		M18/M15	Sig. diff.	0.030
						M18/M16	-	0.983
						M18/M17	-	0.284
						M19/M12	Sig. diff.	0.002
	Mix-18	9.8	0.55	6.0		M19/M13	Sig. diff.	4.1 E-4
						M19/M14	-	0.834
						M19/M15	Sig. diff.	2.8 E-4
						M19/M16	Sig. diff.	0.043
	Mix-19	9.2	0.14	2.0		M19/M17	-	0.890
						M19/M18	-	0.133

The statistical analysis of 8 mixtures having similar mixture design is shown in Table 6.5. The results of ANOVA expressed a significant difference between the resistivity measurements of concrete mixtures followed by Tukey's test and t-test, which determines no significant difference in mean resistivity values of mixtures 13 and 14, 14 and 16, 14 and 17, 14 and 18, 14 and 19, 16 and 17, 16 and 18, 17 and 18, 17 and 19, and 18 and 19. Where, mixture 14 achieved the maximum COV of 11%. The figure and analysis have shown the significant difference between the mixtures may be due to lack of quality control and inconsistency among the mixtures. However, there is no difference found in materials and sources used to prepare concrete mixtures.

The concrete producer-1 manufactured 3 concrete mixtures of 0.38 w/cm with no fly ash content and 25% paste fraction for two residencies (Table 6.2). The time-resistivity behavior of the mixtures is shown in Figure 6.6, named as mix-20, mix-21 and mix-22. From the figure, results have shown that the mixtures 1 and 2 coincide with each other for gaining resistivity with time, whereas, mixture-3 obtained lower resistivity measurements throughout the testing period. According to 28-day permeability classifications [5,7], mixtures 20 and 21, mean resistivity value falls under moderate chloride ion penetrability level, whereas, mixture 22 remains in low chloride ion penetrability level. This gives an indication of difference in micro-structure development and ion transport mechism of mixture 22 compared to 20 and 21 concrete mixtures.

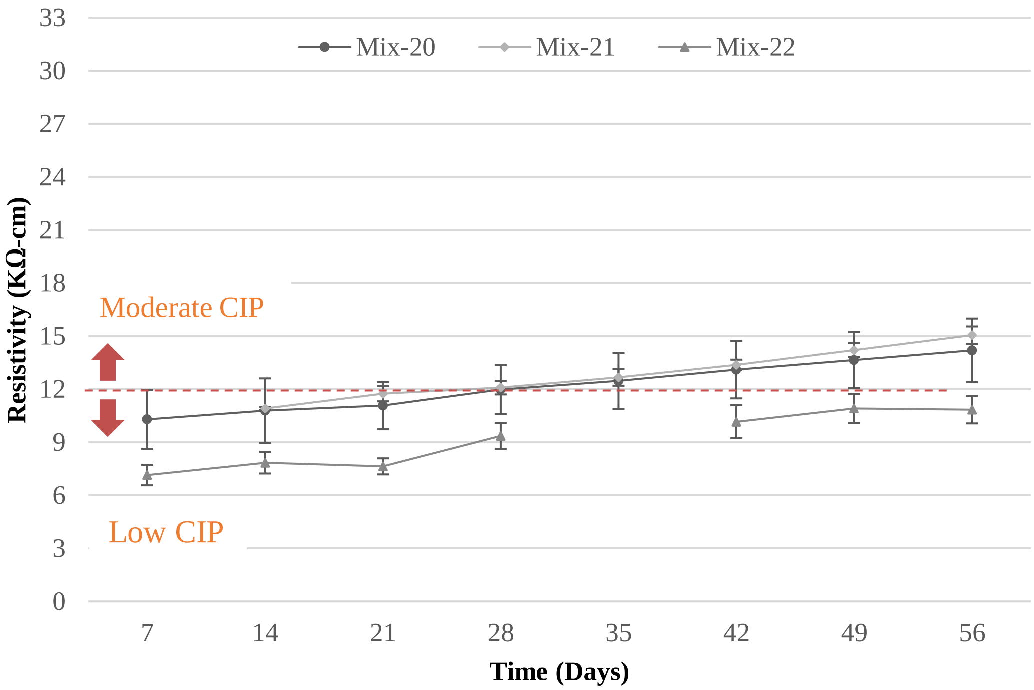


Fig. 6.6 Concrete mixtures manufactured by concrete producer-1

Table 6.6 Statistical Analysis of Concrete Resistivity from Producer-1

	Mixtures	Resistivity (KΩ-cm)			ANOVA	Comp.	Tukey's Test	T-test
		Mean	Std. Dev.	COV (%)	p-value			
Concrete Producer-1	Mix-20	12.0	0.69	6.0	5.7 E-4	M20/M21	-	0.806
	Mix-21	12.1	0.19	2.0		M20/M22	Sig. diff.	0.004
	Mix-22	9.4	0.37	4.0		M22/M23	Sig. diff.	3.3 E-4

The statistical analysis of the mixtures is shown in Table 6.6. The results of ANOVA determine a significant difference between the mixtures followed by Tukey's test and t-test. The post-hoc tests show no significant difference in resistivity between mixtures 20 and 21, whereas, a significant difference found between mixtures 20 and 22, and mixtures 22 and 23. The results show an inconsistency between the concrete mixtures.

The 22 concrete mixtures prepared by concrete producer-1 and delivered to 6 residencies in Oklahoma were divided into four groups according to their mixture design. The results of time-resistivity curves and statistical analysis have shown that concrete producer-1 remained unsuccessful to maintain consistency in the reproduction of concrete mixtures. The surface resistivity testing can be applied as a quality control criterion to determine the consistency of concrete production.

6.3.2 Concrete Producer-2

The concrete producer-2 manufactured 4 concrete mixtures of 0.38 w/cm with 20% fly ash replacement and paste fraction of 20% for three residencies at different times. It is noted from the mixture design details that the source of cement of mixture-1 is different from mixtures 2, 3, and 4. In addition, the aggregates of 4 concrete mixtures are sourced from different origins. The resistivity verses timeline plots are shown in Figure 6.7. The gain in resistivity over the testing period is different for all the mixtures. Mixture 4 has attained higher resistivity compared to other mixtures, whereas, mixture-1 achieved the lowest resistivity profile. This shows difference in development of microstructure and change in permeability during the testing period for all the mixtures having similar mixture design. The mean resistivity of mixture 4 falls in moderate chloride ion penetrability zone, according to 28-day permeability classification [5,7], whereas, rest of the mixtures are at a high risk of chloride ion permeability. This could lead to corrosion and other durability issues at an early age.

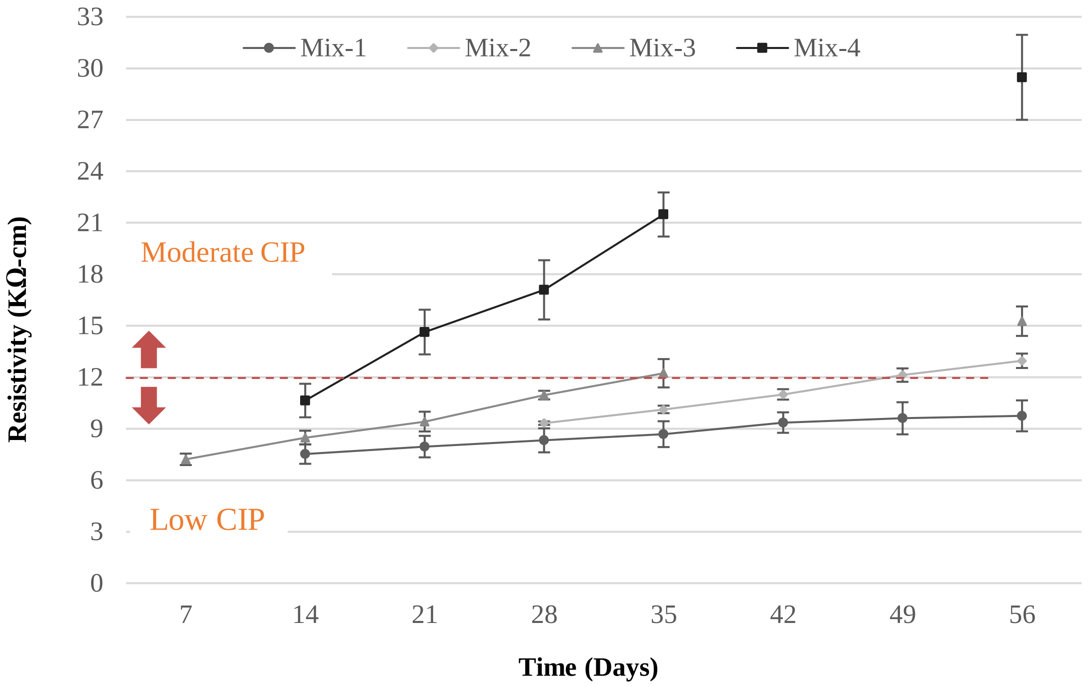


Fig. 6.7 Concrete mixtures manufactured by concrete producer-2

Table 6.7 Statistical Analysis of Concrete Resistivity from Producer-2

	Mixtures	Resistivity (KΩ-cm)			ANOVA	Comp.	Tukey's Test	T-test
		Mean	Std. Dev.	COV (%)	p-value			
Concrete Producer-2	Mix-1	8.3	0.35	4.0	6.1 E-8	M1/M2	Sig. diff.	0.036
						M1/M3	Sig. diff.	2.5 E-4
	Mix-2	9.3	0.05	1.0		M2/M3	Sig. diff.	3.1 E-5
	Mix-3	11.0	0.13	1.0		M4/M1	Sig. diff.	0.001
						M4/M2	Sig. diff.	1.0 E-4
	Mix-4	17.1	0.86	5.0		M4/M3	Sig. diff.	0.006

The statistical analysis is shown in Table 6.7. The results of ANOVA analysis have shown a significant difference between the concrete mixtures. The post-hoc analysis also confirms the significant between all the mixtures with maximum COV of 5%. The reason could be due to different sources of aggregates or cement that influenced the resistivity of concrete or lack of quality control during concrete production. Hence, there is no consistency in concrete production by concrete producer-2 is observed.

6.3.3 Concrete Producer-3

A group of 3 concrete mixtures were prepared by concrete producer-3 and delivered to 2 residencies (Table 6.2). The mixture design consists of 0.42 w/cm, 15% fly ash replacement and 23% paste fraction. The time-resistivity behavior of the mixtures is shown in Figure 6.8, and similarity in gain of resistivity over time for all the concrete mixtures can be seen. The concrete mixtures were prepared with the same mixture design and materials. The mean resistivity values of concrete mixtures at each testing day are very close to each other. The time-resistivity curves of concrete mixtures based on mean resistivity measurements represent good control of mixture parameters during production. However, at day 28, the mean resistivity of all the mixtures are in low chloride ion penetration zone, which can be alarming for occurrence to durability issues at early age due to easy access of foreign components into the concrete.

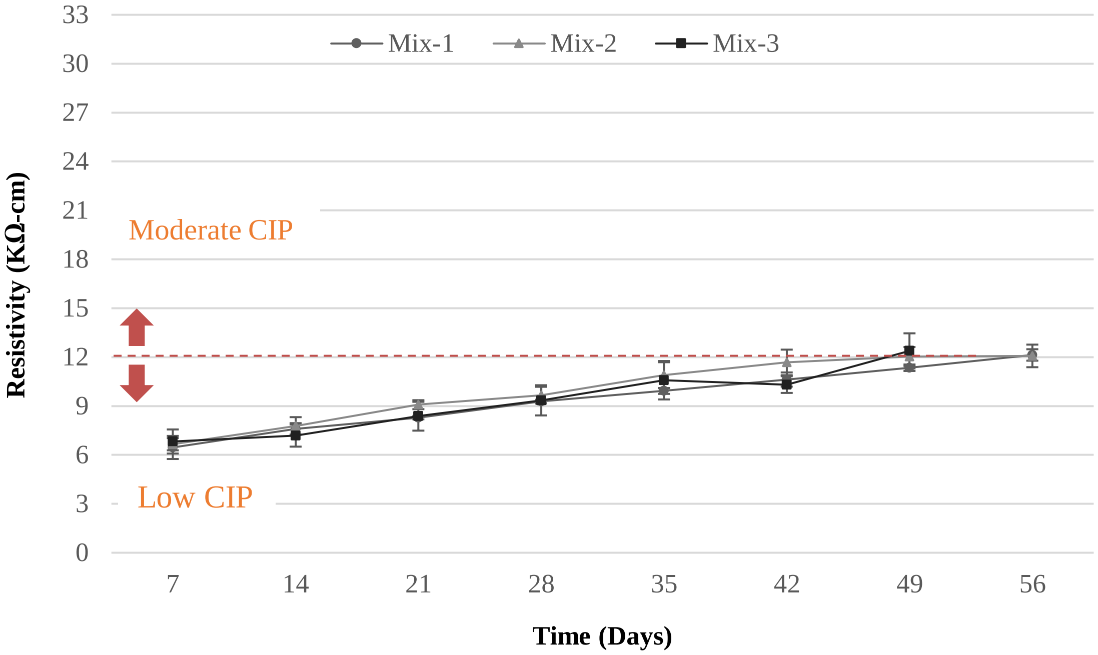


Fig. 6.8 Concrete mixtures manufactured by concrete producer-3

Table 6.8 Statistical Analysis of Concrete Resistivity from Producer-3

Concrete Producer-3	Mixtures	Resistivity (KΩ-cm)			ANOVA	Comp.	Tukey's Test	T-test
		Mean	Std. Dev.	COV (%)	p-value			
	Mix-1	9.3	0.05	1.0	0.33	M1/M2	-	0.064
	Mix-2	9.7	0.26	3.0		M1/M3		0.816
	Mix-3	9.4	0.46	5.0		M2/M3		0.359

The statistical analysis of the mixtures made by producer-3 is shown in Table 6.8. The results of ANOVA analysis show no significant difference between the resistivity of concrete mixtures followed by t-test. The maximum COV obtain is 5% from mixture 3. Hence, it can be concluded that the concrete producer-3 is successful in maintaining the consistency of concrete reproduction.

6.3.4 Concrete Producer-4

Three concrete mixtures were prepared by concrete producer 4 having 0.44 w/cm with replacement of 20% fly ash content and 28% paste fraction for a residency (Table 6.2). The time-resistivity curves of three mixtures are shown in Figure 6.9. The curves are comparable to each other and show similarity in gain of resistivity over the testing period. All the concrete mixtures were prepared with same mixture design and materials. However, the mixture design details show the source of cement used for mixture 3 is different from mixtures 1 and 2. The mean resistivity values of concrete mixtures at each testing day are very close to each other. The time-resistivity curves of concrete mixtures based on mean resistivity values represent a good control of mixture parameters during production. According to 28-day permeability classifications, all the mixtures falls in low chloride ion penetrability zone.

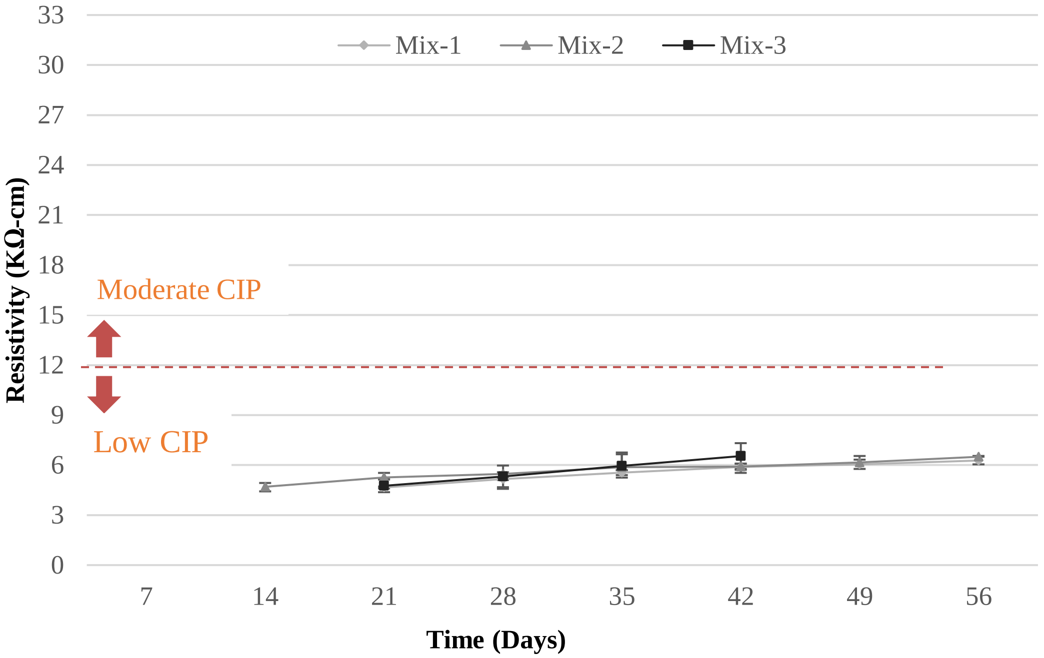


Fig. 6.9 Concrete mixtures manufactured by concrete producer-4

Table 6.9 Statistical Analysis of Concrete Resistivity from Producer-4

	Mixtures	Resistivity (KΩ-cm)			ANOVA	Comp.	Tukey's Test	T-test
		Mean	Std. Dev.	COV (%)	p-value			
Concrete Producer-4	Mix-1	5.2	0.03	1.0		M1/M2		0.001
	Mix-2	5.5	0.05	1.0	0.24	M1/M3	-	0.448
	Mix-3	5.3	0.33	6.0		M2/M3		0.530

The statistical analysis of three mixtures are shown in Table 6.9. The results of ANOVA analysis have shown that the null hypothesis is failed to reject and there is no significant difference among the resistivity data set of the mixtures. Whereas, t-test has shown difference in resistivity values between mixtures 1 and 2. Mixture 6 achieved the maximum COV of 6%. Hence, the concrete producer 4 remain successful in maintaining the consistency of concrete reproduction.

6.3.5 Concrete Producers 5,6,7 and 8

There are four concrete producers 5, 6, 7 and 8 that each produced two concrete mixtures with similar mixture design for a residency (Table 6.2). The comparison of time-resistivity curves of the mixtures is shown in Figures 6.10, 6.11, 6.12 and 6.13 and statistical analyses are presented in Tables 6.10, 6.11, 6.12 and 6.13.

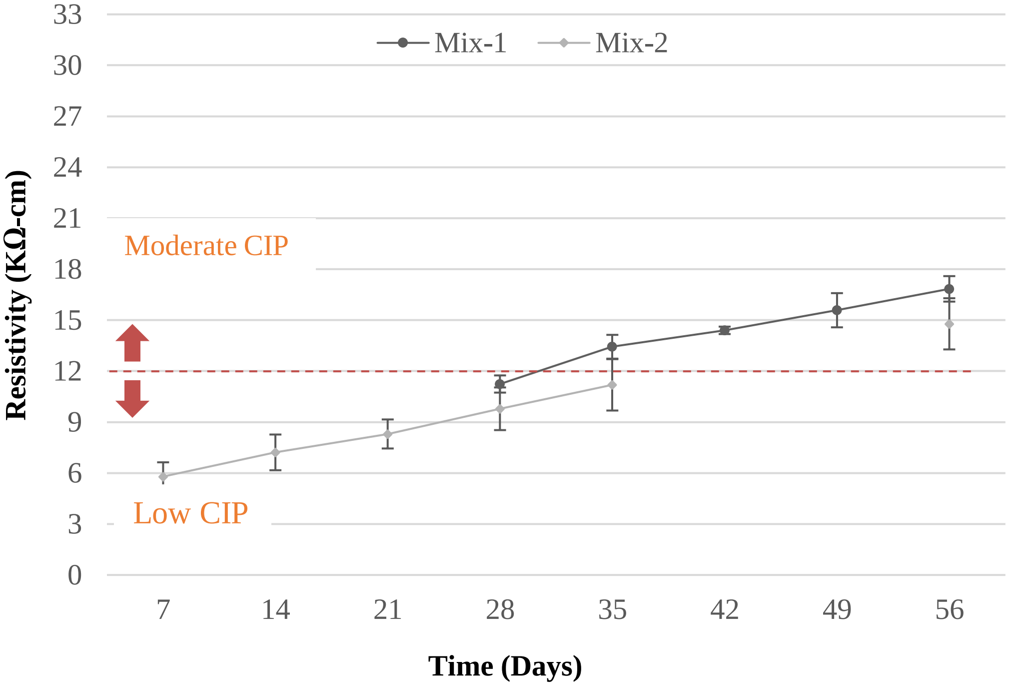


Fig. 6.10 Concrete mixtures manufactured by concrete producer-5

Table 6.10 Statistical Analysis of Concrete Resistivity from Producer-5

Concrete Producer-5	Mixtures	Resistivity (KΩ-cm)			T-test
		Mean	Std. Dev.	COV (%)	p-value
	Mix-1	4.9	0.09	2.0	0.042
	Mix-2	5.2	0.03	1.0	

The concrete producer 5 manufactured two concrete mixtures with 0.44 w/cm, 20% fly ash, and 24% paste fraction (Table 6.2). The aggregates and fly ash source information was not available for mixture 2. On comparing time-resistivity curves of both mixtures, the mean resistivity of mixture 1 is higher than mixture 2. However, the increase in resistivity over time appeared to be same. At 28-day, both concrete mixtures are found in low chloride penetration zone [5,7], which determins high risk of durbility problems to the mixtures. The statistical analysis is shown in Table 6.10. The COV of concrete mixtures are calculated up to 2%. The t-test was performed to analyze the difference between the two resistivity data sets. The results of t-test at 28-day resistivity shows a significant difference in resistivity data sets of both mixtures. Therefore, with a minor difference in mean resistivity values, the consistency of both mixtures is not considered to be same and the reason of inconsisdentcy can be lack of quality control during production of concrete.

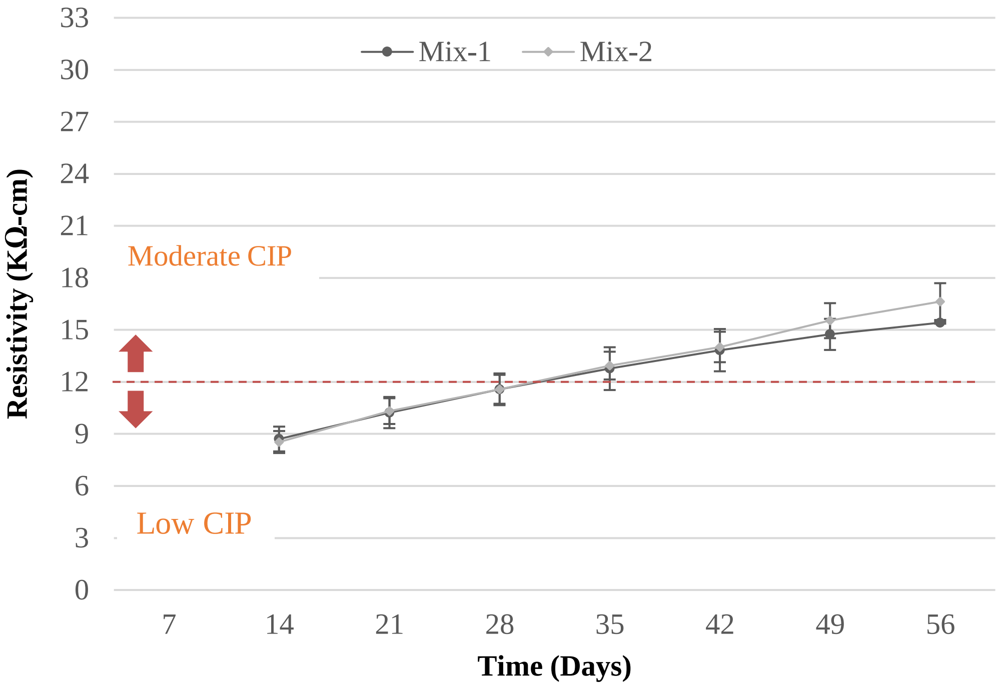


Fig. 6.11 Concrete mixtures manufactured by concrete producer-6

Table 6.11 Statistical Analysis of Concrete Resistivity from Producer-6

Concrete Producer-6	Mixtures	Resistivity (KΩ-cm)			T-test
		Mean	Std. Dev.	COV (%)	p-value
	Mix-1	11.6	0.42	4.0	1.00
	Mix-2	11.6	0.46	4.0	

The concrete producer 6 manufactured two concrete mixtures having 0.41 w/cm with 20% fly ash replacement, and 24% paste fraction (Table 6.2). The mixture design and aggregate sources are similar for both mixtures. The plot between resistivity and testing period is shown in Figure 6.12. The time-resistivity curves exactly match each other on comparing both mixtures. But, the 28-day resistivity falls in low chloride ion penetrability zone, which indicates high risk of corrosion and durability issues to concrete. The statistical analysis is shown in Table 6.12. The results of t-test at 28-day resistivity show no significant difference in resistivity data sets of both mixtures with COV of 4%. Therefore, it is concluded that the concrete producer 6 remain successful in maintaining consistency in reproducing concrete mixtures.

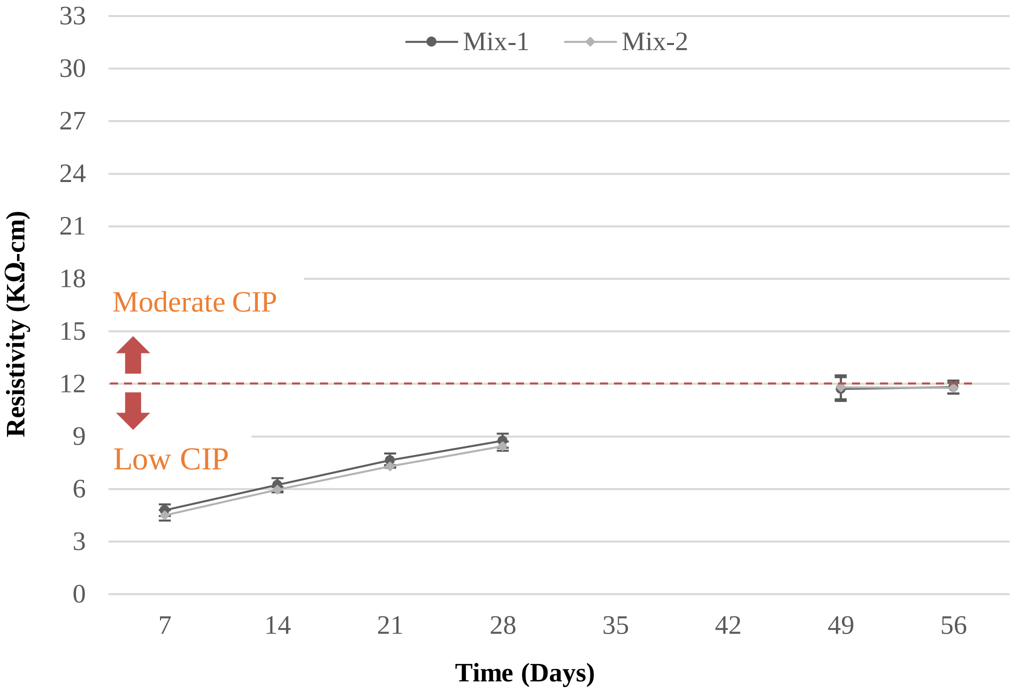


Fig. 6.12 Concrete mixtures manufactured by concrete producer-7

Table 6.12 Statistical Analysis of Concrete Resistivity from Producer-7

	Mixtures	Resistivity (KΩ-cm)			T-test
		Mean	Std. Dev.	COV (%)	p-value
Concrete Producer-7	Mix-1	8.8	0.20	2.0	0.101
	Mix-2	8.5	0.13	2.0	

Two concrete mixtures were manufactured by producer 7 bearing mixture design of 0.41 w/cm with 20% fly ash content replacement and 27% paste fraction (Table 6.2). The mixture design and aggregate sources are similar for both mixtures. The time-resistivity curves are shown in Figure 6.13, and it exactly match with each other on comparing both mixture's resistivity results. The results of statistical analysis are shown in Table 6.12. The results of t-test at 28-day resistivity show no significant difference in resistivity data sets of both mixtures with COV of 2%. Therefore, it is concluded that the concrete producer 7 is successful in maintaining consistency in reproducing concrete mixtures.

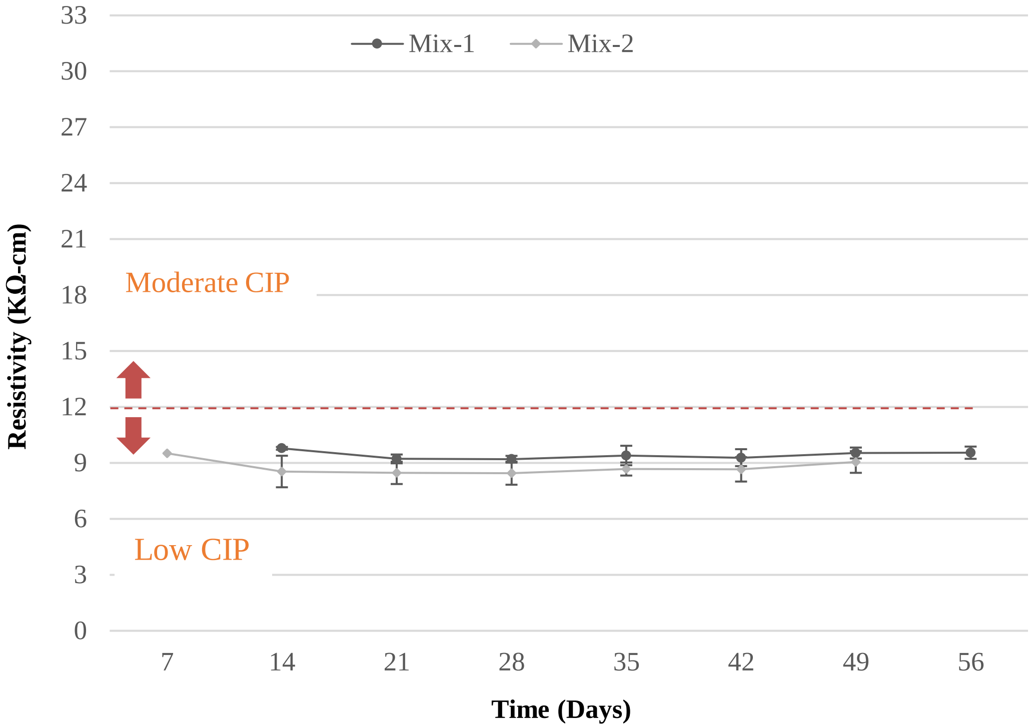


Fig. 6.13 Concrete mixtures manufactured by concrete producer-8

Table 6.13 Statistical Analysis of Concrete Resistivity from Producer-8

	Mixtures	Resistivity (KΩ-cm)			T-test
		Mean	Std. Dev.	COV (%)	p-value
Concrete Producer-8	Mix-1	9.2	0.09	1.0	0.050
	Mix-2	8.5	0.31	4.0	

The two concrete mixtures were manufactured by concrete producer 8 having 0.44 w/cm with no fly ash content replacement and 28% paste fraction (Table 6.2). The mixture design and aggregate sources are similar for both mixtures.The resistivity verses time plots are shown in Figure 6.13. On comparing time-resistivity curves of both mixtures, the resistivity stayed constant over time and no increase in resistivity over the testing period is observed. Further investigation is recommended to determine the cause of no change in resistivity with the age of concrete. Moreover, the 28-day resistivity falls in low chloride ion penetrability zone according to 28-day permeability classification [5,7]. The allows the concrete mixtures to be under threat of ingress of foreign components to cause durability issues. The statistical analysis is show in Table 6.13. The results of t-test at 28-day resistivity showed that there is no significant difference in resistivity data sets of both mixtures with 1% COV in mixture 1 and 4% COV in mixture 2 resistivity values. No increase in resistivity up to 56 days of samples concluded that the microstructure of paste medium might be changing at a very slow pace due to the slow process of hydration, which may not be in favor of concrete's servisable life.

6.4 Conclusions

Concrete is a composite material, which undergoes health problems mainly due to durability issues. The timeline for visible evidence of durability problems depends on the quality of concrete and implementation of mixture design. The mixture design could be evaluated and approved but maintaining the quality of concrete especially the consistency of concrete mixtures when it is being produced multiple times is a challenge. This study evaluated the consistency of concrete mixtures produced by various concrete producers at different times by using surface resistivity method and concluded the performance and credibility of the concrete producers.

The concrete producer-1 has manufactured 22 concrete mixtures, delivered to 6 residencies in Oklahoma are divided into four groups, according to their mixture design. The time-resistivity curves and statistical analysis have shown that concrete producer-1 may not be able to maintain consistency in the reproduction of concrete mixtures. In this case, further investigation is required to develop a quality control criterion to determine the consistency in concrete production.

The concrete producer-2 have produced 4 concrete mixtures for three different residencies. The producer-2 was not able to maintain the consistency in the reproduction of concrete mixtures having similar mixture design. The reason could be different sources of cement and aggregates that influenced the resistivity of concrete or lack of quality control during concrete production.

The concrete producer-3 has prepared 3 concrete mixtures for two different residencies. The time-resistivity curves and statistical analysis proved that the concrete producer-3 was successful in maintaining the consistency of concrete reproduction.

The concrete producer-4 has also manufactured 3 concrete mixtures for a residency in Oklahoma. It is concluded from time-resistivity curves and statistical analysis that the concrete producer-4 has successfully maintained the consistency in the reproduction of concrete mixtures.

The concrete producers 5, 6, 7 and 8, each manufactured two concrete mixtures for a residency. The concrete producer 6, 7 and 8 successfully produced consistent concrete mixtures both times according to the results obtained from statistical analysis and comparison of time-resistivity behavior. Whereas, concrete producers 5 was not able to maintain consistency in reproduction. In case of concrete producer-8, the time-resistivity curves of both mixtures showed no gain in resistivity with an increase up to 56 days. Therefore, it is concluded that the concrete parameters might have a considerable difference with the approved mixture design.

The preliminary results of this study showed that it is required to develop a quality control criterion to determine the consistency in concrete production. The surface resistivity testing can be used to determine the consistency of concrete mixtures produced by a concrete producer. It can help to provide a tool for evaluating the quality of concrete along with compressive strength. This procedure can also be used to develop a long-term credential rating for the concrete producer, which can provide assistance in technical evaluation of concrete producer.

Acknowledgements

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CHAPTER 7

COMPARATIVE STUDY OF SORPTIVITY, ABSORPTION AND COMPRESSIVE STRENGTH WITH SURFACE RESISTIVITY OF CONCRETE

Preface

In this study, the author and undergrad research team, conducted sorptivity, absorption and compressive strength tests on various concrete samples, under the supervision of Dr. Julie Ann Hartell at Bert Cooper Engineering Lab. The statistical analysis is performed by the author.

Abstract

The electrical resistivity method can serve as a quality control indicator of strength, and durability by assessing the fluid transport processes in concrete. In comparison, the relationship between surface resistivity and sorptivity, total absorption, and compressive strength does not prove to be a strong precedent for evaluation of concrete. However, by individually investigating the concrete parameters such as w/cm, fly ash content, fly ash source, aggregate type and size, the role of chemical admixtures and paste fraction could help to better understand the relationship of resistivity with sorptivity, total absorption, and compressive strength. By knowing the materials in the concrete mixture, the effect of a change in a single parameter could be assessed by surface resistivity, and the results of other mechanisms like sorptivity, absorption, and compressive strength could be anticipated. In addition, this study could help to strengthen the surface resistivity method as a quality assurance tool for durability and strength of concrete.

Keywords: Surface resistivity; Sorptivity; Absorption; Compressive strength; Fly Ash

7.1 Introduction

The resistivity property of concrete is becoming imperative and prominent in civil engineers because the resistance to the flow of current under a potential difference is analogous to major types of fluid transport through concrete; absorption, permeability, and diffusion. Moreover, resistivity method has been found to be less expensive and fast-track technique to perform testing. The electrical resistivity method can serve as the quality control indicator of durability by assessing the fluid transport processes [1]. Therefore, providing motivation for the implementation of the method in routine control activities.

The researchers and scholars have completed studies in the past to analyze the comparison of electrical resistivity with transport properties and strength of concrete. A linear correlation was found between electrical resistivity and diffusion coefficient. It was concluded that surface resistivity could be used as a reliable method to determine diffusion coefficient in SSD (saturated surface dry) condition [2]. In addition, the comparison has been made between resistivity and permeability, and a good correlation ($R^2 = 87\%$) was found among them for the same type of cementitious material, while the correlation coefficient reduced ($R^2 = 82\%$) by using different types of cementitious materials [3]. Moreover, little work has been done to compare surface resistivity and rate of absorption (sorptivity) and a good correlation was determined as both mechanism depends on pore size, connectivity between pores, tortuosity, and mobility through the porous system [4]. Furthermore, the comparison between resistivity and compressive strength has also been made. It was concluded that for similar cementitious materials a good correlation could be obtained because resistivity and strength increase with age. While by using different cementitious materials, there is no sensible correlation found between resistivity and compressive strength because resistivity depends on pore water concentration and saturation condition whereas compressive strength depends on the strength of Interlayer Transition Zone (ITZ) between paste and aggregates [3,5-6]. Furthermore, no studies in the literature have been found on comparing resistivity with total volume of absorption in concrete. Therefore, a great potential was found to investigate the relationship of surface resistivity method with absorption, the rate of absorption and compressive strength of concrete by varying water-to-cement (w/cm) ratio and secondary cementitious material such as Class-C fly ash in the concrete mixtures. Besides, it is required to analyze the effect of a change in concrete parameters on resistivity relationship with sorptivity, absorption and compressive strength to support the implementation of surface resistivity method to evaluate the transport properties of a concrete mixture.

The focus of this study is to analyze the relationship of surface resistivity method with sorptivity, percentage absorption and compressive strength of Class-AA (ODOT specification) concrete by varying the concrete parameters, such as w/cm, fly ash content, fly ash source, aggregate type and size, addition of chemical admixtures, and paste volume. Each of these parameters has an influence on transport properties and strength of concrete. The variation in these parameters could help to compare the change in sorptivity, percentage absorption and compressive strength with surface resistivity through comparative statistical analysis.

7.2 Experimental Design

The experimental method was designed to accomplish the stated objectives of the study, first to determine the relationship of surface resistivity method with sorptivity, percentage absorption and compressive strength tests for varying water-to-cement (w/cm) ratios and fly ash content concrete mixtures. Secondly, investigate the effect of change in concrete parameters such as w/cm, fly ash content, fly ash source, aggregate type and size, addition of water reducer (WR) and air entrainment (AE), and paste volume on relationship between surface resistivity and sorptivity, percentage absorption and compressive strength tests. The materials used, and experimental procedures followed are detailed in the following sections.

7.2.1 Materials

A total of eighteen concrete mixtures of varying water-to-cement ratio, varying percentages of fly ash, fly ash from different sources, aggregate types, and sizes, by adding WR and AE and varying paste volume were prepared for this study. All materials were batched and mixed in a temperature-controlled environment and samples were cast respecting standard methods of preparing concrete samples in a laboratory environment (ASTM C 192) [7]. All materials used in this study were sourced and manufactured in the state of Oklahoma. The chemical compositions of the Portland cement aggregates and fly ash sources are given in Table 7.1. All the concrete mixtures are summarized in Table 7.2.

Table 7.1 Chemical Properties of Coarse Aggregate, Portland Cement, and Fly Ash Sources

Chemicals	(%) Limestone	(%) Dolomite	(%) Granite	Cement (Type-I)	Fly Ash (Source-I)	Fly Ash (Source-II)	Fly Ash (Source-III)
Ca	35.93	20.67	7.24	-	-	-	-
CaO	50.27	28.92	10.13	62.9	23.12	29.74	24.41
$CaCO_3$	89.73	51.62	18.08	-	-	-	-
Mg	1.02	9.74	1.07	-	-	-	-
MgO	1.69	16.15	1.77	1.9	5.55	7.46	5.87
$MgCO_3$	3.54	33.77	3.71	-	-	-	-
Fe_2O_3	0.25	0.85	4.07	3.4	5.88	5.58	6.28
Al_2O_3	0.6	2.08	16.91	5.1	18.82	18.37	19.17
Si	3.38	4.03	24.3	-	-	-	-
SiO_2	7.24	8.63	51.99	19.4	38.71	32.88	36.27
K_2O	-	-	-	-	0.58	0.41	0.46
SO_3	-	-	-	3.3	1.27	1.89	1.07
Na_2O_3	-	-	-	-	-	-	-
Sodium Oxide	-	-	0.42		-	-	-
Titanium Dioxide	-	-	0.16	-	-	-	-
Potassium Oxide	-	-	0.31	-	-	-	-

Table 7.2 Summary of Concrete Mixtures

	Mixture	w/cm	Fly Ash (%)	Water (kg/m^3)	Cement (kg/m^3)	Fly Ash (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Paste (%)
Limestone FA (S1)	1	0.40	0%	145.4	362.5	0	1097.6	714.9	27.8%
	2	0.40	10%	145.4	326.25	36.25	1097.6	714.9	27.8%
	3	0.40	20%	145.4	290.0	72.5	1097.6	714.9	27.8%
	4	0.45	0%	163.2	362.5	0	1097.6	714.9	29.2%
	5	0.45	10%	163.2	326.25	36.25	1097.6	714.9	29.2%
	6	0.45	20%	163.2	290.0	72.5	1097.6	714.9	29.2%
	7	0.50	0%	181.5	362.5	0	1097.6	714.9	30.5%
	8	0.50	10%	181.5	326.25	36.25	1097.6	714.9	30.5%
	9	0.50	20%	181.5	290.0	72.5	1097.6	714.9	30.5%
FA (S2)	10	0.40	0%	145.4	362.5	0	1097.6	714.9	27.8%
FA (S3)	11	0.40	0%	145.4	362.5	0	1097.6	714.9	27.8%
Dolomite (#56)	12	0.40	0%	145.4	362.5	0	1163.5	816.6	25.8%
Granite (#57)	13	0.40	0%	145.4	362.5	0	1145.5	861.1	26.1%
Limestone (#67)	14	0.40	0%	145.4	362.5	0	1097.6	714.9	27.8%
WR&AE	15	0.40	0%	145.4	362.5	0	1097.6	714.9	27.8%
WR&AE	16	0.40	20%	145.4	290.0	72.5	1097.6	714.9	27.8%
Paste (30%)	18	0.40	0%	145.4	362.5	0	1014.5	617.0	30.1%
Paste (33%)	19	0.40	0%	145.4	362.5	0	889.9	533.9	33.0%

In order to carry out the testing regimen, eight-cylinder replicates (Ø100 mm x 200 mm) per concrete batch were prepared and demolded after 24 hours. All the concrete cylinders were cured in saturated limewater storage, maintained at curing temperature of 23.0 °C ± 2.0 °C.

7.2.2 Surface Resistivity Testing

Surface resistivity testing was performed on six cylinders in accordance with the AASHTO TP 95 standard procedure [8]. The resistivity meter with a fixed probe spacing of 38 mm was used to take the surface resistivity measurements as shown in Figure 7.1. After demolding the samples, each cylinder was marked at four different points equally distant at 90° of the transverse axis to ensure repetition of the resistivity measurements at the same location for the testing period. Then, prior to commencing curing, resistivity measurements were taken on day-1 (after cylinder demolding). Thereafter, the cylinders were placed in a temperature-controlled limewater storage and allowed to cure up to 56 days. During this time, resistivity measurements were recorded on days 3 and 7 during the first week and once a week up to 56 days. Prior to taking the measurement, the samples were lightly sprayed with tap water and patted with a paper towel to remove any salt accumulation and limewater on the test surface of the cylinder while ensuring a saturated and moist test surface. The ambient temperature of the test environment was kept within standard limits (AASHTO TP95) of 20°C and 25°C to minimize the variability in the measurements.

The apparent resistivity value can be determined from Equation 7.1. The apparent resistivity value obtained can be factorized by applying a factor to compensate for specimen geometry, based on a ratio of cross-sectional area to length of the specimen [9]. The values presented herein are not factorized; therefore, they correspond to the apparent resistivity of a Ø100 mm x 200 mm-cylindrical sample.

$$\rho = \frac{2\pi sV}{I} \tag{7.1}$$

Where ρ represents the apparent resistivity (ohm-cm), s is the spacing between probes (cm), V is measured voltage (volts), and I is the amplitude of alternating current (amps).

Fig. 7.1 Illustration of surface resistivity

7.2.3 Sorptivity Test

The sorptivity test was conducted by following the ASTM C 1585 [10] standard procedure. A set of three concrete cylinders were used for testing after 28 days of curing. The samples were prepared for testing by cutting the cylinders from the top and bottom up to 50 mm depth, having finished surface and cast surface. The samples were placed in the environmental chamber for three days after washing with tap water. The temperature and humidity of environmental chamber were maintained at 50 °C and 80%. After three days, the samples were taken out of the environmental chamber and sealed in plastic containers for 15 days for conditioning. After 15 days, each sample was coated with hot wax from sides and cut surface to prevent moisture absorption and evaporation during testing. The samples with finished surface and cast surface were tested for 6 hours on day-1 (initial sorptivity) and once a day for next eight consecutive days (secondary sorptivity) to complete the test procedure, as explained in the standard. The initial and secondary coefficients considered for analysis were based on two sample readings. The finished surface of the sample was rough and more porous than the cast surface.

7.2.4 Percentage Absorption Test

The percentage absorption test was performed in accordance with ASTM C 642 [11] standard procedure at the sample age of 56 days. In most of the concrete mixtures, there was only one cylinder prepared to conduct the absorption test. The cylinder was cut from top and bottom to the depth of 45 mm, having finished surface and casted surface for testing, as explained in the standard. After cutting, the sample was washed with tap water and placed in the oven, controlled at 110°C temperature. The mass of sample was determined approximately, after 24 hours every day until the mass became constant. After obtaining the constant measurement of oven-dried mass, the samples were submerged in water, and mass measurements were taken until it becomes stable. The percentage absorption was calculated by using oven-dried mass (A) and water saturated mass (B) of the sample by using Equation 7.2.

$$\% Absorption = \left[\frac{\mathrm{B}-\mathrm{A}}{\mathrm{A}}\right] * 100 \tag{7.2}$$

7.2.5 Compression Test

The compression test was conducted to determine the compressive strength of concrete cylinder by following the ASTM C 39 [12] standard procedure. Two samples from each mixture were tested and analyzed for comparative analysis at the age of 28 days.

7.3 Results and Discussions

The results of the four test procedures; surface resistivity, sorptivity, percentage absorption and compressive strength were statistically analyzed using analysis of variation, ANOVA, followed by Tukey's test and Student's t-test. The standard deviation and coefficient of variation (COV) were also calculated for each data set. The null hypothesis (statistical analysis) that proposes there is no significant difference among the data sets, and an alternative hypothesis that determines a significant difference among the data sets (population) is performed, which helps to quantify the effect of a change in tested parameters for each test and comparison with surface resistivity method.

7.3.1 Comparison of Surface Resistivity with Sorptivity, Absorption and Compressive Strength

A set of eight concrete samples prepared from concrete mixtures described in Table 7.2 were investigated using surface resistivity test, sorptivity test, percentage absorption test and compression test. In Figures 7.2, 7.3 and 7.4, a comparison between sorptivity, absorption, and compression strength properties with respect to resistivity properties are shown for concrete mixtures having 0.40, 0.45 and 0.50 w/cm with 0%, 10%, and 20% cement replacement with class-C fly ash.

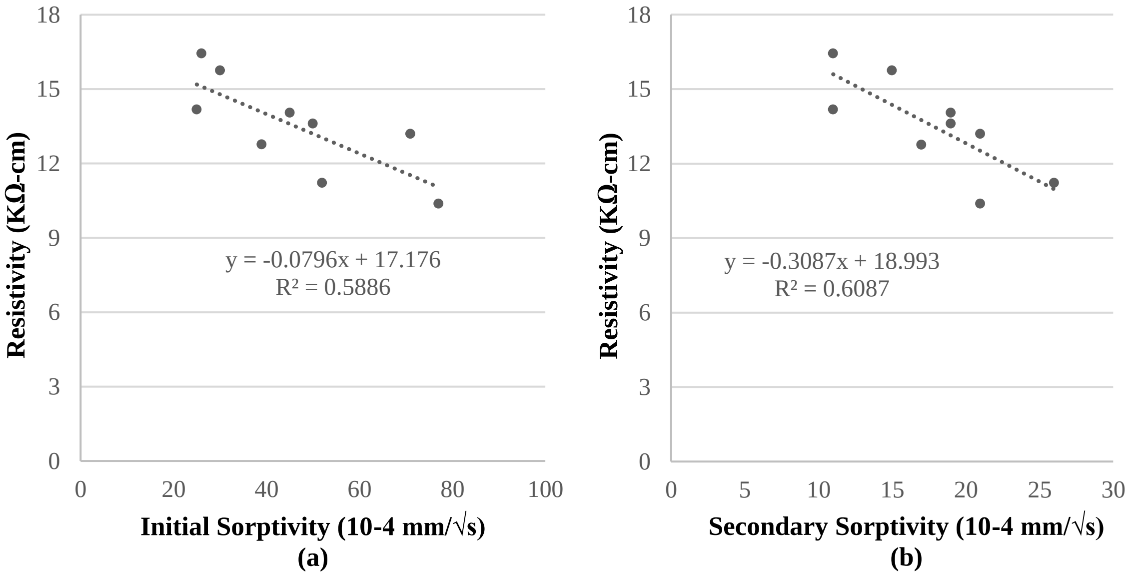


Fig. 7.2 Comparison of resistivity and (a) initial sorptivity and (b) secondary sorptivity for 0.40, 0.45 and 0.50 w/cm with 0%, 10% and 20% fly ash content concrete mixtures

In Figure 7.2 (a,b), the results obtained for the 28-day resistivity test are compared to that of the sorptivity test where initial and secondary sorptivity are shown. For initial sorptivity, the linear correlation gave an R^2 of 59%, and for secondary sorptivity, an R^2 of 61% was obtained. This shows that resistivity and sorptivity do not correlate well with each other. The reason for poor correlation might be due to the difference in the transport mechanism. The resistivity measurement highly depends on the degree of saturation of the porous matrix and concentration of pore solution as the conductivity of an electrolyte varies with its concentration and ionic content. Whereas sorptivity measures the capacity of the material to absorb water via capillarity. The rate of absorption highly depends on pore size, distribution, shape, tortuosity, and continuity of the pores [13]; it is indifferent to solution type. The results of this study corroborate with the findings of Shahroodi [4], which states that higher w/cm results in high porosity and connectivity between pores and the addition of SCM's reduces the water absorption. However, a non-linear correlation with $R^2 = 0.95$ was reported for secondary sorptivity based on 0.40, 0.45 and 0.45+ w/cm mixtures with no SCM's, and 25% replacement of blast furnace slag and blend of slag and silica fume. There is a noticeable trend where resistivity increases while sorptivity decreases. This is in agreement with the concept of refinement of pore structure and improved fluid transport properties.

Next, the total volume of water that an oven dried concrete sample could absorb (% absorption) was determined, which provides the measure of possible permeable pore space of a given concrete sample. The results of absorption in percentage were compared to the resistivity measurements obtained at 56 days (Figure 7.3). The increase in w/cm by a factor of 0.5 resulted in increase in porous structure and total absorption but decrease in resistivity by a factor of 2. The addition of fly ash content results in high resistivity and decrease in total absorption by a factor of

0.5. The increase or decrease in resistivity by a factor of 2 compared total absorption could be due to the connectivity between the pores, which is a major factor influencing the resistivity of concrete. However, the linear correlation gave an R^2 value of 70%, which correlate well with resistivity and rate of absorption. It indicates that increase in the volume of pores of concrete increases its ability to absorb more quantity of water and became a source of ionic transport depending on connectivity between porous network, which results in a low resistivity of concrete.

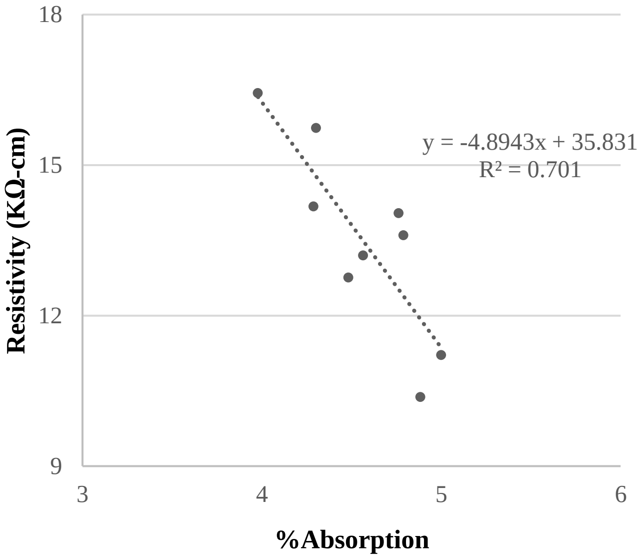


Fig. 7.3 Comparison of resistivity and absorption for 0.40, 0.45 and 0.50 w/cm with 0%, 10% and 20% fly ash content concrete mixtures

The compressive strengths of the concrete mixtures were compared to resistivity measurements as shown in Figure 7.4. The linear correlation gave a low R^2 value of 22%. Although the resistivity of concrete is directly proportional to its strength, the concrete made from different cementitious materials showed no functional relationship between strength and resistivity. The reason for weak correlation could be due to the different mechanisms involved for development of compressive strength and resistivity of concrete. The compressive strength is influenced by the bonding of Interlayer Transition Zone (ITZ), which does not have a significant effect on the resistivity of concrete. Whereas the concentration of pore solution and degree of saturation has a high impact on resistivity measurements, which does not significantly, influence the compressive strength results. The findings of this study support the conclusions of Ramezanianpour and Norman [3,14], which did not show good correlation between resistivity and compressive strength.

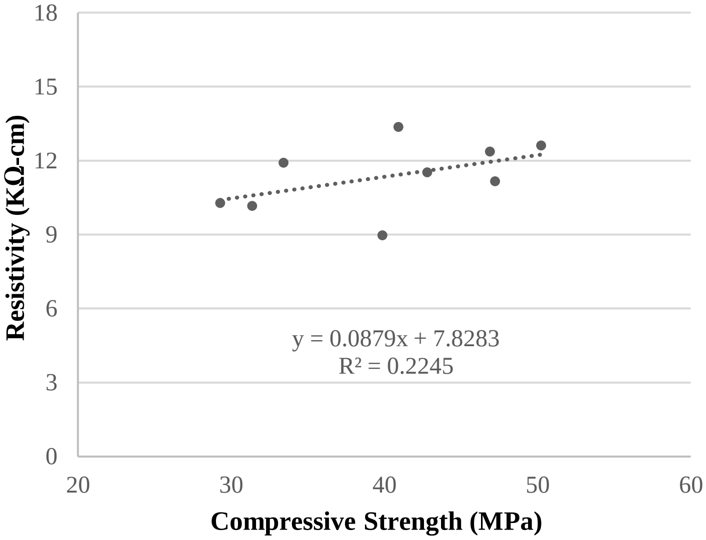


Fig. 7.4 Comparison of resistivity and compressive strength for 0.40, 0.45 and 0.50 w/cm with 0%, 10% and 20% fly ash content concrete mixtures

The comparison of resistivity with sorptivity, percentage absorption, and compressive strength have not shown high correlation for all concrete mixtures, but results of the individual concrete mixture could be related. However, the concrete resistivity could be compared to sorptivity, absorption and compressive strength by analyzing the change in concrete parameters such as w/cm, fly ash content, fly ash source, aggregate type and size, addition of WR and AE, and paste volume because each of these parameters has an impact on properties of concrete. The interest of this study is to have a better understanding on aspect of each parameter in concrete and its influence on comparative analysis.

7.3.2 Effect of w/cm

The effect of a change in w/cm of concrete mixtures was determined by testing the concrete samples with surface resistivity method, sorptivity test, absorption test and compression test. All the tests were conducted on samples made with 0.40, 0.45 and 0.50 w/cm with no added fly ash content. The analysis of variations, ANOVA, was performed on results obtained from each test method to determine whether the w/cm of a concrete mixture will influence the outcome of these test methods. Post hoc tests were performed (Tukey's test and Student's t-test) to analyze which data sets are significantly different from the other.

The resistivity of concrete samples with varying w/cm was observed at the age of 28 and 56 days. The COV remains within 6%. The results obtained from ANOVA, Tukey's test and t-test for surface resistivity at the ages 28 and 56 days are shown in Tables 7.3.

Table 7.3 Results of Statistical Analysis for Effect of w/cm on Surface Resistivity

Age	w/cm	Resistivity (KΩ-cm)			ANOVA	Comp.	Tukey test	Student t-test
(Days)		Mean	Std. Dev.	COV (%)	p-value			
28	0.40	12.4	0.47	3.8	2.1E-05	0.40/0.45	Sig. difference	0.040
	0.45	11.5	0.74	6.4		0.40/0.50	Sig. difference	1.0 E-4
	0.50	10.2	0.40	3.9		0.45/0.50	Sig. difference	0.003
56	0.40	14.2	0.55	3.9	4.4E-07	0.40/0.45	Sig. difference	0.003
	0.45	12.8	0.70	5.5		0.40/0.50	Sig. difference	3.6 E-7
	0.50	11.2	0.28	2.5		0.45/0.50	Sig. difference	0.001

The results from Table 7.3 show that the null hypothesis is rejected, and there is a significant difference between the resistivity values of 0.40, 0.45 and 0.50 w/cm concrete mixtures. Tukey's test and t-test also determine significant difference among each of the w/cm mixtures. The resistivity of concrete mixtures decreases with increase in w/cm because more water is available for the hydration process, changing the porous structure and the chemistry of the pore solution, which are the influential factors to the resistivity of the concrete material.

For the sorptivity test, two samples from each concrete cylinder were obtained having finished surface and cast surface. The finished surface of the concrete sample was rough and more porous compared to cast surface. The initial and secondary coefficients of sorptivity were calculated at the age of 28 days. The results of finished surface and cast surface are shown together for comparison. The cast surface samples obtained higher COV than finished surface samples. The COV for the finished surface samples was under the allowable standard limit of 6%, except for the 0.45 w/cm mixture samples recording a COV of 7.3%.   However, the COV of cast surface samples were as high as 25.7%. The results of ANOVA, Tukey's test and t-test for initial and secondary sorptivity at the age of 28 days are shown in Table 7.4(a,b).

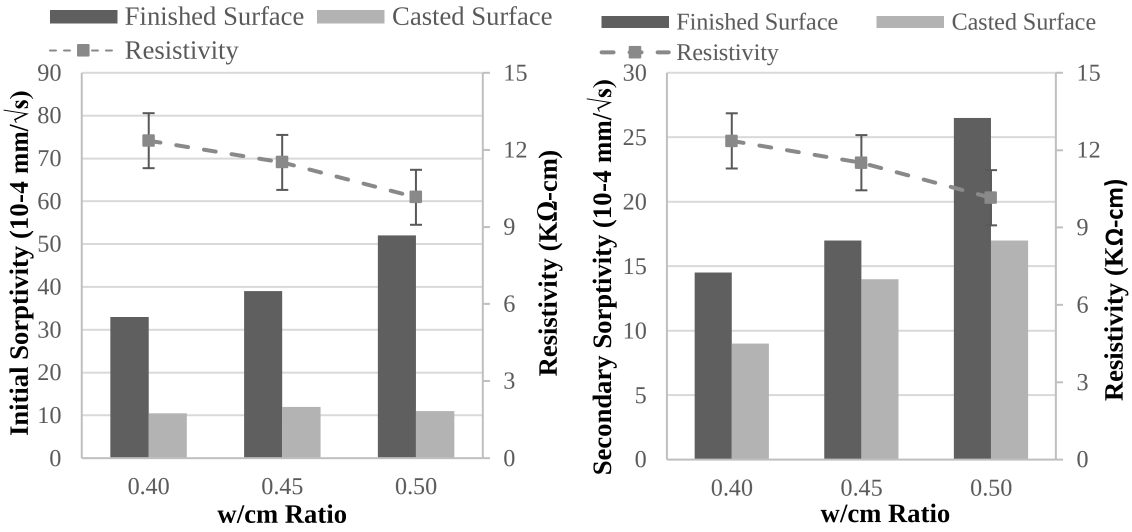
Table 7.4(a) Results of Statistical Analysis for Effect of w/cm on Initial Sorptivity

Sample Surface	w/cm	Initial Sorptivity (10-4 mm/√s)			ANOVA	Comp.	Tukey test	Student t-test
		Mean	Std. Dev.	COV (%)	p-value			
Finished Surface (FS)	0.40	33.0	0.00	0.0	0.003	0.40/0.45	Sig. difference	-
	0.45	39.0	2.83	7.3		0.40/0.50	Sig. difference	-
	0.50	52.0	1.41	2.7		0.45/0.50	Sig. difference	0.026
Casted Surface (CS)	0.40	10.5	0.71	6.7	0.740	0.40/0.45	-	0.312
	0.45	12.0	1.41	11.8		0.40/0.50		0.831
	0.50	11.0	2.83	25.7		0.45/0.50		0.698

Table 7.4(b) Results of Statistical Analysis for Effect of w/cm on Secondary Sorptivity

Sample Surface	w/cm	Secondary Sorptivity (10-4 mm/√s)			Anova	Comp.	Tukey test	Student t-test
		Mean	Std. Dev.	COV (%)	p-value			
Finished Surface (FS)	0.40	14.5	0.71	4.9	0.0005	0.40/0.45	Sig. difference	-
	0.45	17.0	0.00	0.0		0.40/0.50	Sig. difference	0.003
	0.50	26.5	0.71	2.7		0.45/0.50	Sig. difference	-
Casted Surface (CS)	0.40	9.0	0.00	0.0	0.0873	0.40/0.45	-	-
	0.45	14.0	2.83	20.2		0.40/0.50		-
	0.50	17.0	2.83	16.6		0.45/0.50		0.400

The results demonstrate that for initial and secondary sorptivity, there is a significant difference between the values of 0.40, 0.45 and 0.50 w/cm concrete mixtures, whereas the cast surface samples results could not differentiate between w/cm. It may be due to the improper conditioning of samples such that they may failed to maintain 80% humidity, which resulted in high COV. The resistivity of samples decreases with the increase of w/cm due to increase in porosity and continuity of the porous structure. The comparison of resistivity with initial and secondary sorptivity is shown in Figure 7.5(a,b). The analyses and figures show that the resistivity decrease with increase in w/cm whereas sorptivity increases. Hence, both properties are inversely proportional to each other.



(a) (b)

Fig. 7.5 Comparison of resistivity and (a) initial sorptivity and (b) secondary sorptivity

One concrete cylinder with a finished surface and a cast surface sample from each mixture were tested for w/cm at the age of 56 days. Therefore, it was not possible to statistically analyze the absorption data. However, increase in w/cm showed increased in percentage absorption of concrete samples. An increase of 20% absorption for finished surface sample and 5% absorption for cast surface sample by increasing the w/cm from 0.40 to 0.45 w/cm, and an increase of 5% absorption for finished surface sample and 11% absorption for cast surface sample by increasing w/cm from 0.45 to 0.50 were calculated. The comparison of resistivity and percentage absorption for concrete mixtures are shown in Figure 7.6. It is concluded from the figure that resistivity decreases with increase in resistivity and percentage absorption increases due to increase in porous volume. Hence, both properties are inversely proportional to one another.

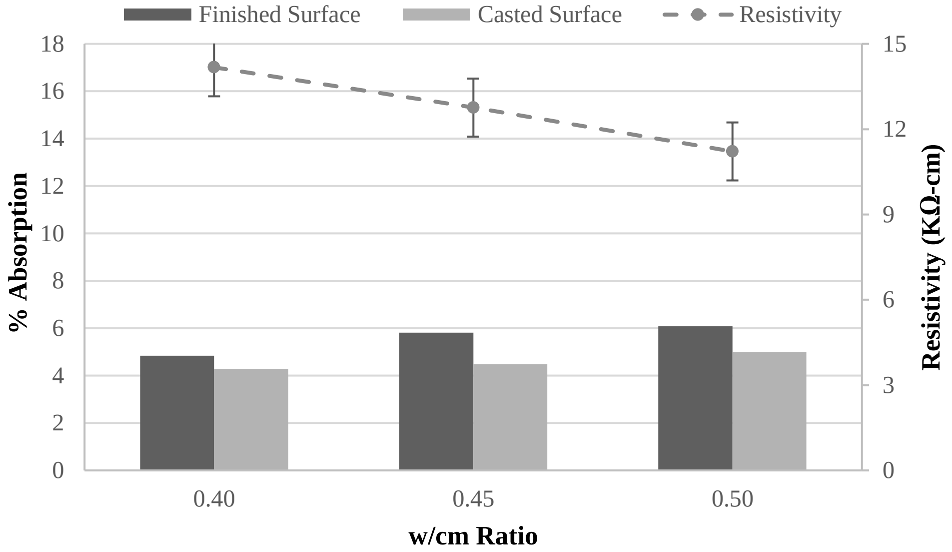


Fig. 7.6 Comparison of resistivity and percentage absorption

The compression test was conducted at the age of 28 days. The COV for 0.40 and 0.50 w/cm mixtures are higher than the allowable limit of 3.2%, except for 0.45 w/cm mixture samples having COV of 1.4%. The results of ANOVA, Tukey's test, and t-test are shown in Table 7.5.

Table 7.5 Results of Statistical Analysis for Effect of w/cm on Compressive Strength

w/cm	Compressive Strength (MPa)			ANOVA	Comp.	Tukey's test	Students T-Test
	Mean	Std. Dev.	COV (%)	p-value			
0.40	46.92	665.38	9.8	0.024	0.40/0.45	No difference	0.337
0.45	42.82	89.1	1.4		0.40/0.50	Sig. difference	0.045
0.50	31.39	222.7	4.9		0.45/0.50	Sig. difference	0.010

The results of the ANOVA test show that the null hypothesis is rejected and there is a significant difference between the compressive strength values and the three w/cm concrete mixtures. A decrease in compressive strength is noted with the increase in w/cm of the concrete mixtures. However, post hoc tests (Table 7.5), show no significant difference in compressive strength results between 0.40 and 0.45 w/cm samples, whereas a significant difference between 0.40 and 0.50 w/cm, and 0.45 and 0.50 w/cm is determined. The comparison of resistivity and compressive strength is shown in Figure 7.7. The resistivity and strength of concrete decrease with increase in w/cm.

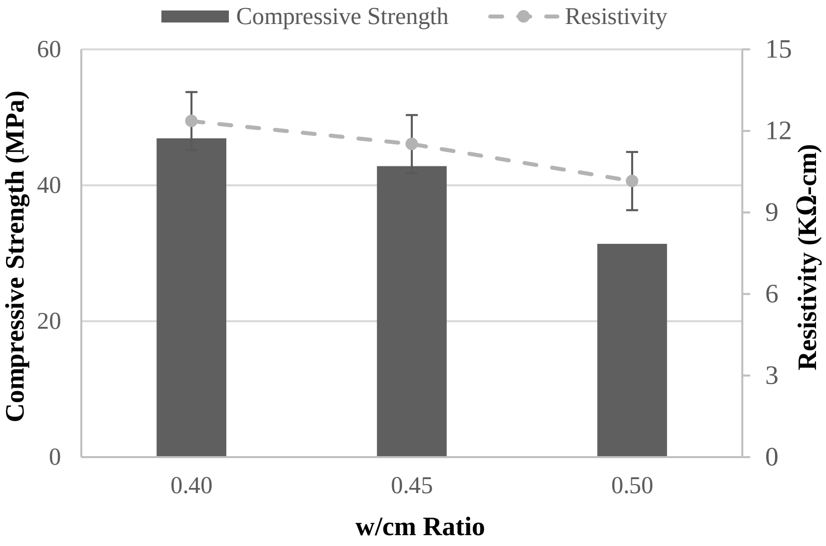


Fig. 7.7 Comparison of resistivity and compressive strength

7.3.3 Effect of Fly Ash Content

The effect of a change in fly ash content of concrete was determined from testing concrete samples with surface resistivity method, sorptivity test, absorption test and compression test. These tests were conducted on samples having mixture design of 0.40 w/cm with 0%, 10% and 20% fly ash content. The ANOVA test, Tukey's test and t-test were performed on the results obtained from the tests.

The resistivity of concrete samples with varying fly ash content was observed at the ages of 28 and 56 days. The analysis of results from surface resistivity test at the ages of 28 and 56 days is shown in Tables 7.6.

Table 7.6 Results of Statistical Analysis for Effect of Fly Ash Content on Surface Resistivity

Age	% Fly Ash	Resistivity (KΩ-cm)			ANOVA	Comp.	Tukey test	Student t-test
(Days)		Mean	Std. Dev.	COV (%)	p-value			
28	0%	12.4	0.47	3.8	0.05	0%/10%	-	0.014
	10%	13.4	0.69	5.2		0%/20%		0.513
	20%	12.6	0.77	6.1		10%/20%		0.105
56	0%	14.2	0.55	3.9	0.001	0%/10%	Sig. difference	0.003
	10%	15.7	0.80	5.1		0%/20%	Sig. difference	0.001
	20%	16.4	0.99	6.0		10%/20%	No difference	0.215

The results from Table 7.6 showed that the null hypothesis is not rejected, and there is no difference found between the resistivity values of 0%, 10% and 20% fly ash content concrete samples at the age of 28 days; however, the results of the t-test show a significant difference in resistivity values between 0% and 10% fly ash content samples. Prior to 28 days, there is no clear trend on the effects of fly ash replacements as the pozzolanic reaction kinetics vary; however, after 28 days, the trend diversifies, and the resistivity of concrete mixtures increase with an increase in fly ash content. At day 56, a significant difference among the three fly ash content samples are found; however, based on Tukey's test and t-test, the gain in resistivity obtained between 10% and 20% fly ash samples is not substantial.

From each concrete cylinder, samples with a finished surface and a cast surface was obtained for the sorptivity test. The initial and secondary coefficients of sorptivity were calculated at the age of 28 days. The COV for finished surface samples remained within 6%, whereas higher COV between cast surface samples was observed to 15.7%. The ANOVA, Tukey's test and t-test results for initial and secondary sorptivity at the age of 28 days are shown in Table 7.7(a,b).

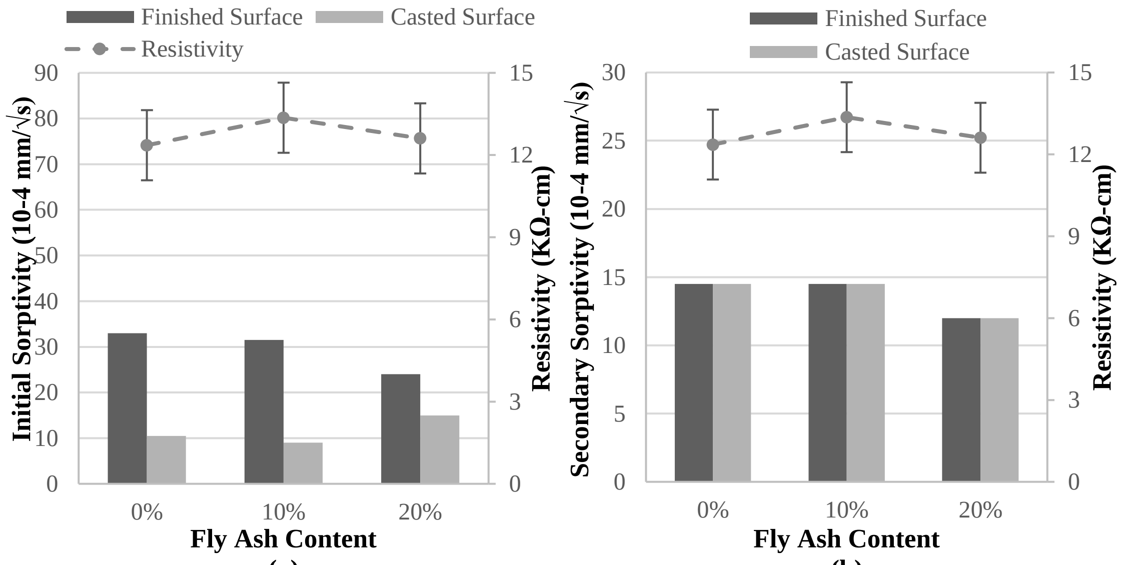
Table 7.7(a) Results of Statistical Analysis for Effect of Fly Ash Content on Initial Sorptivity

Sample Surface	% Fly Ash	Initial Sorptivity (10-4 mm/√s)			ANOVA	Comp.	Tukey test	Student t-test
		Mean	Std. Dev.	COV (%)	p-value			
Finished Surface (FS)	0%	33.0	0.00	0.0	0.0004	0%/10%	Sig. difference	-
	10%	31.5	0.71	2.2		0%/20%	Sig. difference	-
	20%	24.0	0.00	0.0		10%/20%	Sig. difference	-
Casted Surface (CS)	0%	10.5	0.71	6.7	0.015	0%/10%	No difference	0.312
	10%	9.0	1.41	15.7		0%/20%	Sig. difference	-
	20%	15.0	0.00	0.0		10%/20%	Sig. difference	-

Table 7.7(b) Results of Statistical Analysis for Effect of Fly Ash Content on Secondary Sorptivity

Sample Surface	% Fly Ash	Secondary Sorptivity (10-4 mm/√s)			ANOVA	Comp.	Tukey test	Student t-test
		Mean	Std. Dev.	COV (%)	p-value			
Finished Surface (FS)	0%	14.5	0.71	4.9	0.035	0%/10%	No difference	1.000
	10%	14.5	0.71	4.9		0%/20%	Sig. difference	-
	20%	12.0	0.00	0.0		10%/20%	Sig. difference	-
Casted Surface (CS)	0%	9.0	0.00	0.0	0.829	0%/10%	-	-
	10%	9.0	1.41	15.7		0%/20%		-
	20%	8.5	0.71	8.3		10%/20%		0.698

The results have shown that for initial and secondary sorptivity, there is a significant difference between the values of 0%, 10% and 20% concrete samples with finished surfaces, whereas for cast surface samples, a significant difference was determined for initial sorptivity, but no significant difference in secondary sorptivity was found. It might be due to improper preparation of samples, which resulted in high COV of variation in cast surface samples. However, a decrease in sorptivity is observed by adding fly ash content from 0% to 20% in the mixtures. The post hoc analysis shows a significant difference between the %fly ash mixtures for finished and cast surface samples except 0% and 10% fly ash samples with no significant difference. Some sample sets have same values of sorptivity coefficients resulted in zero standard deviation. Therefore, t-test was not applicable to those data sets. The comparisons of resistivity with initial and secondary sorptivity are shown in Figure 7.8(a,b), where the change in sorptivity with a change in fly ash percentage can be observed compared to change in resistivity. It is concluded from the analyses and figures that at the age of 28 days, the resistivity cannot be related to sorptivity for varying fly ash content of concrete mixtures because different percentages of fly ash in concrete reacts with different rate at a given day.



(a) (b)

Fig. 7.8 Comparison of resistivity and (a) initial sorptivity and (b) secondary sorptivity

Only one concrete cylinder with a finished surface and a cast surface samples from each mixture were tested for percentage absorption at the age of 56 days. Therefore, it was not possible to statistically analyze the absorption data. However, increase in fly ash content show a decrease in percentage absorption of concrete samples (Fig. 7.9) because at the age of 56 days, fly ash contributes to the hydration process and densify the microstructure of concrete. The addition of 20% fly ash reduced the absorption by 7%. The resistivity of concrete increases with increase in fly ash from 0% to 20% at the age of 56 days. The comparison of resistivity and percent absorption for concrete mixtures are shown in Figure 7.9.

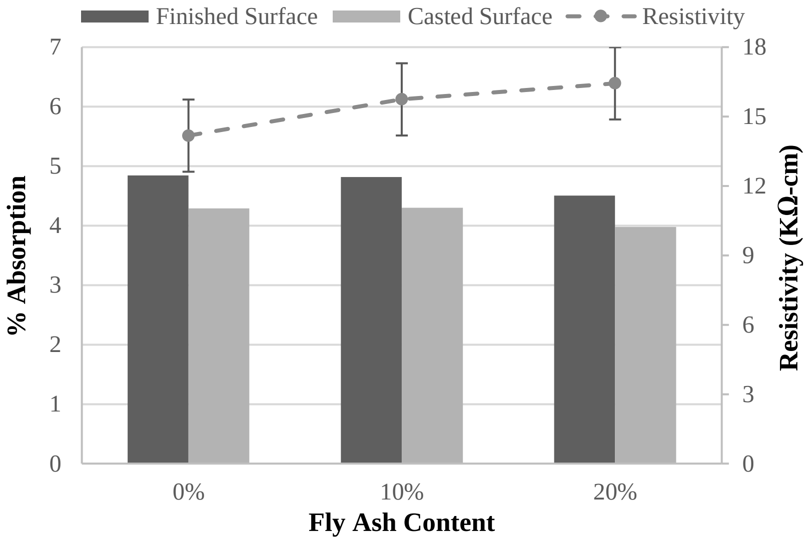


Fig. 7.9 Comparison of resistivity and percentage absorption

The compression test was conducted at the age of 28 days. The COV for all mixtures remains under allowable 9%, except for 0.40 w/cm mixture samples having COV of 9.7%. The ANOVA and t-test results of compression test are shown in Table 7.8.

Table 7.8 Results of Statistical Analysis for Effect of Fly Ash Content on Compressive Strength

% Fly Ash	Compressive Strength (MPa)			ANOVA	Comp.	Tukey's test	Students T-Test
	Mean	Std. Dev.	COV (%)	p-value			
0%	46.92	665.38	9.8	0.253	0%/10%	-	0.533
10%	44.38	210.01	3.3		0%/20%		0.490
20%	50.25	21.92	0.30		10%/20%		0.029

The null hypothesis is not rejected, which means there is no significant difference among the compressive strength values for 0%, 10% and 20% fly ash content concrete samples. However, according to the t-test, there is a significant difference in resistivity values among the two levels of fly ash content 10% and 20% FA. This may be attributed to the low COV obtained for both tests. The comparison of resistivity and compressive strength is shown in Figure 7.10. As seen, there are no noticeable trends between 28-day compressive strength and resistivity.

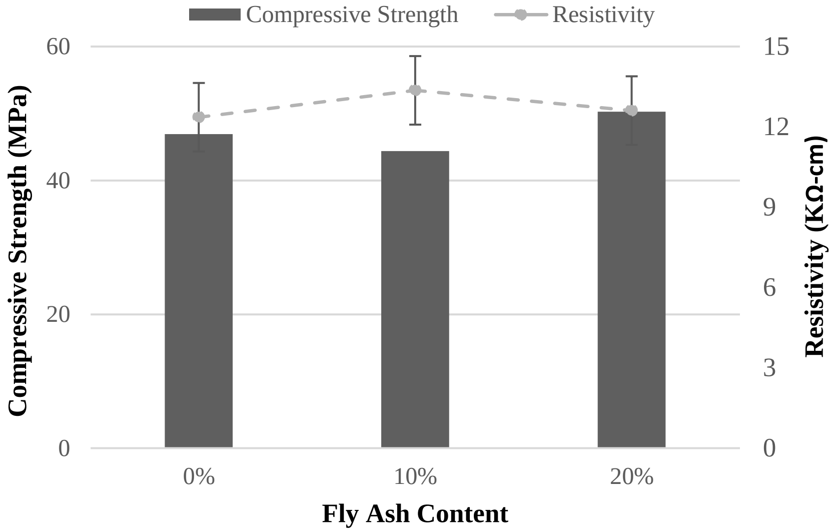


Fig. 7.10 Comparison of resistivity and compressive strength

7.3.4 Effect of Fly Ash Source

The effect of a change in the source of fly ash was determined by testing the concrete samples with surface resistivity method, sorptivity test, absorption test and compression test. All these tests were conducted on samples made with three different sources of fly ash with similar chemical properties (Table 7.1) having 20% fly ash content and 0.40 w/cm in concrete mixtures. The analysis of variations, ANOVA, Tukey’s test and t-test were performed on results of surface resistivity, sorptivity, absorption and compressive strength tests.

The resistivity of concrete samples with three fly ash sources was observed at the age of 28 and 56 days. The results obtained from statistical analysis for surface resistivity at the ages 28 and 56 days are shown in Tables 7.9.

Table 7.9 Results of Statistical Analysis for Effect of Fly Ash Source on Surface Resistivity

Age	Fly Ash Source	Resistivity (KΩ-cm)			ANOVA	Comp.	Tukey test	Student t-test
(Days)		Mean	Std. Dev.	COV (%)	p-value			
28	Source-I (S1)	12.6	0.77	6.1	0.13	S1/S2	-	0.757
	Source-II (S2)	12.7	0.68	5.3		S1/S3		0.106
	Source-III (S3)	13.7	1.28	9.3		S2/S3		0.139
56	Source-I (S1)	16.4	0.99	6.0	0.223	S1/S2	-	0.623
	Source-II (S2)	16.1	1.04	6.5		S1/S3		0.160
	Source-III (S3)	17.4	0.60	3.5		S2/S3		0.121

In Table 7.9, the results have shown that the null hypotheses failed to rejected, and there is no significant difference found among the three different sources of fly ash concrete samples at days 28 and 56. No significant difference in resistivity data of three sources may be due to similar chemical properties of fly ash.

From each cylinder, samples having a finished surface and a cast surface were obtained from three different sources of fly ash mixtures. The initial and secondary coefficients of sorptivity were calculated at the age of 28 days. The ANOVA, Tukey's test and t-test results for initial and secondary sorptivity are shown in Table 7.10(a,b).

Table 7.10(a) Results of Statistical Analysis for Effect of Fly Ash Source on Initial Sorptivity

Sample Surface	Fly Ash Source	Initial Sorptivity (10-4 mm/√s)			ANOVA	Comp.	Tukey test	T-test
		Mean	Std. Dev.	COV (%)	p-value			
Finished Surface (FS)	Source-I (S1)	24.0	0.00	0.0	6.9 E-7	S1/S2	Sig. difference	-
	Source-II (S2)	6.0	0.00	0.0		S1/S3	Sig. difference	-
	Source-III (S3)	82.5	0.71	0.9		S2/S3	Sig. difference	-
Casted Surface (CS)	Source-I (S1)	15.0	0.00	0.0	0.006	S1/S2	No difference	-
	Source-II (S2)	4.5	0.71	15.7		S1/S3	Sig. difference	-
	Source-III (S3)	58.5	10.60	18.1		S2/S3	Sig. difference	0.02

Table 7.10(b) Results of Statistical Analysis for Effect of Fly Ash Source on Secondary Sorptivity

Sample Surface	Fly Ash Source	Secondary Sorptivity (10-4 mm/√s)			ANOVA	Comp.	Tukey test	T-test
		Mean	Std. Dev.	COV (%)	p-value			
Finished Surface (FS)	Source-I (S1)	12.0	0.00	0.0	0.004	S1/S2	Sig. difference	-
	Source-II (S2)	3.0	0.00	0.0		S1/S3	Sig. difference	-
	Source-III (S3)	16.5	2.10	12.9		S2/S3	Sig. difference	-
Casted Surface (CS)	Source-I (S1)	8.5	0.71	8.3	0.001	S1/S2	Sig. difference	-
	Source-II (S2)	2.0	0.00	0.0		S1/S3	Sig. difference	0.009
	Source-III (S3)	20.0	1.40	7.1		S2/S3	Sig. difference	-

The null hypotheses for initial and secondary sorptivity have rejected, which means that there is a significant difference found between the sources of fly ash samples, followed by Tukey’s test. The Source-III fly ash concrete samples obtained higher sorptivity coefficients than Sources I and II concrete samples. The high variation in results could be due to improper preparation or conditioning of the samples. The comparison between resistivity and initial and secondary sorptivity are shown in Figure 7.11(a,b). A high variation in results is observed from the analysis and results. It is recommended to repeat the sorptivity test.

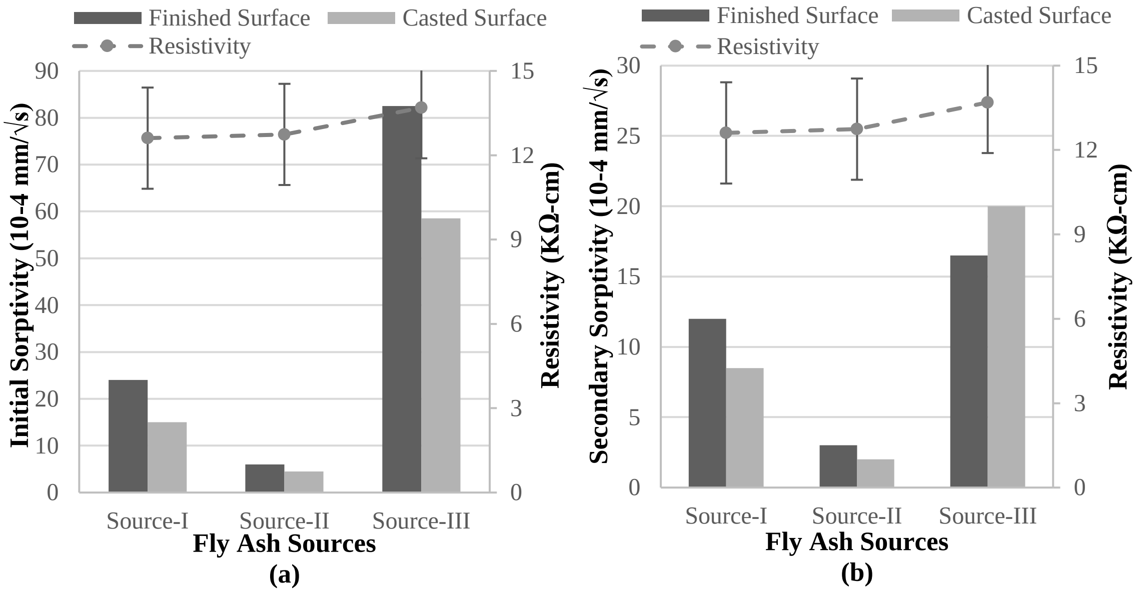


Fig. 7.11 Comparison of resistivity and (a) initial sorptivity and (b) secondary sorptivity

Only one cylinder from Source-I fly ash mixture and a set of three concrete cylinders from Source-II and Source-III concrete mixtures with finished surface and casted surface samples were tested for percentage absorption at the age of 56 days. The ANOVA, Tukey's and t-test results of percentage absorption are shown in Table 7.11.

Table 7.11 Results of Statistical Analysis for Effect of Fly Ash Source on Percentage Absorption

Sample Surface	Fly Ash Source	% Absorption			ANOVA	Comp.	Tukey test	Student t-test
		Mean	Std. Dev.	COV (%)	p-value			
Finished Surface (FS)	Source-I (S1)	4.5	-	-	0.3879	S1/S2	-	-
	Source-II (S2)	5.1	0.12	0.5		S1/S3		-
	Source-III (S3)	5.2	2.30	10.0		S2/S3		0.361
Casted Surface (CS)	Source-I (S1)	4.0	-	-	0.293	S1/S2	-	-
	Source-II (S2)	4.3	0.13	2.9		S1/S3		-
	Source-III (S3)	4.2	0.18	4.2		S2/S3		0.606

The results have shown that the null hypothesis has failed to reject and there is no significant difference between the three sources of fly ash content data. The comparison of resistivity and percentage absorption is shown in Figure 7.12.

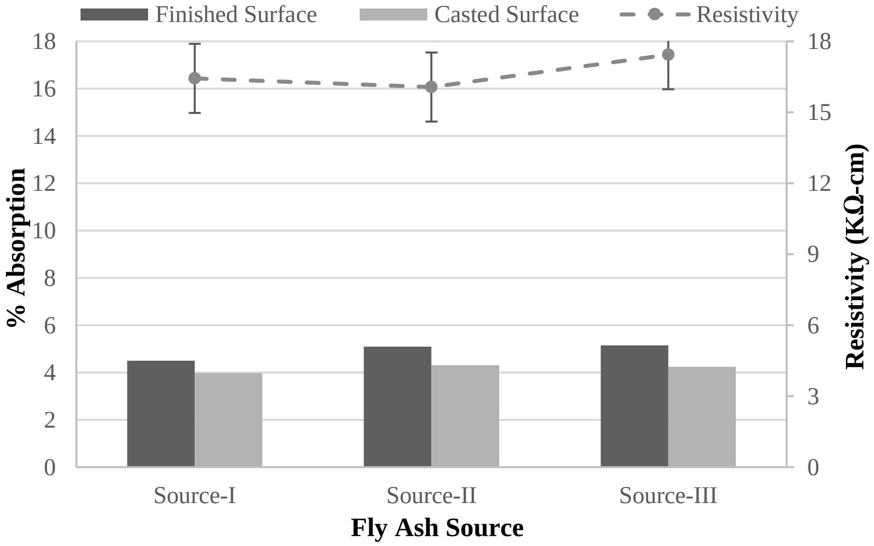


Fig. 7.12 Comparison of resistivity and percentage absorption

The results of ANOVA and t-test for compression test conducted at the age of 28 days are shown in Table 7.12.

Table 7.12 Results of Statistical Analysis for Effect of Fly Ash Source on Compressive Strength

Fly Ash Source	Compressive Strength (Mpa)			ANOVA	Comp.	Tukey test	Student t-test
	Mean	Std. Dev.	COV (%)	p-value			
Source-I (S1)	50.25	21.92	0.3	0.069	S1/S2	-	0.495
Source-II (S2)	51.02	190.21	2.6		S1/S3		0.057
Source-III (S3)	54.32	207.18	2.6		S2/S3		0.138

The results from Table 7.12 showed that the null hypothesis has failed to reject and there is no significant difference between the resistivity values of three sources of fly ash content samples. The comparison of resistivity and compressive strength is shown in Figure 7.13. It could be established from the analysis and figure that the resistivity could be compared with the compressive strength of concrete samples having similar chemical properties of fly ash.

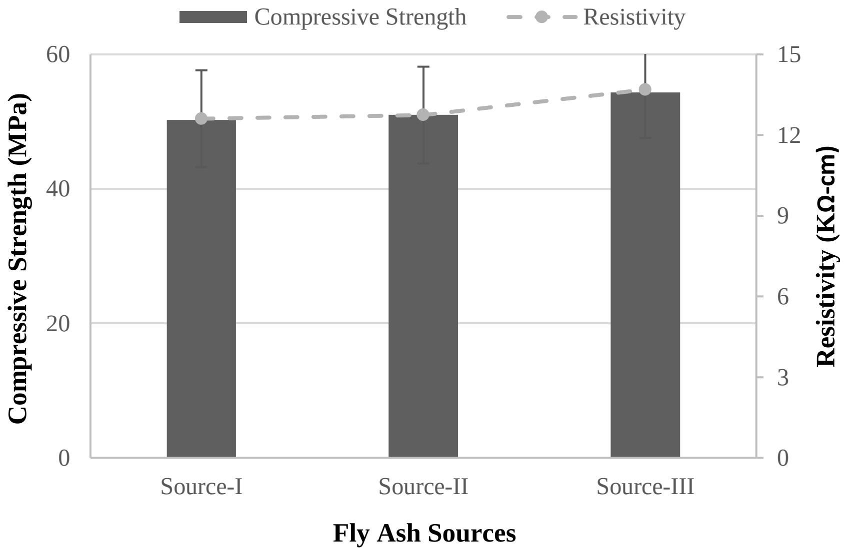


Fig. 7.13 Comparison of resistivity and compressive strength

7.3.5 Effect of Aggregate Type

The effect of a change in the type of aggregates in concrete was analyzed by testing the concrete samples with surface resistivity, sorptivity test, absorption test and compression test. All these tests were conducted on samples made with 0.40 w/cm and no added fly ash content, with Limestone, Dolomite or Granite aggregates. The analysis of variations, ANOVA, Tukey's test and t-test was performed on results of surface resistivity, sorptivity, absorption and compressive strength tests.

The resistivity of concrete samples at the ages of day 28 and day 56 with three aggregate types was analyzed. The results obtained from statistical analysis for surface resistivity at the ages 28 and 56 days are shown in Tables 7.13.

Table 7.13 Results of Statistical Analysis for Effect of Aggregate Type on Surface Resistivity

Age	Aggregate Type	Resistivity (KΩ-cm)			ANOVA	Comp.	Tukey test	Student t-test
(Days)		Mean	Std. Dev.	COV (%)	p-value			
28	Limestone (L)	12.4	0.47	3.8	2.14E-4	L/D	Sig. difference	0.0005
	Dolomite (G)	14.1	0.67	4.8		L/G	Sig. difference	0.001
	Granite (G)	13.6	0.46	3.4		D/G	No difference	0.167
56	Limestone (L)	14.2	0.55	3.9	0.003	L/D	Sig. difference	0.004
	Dolomite (G)	16.4	1.07	6.5		L/G	No difference	0.230
	Granite (G)	14.6	0.19	1.3		D/G	Sig. difference	0.05

The results have shown that the null hypothesis is rejected and there is a significant difference between the resistivity values of three types of aggregate concrete samples at days 28 and 56. It might be because of the influence of the difference in chemical composition of aggregates on pore solution, which made the resistivity data significantly different from each other. However, t-test shows no significant difference in resistivity between Dolomite and Granite samples at 28 days, and Limestone and Granite samples at the age of 56 days.

From each cylinder, samples having a finished surface and a cast surface were obtained from concrete mixtures containing three types of aggregates. The initial and secondary coefficients of sorptivity were determined at the age of 28 days. The ANOVA, Tukey's test and t-test results for initial and secondary sorptivity are shown in Table 7.14(a,b).

Table 7.14(a) Results of Statistical Analysis for Effect of Aggregate Type on Initial Sorptivity

Sample Surface	Aggregate Type	Initial Sorptivity (10-4 mm/√s)			ANOVA	Comp.	Tukey test	T-test
		Mean	Std. Dev.	COV (%)	p-value			
Finished Surface (FS)	Limestone (L)	33.0	0.00	0.0	0.007	L/D	Sig. difference	-
	Dolomite (G)	55.0	8.49	15.4		L/G	Sig. difference	-
	Granite (G)	77.0	1.41	1.8		D/G	Sig. difference	0.069
Casted Surface (CS)	Limestone (L)	10.5	0.71	6.7	2.9 E-5	L/D	Sig. difference	-
	Dolomite (G)	32.0	0.00	0.0		L/G	Sig. difference	0.0005
	Granite (G)	42.5	0.71	1.7		D/G	Sig. difference	-

Table 7.14(b) Results of Statistical Analysis for Effect of Aggregate Type on Secondary Sorptivity

Sample Surface	Aggregate Type	Secondary Sorptivity (10-4 mm/√s)			ANOVA	Comp.	Tukey test	T-test
		Mean	Std. Dev.	COV (%)	p-value			
Finished Surface (FS)	Limestone (L)	14.5	0.71	4.9	0.014	L/D	Sig. difference	0.010
	Dolomite (G)	21.5	0.71	3.3		L/G	No difference	0.089
	Granite (G)	18.0	1.41	7.9		D/G	Sig. difference	0.089
Casted Surface (CS)	Limestone (L)	9.0	0.00	0.0	0.005	L/D	Sig. difference	-
	Dolomite (G)	12.5	0.71	5.7		L/G	Sig. difference	-
	Granite (G)	9.0	0.00	0.0		D/G	Sig. difference	-

The COV of Dolomite (Table 7.7a) and Granite (Table 7.7b) for finished surface samples are higher than the allowable standard limit of 3.2%. The null hypotheses for initial and secondary sorptivity were rejected, which means there is a significant difference among the initial and secondary sorptivity values of three aggregate type concrete mixtures. The concrete samples made with Granite aggregates show higher initial sorptivity coefficients than Limestone and Dolomite aggregate samples, and Dolomite aggregates samples show the highest secondary coefficient of sorptivity. A t-test between Limestone and Granite did not show a significant difference in coefficients of secondary sorptivity. Some sample sets have same values of sorptivity coefficients resulted in zero standard deviation. Therefore, a t-test was not applicable to those data sets. The comparison between resistivity and initial and secondary sorptivity are shown in Figure 7.14(a,b). It is concluded from the analyses and figures that, the difference of chemical properties of aggregates may be influencing the resistivity and sorptivity (secondary) in a similar way.

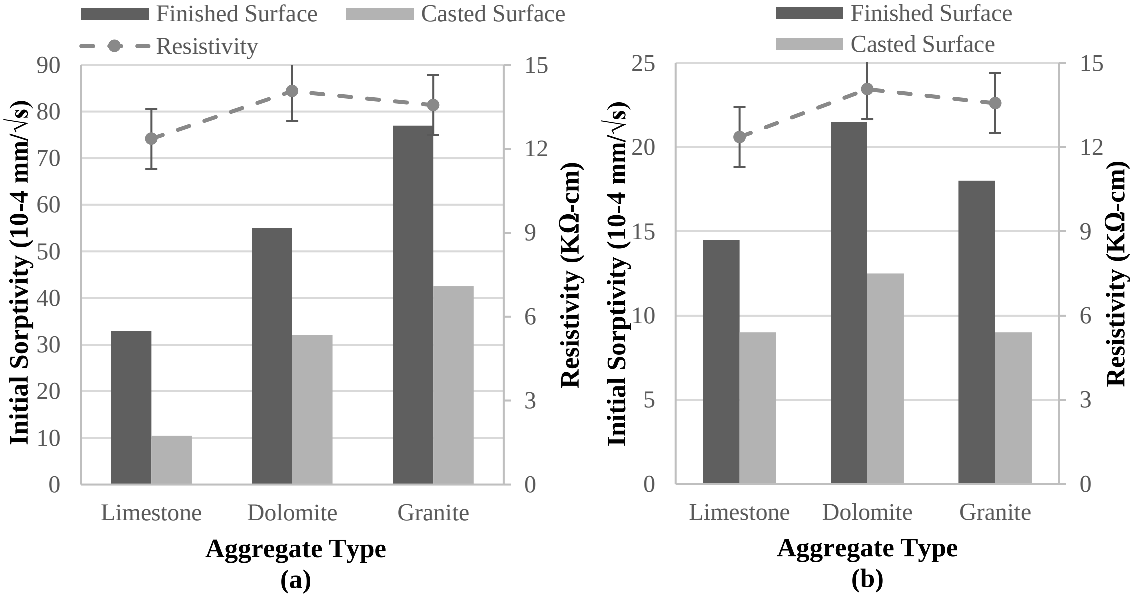


Fig. 7.14 Comparison of resistivity and (a) initial Sorptivity and (b) secondary sorptivity

Only one cylinder made from Limestone aggregates, and a set of three concrete cylinders from Dolomite and Granite aggregates concrete cylinders with finished surface and casted surface samples were tested for percentage absorption at the age of 56 days. The ANOVA and t-test results of percentage absorption are shown in Table 7.15.

Table 7.15 Results of Statistical Analysis for Effect of Aggregate Type on Percentage Absorption

Sample Surface	Aggregate Type	% Absorption			ANOVA	Comp.	Tukey test	Student t-test
		Mean	Std. Dev.	COV (%)	p-value			
Finished Surface (FS)	Limestone (L)	4.9	0.00	0.0	0.928	L/D	-	-
	Dolomite (G)	4.8	0.32	6.6		L/G		-
	Granite (G)	4.8	0.16	3.3		D/G		0.928
Casted Surface (CS)	Limestone (L)	4.3	0.00	0.0	0.169	L/D	-	-
	Dolomite (G)	4.0	0.05	1.2		L/G		-
	Granite (G)	4.3	0.26	6.0		D/G		0.169

The results have shown that the null hypothesis failed to reject and there is no significant difference between the percentage absorption of three aggregate types' concrete mixtures. The comparison of resistivity and percentage absorption is shown in Figure 7.15. From the figure and analysis, it is concluded that the resistivity and percentage absorption are not related to each other when aggregate types with different chemical compositions are used in concrete mixtures because the resistivity measurements have shown a significant difference between the three aggregate types.

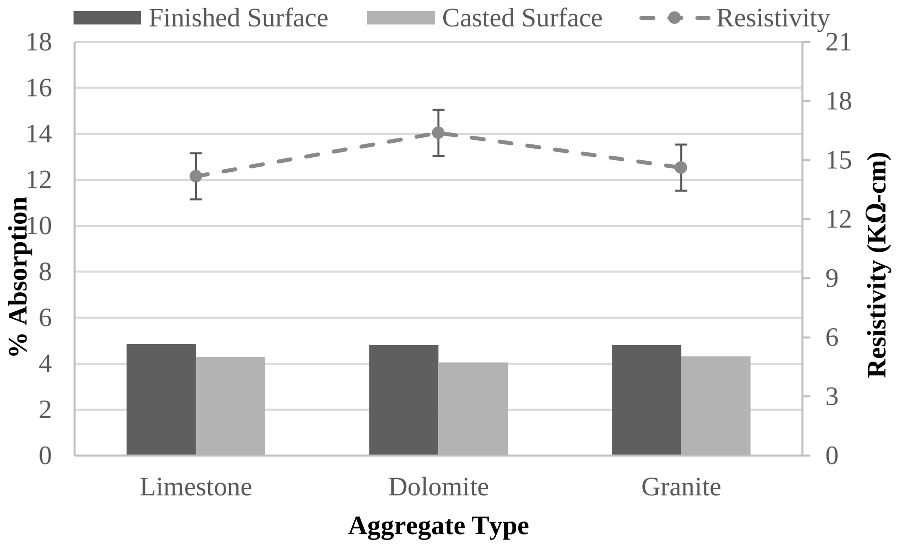


Fig. 7.15 Comparison of resistivity and percentage absorption

The results of ANOVA and t-test for compression test conducted at the age of 28 days are shown in Table 7.16.

Table 7.16 Results of Statistical Analysis for Effect Aggregate Type on Compressive Strength

Aggregate Type	Compressive Strength (Mpa)			ANOVA	Comp.	Tukey test	Student t-test
	Mean	Std. Dev.	COV (%)	p-value			
Limestone (L)	46.9	665.39	9.8	0.100	L/D	-	0.160
Dolomite (G)	54.8	306.88	3.9		L/G		0.225
Granite (G)	55.7	14.14	0.2		D/G		0.595

The results in Table 7.16 showed that the null hypothesis has failed to reject and there is no significant difference between the compressive strength values of three aggregate types' samples. It might be because the surface texture of the three types of aggregate was same and could have a comparative strength between cement paste and aggregates. However, the mean compressive strength of Limestone aggregate samples attained lower strength compared to Dolomite and Granite aggregate samples. The COV of limestone and dolomite aggregate samples is higher than the allowable standard limit of 3.2%. The comparison of resistivity and compressive strength is shown in Figure 7.16. It could be established from the analysis and figure that the resistivity cannot be compared to the compressive strength of concrete samples made with different types of aggregates because different chemical properties of aggregate may not affect the strength of concrete.

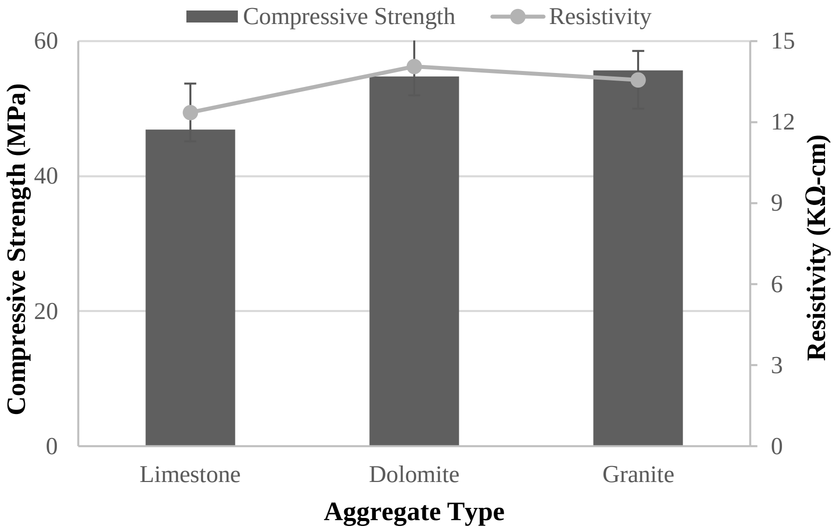


Fig. 7.16 Comparison of resistivity and compressive strength

7.3.6 Effect of Aggregate Size

The effect of aggregate size was analyzed by using #56 and #67 aggregate sizes in concrete mixtures. The concrete samples were tested with surface resistivity, sorptivity test, absorption test and compression test. All these tests were conducted on samples made with 0.40 w/cm and no added fly ash content. The statistical results of resistivity at day 28 and 56 are shown in Table 7.17.

Table 7.17 Results of Statistical Analysis for Effect of Aggregate Size on Surface Resistivity

Age	Aggregate Size	Resistivity (KΩ-cm)			Student t-test
(Days)		Mean	Std. Dev.	COV (%)	
28	#56	12.4	0.47	3.8	0.0342
	#67	13.0	0.41	3.2	
56	#56	14.2	0.55	3.9	0.690
	#67	14.1	0.29	2.1	

The statistical analysis was performed by using t-test between the data set of two aggregate sizes samples. It was concluded from the results that there is a significant difference between the resistivity values at the age of 28 days between the two aggregate sizes. However, the mean resistivity values were close to each other. The t-test showed no significant difference between the resistivity values of two aggregates sizes at the age of 56 days. It might be because of development of cement paste that reduced the difference in mean resistivity data.

From each cylinder, samples having a finished surface and a cast surface were obtained from concrete mixtures containing two different sizes of aggregates. The initial and secondary coefficients of sorptivity were determined at the age of 28 days. The statistical analysis results for initial and secondary sorptivity are shown in Table 7.18(a,b).

Table 7.18(a) Results of Statistical Analysis for Effect of Aggregate Size on Initial Sorptivity

Sample Surface	Aggregate Size	Initial Sorptivity (10-4 mm/√s)			Student t-test
		Mean	Std. Dev.	COV (%)	
Finished Surface (FS)	#56	33.0	0.00	0.0	0.012
	#67	14.5	0.70	4.9	
Casted Surface (CS)	#56	10.5	0.70	6.7	0.500
	#67	9.0	0.00	0.0	

Table 7.18(b) Results of Statistical Analysis for Effect of Aggregate Size on Secondary Sorptivity

Sample Surface	Aggregate Size	Secondary Sorptivity (10-4 mm/√s)			Student t-test
		Mean	Std. Dev.	COV (%)	
Finished Surface (FS)	#56	5.5	0.70	12.9	0.004
	#67	3.5	0.70	20.2	
Casted Surface (CS)	#56	10.0	0.00	0.0	-
	#67	20.0	0.00	0.0	

The t-test analysis is performed on initial and secondary sorptivity coefficients, determined at 28 days of age, and a significant difference found among the initial and secondary sorptivity data for two aggregate sizes with finished surface concrete samples, whereas no significant difference found for cast surface for initial sorptivity coefficients. The #67 samples (CS) have same values of sorptivity coefficients resulted in zero standard deviation. Therefore, the t-test is not applicable. The comparison of resistivity with initial and secondary sorptivity are shown in Figure 7.17(a,b). Due to high variation in results, there is no particular trend could be seen in sorptivity with a change in aggregate size and the variation in sorptivity results might be due to improper preparation or conditioning of samples. However, decrease in sorptivity with the change in aggregate size from #56 to #67 can be noticed for FS samples in Figure 7.17(a,b).

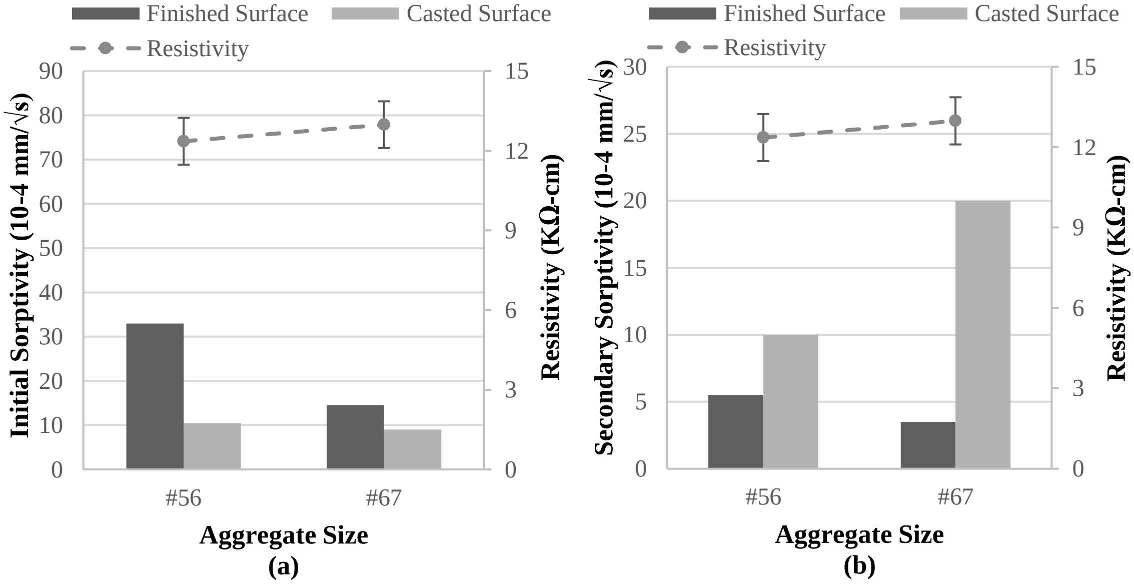


Fig. 7.17 Comparison of resistivity and (a) initial sorptivity and (b) secondary Sorptivity

There was only one concrete sample for percentage absorption test from both aggregate sizes mixtures; therefore, it was not possible to statistically analyze absorption data. However, there is an increase in percentage absorption observed from #56 to #67 sizes concrete samples at the age of 56 days. The comparison of resistivity and percentage absorption for concrete mixtures are shown in Figure 7.18. The resistivity of two aggregate sizes samples did not show a significant difference in resistivity values, but percentage absorption of #67 samples with the finished surface is higher, compared to cast surface. Hence, further testing is recommended. It can be assessed from cast surface samples that resistivity may be related to percentage absorption, but the further investigation could give a clear picture.

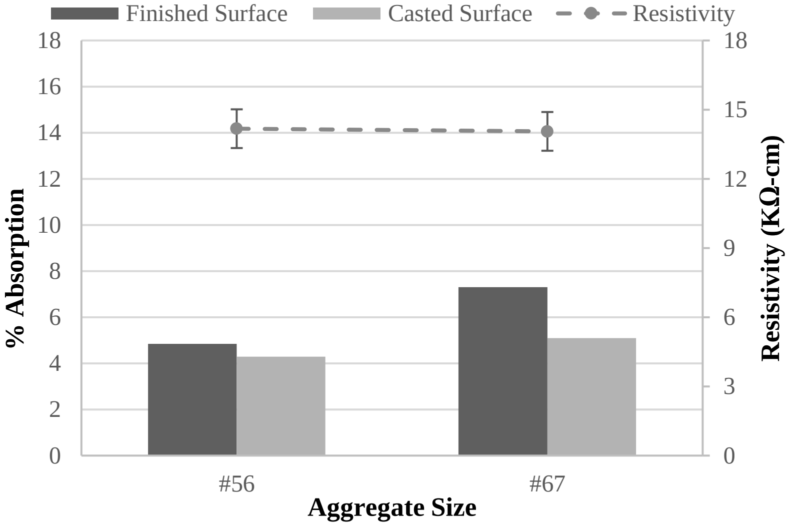


Fig. 7.18 Comparison of resistivity and percentage absorption

In Table 7.19, the t-test is done for compressive strength values of two aggregate sizes concrete samples, and no significant difference among the compressive strength values was found. However, there is a decrease in strength observed from #67 to #57 aggregate size concrete samples at the age of 28 days. The COV of #56 aggregate sample is higher than the allowable standard limit of 3.2%. The comparison of resistivity and compressive strength is shown in Figure 19. The resistivity and percentage absorption at the age of 28 days could be related to each other for concrete having #67 and #56 size aggregates.

Table 7.19 Results of Statistical Analysis for Effect of Aggregate Size on Compressive Strength

Aggregate Size	Compressive Strength (Mpa)			Student t-test
	Mean	Std. Dev.	COV (%)	
#56	46.9	665.4	9.8	0.499
#67	50.1	166.2	2.3	

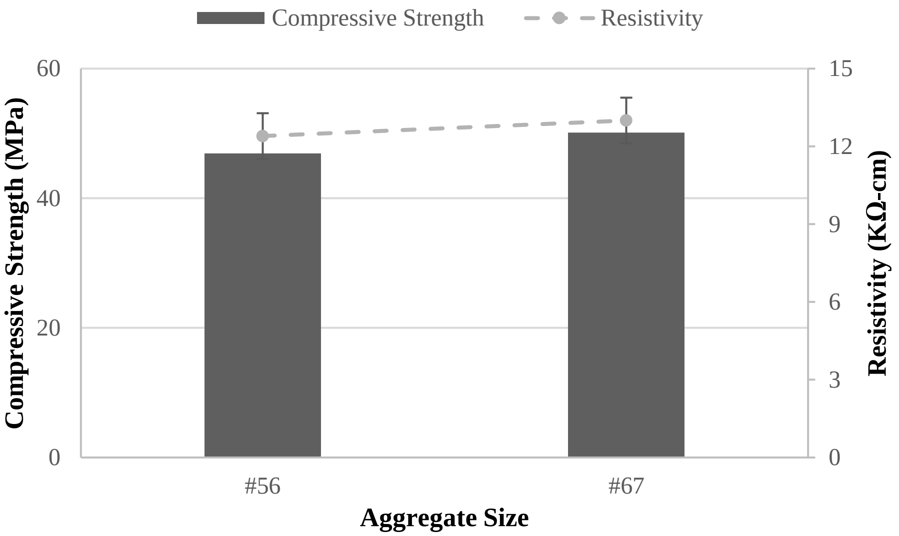


Fig. 7.19 Comparison of resistivity and compressive strength

7.3.7 Effect of Water Reducer and Air Entrainment

The effect of the addition of WR and AE with no fly ash and fly ash content mixtures was analyzed by testing the concrete samples with surface resistivity method, sorptivity test, absorption test and compression test. All these tests were conducted on samples made with 0.40 w/cm having 0% and 20% fly ash content with and without the addition of WR and AE in concrete mixtures. The Student's t-test analysis was performed individually on results of surface resistivity, sorptivity, absorption and compressive strength tests.

The results of the statistical analysis are shown in Table 7.20(a,b) for 0% fly ash and 20% fly ash content concrete mixtures. The resistivity measurements were taken on samples with no admixture and samples with WR and AE. The COV for all the samples remained within 9%. The t-test was performed on resistivity values of concrete mixtures with no admixtures and with WR and AE, both having no fly ash content. There is a significant difference found in resistivity data at the age of 28 days, whereas there is no difference found at day 56 among the resistivity measurements. It means that with the addition of WR and AE in the concrete mixtures, it affects the development of microstructure of concrete compared to concrete with no added admixtures up to 28 days age but the difference in resistivity minimizes by the age of 56 days, and no significant difference is found statistically. When 20% fly ash is added to the mixtures, there is a significant difference in resistivity data observed at the age of 28 and 56 days. It was observed that with the addition of WR and AE in concrete mixtures having fly ash content, the resistivity shows a significant difference compared to the mixtures with no fly ash content. It might happen because the addition of WR and AE in the concrete mixture in the presence of fly ash may restrict the reaction of fly ash particles with hydration products, which may cause a delay in a gain of resistivity.

Table 7.20(a) Results of Statistical Analysis for Effect of WR & AE on Surface Resistivity (0%FA)

Age	Admixtures	Resistivity (KΩ-cm)			Student t-test
(Days)		Mean	Std. Dev.	COV (%)	
28	No Admix	12.4	0.47	3.8	0.0007
	WR & AE	11.1	0.37	3.4	
56	No Admix	14.2	0.55	3.9	0.764
	WR & AE	13.9	1.23	8.8	

Table 7.20(b) Results of Statistical Analysis for Effect of WR & AE on Surface Resistivity (20%FA)

Age	Admixtures	Resistivity (KΩ-cm)			Student t-test
(Days)		Mean	Std. Dev.	COV (%)	
28	No Admix	12.6	0.77	6.1	0.0002
	WR & AE	10.1	0.34	3.3	
56	No Admix	16.4	0.99	6.0	0.003
	WR & AE	14.2	0.53	3.7	

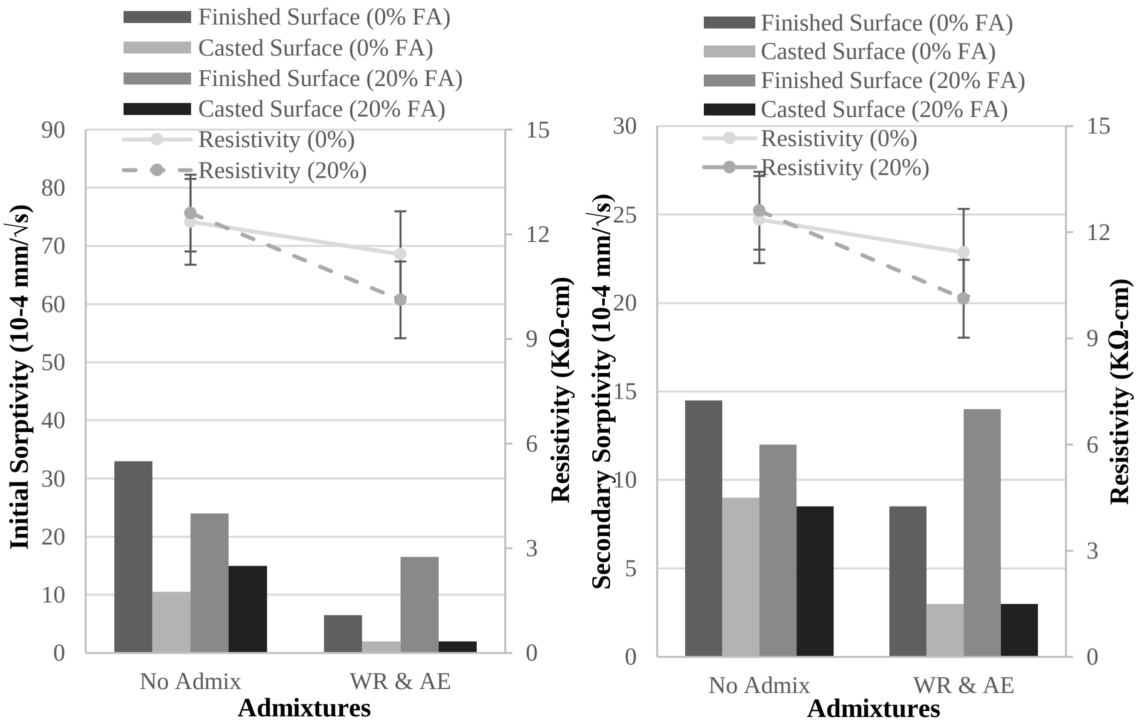
The t-test analysis was conducted on initial and secondary sorptivity results, as shown in Table 7.21(a,b). The significant difference among the initial and secondary sorptivity values was found from t-test with and without the addition of WR and AE for 0% and 20% fly ash content concrete mixtures, except for cast surface samples with 20% fly ash content. Some sample sets have same values of sorptivity coefficients resulted in zero standard deviation. Therefore, a t-test was not applicable to those data sets. The comparison of resistivity with initial and secondary sorptivity are shown in Figure 7.20(a,b). A trend of decrease in sorptivity coefficients observed from no admixture added samples to WR and AE added concrete samples in case of no fly ash and 20% fly ash in the mixtures (Figure 7.7a,b). It could be determined from analysis and figures that in both cases, 0% fly ash and 20% fly ash content concrete samples, no admixtures samples attained higher resistivity with higher initial and secondary sorptivity, whereas samples with WR and AE has lower resistivity with lower sorptivity coefficients. This indicates that WR and AE in the presence of fly ash content do effect the porous structure and connectivity between them.

Table 7.21(a) Results of Statistical Analysis for Effect of WR & AE on Initial Sorptivity

0.40 w/cm	Sample Surface	Admixtures	Initial Sorptivity (10-4 mm/√s)			Student t-test
			Mean	Std. Dev.	COV (%)	
0%	FS	No Admix	33.0	0.00	0.0	0.012
		WR & AE	6.5	0.71	10.9	
	CS	No Admix	10.5	0.71	6.7	0.037
		WR & AE	2.0	0.00	0.0	
20%	FS	No Admix	24.0	0.00	0.0	-
		WR & AE	16.5	2.12	12.9	
	CS	No Admix	15.0	0.00	0.0	-
		WR & AE	2.0	0.00	0.0	

Table 7.21(b) Results of Statistical Analysis for Effect of WR & AE on Secondary Sorptivity

0.40 w/cm	Sample Surface	Admixtures	Secondary Sorptivity (10-4 mm/√s)			Student t-test
			Mean	Std. Dev.	COV (%)	
0%	FS	No Admix	14.5	0.71	4.9	0.014
		WR & AE	8.5	0.71	8.3	
	CS	No Admix	9.0	0.00	0.0	-
		WR & AE	3.0	0.00	0.0	
20%	FS	No Admix	12.0	0.00	0.0	-
		WR & AE	14.0	0.00	0.0	
	CS	No Admix	8.5	0.70	8.3	0.058
		WR & AE	3.0	0.00	0.0	



(a)

(b)

Fig. 7.20 Comparison of resistivity and (a) initial Sorptivity and (b) secondary Sorptivity

There was only one concrete sample tested for percentage absorption with no admixture and with the addition of WR and AE for 0% and 20% fly ash content concrete mixtures. Therefore, it was not possible to statistically analyze absorption data at the age of 56 days. However, the comparative values are very close to each other in case of 0% fly ash with and without WR and AE, no significant difference is seen. Although, there is a decrease in comparative values observed with the addition of 20% fly ash content and on average 22% increase in percentage absorption was noticed with the addition of WR and AE. The comparison of resistivity and percentage absorption for concrete mixtures are shown in Figure 7.21. It is concluded from the figure that resistivity can be related to percentage absorption for mixtures added with WR and AE.

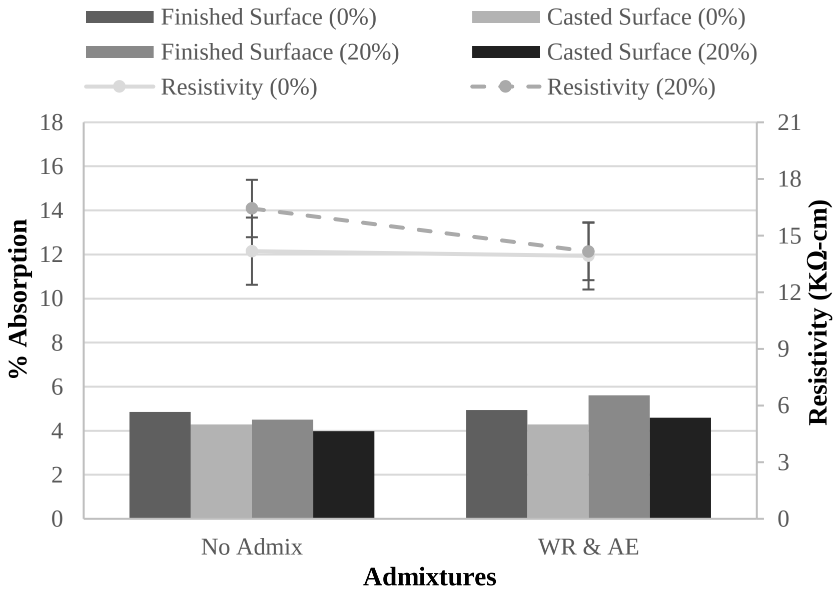


Fig. 7.21 Comparison of resistivity and percentage absorption

The compression test was conducted at the age of 28 days on all concrete samples with or without WR and AE. In Table 7.22, t-test results for compressive strength values show no significant difference found between the mean compressive strength of concrete mixtures with and without WR and AE for no-fly ash content. Whereas, a significant difference among the compressive strengths is noted for concrete mixtures for 20% fly ash content with increase in strength of the samples. The comparison of resistivity and compressive strength is shown in Figure 7.22. It is determined from analysis and figure that resistivity cannot be related to compressive strength for

WR and AE added concrete mixtures because the addition of WR and AE effects the resistivity and compressive strength differently in the presence of fly ash.

Table 7.22 Results of Statistical Analysis for Effect of WR & AE on Compressive Strength

0.40 w/cm	Admixtures	Compressive Strength (Mpa)			Student t-test
		Mean	Std. Dev.	COV (%)	
0%	No Admix	46.9	665.39	9.8	0.569
	WR & AE	49.9	124.07	1.7	
20%	No Admix	50.3	21.92	0.3	0.008
	WR & AE	52.9	11.11	0.1	

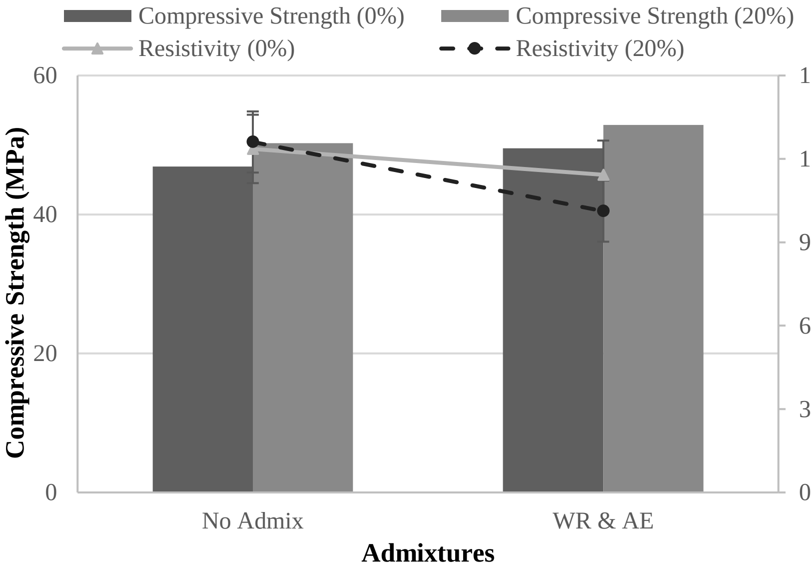


Fig. 7.22 Comparison of resistivity and compressive strength

7.3.8 Effect of Paste Fraction

The effect of a change in paste fraction from 27% to 30% and 33% was analyzed by testing the concrete samples with surface resistivity method, sorptivity test, absorption test and compression test. The tests were conducted on samples made with 0.40 w/cm with no added fly ash content concrete mixtures. The ANOVA, Tukey's test, and t-test were conducted on results of surface resistivity, sorptivity, absorption and compressive strength tests.

The surface resistivity test results were obtained at the age of day 28 and day 56, as shown in Table 7.23. The COV of all resistivity results stayed under 7%. The statistical analysis was performed to determine the difference in resistivity values between 27%, 30% and 33% paste fractions concrete samples. A significant difference in mean resistivity values among the three paste fractions are determined at ages of days 28 and 56 due to increasing in porous structure and connectivity between pores, which increase with greater paste volume.

Table 7.23 Results of Statistical Analysis for Effect of Paste Fraction on Surface Resistivity

Age	Paste Fraction	Resistivity (KΩ-cm)			ANOVA	Comp.	Tukey test	Student t-test
(Days)		Mean	Std. Dev.	COV (%)	p-value			
28	27%	12.4	0.47	3.8	9 E-11	27/30	Sig. difference	3.0 E-5
	30%	14.7	0.63	4.3		27/33	Sig. difference	5.3 E-7
	33%	9.4	0.45	4.8		30/33	Sig. difference	1.1 E-8
56	27%	14.2	0.55	3.9	0.0001	27/30	No difference	0.040
	30%	15.1	0.48	3.2		27/33	Sig. difference	1.5 E-5
	33%	9.8	0.68	6.9		30/33	Sig. difference	3.7 E-4

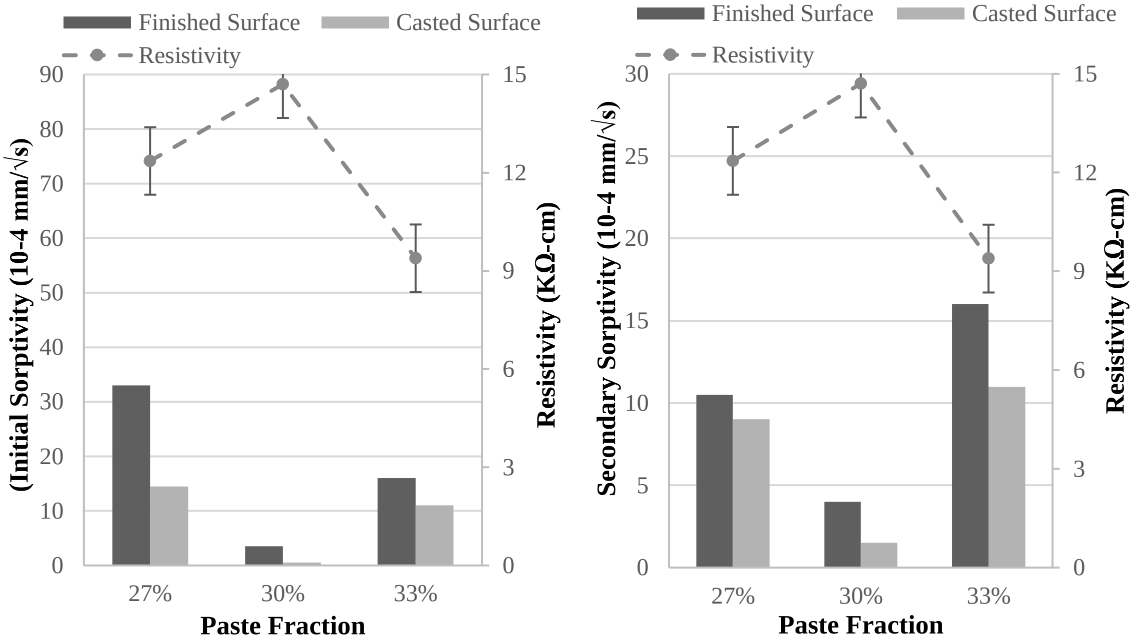
The initial and secondary sorptivity coefficients were determined at day 28. In Table 7.24(a,b), the results of ANOVA, Tukey’s test and t-test for initial and secondary sorptivity have shown that there is a significant difference between the initial and secondary values of 27%, 30% and 33% paste volume concrete samples with the finished and cast surfaces. However, there is a high variation in results noted, might be due to improper preparation and conditioning of the samples. The comparison of resistivity with initial and secondary sorptivity are shown in Figure 7.23(a,b). The sorptivity results of paste mixtures are not reliable due to high variation especially 33% paste samples. However, it is concluded from analyses and figures that with an increase of paste fraction from 27% to 33% the resistivity decreases and sorptivity increases because of increase in a porous structure in concrete.

Table 7.24(a) Results of Statistical Analysis for Effect of Paste Fraction on Initial Sorptivity

Sample Surface	Paste Fraction	Initial Sorptivity (10-4 mm/√s)			ANOVA	Comp.	Tukey test	Student t-test
		Mean	Std. Dev.	COV (%)	p-value			
Finished Surface (FS)	27%	33.0	0.00	0.0	0.0002	27/30	Sig. difference	-
	30%	3.5	0.71	20.2		27/33	Sig. difference	-
	33%	16.0	1.41	8.8		30/33	Sig. difference	0.008
Casted Surface (CS)	27%	10.5	0.71	6.7	0.001	27/30	Sig. difference	-
	30%	0.5	0.00	0.0		27/33	Sig. difference	0.039
	33%	16.0	1.41	8.8		30/33	Sig. difference	-

Table 7.24(b) Results of Statistical Analysis for Effect of Paste Fraction on Secondary Sorptivity

Sample Surface	Paste Fraction	Secondary Sorptivity (10-4 mm/√s)			ANOVA	Comp.	Tukey test	Student t-test
		Mean	Std. Dev.	COV (%)	p-value			
Finished Surface (FS)	27%	14.5	0.71	4.9	0.0003	27/30	Sig. difference	-
	30%	4.0	0.00	0.0		27/33	Sig. difference	-
	33%	11.0	0.00	0.0		30/33	Sig. difference	-
Casted Surface (CS)	27%	9.0	0.00	0.0	0.0003	27/30	Sig. difference	-
	30%	1.5	0.71	47.1		27/33	Sig. difference	-
	33%	11.0	0.00	0.0		30/33	Sig. difference	-



(a) (b)

Fig. 7.23 Comparison of resistivity and (a) initial sorptivity and (b) secondary Sorptivity

There was only one concrete sample tested for percentage absorption for 27%, 30% and 33% paste volume concrete mixtures at the age of 56 days. Therefore, statistically analyzing the absorption data was not possible. However, the comparative values show an increase in percentage absorption when paste volume is increased from 27% to 33%. Whereas, the 30% and 33% paste volume samples show comparative values of absorption. The percentage absorption has increased by 6% by increasing the paste volume from 27% to 33%. The comparison of resistivity and percentage absorption of concrete mixtures are shown in Figure 7.24. The resistivity of concrete can be related to variable paste volume concrete mixtures.

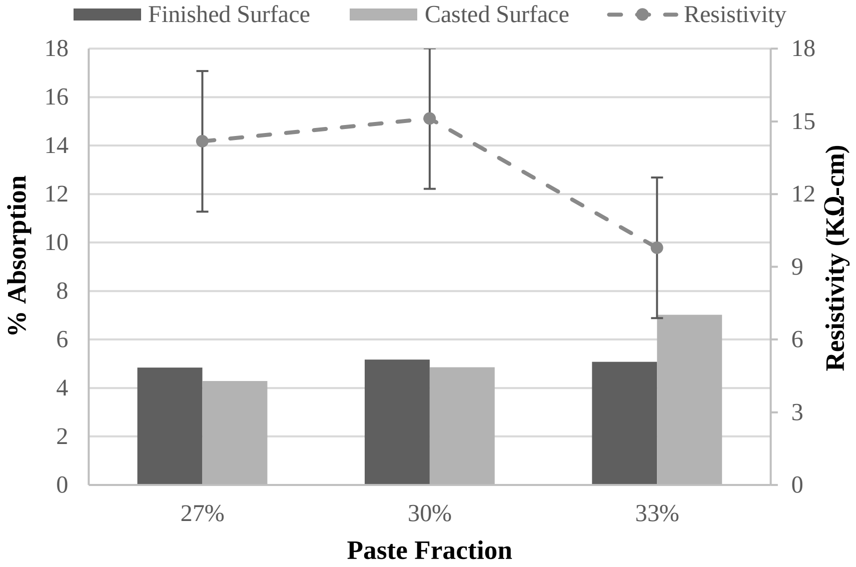


Fig. 7.24 Comparison of resistivity and percentage absorption

The compression test was conducted on concrete samples at the age of 28 days. The statistical analysis is shown in Table 7.25. The COV of 30% and 33% paste mixtures are under the allowable limit of 3.2% except for 27% paste content samples having COV of 9.7%. The ANOVA and t-test analysis was performed on compressive strength data for 27%, 30%, and 33% paste volume concrete samples. There is no significant difference observed among the compressive strength values. However, t-test shows significant difference among 30% and 33% paste volume sample strengths. The comparison of resistivity and compressive strength is shown in Figure 7.25. It can be concluded from table and figure that the resistivity cannot be related to compressive strength having paste fractions of 27%, 30% and 33%.

Table 7.25 Results of Statistical Analysis for Effect of Paste Fraction on Compressive Strength

Paste Fraction	Compressive Strength (MPa)			ANOVA	Comp.	Tukey test	Student t-test
	Mean	Std. Dev.	COV (%)	p-value			
27%	46.92	665.39	9.78	0.221	27/30	-	0.317
30%	51.21	38.89	0.52		27/33		0.717
33%	45.37	3.59	0.05		30/33		0.001

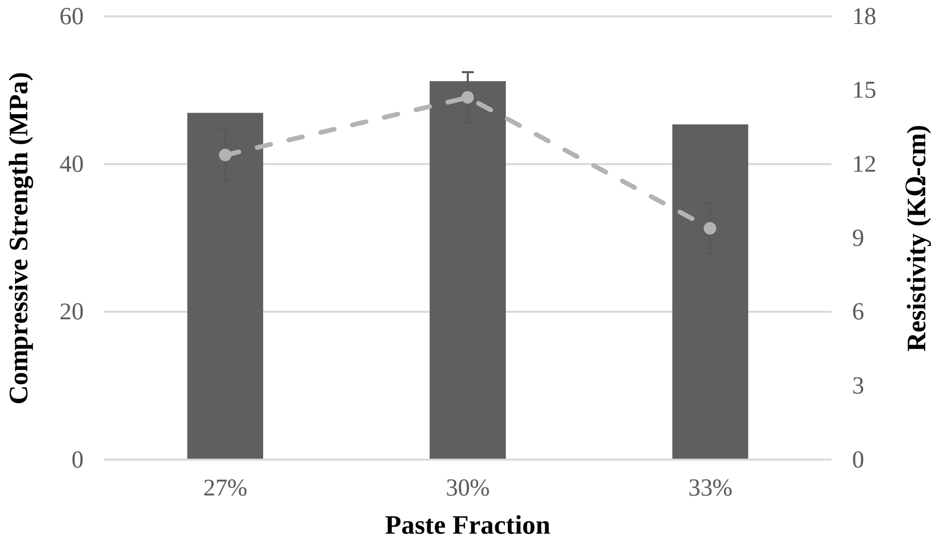


Fig. 7.25 Comparison of resistivity and compressive strength

7.4 Conclusions and Recommendations

The variation of any single parameter in a concrete mixture can change the properties of the concrete, which could affect its durability and strength. The prominent parameters analyzed in this study include, w/cm, fly ash content, fly ash source, aggregate type and size, the addition of chemical admixtures, and paste volume by using surface resistivity test, sorptivity test, absorption test and compression test. The surface resistivity measurements were compared with the results of sorptivity, percentage absorption, and compressive strength by varying the parameters of concrete mixtures.

In case of all concrete mixtures with varying w/cm and fly ash content, the comparison of surface resistivity measurements with sorptivity coefficients, percentage absorption, and compression tests results, did not prove to be well correlated by performing regression analysis. The linear correlation for all the concrete mixtures, resistivity versus sorptivity gave R^2 of 60%, resistivity versus percentage absorption gave R^2 of 70%, and resistivity versus compressive strength gave R^2 of 22%. The results of percentage absorption are very limited, and a strong conclusion cannot be made, however, the percentage absorption shows a better correlation with resistivity. Further investigation is recommended in this area. The comparison showed that the sorptivity, percentage absorption, and compressive strength mechanisms could not be evaluated for all concrete mixtures by using surface resistivity method.

The effect of a change in w/cm of concrete mixtures on surface resistivity can be related to sorptivity coefficients, percentage absorption, and compression tests results. The change in w/cm from 0.40 to 0.50 w/cm resulted in a decrease in resistivity at day 28 and day 56, increase in sorptivity coefficients and percentage absorption and decrease in compressive strength.

The change in fly ash content from no fly ash to 20% in a concrete mixture showed an increase in resistivity with age depending on the content of fly ash in the concrete mixture; however, at day 28, concrete with 10% fly ash content attained the maximum resistivity. The decrease in sorptivity coefficients and percentage absorption, and no significant difference in compressive strength was observed. The analysis showed that at the age of 28 days, the resistivity measurements could not be correlated with sorptivity coefficients and percentage absorption, and compressive strength methods for varying fly ash content in concrete mixtures because at 28-day age, the resistivity depends on the content of fly ash in the mixture.

The comparison of fly ash source, having similar chemical composition show the good relation between resistivity, percentage absorption, and compressive strength. There was no significant difference found in resistivity, percentage absorption, and compressive strength by changing the source of class-C fly ash. Whereas, sorptivity coefficients showed a significant difference and did not show a good relationship with resistivity. It might be because of high COV, and samples may have failed to meet the conditioning requirements of the standard. It is recommended to retest the similar concrete mixtures for the sorptivity test.

The change in aggregate type, Limestone, Dolomite, and Granite in concrete mixtures was analyzed, and comparison showed that the resistivity did not relate to sorptivity, absorption and compressive strength of concrete. It might be due to their different chemical composition and absorption characteristics, which may affect the pore size and tortuosity, and pore water concentration. Further investigation is recommended in this area.

The change in aggregate sizes from #56 to #67 presented no significant difference in measured values and resistivity can be related to percentage absorption and compressive strength. The reason could be the similar chemical properties of aggregates and cementitious material that influence of aggregate size was not substantial. It is recommended to repeat the concrete mixtures and test procedures with different aggregate sizes to further verify the correlation.

The addition of WR and AE in a concrete mixture having fly ash content could cause a reduction in resistivity compared to the resistivity of a concrete mixture having fly ash and no added chemical admixtures. The results of resistivity were found related to sorptivity, the addition of WR and AE in the presence of fly ash resulted in higher sorptivity coefficients and low resistivity, whereas, in case of no-fly ash concrete, there is no significant difference found in resistivity and sorptivity coefficients. The resistivity is found related to percentage absorption, the resistivity decreases and absorption increases in the presence of WR and AE in the fly ash concrete mixture, whereas, there is no significant difference found in resistivity and sorptivity when there is no fly ash content in the concrete mixture. Like resistivity, compressive strength is also affected by the addition of WR and AE in the presence of fly ash content in the mixture.

The change in paste volume of concrete from 27% to 33% resulted in a decrease of surface resistivity due to increase in a porous structure of concrete. Although, the resistivity of 30% paste volume samples attained higher resistivity at days 28 and 56. However, the change in resistivity due to change in paste fraction can be related to increasing in percentage absorption but cannot be related to compressive strength because statistical analysis showed no significant difference in compressive strength by increasing the paste content to 6%. It is difficult to correlate resistivity with initial and secondary sorptivity results because of high variation in coefficients. It might be due to improper conditioning or procedural error of samples. Further testing is recommended to verify the correlation of sorptivity with resistivity due to change in paste fraction.

Based on the preliminary results, this study explains the relationship of surface resistivity with sorptivity, percentage absorption, and compressive strength by varying different parameters in concrete. Further investigation is recommended for change in each parameter and to verify their effects with comparative analysis.

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CHAPTER 8

COMPARATIVE ANALYSIS OF STATISTICAL MODELS TO PREDICT SURFACE RESISTIVITY OF CONCRETE

Preface

This study includes experimental work and statistical analysis. The experimental work consists of surface resistivity testing of cylindrical samples at Bert Cooper Engineering Laboratory completed by the author and undergrad team members under the supervision of Dr. Julie Ann Hartell. The statistical analysis was performed in collaboration with Cristian Contreras-Nieto by using SAS Enterprise Minor. A comparative study was done by using three statistical techniques on surface resistivity data, to select the best and simple model to predict resistivity and develop a new quality control criterion to determine the key mixture parameters in compliance with its mixture design.

Abstract

The electrical resistivity method is a well-known quality control indicator, for not only durability issues due to movement of chloride or sulfate ions and as a corrosion indicator, but it can also be used to differentiate between, the concrete mixtures based on their mixture proportions. This specific quality of resistivity testing was used to investigate three modeling techniques, multiple regression (MR), decision trees (DT) and neural networks (NN) by using resistivity data for thirty concrete mixtures. The best suitable model was selected to predict the resistivity value of a concrete mixture and the development of resistivity prediction intervals to identify the mixture parameters. It is possible to predict the resistivity values representing a concrete mixture for a particular day, but the prediction intervals of resistivity were found not adequate to differentiate between components of a concrete mixture due to overlapping of resistivity ranges of various concrete mixtures.

Keywords Surface resistivity · Fly ash · Multiple Regression · Decision Trees · Neural Networks · Prediction intervals

8.1 Introduction

The addition of water in fresh concrete at a construction site is a very common practice. It may help to retain the workability of concrete due to placement delays, but it disturbs the designed water-to-cement ratio (w/cm) and pastes volume. The increase of water content in concrete will result in durability issues, which may start appearing after few years. During construction, tests are executed on fresh and hardened concrete for quality control of concrete mixtures. Usually, slump, unit weight, and air pressure tests are performed on fresh concrete and compression or flexure tests are conducted on hardened concrete. These tests do provide some information about consistency, workability and air content in the fresh concrete mixture, and strength of the hardened concrete. However, it does not provide information that how much water-to-cement ratio has been increased with the addition of extra water in concrete nor how greatly it could affect the service life of concrete.

In-service, the concrete structure may experience an ingress of foreign components in the form of fluids (e.g., chlorides or sulfates) or gas (e.g., carbon dioxide) into the porous cementitious matrix causing various durability issues and corrosion of rebar in cases of reinforced concrete. This ionic movement depending upon the saturated condition of pore system is, in part, responsible for the unfavorable altering effects in the system. The mechanisms that involve ion transport are capillary action, diffusion, migration in the electrical field and the permeation due to the pressure gradient, to name a few [1]. Field structures are often subjected to combinations of these transport mechanisms, which makes it difficult to single out the ongoing process. The current standard methods for measuring these principles are considered time-consuming, variable and impractical. Still, it is well known that resistance against ionic or fluid penetration is the best defense mechanism for concrete against durability issues. Therefore, there is a need for finding an economical and rapid nondestructive method for measuring these processes [2].

The non-destructive electrical methods are capable of determining the ionic movement in concrete. The saturated condition of a porous matrix of concrete makes it particularly sensitive to electrical resistivity. The past investigations have demonstrated that non-destructive electrical methods such as the surface resistivity and bulk resistivity methods are accurate means for assessing the quality of a concrete mixture based on its performance in resisting ionic flow and are cost-effective [3-5]. Efforts lead to the development of AASHTO TP 95: *Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration* [6]. Also, studies have revealed that the resistivity method is capable of differentiating between concrete mixtures with a diversion in parameters, such as water-to-cement ratio (w/cm) and supplementary cementitious materials [4,5,7], but there is no criterion developed to determine the quality of concrete mixtures in compliance with approved mixture designs. This stimulating aptitude of resistivity method could be instigated by modeling techniques to introduce a quality control and compliance criterion to predict the future resistivity value of concrete and to identify the potential parameters used in the concrete mixture. The resistivity measurements could be modeled by using techniques, Multiple Regression (MR), Decision Trees (DT) and Neural

Networks (NN). The literature based on the application of these techniques in the field of concrete materials could be found in previous studies.

In the past, various studies have shown that the regression models were most widely used to analyze the electrical resistivity or conductivity data, and the relationships were found with strength and several transport properties of concrete. According to Neithalath et al. [8], the linear relationships, concrete conductivities from electrical impedance spectroscopy versus rapid chloride permeability values and non-steady state migration coefficients, pore connectivity factor versus rapid chloride permeability and non-steady state migration values were found by using the regression models. Pacheco et al. and Ranade et al. [9-10] found the relationship between electrical resistance and crack opening displacement and load; the relationship was found linear by implementing regression analysis to the data. Silva et al. and Spragg et al. [11-12] found the linear correlation between electrical resistivity determined through Wenner method and two-place electrode method by using regression model. The regression model was also used to obtain a correlation between the electrical resistivity of concrete versus diffusion coefficients by Ghods et al. and Kessler et al. [13, 3], and chloride penetration resistance by Kessler et al. and Ramezanianpour et al. [3, 14]. The linear relationships were found from the studies. The relationship between electrical resistivity versus water penetration [14] and compressive strength was determined through regression analysis by Ferreira et al., Ramezanianpour et al. and Xiao et al. [14-16].

Karbassi et al. [17] used Decision Trees model for predicting damage in reinforced concrete buildings in future earthquake scenarios in the form of learning algorithms, trained from results of large series of nonlinear dynamic analysis. The first algorithm predicts whether or not there is a damage occurred in the building. In the case of damage, the second algorithm predicts the severity of the damage. Shin et al. [18] proposed a formwork method selection model based on boosted decision trees for appropriate selection of framework method in the construction of tall buildings with reinforced concrete structures. The proposed model has advantages such as single parameter setting, accuracy, and stability improvement, and a comprehensible process in decision-making. Ikiz and Galip [19] developed a computerized decision tree model for pretreatment or anti-icing applications based on laboratory and field testings. The field tests were conducted to determine the factors, such as, time and traffic, affecting the performance of pretreatment applications, and the laboratory tests were conducted to modify the resultant errors that came up during the field tests. The results were integrated and cited in the decision tree. Saad and Fu [20] created decision tree model for assessing the current condition or remaining strength of substructures undergoing degradation. To analyze some probabilities of failure associated with degradation factors, a nondestructive evaluation technique was used.

Kim and Kim [21] used neural network technique to predict the compressive strength of concrete based on mixture proportions. The two data sets of mixture proportions were used for training and testing, and trial and error predicted the compressive strength. The neural networks technique was found very efficient and accurate on predicting the compressive strength by comparing with compressive strengths determined in the laboratory. The maximum error was found 3.2 percent. Sadowski and Nikoo [22] used the artificial neural network (ANN) to predict the corrosion density in concrete in combination with the imperialist competitive algorithm (ICA) used to optimize weights of artificial neural network. The authors have used temperature, alternating current resistivity over the steel bar, alternating current resistivity remote from the steel bar, and the direct current resistivity over the steel bar as input parameters and corrosion current density as an output parameter. The ICA-ANN model combination was found reliable and accurate. Sadowski [23] concluded in his study that the corrosion current density in steel reinforced concrete could be predicted by using artificial neural networks model without a direct connection to the reinforcement. The model is based on the results of two non-destructive resistivity measurement techniques; Wenner-probe resistivity method and galvanostatic resistivity measurement. Sbartai et al. [24] used artificial neural networks to predict the properties of concrete such as strength and water content by fusion of non-destructive measurements from GPR, electrical resistivity, and ultrasonic pulse velocity. It was found that artificial neural networks model is more efficient than response surface method.

The literature review has demonstrated the application of these statistical techniques in the field of concrete materials. There is no evidence found in past that these techniques were comparatively analyzed for resistivity data, and a model is developed to prepare the quality control criterion for concrete. Therefore, there is an immense need to develop a model, which can predict resistivity values, and quality control criterion to determine the key parameters of a concrete mixture such as, w/cm and supplementary cementitious material (fly ash) content after placement to compliance with the mixture design of concrete.

8.2 Experimental Program

In this study, surface resistivity method is experimentally and statistically investigated. In experimental phase, 30 concrete mixtures were prepared in the laboratory with varying water-to-cement ratios (0.40, 0.45, 0.50, 0.55 and 0.60) and varying percentages of fly ash (0%, 5%, 10%, 15%, 20% and 25%) for investigation. A set of six cylindrical replicates (Ø100 x 200) were produced from each mixture. Each cylinder was tested for surface resistivity at the age of 1, 3, 7, 14, 21 and 28 days. Therefore, a total of 720 observations were recorded, and 180 resistivity values were considered based on an average of four resistivity measurements per specimen.

8.2.1 Materials

The concrete mixtures were prepared with a # 57 crushed limestone concrete aggregate and a natural sand for the fine aggregate proportion. A type-I cement and a Class-C fly ash manufactured in Oklahoma was used. The chemical compositions of the cement and fly ash are given in Table 8.1. No chemical admixture was added to the mixtures. Mixture proportions are presented in Table 8.2.

Table 8.1 Chemical Properties of Portland Cement and Fly Ash

Chemical composition of Portland cement (% of weight)					
MgO	CaO	SO_3	SiO_2	Al_2O_3	Fe_2O_3
1.9	62.9	3.3	19.4	5.1	3.4

Chemical composition of Red Rock fly ash (% of weight)							
K_2O	MgO	CaO	SO_3	Na_2O	SiO_2	Al_2O_3	Fe_2O_3
0.58	5.55	23.12	1.27	1.78	38.71	18.82	5.88

Table 8.2 Mixture design details

Mixture	w/cm	Fly Ash (%)	Water (kg/m^3)	Cement (kg/m^3)	Fly Ash (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Paste (%)
1	0.40	0%	145.4	362.5	0	1097.6	714.9	27.8%
2	0.40	5%	145.4	326.2	36.2	1097.6	714.9	27.8%
3	0.40	10%	145.4	309.9	52.6	1097.6	714.9	27.8%
4	0.40	15%	145.4	263.4	99.1	1097.6	714.9	27.8%
5	0.40	20%	145.4	210.8	151.7	1097.6	714.9	27.8%
6	0.40	25%	145.4	158.1	204.4	1097.6	714.9	27.8%
7	0.45	0%	163.2	362.5	0	1097.6	714.9	29.2%
8	0.45	5%	163.2	326.2	36.2	1097.6	714.9	29.2%
9	0.45	10%	163.2	309.9	52.6	1097.6	714.9	29.2%
10	0.45	15%	163.2	263.4	99.1	1097.6	714.9	29.2%
11	0.45	20%	163.2	210.8	151.7	1097.6	714.9	29.2%
12	0.45	25%	163.2	158.1	204.4	1097.6	714.9	29.2%
13	0.50	0%	181.5	362.5	0	1097.6	714.9	30.5%
14	0.50	5%	181.5	326.2	36.2	1097.6	714.9	30.5%
15	0.50	10%	181.5	309.9	52.6	1097.6	714.9	30.5%
16	0.50	15%	181.5	263.4	99.1	1097.6	714.9	30.5%
17	0.50	20%	181.5	210.8	151.7	1097.6	714.9	30.5%
18	0.50	25%	181.5	158.1	204.4	1097.6	714.9	30.5%
19	0.55	0%	199.3	362.5	0	1097.6	714.9	31.8%
20	0.55	5%	199.3	326.2	36.2	1097.6	714.9	31.8%
21	0.55	10%	199.3	309.9	52.6	1097.6	714.9	31.8%
22	0.55	15%	199.3	263.4	99.1	1097.6	714.9	31.8%
23	0.55	20%	199.3	210.8	151.7	1097.6	714.9	31.8%
24	0.55	25%	199.3	158.1	204.4	1097.6	714.9	31.8%
25	0.60	0%	217.7	362.5	0	1097.6	714.9	33.0%
26	0.60	5%	217.7	326.2	36.2	1097.6	714.9	33.0%
27	0.60	10%	217.7	309.9	52.6	1097.6	714.9	33.0%
28	0.60	15%	217.7	263.4	99.1	1097.6	714.9	33.0%
29	0.60	20%	217.7	210.8	151.7	1097.6	714.9	33.0%
30	0.60	25%	217.7	158.1	204.4	1097.6	714.9	33.0%

8.2.2 Testing Procedures

Resistivity methods were initially used in geotechnical areas to measure the resistivity of soils to provide an indication of their permeability characteristics. The four-point Wenner probe was originally developed for that purpose by Wenner in the early 1900's. It has now gained popularity as a non-destructive surface method to measure the ability of concrete to conduct current. As seen in Figure 8.1, the four probes are electrically connected to a concrete surface through adequate contact, and the outer probes produce a small alternating current. Meanwhile, the inner two probes connected to a voltmeter measure the response to current flow [26]. The apparent resistivity value is determined from Equation 8.1. The apparent resistance value obtained can be factorized to compensate for specimen geometry by simply applying a factor based on a ratio of sample cross-sectional area to length [27]. The values presented herein are not factorized; therefore, they correspond to the apparent resistivity of a Ø100 mm x 200 mm-cylindrical sample.

$$\rho = \frac{2\pi sV}{I} \tag{8.1}$$

Where,

ρ: apparent resistivity (ohm-cm)

S: spacing between probes (cm)

V: measured voltage (volts)

I: amplitude of alternating current (amps)

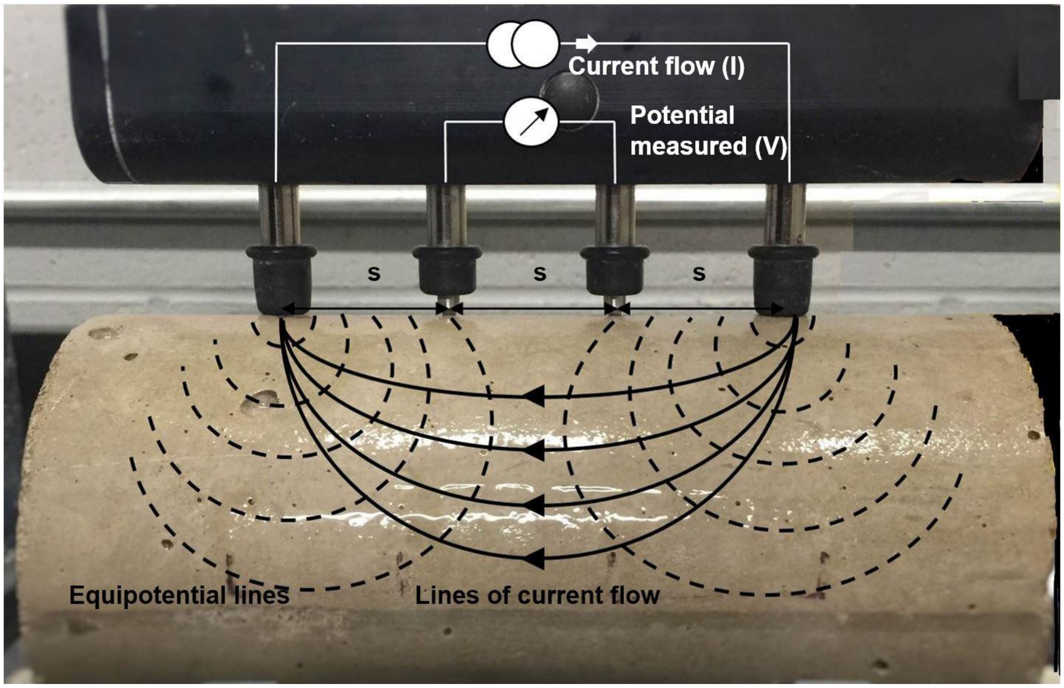


Fig. 8.1 Illustration of surface resistivity principle

The surface resistivity test was performed using a resistivity meter with a probe spacing of 38 mm. The test was performed in accordance with the AASHTO TP 95 standard, Standard Test Method for Surface Resistivity of Concrete's Ability to Resist Chloride Ion Penetration [6]. First, each cylinder was carefully marked to ensure repetition of the non-destructive reading at the same test location on the cylinder. Resistivity measurements were taken on day-1 (after cylinder demolding), on day-3 and day-7 during the first week of curing. Then, readings were taken weekly up to 56 days of curing. Resistivity values presented in the results section represent the calculated average resistivity value for a set of six cylinders replicates. During the testing period, the cylinders were cured in saturated limewater tank maintained at 25 °C temperature.

Special care in surface preparation before each test was performed to minimize within the batch variability of the resistivity measurements. Cylinder removed from the saturated limewater tanks were lightly sprayed with tap water to remove any accumulated salts on the test surface. And, surfaces were kept moist (but not too wet), while conducting the test. The testing environment was strictly monitored to 25 °C and 50% humidity to minimize the variability in measurements.

8.3 Modelling

The focus of this study is to find a simple model through comparatively analyzing the multiple regression, decision trees, and neural networks to forecast resistivity values for a concrete mixture by using mixture parameters such as the w/cm, fly ash percentage and the day of testing. Further, select and implement the best model to predict the resistivity values. Thus, a quality control method could be proposed to determine the w/cm and fly ash content by developing prediction intervals to differentiate the concrete mixtures for each w/cm and percentage of fly ash combinations.

A total of 720 observations were recorded from specimens prepared from 30 concrete mixtures, and 180 resistivity values were considered based on an average of four resistivity measurements per specimen. For the analysis, resistivity is the output variable that is considered continuous, whereas, w/cm and %fly ash are the input variables, which are considered ordinal.

Also, the dataset was randomly partitioned. While 80% of the total dataset was used for developing the models (training), 20% was used for model validation (validation). To determine the stability of the models, two different randomly selected training and validation datasets were used.

8.3.1 Multiple Regression

Regression models are expressed mathematically in the general form Equation 8.2,

$$Y=\beta 0+\beta 1X1+\beta 2X2+\ldots+\beta nXn \qquad (8.2)$$

Where Y is the target variable; $X1$ to Xn are predictor variables; and $\beta0$ to βn are coefficients. Nevertheless, this equation can be modified to second or third degree by increasing the order of the predictors' variables. Multiple regression models were developed in this study including a linear model and two polynomial models (upto third degree). Also, the approach of selecting the model parameters was stepwise [28]. The validation error was used for selecting the best model among three regression models.

8.3.2 Decision Trees

A decision tree is another powerful modeling technique [28]. This scheme divides the data into "pure" groups (leaves). The observations with similar target values are assigned to the same group. As a result, the final model consists of a series of rules, which divide the dataset into groups using most important variables that are selected by the decision tree algorithm [29]. The expression is shown in Equation 8.3.

$$logworth = -log(chi\, squared\, p - value) \tag{8.3}$$

Those rules are known as English Rules that are the output of the algorithm. With this method, two decision tree models were developed. Both of them are created interactively, which means the authors analyzed the Longworth values of the inputs and used their expertise/knowledge on the topic to create the division of the data. The difference between these two decision tree models is the maximum number of leaves; while one model has four, the other model has just two.

8.3.3 Neural Networks

The neural network represents the simplified way of working of the human brain. It helps to solve problems that are difficult to solve through conventional methods by using traditional computations. Neural networks are superior in handling problems with non-linear functions.

Although the interpretation of this model is difficult to perform, this methodology is well known as “black box,” but it is a prevailing and flexible procedure in supervised prediction analysis [21, 25, 29]. In the field of civil engineering, the neural networks technique was used to detect structural damage, structural system identification, the modeling of material behavior, structural optimization, structural control, concrete mixture proportions and groundwater monitoring. The neural networks are a combination of many simple processes that includes units, nodes or neurons, which are connected in parallel but densely populated. These connections are known as synapses. Every neuron receives weighted inputs (signals) from other neurons and transfers them in the form of outputs (signals) to other neurons. The neural networks might be single or multi-layered. The methodology of neural networks consists of network training, testing, and implementation [21].

It is a useful tool for approximate functions. In fact, the particular inputs are adjusted or trained to obtain the target output. It is the ability of this technique to learn from experience and examples and adjust changes with the situation to achieve the desired goal. The determination of architecture, determination of learning process, training of networks, and testing of the trained networks for generalization evaluation are the key steps to developing neural network model [25].

8.3.4 Models Comparison

SAS Enterprise Miner is capable of comparing different models based on the result of a single statistic (misclassification rate, average profit, or average square error) through the Comparison Node (SAS® Enterprise Miner 14.1, 2015). Because of the data independence assumption of the techniques implemented in this study, it is important to note that the best model is selected for each testing day, instead of selecting a unique model for the complete data. In this study, the objective was to predict a numerical variable (resistivity); therefore, the average squared error (ASE) is used as the selection criterion (see Equation 8.4). According to the ASE criterion, the lowest value is the best because the model is less biased than a model with a higher value (Christie, 2011). As a result, the best model was chosen by comparing the ASE values of the six models developed.

$$\mathrm{ASE} = \frac{1}{\mathrm{n}}\sum_{\mathrm{i}=0}^{\mathrm{n}}\left(\tilde{\mathrm{f}}(\mathrm{i}) - \mathrm{f}(\mathrm{i})\right)^2 \qquad (8.4)$$

where n is the number of observations in the dataset; $\tilde{f}(x)$ is an estimate of the observation i; f(x) is the true value of the observation i.

8.3.5 Model Implementation

After the selection of best model based on least ASE value, the model is implemented by using w/cm and percentage of fly ash for predicting resistivity values, at a particular day of interest. Then, 95% prediction intervals were determined with Equation 8.5. The 95% prediction intervals mean that it is 95% confident that this range includes the resistivity of the next sample with a w/cm and the percentage of fly ash.

$$\hat{y} \pm t^{*}_{\propto/2\,,n-2} MSE\sqrt{1+\frac{1}{n}} \qquad (8.5)$$

If $\widetilde{\mathrm{Y}}$ is a vector of n predictions, and Y is the vector of observed values corresponding to the inputs of the function which generated the predictions, then MSE of the predictor can be estimated by Equation 8.6.

$$\mathrm{MSE} = \frac{1}{\mathrm{n}}\sum_{\mathrm{i}=0}^{\mathrm{n}}\left(\widetilde{\mathrm{Y}}(\mathrm{i}) - \mathrm{Y}(\mathrm{i})\right)^2 \qquad (8.6)$$

where MSE is the mean ($\frac{1}{\mathrm{n}}\sum_{\mathrm{i}=0}^{\mathrm{n}}$) of the square of errors$\left(\widetilde{\mathrm{Y}}(\mathrm{i}) - \mathrm{Y}(\mathrm{i})\right)^2$.

8.4 Results & Discussion

8.4.1 Electrical Resistivity

The four-probe electrical method was conducted to determine the surface resistivity measurements for all thirty concrete mixtures. An example of resistivity measurements taken for 0.40 w/cm with 0%, 10% and 20% fly ash content concrete mixtures from day-1 to day-56 of testing period is shown in Table 8.3. The measurements were taken on six replicates of each concrete mixture, and the average of four measurements for each sample represents the resistivity value of a single sample on a testing day. The statistical analysis has shown the average resistivity of six replicates on each day with standard deviation and percentage of coefficient of variation. The average coefficient of variation of three mixtures throughout the testing period ranges from 4.2% to 6.8%. The increase in resistivity over time for these three mixtures is graphically presented in Figure 8.2.

Table 8.3 Surface resistivity measurements of 0.40 w/cm – 0%, 10% & 20% fly ash concrete mixtures

0.40 w/cm - 0% Fly Ash

Samples	Days									
	1	3	7	14	21	28	35	42	49	56
1	4.95	6.23	8.55	9.98	10.73	11.45	12.15	13.03	12.68	13.15
2	5.43	7.10	9.38	11.15	11.75	12.48	12.98	13.73	13.90	14.50
3	5.20	6.98	9.28	10.98	11.58	12.40	13.10	13.53	14.15	14.00
4	5.55	7.20	9.40	11.20	11.95	12.40	13.18	14.05	13.80	14.38
5	5.25	7.00	9.33	11.48	12.08	12.70	13.50	14.15	13.93	14.35
6	5.58	7.30	9.48	11.50	12.28	12.73	13.68	13.93	14.18	14.68
Average	5.33	6.97	9.23	11.05	11.73	12.36	13.10	13.73	13.77	14.18
St. Dev.	0.24	0.38	0.34	0.56	0.55	0.47	0.53	0.41	0.56	0.55
C. Var. (%)	4.48	5.50	3.69	5.08	4.67	3.78	4.06	3.01	4.04	3.87

0.40 w/cm - 10% Fly Ash

Samples	Days									
	1	3	7	14	21	28	35	42	49	56
1	4.33	7.23	10.00	11.93	13.35	13.73	15.00	15.25	15.40	15.78
2	5.53	7.20	10.43	12.58	13.45	13.58	15.08	15.88	15.53	16.08
3	4.38	6.98	9.80	11.70	12.83	13.38	14.35	14.95	15.10	15.65
4	4.38	6.80	9.00	10.88	11.68	12.40	13.33	13.95	13.98	14.80
5	4.90	7.95	11.25	13.38	14.08	14.33	15.98	16.18	16.45	17.08
6	4.15	6.63	9.65	11.28	12.63	12.78	13.58	14.43	13.70	15.08
Average	4.61	7.13	10.02	11.95	13.00	13.36	14.55	15.10	15.03	15.74
St. Dev.	0.51	0.46	0.76	0.91	0.83	0.69	1.00	0.85	1.03	0.80
C. Var. (%)	11.17	6.50	7.60	7.57	6.35	5.16	6.87	5.60	6.84	5.11

0.40 w/cm - 20% Fly Ash

Samples	Days									
	1	3	7	14	21	28	35	42	49	56
1	3.83	6.40	8.55	10.23	11.18	12.28	13.25	14.48	14.70	15.65
2	4.48	6.80	9.75	11.00	12.35	13.05	14.55	15.80	16.15	17.33
3	4.73	7.20	8.23	11.35	12.58	13.38	14.78	16.20	16.70	17.75
4	4.10	6.20	8.98	9.95	10.70	11.30	12.83	13.45	14.30	15.13
5	4.00	6.58	7.75	10.55	11.35	12.45	13.30	14.73	14.95	16.18
6	4.38	6.65	7.98	10.95	11.73	13.20	14.10	15.15	15.78	16.58
Average	4.25	6.64	8.54	10.67	11.65	12.61	13.80	14.97	15.43	16.43
St. Dev.	0.33	0.34	0.73	0.53	0.72	0.77	0.79	0.98	0.93	0.99
C. Var. (%)	7.86	5.20	8.60	4.92	6.16	6.12	5.71	6.58	6.00	6.05

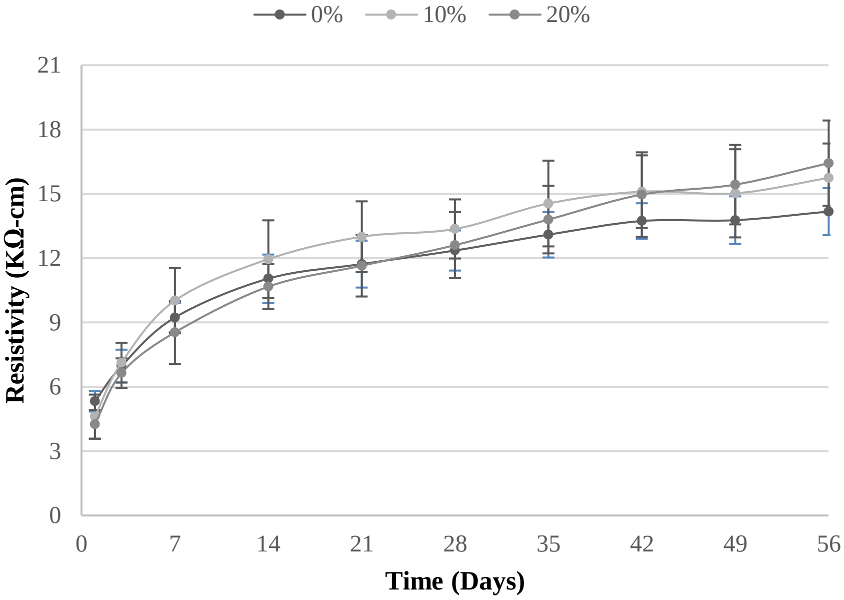


Fig. 8.2 Graphical representation of surface resistivity measurements of 0.40 w/cm concrete mixtures

8.4.2 Model Comparison by Day

For each of the six testing days (1, 3, 7, 14, 21 and 28), the models, multiple regression, decision trees and neural networks were run and evaluated by determining average square error (ASE) values. The ASE values were compared for both randomly selected training/validation datasets; it was verified the consistency of the models because there was no significant difference between the ASE values for both training/validation datasets for each day in the models. The model comparison in Table 8.4 shows that comparison through day-1 to day-28. Neural networks model obtained the lowest ASE values, 0.27 and 0.48, at day 1 and day 28 respectively. At days 3, 7, 14 and 21, multiple regression model achieved the lowest ASE values 0.24, 0.31, 0.36 and 0.63, for first training/validation dataset. In the case of second training/validation dataset, at days 7, 14, 21 and 28, neural networks model demonstrated the lowest ASE values, 0.29, 0.33, 0.47 and 0.46. At days 1 and 3, multiple regression models attained the ASE values of 0.19 and 0.23, compared to the other models. Overall, the difference between the two training/validation datasets showed the stability in the model and consistency of the whole dataset. Also, the difference in ASE values among the multiple regression and neural networks models was not found substantial. Therefore, further analysis was followed by analyzing the first randomly selected dataset.

Table 8.4 Comparison of Models by Day

Day	Type of Models	ASE		Observations
		1st Dataset	2nd Dataset	
1	NN	0.27	0.21	w/c is the most important variable; fly ash is 0.71 important with respect to w/c
	MR	0.29	0.19	Parameters: fly ash & w/c & fly ash* w/c R^2 = 81.7% (R^2 = 80.0%)
3	MR	0.24	0.23	Parameters: fly ash & w/c & fly ash* w/c R^2 = 85.6% (R^2 = 86.4%)
	NN	0.24	0.25	w/c is the most important variable; fly ash is 0.25 important with respect to w/c
7	MR	0.31	0.3	Parameters: w/c & fly ash* w/c R^2 = 87.0% (R^2 = 87.1%)
	NN	0.31	0.29	w/c is the most important variable; fly ash is 0.24 important with respect to w/c
14	MR	0.36	0.37	Parameters: fly ash & w/c & fly ash* w/c R^2 = 87.9% (R^2 = 88.3%)
	NN	0.39	0.33	w/c is the most important variable; fly ash is 0.16 important with respect to w/c
21	MR	0.63	0.48	Parameters: w/c & fly ash* w/c R^2 = 88.0% (R^2 = 87.0%)
	NN	0.63	0.47	w/c is the most important variable; fly ash is 0.19 important with respect to w/c
28	NN	0.48	0.46	w/c is the most important variable; fly ash is 0.19 important with respect to w/c
	MR	0.54	0.54	Parameters: w/c & fly ash* w/c R^2 = 87.5% (R^2 = 87.8%)

From the analysis, at day-1, it was observed that the neural network model, w/cm is the most important variable, whereas, percentage fly ash has 71% importance with respect to w/cm. For multiple regression models, the parameters that form the model are as follows, fly ash, w/cm, and fly ash*w/cm

It means that the model consists of fly ash, w/cm and interaction between fly ash and w/cm variables. Whereas R^2 = 81.7% for first dataset analysis and R^2 = 80.0% for second dataset analysis was found, which is consistent.

At day-3, the parameters observed in the regression model,

fly ash, and w/cm and fly ash* w/cm

Similarly, as day-1, the day-3 model consists of fly ash, w/cm and interaction between fly ash and w/cm variables. Where R^2 = 85.6% for first dataset analysis, and R^2 = 86.4% for second dataset analysis, which is also found very reliable.

For neural networks model, w/cm is again the most important variable, whereas, percentage fly ash has 25% importance with respect to w/cm. There is a drop of 46% in importance with respect to w/cm from day 1 to day 3 because at day 1, fly ash may be acting as a filler and may not be participating in the hydration process. It started hydrating at day 3 and producing hydration products. Therefore, the function of fly ash in the concrete mixture changes from day 3 and onwards.

At day-7, the parameters observed in the regression model,

w/cm, and fly ash* w/cm

The w/cm and interaction between fly ash and w/cm are the important variables in the model. Where R^2 = 87.0% for first dataset analysis, and R^2 = 87.1% for second dataset analysis, which is also found very reliable.

For neural networks model, w/cm is again the most important variable, whereas, percentage fly ash has 24% importance with respect to w/cm.

At day-14, the parameters observed in the regression model,

fly ash, and w/cm, and fly ash* w/cm

The model consists of fly ash, w/cm and interaction between fly ash and w/cm variables. Where R^2 = 87.9% for first dataset analysis, and R^2 = 88.3% for second dataset analysis, which is also found very dependable.

For neural networks model, w/cm is again the most important variable, whereas, percentage fly ash has 16% importance with respect to w/cm.

At day-21, the parameters observed in the regression model,

w/cm, and fly ash* w/cm

The model is based on w/cm and interaction between fly ash and w/cm. Where R^2 = 88.0% for first dataset analysis, and R^2 = 87.0% for second dataset analysis, which is also found very reliable.

For neural networks model, w/cm is again the most important variable, whereas, percentage fly ash has 19% importance with respect to w/cm.

At day-28, it was observed that the neural network model, w/cm is the most important variable, whereas, percentage fly ash has 19% importance with respect to w/cm. For multiple regression models, the parameters that form the model are as follows,

w/cm, and fly ash* w/cm

The model is again based on w/cm and interaction between fly ash and w/cm. Whereas R^2 = 87.5% for first dataset analysis and R^2 = 87.8% for second dataset analysis, which is found very stable.

8.4.3 Example of Models Comparison of Day-3

An example of day-3 was arbitrarily selected to discuss the comparison of models in detail. As shown in Table 8.5, the models are analyzed with multiple possible approaches.

Table 8.5 Comparison of Models of Day-3

Day	Type of Models	ASE	Observations
3	MR^1	0.24	Parameters: fly ash, w/cm, and fly ash* w/cm R^2 = 85.6%
	MR^2	0.24	Parameters: fly ash, w/cm, and fly ash* w/cm R^2 = 85.6%
	NN^3	0.24	w/cm is the most important variable; fly ash is 0.25 important with respect to w/cm
	DT^4	0.42	w/cm is the most important variable; fly ash is 0.39 important with respect to w/cm
	DT^5	0.48	w/cm is the most important variable; fly ash is 0.28 important with respect to w/cm
	MR^6	0.57	Parameters: fly ash and w/cm R^2 = 73.2%

All the models with different approaches were categorized with respect to ASE values. The multiple regression models (MR^1 and MR^2) and neural networks (NN^3) determined the lowest ASE values i-e, 0.24. For multiple regression (MR^1, $MR^{2,}$ and MR^6), three approaches were investigated, MR^1 is a polynomial model (2nd degree), and stepwise selection approach is used in the model. MR^2 is also a polynomial model (up to 3rd degree), and stepwise selection approach is used. The regression models, MR^1 and MR^2, parameters involved are w/cm, fly ash and interaction between w/cm and fly ash,

fly ash, w/cm, and fly ash* w/cm

Whereas, MR^6 is a linear model with w/cm and percentage fly ash used as independent variables determined highest ASE value of 0.57 among other models. The model formed by the parameters,

fly ash and w/c

Where, R^2 = 73.2%.

For neural network model (NN^3), w/cm is the most important variable, whereas, percentage fly ash has 25% importance with respect to w/cm.

For decision trees models (DT^4 and DT^5), obtained 0.42 and 0.48 ASE values. DT^4 has maximum four-branch splits, while, DT^5 has maximum two-branch splits.

8.4.3.1 Best Model of Day-3

Based on the lowest ASE value and usability of a model, multiple regression models were chosen among the other models with different approaches. The best model for day-3 is presented by the statistical analysis as shown in Table 8.6.

Table 8.6 Statistical Analysis

Analysis of Variance					
Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr > F
Model	29	133.286	4.596	30.370	<.0001
Error	114	16.882	0.148		
Corrected Total	143	155.997			
Model Fit Statistics					
R-Square	0.892	Adj R-Sq	0.8642		
AIC	-248.670	BIC	-231.02		
SBC	-159.58	C(p)	30		
Type 3 Analysis of Effects					
Effect	Degrees of Freedom	Sum of Squares	F Value	Pr > F	
Fly Ash	5	4.1	5.52	0.0001	
w/cm	4	104.41	176.27	<.0001	
Fly Ash*w/cm	20	25.16	8.49	<.0001	

The analysis of maximum likelihood estimates is shown in Table 8.7.

Table 8.7 Analysis of Estimates

Analysis of Maximum Likelihood Estimates					
Parameter	Degrees of Freedom	Estimate	Standard Error	t Value	Pr > ItI
Intercept	1	5.611	0.033	171.57	<.0001
Fly Ash 0 %	1	0.235	0.077	3.04	0.0029
Fly Ash 10%	1	-0.072	0.071	-1.03	0.3055
Fly Ash 15%	1	0.189	0.075	2.52	0.0132
Fly Ash 20%	1	-0.101	0.076	-1.33	0.1848
Fly Ash 25%	1	-0.264	0.069	-3.83	0.0002
w/cm 0.40	1	1.052	0.065	16.32	<.0001
w/cm 0.45	1	0.957	0.066	14.42	<.0001
w/cm 0.50	1	-0.313	0.068	-4.59	<.0001
w/cm 0.55	1	-0.633	0.145	-9.76	<.0001
Fly Ash*w/cm 0%-0.40	1	0.068	0.171	0.47	0.6407
Fly Ash*w/cm 0%-0.45	1	-0.16	0.171	-0.94	0.3495
Fly Ash*w/cm 0%-0.50	1	0.376	0.138	2.20	0.0301
Fly Ash*w/cm 0%-0.55	1	-0.4	0.141	-2.88	0.0048
Fly Ash*w/cm 10%-0.40	1	0.605	0.135	4.29	<.0001
Fly Ash*w/cm 10%-0.45	1	0.31	0.153	2.30	0.0235
Fly Ash*w/cm 10%-0.50	1	-0.095	0.141	-0.62	0.5374
Fly Ash*w/cm 10%-0.55	1	-0.161	0.141	-1.14	0.2568
Fly Ash*w/cm 15%-0.40	1	-0.121	0.143	-0.85	0.3982
Fly Ash*w/cm 15%-0.45	1	0.23	0.154	1.50	0.1356
Fly Ash*w/cm 15%-0.5	1	-0.112	0.155	-0.72	0.4718
Fly Ash*w/cm 15%-0.55	1	-0.862	0.144	-6.01	<.0001
Fly Ash*w/cm 20%-0.40	1	-0.036	0.144	-0.26	0.7984
Fly Ash*w/cm 20%-0.45	1	-0.331	0.145	-2.29	0.0239
Fly Ash*w/cm 20%-0.50	1	0.297	0.155	1.91	0.0587
Fly Ash*w/cm 20%-0.55	1	0.348	0.170	2.06	0.0421
Fly Ash*w/cm 25%-0.40	1	-0.599	0.141	-4.27	<.0001
Fly Ash*w/cm 25%-0.45	1	-0.193	0.141	-1.37	0.1746
Fly Ash*w/cm 25%-0.50	1	-0.474	0.142	-3.34	0.0012
Fly Ash*w/cm 25%-0.55	1	0.97	0.133	7.27	<.0001

Analysis of Maximum Likelihood Estimates

Parameter		Degrees of Freedom	Estimate	Standard Error	t Value	Pr > ItI
Intercept		1	5.611	0.033	171.57	<.0001
Fly Ash	0 %	1	0.235	0.077	3.04	0.0029
Fly Ash	10%	1	-0.072	0.071	-1.03	0.3055
Fly Ash	15%	1	0.189	0.075	2.52	0.0132
Fly Ash	20%	1	-0.101	0.076	-1.33	0.1848
Fly Ash	25%	1	-0.264	0.069	-3.83	0.0002
w/cm	0.40	1	1.052	0.065	16.32	<.0001
w/cm	0.45	1	0.957	0.066	14.42	<.0001
w/cm	0.50	1	-0.313	0.068	-4.59	<.0001
w/cm	0.55	1	-0.633	0.145	-9.76	<.0001
Fly Ash*w/cm	0%-0.40	1	0.068	0.171	0.47	0.6407
Fly Ash*w/cm	0%-0.45	1	-0.16	0.171	-0.94	0.3495
Fly Ash*w/cm	0%-0.50	1	0.376	0.138	2.20	0.0301
Fly Ash*w/cm	0%-0.55	1	-0.4	0.141	-2.88	0.0048
Fly Ash*w/cm	10%-0.40	1	0.605	0.135	4.29	<.0001
Fly Ash*w/cm	10%-0.45	1	0.31	0.153	2.30	0.0235
Fly Ash*w/cm	10%-0.50	1	-0.095	0.141	-0.62	0.5374
Fly Ash*w/cm	10%-0.55	1	-0.161	0.141	-1.14	0.2568
Fly Ash*w/cm	15%-0.40	1	-0.121	0.143	-0.85	0.3982
Fly Ash*w/cm	15%-0.45	1	0.23	0.154	1.50	0.1356
Fly Ash*w/cm	15%-0.5	1	-0.112	0.155	-0.72	0.4718
Fly Ash*w/cm	15%-0.55	1	-0.862	0.144	-6.01	<.0001
Fly Ash*w/cm	20%-0.40	1	-0.036	0.144	-0.26	0.7984
Fly Ash*w/cm	20%-0.45	1	-0.331	0.145	-2.29	0.0239

Fly Ash*w/cm	20%-0.50	1	0.297	0.155	1.91	0.0587
Fly Ash*w/cm	20%-0.55	1	0.348	0.170	2.06	0.0421
Fly Ash*w/cm	25%-0.40	1	-0.599	0.141	-4.27	<.0001
Fly Ash*w/cm	25%-0.45	1	-0.193	0.141	-1.37	0.1746
Fly Ash*w/cm	25%-0.50	1	-0.474	0.142	-3.34	0.0012
Fly Ash*w/cm	25%-0.55	1	0.97	0.133	7.27	<.0001

The table explains that according to the coefficients, lower the w/cm, higher is the estimated resistivity values. For example, w/cm 0.40 has the maximum estimated coefficient of 1.0521 compared to higher w/cm. Similarly, lower the percentage of fly ash, higher is the estimated resistivity values. For example, 0% fly ash has the highest coefficient value (0.2345) compared to the other percentages of fly ash content. The statistical analysis details have shown that the model is significant to explain the variability in the data with an adjusted R^2 of 86.42% and the three parameters are significant.

From Table 8.7, at day-3, the most commonly used fly ash percentages, 0%, 10% and 20% in combination with 0.40, 0.45, 0.50, 0.55 and 0.60 w/cm in concrete mixtures, the intercepts, coefficients, and their interactions could be summarized in Table 8.8.

Table 8.8 Analysis of Estimates

Fly ash	w/cm	Intercept	Fly ash	w/cm	Fly ash*w/cm
0%	0.40	5.61	0.23	1.05	0.07
	0.45	5.61	0.23	0.96	-0.16
	0.50	5.61	0.23	-0.31	0.38
	0.55	5.61	0.23	-0.63	-0.40
	0.60	5.61	0.23	-1.07	0.11
10%	0.40	5.61	-0.07	1.05	0.60
	0.45	5.61	-0.07	0.96	0.31
	0.50	5.61	-0.07	-0.31	-0.09
	0.55	5.61	-0.07	-0.63	-0.16
	0.60	5.61	-0.07	-1.06	-0.66
20%	0.40	5.61	-0.10	1.05	-0.04
	0.45	5.61	-0.10	0.96	-0.33
	0.50	5.61	-0.10	-0.31	0.30
	0.55	5.61	-0.10	-0.63	0.35
	0.60	5.61	-0.10	-1.06	-0.28

The information of intercepts, coefficients and their interaction for different w/cm and percentage of fly ash concrete mixtures provided in table-8 were used to predict the resistivity values at day-3. Similarly, it can be done with the outcome of the models of day-7, 14 and 21 (multiple regression models) in order to determine the predicted resistivity values.

8.4.4 Prediction of Resistivity Values

The predicted resistivity values are shown in Table 8.9, determined from the best model of each day representing the specified w/cm with percentages of fly ash 0%, 10% and 20% respectively.

Table 8.9 Predicted Values of Resistivity

w/cm		0.40	0.45	0.50	0.55	0.60
Days	Models			0% Fly Ash		
1	NN	5.35	5.56	5.02	4.15	4.38
3	MR	6.96	6.64	5.91	4.82	4.89
7	MR	9.37	9.37	7.39	6.37	6.73
14	MR	11.06	10.13	8.78	7.42	7.87
21	MR	11.62	10.63	9.18	8.06	8.39
28	NN	12.24	11.41	9.87	8.51	8.88
Days	Models			10% Fly Ash		
1	NN	4.65	4.77	2.98	3.26	2.77
3	MR	7.19	6.80	5.13	4.75	3.82
7	MR	9.36	9.36	7.26	6.35	5.36
14	MR	12.17	10.45	7.94	7.84	6.24
21	MR	13.08	11.09	8.19	8.78	6.73
28	NN	13.56	11.91	8.93	9.24	7.28
Days	Model			20% Fly Ash		
1	NN	4.15	3.77	3.45	3.15	2.94
3	MR	6.53	6.14	5.49	5.23	4.17
7	MR	8.51	8.43	7.44	7.58	5.87
14	MR	10.54	9.27	8.72	8.10	6.62
21	MR	11.54	10.33	9.41	9.34	7.25
28	NN	12.48	11.09	10.28	9.50	7.57

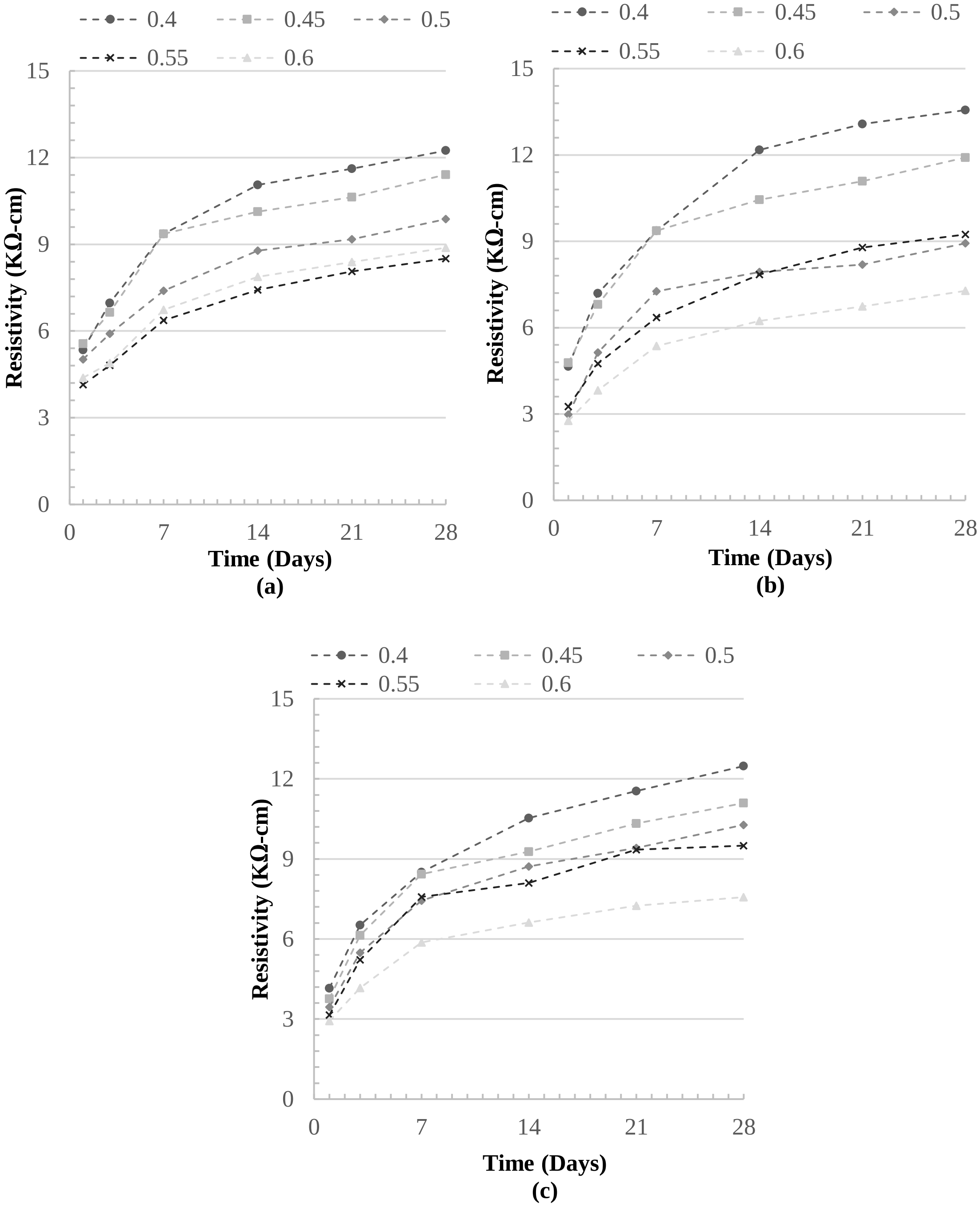
As an example, for 0.40 w/cm and 0% fly ash concrete mixture, the resistivity value can be predicted by using coefficients and intercept values at day-3, shown in Table 8.8.

Y = 5.61 + 0.23(Fly ash 0%) + 1.05(w/cm 0.40) + 0.07(Fly ash*w/cm 0%-0.40)

= 5.61 + 0.23 + 1.05 + 0.07

= 6.96

The calculated resistivity values for each w/cm and 0%, 10% and 20% fly ash content concrete mixtures with most efficient model determined against each day were plotted on graphs. Figures 8.3(a,b,c) are showing a change in resistivity values over time, and the w/cm with respect to the percentage of fly ash content could be differentiated on each graph due to the difference in concrete parameter proportions in the mixtures.



(a)

(b)

(c)

Fig. 8.3 Predicted resistivity values in various w/cm mixtures at (a) 0%, (b) 10%, ad (c) 20% fly ash content

8.4.5 Prediction Intervals of Resistivity Values

The prediction intervals of resistivity values were calculated, and the lower and upper limits for 0%, 10% and 20% fly ash content with 0.40, 0.45, 0.50, 0.55 and 0.60 w/cm are shown in table-10. The prediction intervals for all testing days from day 1 to 28 can be calculated with Equation 8.5.

Table 8.10 Prediction Intervals of Resistivity Values

w/cm	0.4		0.45		0.5		0.55		0.6	
Limits	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
Days	0% Fly Ash									
1	4.49	6.21	3.15	7.97	3.77	6.28	2.82	5.47	2.44	6.33
3	5.60	8.33	5.06	8.22	5.27	6.55	3.94	5.69	3.64	6.15
7	8.05	10.68	6.53	12.20	6.26	8.52	5.33	7.40	4.85	8.62
14	9.06	13.06	7.95	12.32	7.43	10.14	6.17	8.67	5.54	10.21
21	9.62	13.61	8.02	13.25	7.20	11.15	6.65	9.47	5.91	10.87
28	10.52	13.97	8.75	14.08	8.07	11.67	7.38	9.63	6.21	11.56
Days	10% Fly Ash									
1	2.81	6.50	2.53	7.02	2.40	3.57	1.99	4.53	0.39	5.14
3	5.53	8.86	5.37	8.24	4.59	5.67	2.86	6.63	2.90	4.73
7	5.63	13.09	7.46	11.26	6.44	8.07	4.68	8.03	4.43	6.30
14	8.84	15.50	8.64	12.25	7.01	8.87	5.91	9.77	5.33	7.14
21	10.13	16.03	8.53	13.65	6.90	9.48	6.25	11.32	5.15	8.31
28	10.99	16.13	9.47	14.36	8.04	9.82	6.70	11.78	6.23	8.33
Days	20% Fly Ash									
1	2.91	5.40	2.29	5.24	1.40	5.50	2.13	4.17	1.53	4.34
3	5.22	7.83	4.34	7.93	4.22	6.77	4.39	6.06	3.47	4.87
7	5.89	11.12	6.08	10.78	5.97	8.92	6.04	9.12	4.12	7.62
14	8.59	12.48	6.47	12.07	6.79	10.64	7.00	9.20	5.22	8.02
21	8.96	14.12	7.51	13.15	7.46	11.37	7.01	11.68	5.37	9.13
28	9.68	15.27	7.89	14.29	7.92	12.64	7.63	11.37	6.01	9.12

In the past, there were no studies found in these guidelines. Hence, it was observed from the results that there is an overlapping of intervals among the concrete mixtures for each fly ash content mixtures with all w/cm. Therefore, it is not possible to differentiate between the parameters due to the overlapping of resistivity upper and lower limits of various concrete mixtures. However, it is possible to predict resistivity values with high accuracy with the models developed in this research and further work is recommended to determine the efficiency of the models.

8.5 Conclusions

The electrical resistivity can be used as a quality indicator, for not only durability issues due to movement of chloride or sulfate ions and as a corrosion indicator, but it can also be used to differentiate between the concrete mixtures based on their mixture proportions. This specific quality of resistivity testing could be helpful to develop models to predict the resistivity value of a concrete mixture and the development of resistivity prediction intervals to identify the mixture parameters. Thus, the surface resistivity method could be used for quality control and compliance criteria for mixture design parameters.

The three modeling techniques were investigated, multiple regression (MR), decision trees (DT) and neural networks (NN) by using resistivity data for thirty concrete mixtures. The best predicting models are either MR or NN based on ASE values. These two techniques outperformed DT in all days; it means that DT algorithm is not robust enough to predict resistivity values of hardened concrete.

The results from resistivity testing have shown that the various concrete mixtures have a different trend of gain in resistivity over time, and it is because of different proportions of parameters like fly ash and w/cm. Due to this reason, it is possible to predict the resistivity values representing a concrete mixture for a particular day. Further work is recommended to determine the accuracy of prediction models.

It is concluded that by using the prediction intervals, it is not possible to differentiate between components of a concrete mixture due to overlapping of resistivity ranges of various concrete mixtures. However, this analysis introduces a new methodology for data examination in the materials field.

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CHAPTER 9

DEVELOPMENT OF STATISTICAL CRITERIA USING SURFACE RESISTIVITY TESTING FOR QUALITY CONTROL AND COMPLIANCE OF CONCRETE MIXTURES

Preface

This study includes experimental work and statistical modelling. The experimental work consists of surface resistivity testing of cylindrical samples at Bert Cooper Engineering Laboratory completed by the author and undergrad team members under the supervision of Dr. Julie Ann Hartell. The statistical analysis was performed in collaboration with Cristian Contreras-Nieto by using Levene's test, ANOVA, Welch's and Tukey's test on resistivity data. A quality control criterion is developed to determine the presence of fly ash content and potential w/cm of concrete. In this study, the competence of this criterion is also analyzed. The chapter is reviewed by Dr. Hartell, Dr. Mohamed Soliman, and Dr. Yongwei Shan. The chapter is submitted to Journal of Construction and Building Materials and currently under peer review.

It is important to note that the proposed statistical criteria for quality control and compliance of concrete mixtures is in first phase of development. There are some limitations defined for the criteria in order to obtain the precise results. The concrete samples to be used testing should be cylindrical (Ø100 mm x 200 mm) in shape. The statistical criteria is applicable to 0.40, 0.45 and 0.50 w/cm, 0% to 20% Class-C fly ash content, type-I cement or comparable to specifications mentioned in Table 9.1, crushed limestone aggregates, the paste fraction between 27% to 30% with no addition of chemical admixtures. The saturated limewater curing method is recommended. The concrete samples must be tested in accordance with AASHTO TP95 standard.

Abstract

Water-to-cementitious material ratio (w/cm) and secondary cementitious materials are key parameters, which are often necessary to attain the required durability and mechanical properties of concrete. In this study, a simple quality control method was developed to determine the potential fly ash content and w/cm of a concrete mixture. An experimental parametric study was performed to develop the criteria based on surface resistivity testing. It was found, with a 95% confidence level, that fly ash content in a concrete mixture might be determined after 3 days of immersion curing. In addition, the potential w/cm of a concrete mixture containing no fly ash and up to 20% fly ash may be identified by obtaining the resistivity value at a sample age of 14 and 28 days. The developped criteria offers a simple tool for quality control and quality acceptance measures of concrete mixtures with respect to the approved mixture design.

Keywords: Quality Control; Electrical Properties; Durability; Fly Ash; Concrete.

9.1 Introduction

A concrete mixture consists of cement, sand, water, and rocks, in which, the cement and water react to form hydration gel that makes the concrete strong and intact with aggregates. Each material used in making concrete (e.g., cement, water, aggregates) independently affect the overall bulk chemical, physical and mechanical properties of the concrete material. The desired properties depend on the end-use of the material and the method of construction. As such, mixture design and proportioning of each component are of critical importance. The performance of a concrete mixture is based on the initial mixture design (something on performance vs. specifications). Therefore, any changes in mixture proportioning or raw materials used will result in a change in the concrete's properties thus, intended serviceability and durability.

Prior to commencing a project, a concrete mixture design is generally approved for construction based on a set of specifications which may include a prescribed water-to-cementitious material ratio along with cement and supplementary cementitious material contents. During constructions, a variety of quality control and acceptance tests are performed to validate that the correct mixture design is being placed. These may include slump and air content test of fresh concrete, and a compression test on hardened concrete samples.

The standard procedure for a slump test is described in ASTM C 143. The measure of a slump is the decrease in the height of unsupported concrete from upturned cone and rod placed as a reference point to the surface center of concrete mixture; this is known as the slump of a concrete mixture [1-3]. The slump test is used to determine the consistency of fresh concrete.
The slump test is advantageous because it detects the non-uniformity of mixture compared to given specifications. This test is a good indicator for an operator to make an immediate adjustment in the case of very low or very high slump. Although it is an indication of the approximate water-to-cement ratio of a mixture, many other factors may influence the measurement such as alkali and sulfate content of the cementitious proportion, change in aggregate structure, the addition of admixtures such as water-reducing agents, the temperature of the mixture to name a few [1-2]. As such, it cannot be used a reliable means for mixture design identification.

Another test commonly performed in the field for quality control and acceptance of fresh concrete mixtures: the percent air content test (ASTM C 138, ASTM C 173 or ASTM C 231). It measures the total amount of air present in an entire volume of concrete. Since air-entrainment has now become an essential part of concrete for durability purposes, the method is routinely performed for acceptance of a mixture, however; it does not provide information on other mixture constituents nor their proportioning.

Generally, strength is considered the most important property of concrete along with durability and permeability. The compression test is performed on hardened concrete samples by following the standard procedure ASTM C 39. The compressive strength of concrete depends on the cementitious material used, and bonding between the aggregate and hydrated cement paste. Primarily, the strength of concrete is influenced by water-to-cement (w/cm) and degree of compaction at a given day and curing temperature. High w/cm concrete gives low strength due to high water content available for hydration, which may result in high porosity and permeability. However, the high value of compressive strength does not prove the concrete durable. The compressive strength gives no clue of concrete's quality against deterioration and ingress of harmful ions (carbon, sulfates, and chlorides) from outside environment in concrete. The compressive strength does not give any information about the permeability of concrete, cementitious material, or concentration of alkalis in the cement paste. Despite this practice, the concrete can still achieve the required minimum strength. Also, adding water increases the w/cm, changes the paste volume, and as a result, concrete undergoes durability issues like corrosion, cracking, spalling, scaling, etc., and loses strength, which causes early repair and rehabilitation of structure. There is an absolute need to develop a procedure to verify the quality of concrete for compliance with the accepted concrete mixture design that could help to control the durability issues, repair and rehabilitation cost, and increase the service life of the concrete structure made in the future.

In addition to these commonly performed tests, rapid chloride permeability testing (RCPT) may also be specified as part of a quality control and assurance plan to evaluate the performance of a mixture to resist against ionic or fluid penetration, which may lead to durability issues. The porous and ionic nature of a concrete matrix makes it particularly sensitive to ionic transport [4,5]. However, the test takes over a day to prepare and several hours to conduct the actual measurement. Moreover, the test method has often been criticized for producing variable results. Therefore, there is a need for finding alternative methods for measuring these processes [6]. The physical and chemical nature of concrete makes it particularly sensitive to electrical conductivity. Recently, investigations have demonstrated that electrical methods such as the surface resistivity and bulk resistivity methods are accurate means for assessing the quality of a concrete mixture based on its performance in resisting ionic flow established through a comparative relationship with RCPT [7-9]. Efforts lead to the development of AASHTO TP 95: Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration [10] (Table 9.1). The resistivity testing was found less expensive and rapid to perform in comparison to RCPT [11]; therefore, providing motivation for the implementation of the test method. Furthermore, past studies have revealed that the use of various w/cm, secondary cementitious materials, and their combinations has a distinct rate of increase in resistivity [12,13]. Therefore, surface resistivity testing may be capable of differentiating concrete mixtures with changes in accepted in mixture parameters. This fact makes the method interesting as a means for accepting concrete placed during construction by validating its mixture design parameters.

Table 9.1 28-day permeability classifications according to ASTM C1202-12 (RCP limits) and AASHTO TP 95-11 (SR limits)

Chloride Ion Permeability	ASTM C1202* (coulombs)	AASHTO TP 95 (KΩ-cm)
High	>4000	<12
Moderate	2000 to 4000	12 to 21
Low	1000 to 2000	21 to 37
Very Low	100 to 1000	37 to 254
Negligible	<100	>254

* Ø100 x 200 mm concrete cylinder

However, it was deemed challenging to measure consistently the resistivity of a concrete sample as there are procedural factors, which may affect the measurements if an operator is not well-aware such as presence of reinforcing steel [11,14], curing method [9-12], curing temperature and temperature at testing [4,9,10,14-17], saturation condition [4,14], sample surface condition [4,15], and aggregate type [18] and size [15,18]. Still, it was found that performing the test in a laboratory-controlled environment and conditioning the test samples in accordance with the same standard means as for compression testing [19,20], the resistivity method yields reproducible results at a 95% confidence level within the prescribed coefficient of variation of AASHTO TP95 [10]. Consequently, the standard procedure was deemed accurate and reliable for use as a quality control and assurance method.

The purpose of this project is to investigate the potential of surface resistivity testing as a tool for quality control and compliance testing of concrete mixture design parameters such as water-to-cement ratio and presence of supplementary cementitious material. It is based on the time-resistivity behavior of a given concrete mixture with the first 28 days of standard curing; hence, the development of the cementitious matrix in a laboratory-controlled environment. The new non-destructive method, performed on standard 100mm x 200mm cylindrical samples, could be used as a means for quality control and material compliance during the construction stage. This means that strength would no longer be the only value that is used to accept a concrete mixture.

This study presents the development of the systematic approach using surface resistivity testing. The method is based on an experimental parametric study using statistical analysis to develop a classification method to identify the w/cm of an unknown concrete mixture and whether it contains a class-C fly ash or not. To this end, the analysis of variations (ANOVA) is a powerful technique to use through which the concrete mixtures could be categorized due to changes in the parameters used. Previously, in the field of concrete materials, researchers have preferred ANOVA for data analysis [21-28], which is based on the characteristics of the database that fulfills the assumptions of ANOVA analysis. Although little work has been done to analyze surface resistivity data using ANOVA and Tukey's test [29], the application is novel to the field of concrete quality control and quality assurance at time of construction. The development of these guidelines based on resistivity testing, in addition to current standard specifications, would allow stakeholders to produce high quality and durable concrete.

9.2 Experimental Design

9.2.1 Materials

The concrete mixtures were prepared with a # 56 crushed Limestone concrete aggregate and a natural sand for the fine aggregate proportion (ASTM C33). A type-I cement (ASTM C150) and a Class-C fly ash (ASTM C618) were used. The chemical compositions of the cement and fly ash are given in Tables 9.2 and 9.3. No chemical admixture was used in the preparation of the mixtures.

For this study, a total of 30 concrete mixtures were prepared in the laboratory following ASTM C192 [22]. The mixture combinations varied in water-to-cementitious material ratios (0.40, 0.45, 0.50, 0.55 and 0.60) and percentages of fly ash (0%, 5%, 10%, 15%, 20% and 25%). The concrete mixture proportions are presented in Table 9.4. To increase the water-to-cementitious material ratio, the mixtures were devised by varying the water content while keeping the aggregate proportion constant. This was selected to simulate the addition of water to a concrete mixture, which would result in an increase in water-to-cement ratio and, by effect, an increase in paste content of the mixture.

Table 9.2 Chemical properties of Portland cement

Chemical composition (% by weight)					
MgO	CaO	SO_3	SiO_2	Al_2O_3	Fe_2O_3
1.9	62.9	3.3	19.4	5.1	3.4

Table 9.3 Chemical composition of Class-C fly ash

Chemical composition (% by weight)							
K2O	MgO	CaO	SO_3	Na_2O	SiO_2	Al_2O_3	Fe_2O_3
0.58	5.55	23.12	1.27	1.78	38.71	18.82	5.88

Material batching, and concrete mixing along with specimen casting was carried out within a temperature-controlled laboratory. To maximize reproducibility, all aggregate preparation, mixing, casting procedures and common material quality control was performed in accordance with relevant ASTM standardized procedures. The required number of cylindrical specimens (Ø100 mm x 200 mm cylinders) were made from a single batch to ensure reproducibility of test results. For the study presented herein, six specimen replicates for each mixture type were prepared for a total of 180 specimens. They were prepared in three equal layers using rodding as the method of consolidation. Thereafter, they were demolded after 24 hours of curing in their molds and placed in a temperature controlled limewater tank in accordance with ASTM C511 [23].

Table 9.4 Mixture design details

Mixture	w/cm	Fly Ash (%)	Water (kg/m^3)	Cement (kg/m^3)	Fly Ash (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Paste (%)
1	0.40	0%	145.4	362.5	0	1097.6	714.9	27.8%
2	0.40	5%	145.4	344.4	18.1	1097.6	714.9	27.8%
3	0.40	10%	145.4	326.2	36.3	1097.6	714.9	27.8%
4	0.40	15%	145.4	308.2	54.3	1097.6	714.9	27.8%
5	0.40	20%	145.4	290.0	72.5	1097.6	714.9	27.8%
6	0.40	25%	145.4	271.9	90.6	1097.6	714.9	27.8%
7	0.45	0%	163.2	362.5	0	1097.6	714.9	29.2%
8	0.45	5%	163.2	344.4	18.1	1097.6	714.9	29.2%
9	0.45	10%	163.2	326.2	36.3	1097.6	714.9	29.2%
10	0.45	15%	163.2	308.2	54.3	1097.6	714.9	29.2%
11	0.45	20%	163.2	290.0	72.5	1097.6	714.9	29.2%
12	0.45	25%	163.2	271.9	90.6	1097.6	714.9	29.2%
13	0.50	0%	181.5	362.5	0	1097.6	714.9	30.5%
14	0.50	5%	181.5	344.4	18.1	1097.6	714.9	30.5%
15	0.50	10%	181.5	326.2	36.3	1097.6	714.9	30.5%
16	0.50	15%	181.5	308.2	54.3	1097.6	714.9	30.5%
17	0.50	20%	181.5	290.0	72.5	1097.6	714.9	30.5%
18	0.50	25%	181.5	271.9	90.6	1097.6	714.9	30.5%
19	0.55	0%	199.3	362.5	0	1097.6	714.9	31.8%
20	0.55	5%	199.3	344.4	18.1	1097.6	714.9	31.8%
21	0.55	10%	199.3	326.2	36.3	1097.6	714.9	31.8%
22	0.55	15%	199.3	308.2	54.3	1097.6	714.9	31.8%
23	0.55	20%	199.3	290.0	72.5	1097.6	714.9	31.8%
24	0.55	25%	199.3	271.9	90.6	1097.6	714.9	31.8%
25	0.60	0%	217.7	362.5	0	1097.6	714.9	33.0%
26	0.60	5%	217.7	344.4	18.1	1097.6	714.9	33.0%
27	0.60	10%	217.7	326.2	36.3	1097.6	714.9	33.0%
28	0.60	15%	217.7	308.2	54.3	1097.6	714.9	33.0%
29	0.60	20%	217.7	290.0	72.5	1097.6	714.9	33.0%
30	0.60	25%	217.7	271.9	90.6	1097.6	714.9	33.0%

9.2.2 Testing Procedure

Resistivity methods have been well used in the geotechnical field to measure the resistivity of soils to indicate their permeability characteristics. The four-point Wenner probe was initially developed for that purpose by Wenner in the early 1900's [30]. The concrete community has borrowed the principals of the method which is now gaining popularity as a non-destructive method to measure the ability of a concrete material to conduct an electrical current. Figures 9.1 and 9.2 illustrates the instrumentation used for this study along with the test principles of surface resistivity. As seen in Figure 9.2, four probes are electrically connected to a concrete surface through adequate contact, and the external probes produce a small alternating current; while, the inner two probes connected to a voltmeter, measure the response to current flow [31]. Then using Equation 9.1, the apparent resistance of the material can be calculated from the measured voltage and knowledge of current amplitude, probe spacing, and specimen dimensions. The value obtained can be factorized to compensate for specimen geometry by applying a factor based on a ratio of the sample cross-sectional area to length [18]. However, with respect to the AASHTO TP-95 standard, the values presented herein are not factorized; therefore, they correspond to the apparent resistivity of a Ø100 mm x 200 mm-cylindrical sample [10].

$$\rho = \frac{2\pi s V}{I} \tag{9.1}$$

Where,

ρ: apparent resistivity (ohm-cm)

S: spacing between probes (cm)

V: measured voltage (volts)

I: amplitude of alternating current (amps)

Fig. 9.1 Illustration of surface resistivity

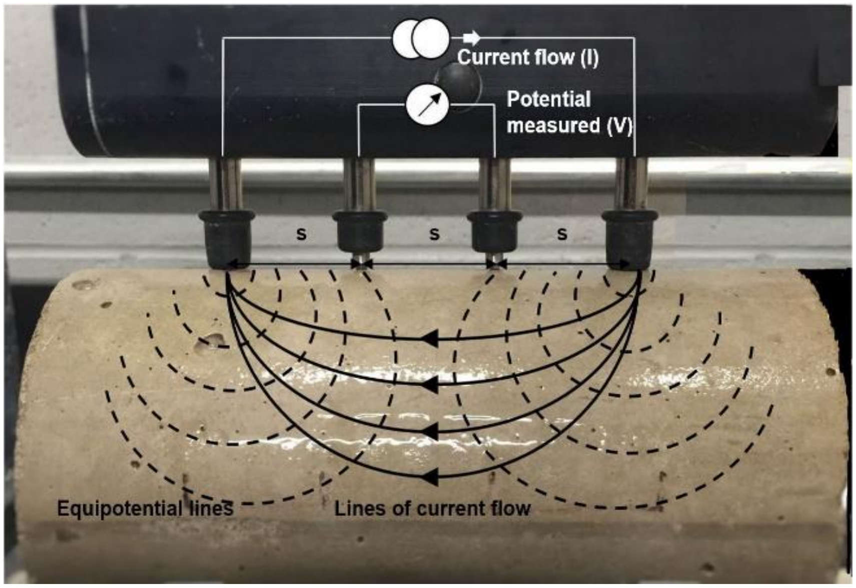


Fig. 9.2 Illustration of surface resistivity test principle

Herein, resistivity testing was performed in accordance with the AASHTO TP 95 standard, *Standard Test Method for Surface Resistivity of Concrete's Ability to Resist Chloride Ion Penetration* [10]. Immediately after demolding a cylinder, it was measured and marked to ensure repetition of the non-destructive reading at the same test location on the cylinder throughout the test period. Special care in surface preparation before each test was performed to minimize within the batch variability of the resistivity measurements. Surfaces were kept moist (not too wet) while conducting the resistivity measurement. Cylinders removed from the saturated limewater curing tank were lightly sprayed with tap water to remove any accumulated salts on the test surface ensuring a clean test surface. During the testing period, below 5 minutes, the cylinders were maintained in a temperature and humidity controlled laboratory environment (ASTM C511). The equipment was also tempered in that same environment to minimize measurement variability due to temperature fluctuations outside that prescribed by ASTM C511 [19]. And, all surface resistivity measurements were taken with a single resistivity meter with a probe spacing of 38 mm.

A total of 6 resistivity tests were performed on each cylinder during the evaluation period of 28 days. Resistivity measurements were taken on day-1 (immediately after cylinder demolding) and, on day-3 and day-7 during the first week of curing. Then, readings were taken weekly up to 28 days of curing. Resistivity values presented in the results section represent the calculated average resistivity value for a set of six-cylinder replicates.

9.3 Results and Discussions

To develop the identification criteria, a total of 180 samples were tested weekly for a period of 28 days. Nearly 8640 measurements were taken which constitutes the data set used to develop the classification method to identify the w/c of an unknown concrete mixture and whether it contains a class-C fly ash or not. Herein, relevant results are presented along with the methodology used for analysis. The discussion is divided into three sections. The two-step indentification process to indentify (step 1) the percentage of class-C fly ash replacement (%FA) and (step 2) the water-to-cementitious material ratio (w/cm). Finally, section 3.3 presents an application of the resistivity method where 15 concrete mixtures of various mixture designs and containing admixtures were investigating to determine the success rate of the method developed.

9.3.1 Identification of %FA

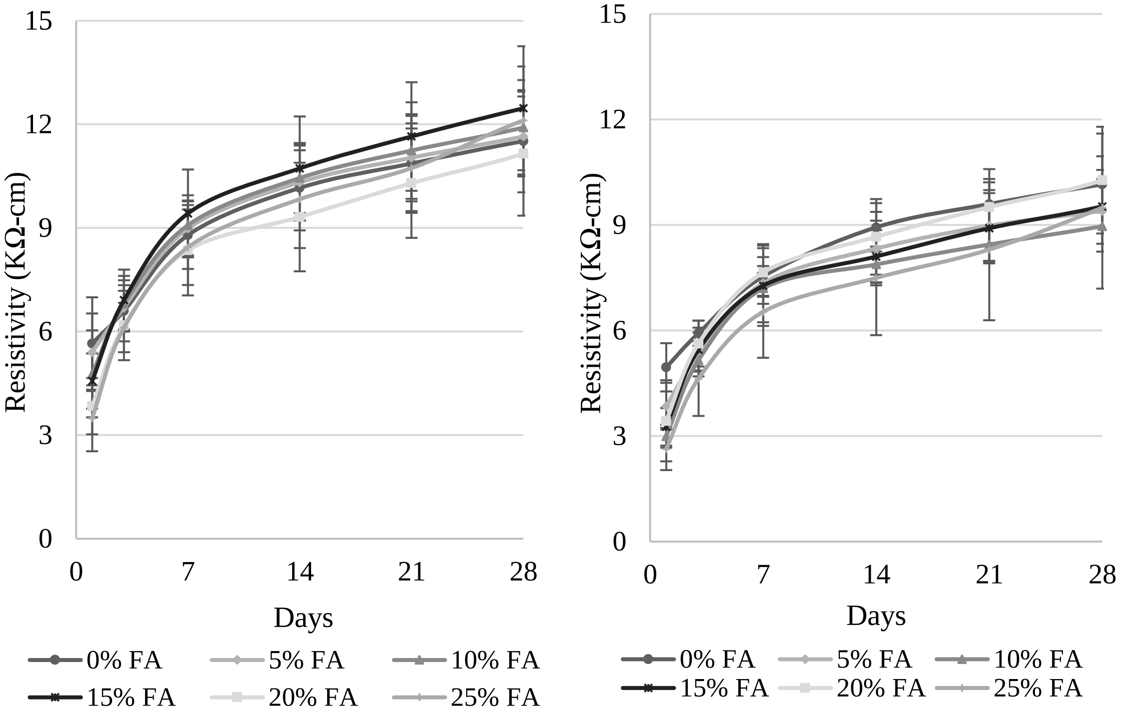
For this investigation, two mixture design parameters (w/cm and %FA) where varied incrementally to evaluate their influence on the surface resistivity measurement and determine whether small changes in these important parameters may be distinguishable using resistivity testing. Surface resistivity measurements were recorded for all 30 concrete mixtures at the defined test age. Table 9.5 presents the average resistivity value calculated from the six-cylinder replicates along with their standard deviations.

Table 9.5 Surface resistivity results of statistical analysis for 30 concrete mixtures varying in w/cm and %FA at ages 1, 3, 7, 14, 21 and 28-days

		Surface Resistivity (kΩ-cm)					
Mixture	Days	1	3	7	14	21	28
0.40 w/cm - 0% FA	Average	5.3	7	9.2	11	11.7	12.4
	St. Dev.	0.2	0.4	0.3	0.6	0.5	0.5
0.40 w/cm - 5% FA	Average	4.7	6.9	9.3	10.9	11.6	12.1
	St. Dev.	0.4	0.4	0.4	0.5	0.5	0.6
0.40 w/cm - 10% FA	Average	4.6	7.1	10	12	13	13.4
	St. Dev.	0.5	0.5	0.8	0.9	0.8	0.7
0.40 w/cm - 15% FA	Average	4.8	6.8	9.3	11.3	11.9	12.7
	St. Dev.	0.5	0.5	0.6	0.5	0.9	0.7
0.40 w/cm - 20% FA	Average	4.3	6.6	8.5	10.7	11.6	12.6
	St. Dev.	0.3	0.3	0.7	0.5	0.7	0.8
0.40 w/cm - 25% FA	Average	3.3	5.7	8.1	9.3	10.4	11.6
	St. Dev.	0.2	0.4	0.5	0.3	0.5	0.4
0.45 w/cm - 0% FA	Average	5.7	6.6	8.8	10.2	10.9	11.5
	St. Dev.	0.7	0.4	0.5	0.6	0.7	0.7
0.45 w/cm - 5% FA	Average	5.4	6.7	9	10.3	11	11.7
	St. Dev.	0.6	0.3	0.4	0.6	0.6	0.6
0.45 w/cm - 10% FA	Average	4.8	6.8	9.1	10.4	11.2	11.9
	St. Dev.	0.6	0.4	0.4	0.5	0.7	0.7
0.45 w/cm - 15% FA	Average	4.6	6.9	9.4	10.7	11.6	12.5
	St. Dev.	0.4	0.4	0.6	0.8	0.8	0.9
0.45 w/cm - 20% FA	Average	3.8	6.2	8.4	9.3	10.3	11.2

	St. Dev.	0.4	0.5	0.7	0.8	0.8	0.9
0.45 w/cm - 25% FA	Average	3.5	6.1	8.4	9.8	10.7	12.1
	St. Dev.	0.5	0.4	0.5	0.7	0.6	0.8
0.50 w/cm - 0% FA	Average	5	5.9	7.5	8.9	9.6	10.2
	St. Dev.	0.3	0.2	0.3	0.3	0.3	0.4
0.50 w/cm - 5% FA	Average	3.9	5.3	7.3	8.3	9	9.4
	St. Dev.	0.3	0.3	0.6	0.5	0.5	0.6
0.50 w/cm - 10% FA	Average	3	5.2	7.2	7.9	8.4	9
	St. Dev.	0.2	0.1	0.2	0.3	0.2	0.2
0.50 w/cm - 15% FA	Average	3.3	5.5	7.3	8.1	8.9	9.5
	St. Dev.	0.3	0.3	0.6	0.4	0.5	0.4
0.50 w/cm - 20% FA	Average	3.4	5.6	7.7	8.7	9.5	10.3
	St. Dev.	0.6	0.3	0.3	0.5	0.5	0.7
0.50 w/cm - 25% FA	Average	2.6	4.6	6.5	7.5	8.3	9.5
	St. Dev.	0.3	0.5	0.7	0.8	1	1.2
0.55 w/cm - 0% FA	Average	4.1	4.8	6.5	7.4	8.2	8.6
	St. Dev.	0.4	0.2	0.3	0.4	0.4	0.3
0.55 w/cm - 5% FA	Average	4.1	5	6.8	8	8.8	9.3
	St. Dev.	0.3	0.5	0.6	0.7	0.7	0.8
0.55 w/cm - 10% FA	Average	3.2	4.7	6.5	7.8	8.8	9.1
	St. Dev.	0.4	0.5	0.4	0.5	0.7	0.7
0.55 w/cm - 15% FA	Average	2.5	4.2	6	6.8	7.8	8
	St. Dev.	0.2	0.2	0.5	0.5	0.5	0.4
0.55 w/cm - 20% FA	Average	3.2	5.3	7.3	8.2	9.4	9.6
	St. Dev.	0.3	0.2	0.2	0.3	0.7	0.5
0.55 w/cm - 25% FA	Average	2.9	5.1	7.1	8	9.5	9.9
	St. Dev.	0.2	0.3	0.4	0.6	0.7	0.8
0.60 w/cm - 0% FA	Average	4.3	4.8	6.6	7.7	8.4	8.9
	St. Dev.	0.5	0.3	0.5	0.6	0.7	0.8
0.60 w/cm - 5% FA	Average	2.7	4.2	5.8	6.9	7.4	7.7
	St. Dev.	0.5	0.3	0.4	0.6	0.6	0.6
0.60 w/cm - 10% FA	Average	2.8	3.8	5.3	6.2	6.9	7.3
	St. Dev.	0.7	0.3	0.3	0.3	0.4	0.3
0.60 w/cm - 15% FA	Average	2.7	4.2	5.7	6.5	7.1	7.4
	St. Dev.	0.4	0.5	0.6	0.8	0.8	0.8
0.60 w/cm - 20% FA	Average	2.8	4.2	5.5	6.6	7.1	7.4
	St. Dev.	0.4	0.2	0.3	0.4	0.5	0.4
0.60 w/cm - 25% FA	Average	2.5	4.6	6.1	7.3	8.1	8.8
	St. Dev.	0.3	0.4	0.6	0.7	0.6	0.8

Figure 9.3(a,b) presents an example of the resistivity behavior in time for a given w/cm, in this case, 0.45 w/cm and 0.50 w/cm with varying fly ash content. It can be seen that for a given w/cm there is a relatively small change in resistivity with increasing %FA. For a young age (below 28 days), it was concluded using ANOVA test that there is no significant difference found among the means of resistivity values for all testing ages. Table 6 provides an example of results obtained using ANOVA, Levene's, Welch's and Tukey's tests performed on the Day-7 data set.



(a) w/cm 0.45

(b) w/cm 0.50

Fig. 9.3 Resistivity behavior in time for (a) 0.45 w/cm and (b) 0.50 w/cm concrete mixtures

Table 9.6 Results of ANOVA, Levene’s, Welch’s and Tukey’s tests comparing the mean resistivity values for concrete mixtures containing 0%, 5%, 10%, 15%, 20% and 25% fly ash replacement

The ANOVA Procedure					
Levene's Test for Homogeneity of Resistivity Variance					
AVOVA of Squared Deviations from Group Means					
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Fly Ash	5	64.46	12.89	6.33	0.001
Error	138	281	2.04		
Welch's ANOVA for Resistivity					
Source	DF	F Value	Pr > F		
Fly Ash	5	0.5	0.774		
Error	63.59				
Tukey's Grouping	Resistivity Mean	N	%Fly Ash		
A	8.02	24	0		
A	8.09	24	5		
A	8.20	24	10		
A	7.99	24	15		
A	7.95	24	20		
A	7.72	24	25		

None-the-less, there are two noticeable trends from Figure 9.3(a,b). On day-1, the resistivity values recorded for the mixtures containing no fly ash are the highest. As seen in Table 9.5, this is the case for all mixtures of varying w/cm. However, in time, the resistivity behavior changes where mixtures containing high amounts of fly ash replacement increase in resistivity thus surpassing their counterparts containing lesser amounts up to none at all. This behavior is due to the increase in resistivity gain over time (slope); because, fly ash replacement slows down the hydration process in the beginning. The alkaline pore solution dissolves the glass content (amorphous aluminosilicate) in fly ash once it reaches a pH of 13.2 due to initiation of cement hydration in the mixture. Then, the products of fly ash start forming which results in a reduction in capillary porosity. As such, the rapid gain in resistivity in comparison to its counterpart containing no supplementary cementitious material was further investigated to determine whether this parameter could be used to distinguish mixtures containing varying amounts in fly ash.

The ANOVA statistical method was used to analyze the variation in the mean gain in resistivity as per level of %FA and w/cm. The first hypothesis test performed compared the percentages of fly ash replacement to determine if there is a significant difference among the mean resistivity gain values between the five contents of fly ash (0%, 5%, 10%, 15%, 20%, and 25%). First, the concrete mixtures were categorized into groups (levels) with respect to their fly ash content (0%, 5%, 10%, 15%, 20% and 25% replacement). The resistivity data were analyzed to determine if there is a significant difference among the levels based on different slope combinations. The possible slope combinations between test days are (1-3), (3-7), (7-14), (7-21), (7-28), (14-21), (14-28) & (21-28). To determine the slope at a given age range, Equation 9.2 was used to calculate the change in resistivity over time.

$$s = \frac{y_2 - y_1}{x_2 - x_1} \qquad (9.2)$$

The surface resistivity measurements were determined at days 1, 3, 7, 14, 21 & 28, which implies that a single concrete cylinder has six resistivity values throughout the testing period; therefore, there is a violation of independency. Although the observations are dependent, the approach used herein considers data obtained for a given day or slope combination as an individual data set. Second, as will be shown later, the errors or residuals are assumed to be normally distributed. This was determined by normally predicted plots, which is the difference between real values and determined values. Third, the Levene's test was performed to determine if the variances in results are equal or significantly different. Levene's test is defined as an inferential statistic used to assess the equality of variances for a variable calculated for two or more groups. If the variance is found equal, ANOVA was performed. ANOVA is the analysis of variations between more than two groups. If at least one variance is significantly different, then Welch's test is used. Welch's test is a two-sample location test, which is used to test the hypothesis that two populations have equal means and unequal variances.

After fulfilling the assumptions of ANOVA, the Null hypothesis was verified to determine whether a slope combination can differentiate mixtures of different fly ash content. Results of the ANOVA analysis for all possible slope combinations are presented in Table 9.7. First, Levene's test was performed to analyze if the hypothesis for equal variance is accepted or rejected. It was found that for slope combinations (1-3), (3-7), (7-14) and (7-21) the results showed equal variances. Whereas, for slopes (7-28), (14-21), (14-28) and (21-28), Levene's test results showed unequal variances and hypothesis was rejected.

Subsequently, ANOVA was used for sets of equal variances, and Welch's test was used for sets of unequal variances. If there is no significant difference found among the mean slopes combination, then that slope combination is rejected. It was established (Table 9.7) that slope combinations (1-3) and (3-7) rejected the null hypothesis meaning there is a significant difference in the resistivity slopes for the fly ash percentages (levels). On the other hand, the slope combinations (7-14) and (7-21) failed to reject the null hypothesis; thus, these slope combinations are not suitable to identify the presence of fly ash content in a concrete mixture. For slope combinations evaluated using Welch's Test, (7-28) accepted the hypothesis meaning that there is no significant difference between the percentages of fly ash. Whereas, the slope combinations (14-21), (14-28) & (21-28) rejected the hypothesis; thus, there is a significant difference between the percentages of fly ash (levels).

Finally, for slope combinations rejecting the Null hypothesis, Tukey's test was used to identify the differences between the %FA groups. It was found that no slope combinations except for slope (1-3) could differentiate between the 0% fly ash (No fly ash concrete mixture) and the 5%, 10%, 15% or 20% fly ash replacement mixture (with fly ash mixtures). Hence, the slope combination (1-3) is the only option that can differentiate between mixtures with “No fly ash” and mixtures containing “Fly ash,” as shown in Table 9.7.

This enabled the development of the first parameter to distinguish mixtures containing fly ash replacement from mixtures containing no supplementary cementitious materials. A range of resistivity values was determined for slope combination (1-3) representing a 95% confidence interval. Presented in Table 9.8, lower and upper limits were calculated for both “No Fly Ash” mixtures and mixtures containing “Fly Ash.”

Table 9.7 Results of Levene’s Test, ANOVA and Tukey’s Test for slope combinations

Slope Combination	Mean of Slope	Equal Variances	ANOVA Test	Tukey’s Test	
				Group-I	Group-II
1-3	0.89	p-val = 0.1419 – Ho	p-val < 0.001 (Ho X)	0%	5% - 20%
3-7	0.49	p-val = 0.2722 – Ho	p-val = 0.027 (Ho X)	10% – 20%	0% - 20%
7-14	0.17	p-val = 0.1056 – Ho	p-val = 0.770 – Ho	No difference	
7-21	0.14	p-val = 0.060 – Ho	p-val = 0.556 – Ho	No difference	
7-28	0.12	p-val = 0.049 (Ho X)	p-val = 0.274 – Ho	No difference	
14-21	0.12	p-val = 0.002 (Ho X)	p-val < 0.001 (Ho X)	10% – 20%	0% - 10%
14-28	0.10	p-val = 0.006 (Ho X)	p-val < 0.001 (Ho X)	20%	0% - 10%
21-28	0.09	p-val < 0.001 (Ho X)	p-val = 0.044 (Ho X)	0% – 20%	0% - 10%

Note: Ho: Null hypothesis, meaning it is correct. HoX: the Null hypothesis is rejected; p-val is the P-value.

Table 9.8 Range in (1-3) resistivity slope (KΩ-cm/day) combination values for concrete mixtures

Fly Ash Content	Slope Mean	Lower Limit	Upper Limit
No Fly Ash	0.5	0.4	0.6
Fly Ash	1.1	>0.6	1.2

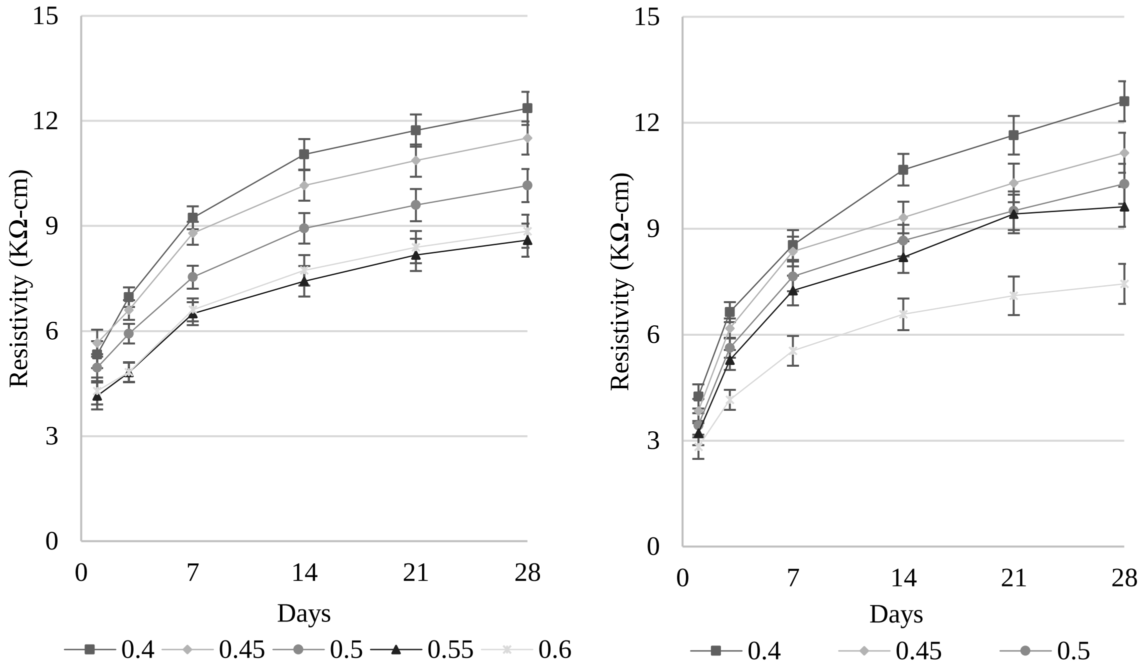
Hence, from the resistivity measurements taken on day-1 (immediately after demolding) and on day-3, the slope between the two data points can be calculated using Equation 9.2 and, using ranges in Table 8, the presence of fly ash in a mixture could be identified. However, there are two possible result outcomes. First, the slope value falls below the lower limits of “No Fly Ash” concrete, in this scenario, the mixture could be considered as inclusive of “No Fly Ash” content, however, there is no certainty in this statement. Second, the slope has a higher value than the upper limit of “Fly Ash” content, in this case, the mixture could be considered inclusive of Fly Ash” content; however, there is no certainty in this statement. Further investigations evaluating multiple mix designs would be required to validate both statements. The upper limit of “No Fly Ash” and lower limit of “Fly Ash” mixtures are very close to each other. However, the analysis showed a significant difference between the two categories at a 95% confidence level.

9.3.2 Identification of w/cm

Subsequently, the potential w/cm used in the mixture could be determined knowing whether a mixture contains fly ash or not. Figure 9.4 provides an example of resistivity behaviors in time for mixtures of various w/cm containing no supplementary cementitious materials and 20% cement replacement with class-C fly ash. Error bars shown represent the 95% confidence intervals from mean resistivity values calculated using Equation 9.3.

$$\hat{y} \pm t^{*}_{n-2} \text{ x SEstd} \qquad (9.3)$$

Where $\hat{y}$ is the predicted value of the dependent variable, t is the t-value, n is the total sample size and SEstd is the standard error of estimate.



(a) 0% FA (b) 20% FA

Fig. 9.4(a,b) Resistivity behavior in time for (a) 0% FA and (b) 20% FA concrete mixtures.

Starting with mixtures containing 0%FA. It can be seen in Figure 9.4a that the mean resistivity values of mixtures of 0.40, 0.45, and 0.50 w/cm are distinct from each other at a 95% confidence level after 14 days of continuous immersion curing. Therefore, testing days 14, 21 and 28 are viable candidates for w/cm identification. As for the 0.55 w/cm and 0.60 w/cm mixtures, they are not significantly different from each other; however, their combined range in values are distinct from that of the 0.50 w/cm. Thus, w/cm identification categories were established for mixtures of 0.40, 0.45 and 0.50 w/cm. The range in resistivity values representing a 95% confidence interval from the mean is shown in Table 9.9. Practically, day-14 was selected to provide a user with an early estimate, and day-28 was selected since other quality control tests such as compression strength are commonly performed on this day. This would permit both tests to be performed sequentially and on the same sample.

Similarly, the 95% confidence limits were calculated for concrete mixtures containing 5%, 10%, 15% and 20% class-C fly ash. Figure 9.4b provides an example of resistivity development in time for the 20% FA mixture only; however, the trend for the other mixtures are similar to that of the 20%FA. For days 14, 21 and 28, the concrete mixtures of lower w/cm (below 0.5) are statistically distinct from each other. However, mixtures of higher w/cm (above 0.5) cannot be differentiated from each. None-the-less, the w/cm identification categories were established for mixtures of 0.40, 0.45 and 0.50 w/cm containing a minimum of 5% FA and a maximum of 20% FA. The range in resistivity values representing a 95% confidence interval from the mean is shown in Table 9.10. As seen in Table 9.10, there is a slight overlap of 0.2 KΩ-cm at the upper boundary of the 0.50 w/cm mixture and lower boundary of the 0.45 w/cm.

Therefore, from the result of the surface resistivity test performed on day-14 or day-28, using ranges in Table 9.10, the w/cm of a mixture could be estimated. However, the presence of gaps between categories or the overlap of categories present zones of uncertainty. Also, in the case of a resistivity value falling below the lower limits of “0.50 w/cm” concrete, in this scenario the mixture could be considered as “> 0.50 w/cm” however, there is no certainty in this statement. Similarly, for resistivity results higher than that of the upper limit of “0.40 w/cm” concrete, the mixture could be considered as “< 0.40 w/cm” however, there is no certainty in this statement. Further investigations evaluating multiple mix designs would be required to validate both statements and increase the accuracy of the proposed categories.

Table 9.9 Surface resistivity 95% confidence limits at test ages 14 and 28 days for concrete mixtures containing no fly ash

w/cm ratio	Day-14			Day-28		
	Mean	95% Conf. Limits		Mean	95% Conf. Limits	
	Surface Resistivity (kΩ-cm)					
0.40	11.0	10.6	11.5	12.4	11.9	12.8
0.45	10.2	9.7	<10.6	11.5	11.0	12.0
0.50	8.9	8.5	9.4	10.2	9.7	10.6

Table 9.10 Surface resistivity 95% confidence limits at test ages 14 and 28 days for concrete mixtures containing fly ash

w/cm ratio	Day-14			Day-28		
	Mean	95% Conf. Limits		Mean	95% Conf. Limits	
	Surface Resistivity (kΩ-cm)					
0.40	10.7	10.2	11.1	12.6	12.0	13.2
0.45	9.3	8.9	9.8	11.2	10.6	11.7
0.50	8.7	8.2	9.1	10.3	9.7	10.8

9.3.3 Validation of mixture parameter identification criteria

The criteria developed was then trialed in a laboratory setting to determine the validity of the method. Several mixtures were prepared for the trial varying %FA replacement and w/cm along with varying paste content. The paste volume of the concrete mixtures ranged from 27% to 31%. Moreover, admixtures such as an air entrainment agent (AEA) and a mid-range water reducer were also added to some of the mixtures (in accordance with recommended manufacturer dosage) to determine their effect on the resulting outcome.

Table 9.11 presents the results obtained for the first step of the method, the calculated slope of resistivity between days 1 and 3. The values were compared with the limits listed in Table 9.8. Out of the 15 concrete mixtures, 13 concrete mixtures were correctly identified (87% success rate) with respect to containing fly ash as a supplementary cementitious material. One mixture which did not meet the criteria did not contain any fly ash. As for the other mixture which failed the validation, the calculated slope for the mixture containing 10% fly ash was superior to the upper boundary of the “Fly Ash” category; therefore, the validation is deemed uncertain.

Table 9.11 Validation of fly ash content in concrete mixtures

Mixture Description	Slope Combination (1-3)	Validated
0.40 w/cm-WR+AEA*-27% Paste	0.4	Yes
0.45 w/cm-WR+AEA*-29% Paste	0.6	Yes
0.50 w/cm-WR+AEA*-30% Paste	0.6	Yes
0.55 w/cm-WR+AEA*-31% Paste	0.3	Yes
0.40 w/cm-30% Paste	0.6	Yes
0.45 w/cm-30% Paste	1.2	No
0.50 w/cm-30% Paste	0.5	Yes
0.45 w/cm-10% Fly ash-AEA*- 29% Paste	0.9	Yes
0.40 w/cm-10% Fly ash-30% Paste	1.4	Uncertain
0.45 w/cm-10% Fly ash-30% Paste	1.1	Yes
0.50 w/cm-10% Fly ash-30% Paste	1.1	Yes
0.45 w/cm-20% Fly ash-AEA*-29% Paste	1.0	Yes
0.40 w/cm-20% Fly ash-30% Paste	1.2	Yes
0.45 w/cm-20% Fly ash-30% Paste	1.2	Yes
0.50 w/cm-20% Fly ash-30% Paste	1.1	Yes

*WR = Water reducer, AEA = Air entraining agent

After successful validation of identification of fly ash content in concrete mixtures, the w/cm of the concrete mixtures were verified with respect to the identified “No Fly Ash” or “Fly Ash” concrete category (Step 2). Here, the mean resistivity values determined from 3 sample replicates were compared to the established criteria in Tables 9.9 and 9.10. Values falling within the gap between category limits are categorized as uncertain.

Starting with the mixtures not containing a class-C fly ash, Table 9.12, mean resistivity values at days 14 and 28 were determined and verified against the criteria developed. For the day-14 assessment, out of 6 concrete mixtures, the w/cm of 3 concrete mixtures were correctly identified (50% success rate) and one mixture (0.55 w/cm) was considered to be above 0.50 w/c which is also a correct interpretation; still, it was deemed as uncertain. For the 28-day analysis, the success rate improved. Only one mixture was misdiagnosed. At first glance, the same mixture was properly identified on day-14. It was noticed that the temperature at the time of test might have affected the result of the test leading to the misinterpretation. Here, maintaining a temperature controlled test environment is imperative for successfully conducting the test procedure [19-20].

Table 9.12 Validation of w/cm with no fly ash content concrete at days 14 and 28

Mixture Description	Resistivity Mean	Determined w/cm	Validated
	Day-14		
0.40 w/cm-WR+AEA*-27% Paste	10.6	0.40	Yes
0.45 w/cm-WR+AEA*-29% Paste	10.0	0.45	Yes
0.50 w/cm-WR+AEA*-30% Paste	8.8	0.50	Yes
0.40 w/cm-30% Paste	7.6	>0.50	No
0.50 w/cm-30% Paste	8.1	>0.50	No
0.55 w/cm-WR+AEA*-31% Paste	7.9	>0.50	Uncertain
	Day-28		
0.40 w/cm-WR+AEA*-27% Paste	11.4	0.45	No
0.45 w/cm-WR+AEA*-29% Paste	11.1	0.45	Yes
0.50 w/cm-WR+AEA*-30% Paste	10.2	0.50	Yes
0.40 w/cm-30% Paste	14.7	< 0.40	Uncertain
0.50 w/cm-30% Paste	10.2	0.50	Yes
0.55 w/cm-WR+AEA*-31% Paste	9.2	>0.50	Uncertain

*WR = Water reducer, AEA = Air entraining agent

Next, the mean resistivity values of the concrete mixtures identified as with “Fly Ash” were compared to the established categories presented in Table 10. Here, boundary conditions were more problematic, producing several uncertain classifications. It was noticed that the effects of temperature variations where more predominant for mixtures containing fly ash. Also, variations in curing temperature outside the ASTM specified limits were observed for mixtures of 0.45 w/cm with 10%FA and 20%FA, which may have contributed to the misinterpretation of the category [19,20]. At day 14, 3 out of 8 mixtures (38% success rate) are either correctly identified or classified as uncertain; whereas, at day 28, the success rate increased at 63%. Still only one positive identification.

None-the-less, the two-step process (identification of concrete mixtures with “No Fly Ash” or “Fly Ash” content from Table 9.8 and indentification of w/cm of mixtures containing “No fly ash” and “Fly Ash” from Tables 9.9 and 9.10) is considered to be successful. Although the number of mixtures and materials evaluated is limited, the method provides great promise for quality control and quality acceptance of important mixture design parameters. With further research, the tool can be improved to incorporate a variety of materials commonly used in the construction industry.

Table 9.13 Validation of w/cm with fly ash content concrete at days 14 & 28

Mixture Description	Resistivity Mean	Determined w/cm	Validated
Day-14			
0.45 w/cm-10% Fly Ash-AEA-29% Paste	10.2	0.40	No
0.40 w/cm-10% Fly ash-30% Paste	12.7	<0.40	Uncertain
0.45 w/cm-10% Fly Ash-30% Paste	11.0	0.40	No
0.50 w/cm-10% Fly ash-30% Paste	7.9	>0.50	No
0.45 w/cm-20% Fly Ash- AEA-29% Paste	9.0	0.50	No
0.40 w/cm-20% Fly Ash-30% Paste	12.3	<0.40	Uncertain
0.45 w/cm-20% Fly Ash-30% Paste	10.3	0.40	No
0.50 w/cm-20% Fly Ash-30% Paste	8.7	0.50	Yes
Day-28			
0.45 w/cm-10% Fly Ash-AEA -29% Paste	12.0	0.40	No
0.40 w/cm-10% Fly ash-30% Paste	15.5	<0.40	Uncertain
0.45 w/cm-10% Fly Ash-30% Paste	12.2	0.40	No
0.50 w/cm-10% Fly ash-30% Paste	9.0	>0.50	Uncertain
0.45 w/cm-20% Fly Ash-AEA-29% Paste	10.7	0.45-0.50	Uncertain
0.40 w/cm-20% Fly Ash-30% Paste	15.6	>0.40	Uncertain
0.45 w/cm-20% Fly Ash-30% Paste	13.2	0.40	No
0.50 w/cm-20% Fly Ash-30% Paste	10.3	0.50	Yes

AEA = Air entraining agent

9.4 Conclusions and Recommendations

The preliminary results of this study offer insight on a new application for surface resistivity testing. The time-resistivity behavior of a given concrete mixture under controlled laboratory conditions seems to be repeatable. And, slight variations in mixture design parameters such as w/cm and class-C fly ash content seem to significantly influence this behavior. Based on these two criteria, it was possible to establish surface resistivity categories one could use to identify with a 95% confidence level whether a mixture contains a class-C fly ash or not and its range in w/cm (0.40, 0.45, 0.50 w/cm).

A small laboratory trial was conducted to determine whether the tool was successful. A total of 15 mixture designs varying in w/cm, %FA, paste content, air entrainer addition were evaluated. With success above 67% at a confidence of 95%, the tool was deemed successful, and further trial testing is underway in order to refine the tool and incorporate an array of materials commonly used in the construction industry.

The developed indetification criteria may provide a simple approach to a user to authenticate the quality/compliance of concrete according to the approved mixture design. In turn, it can help in minimizing potential durability issues, which may arise from increased w/cm of concrete mixtures at the job site or lack of desirable cementitious materials. Overall, improvement of quality control measures at the time of construction is of the essence for improvement of the service life of concrete structures.

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CHAPTER 10

NEW METHOD FOR QUALITY CONTROL AND COMPLIANCE OF CONCRETE MIXTURE DESIGN BY USING SURFACE RESISTIVITY TESTING

Preface

This study evaluates the efficacy of statistical criteria developed for quality and compliance of concrete to determine the fly ash content and w/cm in a concrete mixture. The experimental work is based on surface resistivity testing of cylindrical samples prepared with different sources of fly ash and aggregates completed by the author and undergrad team members at Bert Cooper Engineering Laboratory under the supervision of Dr. Julie Ann Hartell. The statistical criteria are verified with a new set of resistivity data. The chapter is accepted at TRB for presentation and published on their website.

It is important to note that the proposed statistical criteria for quality control and compliance of concrete mixtures is in first phase of development. There are some limitations defined for the criteria in order to obtain the precise results. The concrete samples to be used testing should be cylindrical (Ø100 mm x 200 mm) in shape. The statistical criteria is applicable to 0.40, 0.45 and 0.50 w/cm, 0% to 20% Class-C fly ash content, type-I cement or comparable to specifications mentioned in Table 10.1, crushed limestone aggregates, the paste fraction between 27% to 30% with no addition of chemical admixtures. The saturated limewater curing method is recommended. The concrete samples must be tested in controlled environment of 23 °C ambient temperature and 50% relative humidity.

Abstract

This study proposes a new quality control and compliance method for concrete mixture design using surface resistivity testing. This method helps in determining key mixture parameters such as fly ash content and w/cm of placed concrete. Based on the gain in resistivity over time, it was found that the slope of the surface resistivity versus time curve could be used to differentiate fly ash content after only 3 days of standard immersion curing. And, the resistivity value obtained at a sample age of 14 and 28 days could be used for identifying the water-to-cementitious material ratio of a concrete mixture containing no fly ash and containing up to 20% fly ash. Here, ANOVA and Tukey's test statistical methods were utilized to develop the criteria with a 95% confidence intervals. The method was trialed against fifteen mixture designs of varying fly ash content, w/cm and material sources. The statistical criteria offer a new tool which enables the quality control of placed concrete with respect to the approved mixture design. The method could aid in improving durability problems, diminish repair cost and increase the service life of concrete structures.

Keywords: Quality Control, Compliance, Surface Resistivity, Fly Ash, ANOVA, Tukey's Test

10.1 Introduction

Several properties of fresh and hardened concrete are routinely tested to verify the quality of the construction material with respect to its approved mixture design. Air content, slump and compressive strength may be indicative of certain mixture ingredients; however, there is still a level of uncertainty when it comes to the water-to-cement ratio (w/c) or the presence of beneficial supplementary cementitious materials. Both these parameters are often necessary to attain a required level of durability in accordance with an exposure type (e.g. exposure to sulfate ions, deicing salts or seawater) even if the minimal mechanical properties have been met. Thus far, there is no simple utilitarian test method, which can assess such parameters within a routine quality control and acceptance plan.

Due to its sensitivity to the chemical and physical characteristics of a cementitious material, nondestructive electrical methods such as surface resistivity and bulk resistivity are gaining popularity in the cement and concrete industry. Previous studies demonstrated the existence of a correlation between the conventional method for durability assessment of concrete mixtures, the rapid chloride permeability test (RCPT), and electrical conductivity testing. The latter method was deemed accurate and reliable for determining the corrosion performance of a concrete mixture depending on its performance in resisting ionic flow (*1*-*3*). One can use a simple classification table, derived from the RCPT standard method of testing (ASTM C1202), to estimate the chloride ion penetration level based on the result of a surface resistivity test. (*1*) These studies led to the development of AASHTO TP 95: *Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration* (*4*) and AASHTO TP 119: *Standard Method of Test for Electrical Resistivity of a Concrete Cylinder Tested in a Uniaxial Resistance Test* (*5*). Moreover, resistivity testing has been found to be less expensive to perform in comparison to RCPT; therefore, providing motivation for implementation of the method in routine control activities.

Furthermore, previous studies have demonstrated that the w/cm, various supplementary cementitious materials and their combinations used in the concrete mixtures have their own rate of surface resistivity development. It could help to access the permeability of concrete and to produce a mixture with high surface resistivity and best chloride penetration resistance (*1*,*6*). On the other hand, Medeiros-Junior concluded that different types of cement do have a significant effect on resistivity data, whereas there is no significant difference found in resistivity measurements for different water-to-binder ratios with one type of cement based on the use of ANOVA and Tukey's test to determine the sensitivity of resistivity testing with respect to material variations (*7*).

On that note, researchers have used ANOVA in the field of concrete materials to fulfill different goals such as: optimizing mixture parameters and concrete cover thickness (*8*); analyzing the effects of cracks, freeze-thaw cycles, and carbonation on rebar corrosion (*9*); investigating the effects of leaching and curing time on porosity, water absorption, bulk density, and strength of fly ash-lime mixtures (*10*). Likewise, in this preliminary study, the analysis of variance (ANOVA) and Tukey's tests are used to trial the hypotheses for comparing the percentages of cement replacement with fly ash and water-to-cementitious material ratio of concrete mixtures.

The purpose of this study is to investigate the potential of resistivity testing in assessing key mixture design parameters critical for durability performance of concrete mixtures. The objective is to establish a method based on resistivity criteria to identify the water-to-cement ratio of a given mixture whether the mixture contains a class-C fly ash as a supplementary cementitious material. This will aid in the development of a new quality control and compliance criteria for concrete mixture approval and compliance in addition to currently used test methods and specifications. This would allow infrastructure owners and stakeholders to produce high quality and durable concrete.

10.2 Experimental Method

To accomplish stated objectives, an experimental method was devised to first determine the mixture design acceptance criteria based on a standard mixture design; and, second, to validate the efficacy of the establish criteria to identify two basic mixture design parameters: w/cm and fly ash content while varying the material source. The materials used, and experimental procedures followed are detailed in the following sections.

10.2.1 Materials

A total of twenty-four concrete mixtures of varying water-to-cement ratios (0.40, 0.45 and 0.50) and varying percentages of fly ash (0%, 10%, and 20%) were prepared for this study. All materials were batched and mixed in a temperature-controlled environment and samples were cast respecting standard methods of preparing concrete samples in a laboratory environment (ASTM C 192) (*11*). In order to carry out the testing regimen, six-cylinder replicates (Ø100 mm x 200 mm) per concrete batch were prepared and demolded after 24 hours.

The first nine concrete mixtures, to develop the quality control criteria based on statistical analysis, were prepared with a #56 crushed Limestone aggregates, a natural sand for the fine aggregate proportion along with a type-I cement and Class-C fly ash (Source A). For the validation mixtures, a total of 15 mixtures were prepared with alternate material sources: two Class-C fly ash named Sources B and C, and a crushed dolomite aggregate was also evaluated. For all the concrete mixtures prepared for validation purpose, the same type-I Portland cement and natural sand was used. All materials used in this study were sourced and manufactured in the state of Oklahoma. The paste volume of all the mixtures ranges from 27% to 30%. The chemical compositions of the Portland cement, aggregates and fly ash (Source A, B & C) are given in Table 10.1. No chemical admixture was added to the mixtures. All the concrete mixtures are summarized in Table 10.2.

Table 10.1 Chemical Properties of Coarse Aggregate, Portland Cement and Fly Ash Sources A, B and C

Chemicals	(%) Limestone #56	(%) Dolomite Stone #56	(%) Granite Gabbro #57	Cement (Type-I)	Fly Ash (Source-A)	Fly Ash (Source-B)	Fly Ash (Source-C)
Ca	35.93	20.67	7.24	-	-	-	-
CaO	50.27	28.92	10.13	62.9	23.12	29.74	24.41
$CaCO_3$	89.73	51.62	18.08	-	-	-	-
Mg	1.02	9.74	1.07	-	-	-	-
MgO	1.69	16.15	1.77	1.9	5.55	7.46	5.87
$MgCO_3$	3.54	33.77	3.71	-	-	-	-
Fe_2O_3	0.25	0.85	4.07	3.4	5.88	5.58	6.28
Al_2O_3	0.6	2.08	16.91	5.1	18.82	18.37	19.17
Si	3.38	4.03	24.3	-	-	-	-
SiO_2	7.24	8.63	51.99	19.4	38.71	32.88	36.27
K_2O	-	-	-	-	0.58	0.41	0.46
SO_3	-	-	-	3.3	1.27	1.89	1.07
Na_2O_3	-	-	-	-	-	-	-
Sodium Oxide	-	-	0.422		-	-	-
Tutanium Dioxide	-	-	0.16	-	-	-	-
Potassium Oxide	-	-	0.316	-	-	-	-

Table 10.2 Summary of Concrete Mixtures

Mixture	w/cm	Cement	Fly Ash	Coarse Aggregate	Fine Aggregate
1	0.40	Type-I	0% Source-A	Limestone (#56)	Natural Sand
2	0.40	Type-I	10% Source-A	Limestone (#56)	Natural Sand
3	0.40	Type-I	20% Source-A	Limestone (#56)	Natural Sand
4	0.45	Type-I	0% Source-A	Limestone (#56)	Natural Sand
5	0.45	Type-I	10% Source-A	Limestone (#56)	Natural Sand

6	0.45	Type-I	20% Source-A	Limestone (#56)	Natural Sand
7	0.50	Type-I	0% Source-A	Limestone (#56)	Natural Sand
8	0.50	Type-I	10% Source-A	Limestone (#56)	Natural Sand
9	0.50	Type-I	20% Source-A	Limestone (#56)	Natural Sand
10	0.45	Type-I	0% Source-B	Limestone (#56)	Natural Sand
11	0.45	Type-I	10% Source-B	Limestone (#56)	Natural Sand
12	0.50	Type-I	0% Source-B	Limestone (#56)	Natural Sand
13	0.50	Type-I	20% Source-B	Limestone (#56)	Natural Sand
14	0.40	Type-I	10% Source-C	Limestone (#56)	Natural Sand
15	0.40	Type-I	20% Source-C	Limestone (#56)	Natural Sand
16	0.45	Type-I	10% Source-C	Limestone (#56)	Natural Sand
17	0.45	Type-I	20% Source-C	Limestone (#56)	Natural Sand
18	0.50	Type-I	10% Source-C	Limestone (#56)	Natural Sand
19	0.40	Type-I	10% Source-A	Dolomite (#56)	Natural Sand
20	0.40	Type-I	20% Source-A	Dolomite (#56)	Natural Sand
21	0.45	Type-I	10% Source-A	Dolomite (#56)	Natural Sand
22	0.45	Type-I	20% Source-A	Dolomite (#56)	Natural Sand
23	0.50	Type-I	10% Source-A	Dolomite (#56)	Natural Sand
24	0.50	Type-I	20% Source-A	Dolomite (#56)	Natural Sand

10.2.2 Testing Procedure

Surface resistivity testing was performed on all cylinder sample in accordance with the AASHTO TP 95 standard procedure (*4*). The same resistivity meter with a fixed probe spacing of 38 mm was used to take the surface resistivity measurements (Figure 10.1). After demolding the samples, each cylinder was marked at four different points equally distant at 90° of the transverse axis to ensure repetition of the resistivity measurements at the same location for the duration of the test period. Then, prior to commencing curing, resistivity measurements were taken on day-1 (after cylinder demolding). Thereafter, the cylinders were placed in a temperature-controlled limewater tank and allowed to cure for 28 days. During this time, resistivity measurements were recorded on days 3, 7, 14, 21 and 28. The results of surface resistivity testing reported in the following section represent the average value of six-cylinder replicates. Prior to taking the measurement, the samples were lightly sprayed with tap water and patted with paper towel to remove any salt accumulation and limewater on the test surface of the cylinder while ensuring a saturated and moist test surface. The ambient temperature and humidity of the test environment were also kept within standard limits of 23±°C and 50% relative humidity to minimize the variability in the measurements.

The apparent resistivity value can be determined from Equation 10.1. The apparent resistivity value obtained can be factorized by applying a factor to compensate for specimen geometry, based on a ratio of cross-sectional area to length of the specimen (*12*). The values presented herein are not factorized; therefore, they correspond to the apparent resistivity of a Ø100 mm x 200 mm-cylindrical sample.

$$\rho = \frac{2\pi sV}{I} \qquad (10.1)$$

Where,

ρ: apparent resistivity (ohm-cm)

s: spacing between probes (cm)

V: measured voltage (volts)

I: amplitude of alternating current (amps)

Fig. 10.1 Illustration of surface resistivity

10.3 Results and Discussions

10.3.1 Development of Quality Control Criteria

The surface resistivity test results for the first nine concrete mixtures are presented Table 10.3. The calculated mean, standard deviation and coefficient of variation of each mixture design are based on the recorded measurement for six sample replicates following the experimental procedure described in the previous section. The coefficients of variation obtained throughout the testing regime were under 10%, which was found to be satisfactory according to the standard method of testing.

The analysis of variations ANOVA is a statistical method in which the variation in a set of observations is divided into distinct components or groups. In this study, the hypothesis testing is performed to compare percentages of cement content replacement with fly ash (0%, 10% and 20%) and to compare respective w/cm combinations (0.4, 0.45 and 0.5). Thus, the concrete mixtures prepared with ratios 0.40, 0.45 and 0.50 are categorized into three groups (levels) with respect to their fly ash contents, 0%, 10%, and 20%. The resistivity data collected up to 28 days was analyzed to determine whether there is a significant difference among the three levels.

Table 10.3 Surface Resistivity Results for Concrete Mixtures 1 to 9

Mixture-1 (0.40 w/cm - 0% Fly Ash)						
Day	1	3	7	14	21	28
Mean Resistivity (KΩ-cm)	5.3	7	9.2	11	11.7	12.4
Std. Deviation	0.2	0.4	0.3	0.6	0.5	0.5
COV (%)	4.5	5.5	3.7	5.1	4.7	3.8
Mixture-2 (0.40 w/cm - 10% Fly Ash)						
Day	1	3	7	14	21	28
Mean Resistivity (KΩ-cm)	4.6	7.1	10	12	13	13.4
Std. Deviation	0.5	0.5	0.8	0.9	0.8	0.7
COV	11.2	6.5	7.6	7.6	6.4	5.2
Mixture-3 (0.40 w/cm - 20% Fly Ash)						
Day	1	3	7	14	21	28
Mean Resistivity (KΩ-cm)	4.3	6.6	8.5	10.7	11.6	12.6
Std. Deviation	0.3	0.3	0.7	0.5	0.7	0.8
COV	7.9	5.2	8.6	4.9	6.2	6.1
Mixture-4 (0.45 w/cm - 0% Fly Ash)						
Day	1	3	7	14	21	28
Mean Resistivity (KΩ-cm)	5.7	6.6	8.8	10.2	10.9	11.5
Std. Deviation	0.7	0.4	0.5	0.6	0.7	0.7
COV	11.8	6.7	5.6	6	6.3	6.4
Mixture-5 (0.45 w/cm - 10% Fly Ash)						
Day	1	3	7	14	21	28
Mean Resistivity (KΩ-cm)	4.8	6.8	9.1	10.4	11.2	11.9
Std. Deviation	0.6	0.4	0.4	0.5	0.7	0.7
COV	13.2	5.9	4.8	4.9	6.2	5.8
Mixture-6 (0.45 w/cm - 20% Fly Ash)						
Day	1	3	7	14	21	28
Mean Resistivity (KΩ-cm)	3.8	6.2	8.4	9.3	10.3	11.2
Std. Deviation	0.4	0.5	0.7	0.8	0.8	0.9
COV	10.6	8.1	7.8	8.4	7.7	8

Mixture-7 (0.50 w/cm - 0% Fly Ash)						
Day	1	3	7	14	21	28
Mean Resistivity (KΩ-cm)	5	5.9	7.5	8.9	9.6	10.2
Std. Deviation	0.3	0.2	0.3	0.3	0.3	0.4
COV	6.9	3	3.6	3.9	3.2	3.9
Mixture-8 (0.50 w/cm - 10% Fly Ash)						
Day	1	3	7	14	21	28
Mean Resistivity (KΩ-cm)	3	5.2	7.2	7.9	8.4	9
Std. Deviation	0.2	0.1	0.2	0.3	0.2	0.2
COV	5.5	2.9	3.1	3.2	2.7	2.8
Mixture-9 (0.50 w/cm - 20% Fly Ash)						
Day	1	3	7	14	21	28
Mean Resistivity (KΩ-cm)	3.4	5.6	7.7	8.7	9.5	10.3
Std. Deviation	0.6	0.3	0.3	0.5	0.5	0.7
COV	16.8	5.8	4.5	6.2	5.7	6.5

Based on the gain in resistivity over time, it was found that the slope of the surface resistivity versus time curve could be used to differentiate certain mixture parameters such as fly ash content along with the resistivity value obtained at a given sample age for identifying the water-to-cementitious material ratio. The possible slope combinations established for analysis were derived from the resistivity values obtained on days 1-3, 3-7, 7-14, 7-21, 7-28, 14-21, 14-28 and 21-28. The slopes between the two averaged resistivity values for each mixture were determined using Equation 10.2 where (y) is the resistivity value at a corresponding age (x). All the slope combinations were analyzed to determine which combination has a significant difference of mean resistivity value based on percentage of fly ash replacement.

$$s = \frac{y_2 - y_1}{x_2 - x_1} \tag{10.2}$$

The ANOVA analysis was performed on the initial nine concrete mixtures having 0.40, 0.45 and 0.50 w/cm and 0%, 10% and 20% fly ash content. This analysis can only be applied if the assumptions of ANOVA were fulfilled for the surface resistivity data set generated. The first assumption of independent observations was satisfied by selecting the independent resistivity data for analysis of one day throughout the testing period from day-1 to day-28. For the second assumption, the difference between real values and determined values was observed if the residuals are normally distributed. The resistivity data satisfied the second assumption that residuals were normally distributed. By using Levene's test, it was determined that out of all the groups, some groups have equal variances and some have unequal variances, which fulfilled the third assumption.

Table 10.4 95% Confidence Intervals for (1-3) Day Slope Combination

Fly Ash Content Category	Gain in Surface Resistivity per Day (KΩ-cm/day)		
	Mean	Lower Limit	Upper Limit
No Fly Ash	0.5	0.4	0.6
Fly Ash	1.1	0.9	1.2

First, different slope combinations were analyzed between days (1-3), (3-7), (7-14), (7-21), (7-28), (14-21), (14-28) and (21-28). The significant difference in fly ash content (0%, 10%, and 20%) was determined through ANOVA test and Tukey's test. The Levene's test was performed to analyze if the hypothesis was accepted or rejected. For slopes (1-3), (3-7), (7-14) and (7-21), the results showed equal variances, the hypothesis was accepted. Whereas, for slopes (7-28), (14-21), (14-28) and (21-28), the results showed unequal variances and hypothesis was rejected. The F-test was performed on slope combinations having equal variances and the Welch's test was applied on slope combinations having unequal variances. With a 95% confidence level, slope combinations (1-3), (3-7), (14-21), (14-28) and (21-28) rejected the hypothesis, which means there was a significant difference between the percentages of fly ash (levels) found for these slope combinations. Then, Tukey's test was applied to these slope combinations. It was found that slope (1-3) is the only combination that could differentiate between a concrete mixture containing 0% fly ash (No Fly Ash) and containing 10% or 20% fly ash content (Fly Ash). For slope combination (1-3), 95% confidence limits were determined which means that the interval contains the population means with 95% confidence. The resulting 95% confidence intervals are shown in Table 4 showing lower and upper limits for “No Fly Ash” and “Fly Ash” content mixtures. Thus, based on the results of a surface resistivity test conducted on both day-1 (after demolding) and day-3, the calculated slope between the two data points could indicate the presence of a class-C fly ash in the mixture.

In the case where the value would fall outside the proposed range, there could be three possible outcomes based on the results presented in Table 10.4. First, the slope value falls below the lower limit of the No Fly Ash range, that mixture could be considered as a No Fly Ash mixture. Second, the slope value is higher than the upper limit of the Fly Ash range. That mixture could be interpreted as a mixture containing Fly Ash. However, for both cases, other mixture or procedural parameters could have influenced the results. The last possibility is that the slope value falls between the upper limit of No Fly Ash (0.630) and the lower limit of Fly Ash (0.895); therefore, there is no certainty that the concrete mixture contains fly ash or does not contain fly ash. In this case, the 28-day resistivity value could be useful to validate the presence of the material. This will be further discussed below.

Second, the same statistical methodology was performed to compare the resistivity values recorded for mixtures of different water-to-cementitious material ratios. It was determined at a 95% percent confidence level that the values were distinct for the three water-to-cement ratios mixtures. For the 0% fly ash content mixture (i.e.“No fly ash”) the w/cm (0.40, 0.45 and 0.50) could be differentiated with a 95% confidence intervals for test days 14 and 28. This means that if the result of a surface resistivity test falls within the confidence limits, with 95% confidence, the representative w/cm of the concrete mixture could be identified. For concrete mixtures containing fly ash as a supplementary cementitious material, it was possible to identify the w/cm with a 95% confidence interval at test days 14 and 28 as well. However, calculated confidence intervals for w/cm 0.45, 0.50 slightly overlapped with each other. For day-14 values between 8.9 KΩ-cm and 9.1 KΩ-cm and day-28 values between10.6 KΩ-cm and10.8 KΩ-cm, the method may not be able to differentiate 0.45 from 0.50 w/cm. The mean resistivity values falling below the lower limit of 0.40 w/cm would be considered as a 0.40 or lower w/cm concrete mixture. Similarly, the mean resistivity values falling above the upper limit of 0.50 w/cm would be considered as a 0.50 or higher w/cm concrete mixture. The 95% confidence intervals for No fly ash and Fly ash concrete for 0.40, 0.45 and 0.50 w/cm are shown in Table 10.5.

Table 10.5 Surface Resistivity Value Limits for No Fly Ash and Fly Ash Concrete Mixtures

95% Confidence Intervals for "No Fly Ash" Concrete

	Surface Resistivity (KΩ-cm)					
	Day-14			Day-28		
w/cm	Mean	Lower Limit	Upper Limit	Mean	Lower Limit	Upper Limit
0.4	11.1	10.6	11.5	12.4	11.9	12.8
0.45	10.2	9.7	10.6	11.5	11	12
0.5	8.9	8.5	9.4	10.2	9.7	10.6

95% Confidence Intervals for"Fly Ash" Concrete

	Surface Resistivity (KΩ-cm)					
	Day-14			Day-28		
w/cm	Mean	Lower Limit	Upper Limit	Mean	Lower Limit	Upper Limit
0.4	10.7	10.2	11.1	12.6	12	13.2
0.45	9.3	8.9	9.8	11.2	10.6	11.7
0.5	8.7	8.2	9.1	10.3	9.7	10.8

Therefore, the proposed method for determining the mixture design parameters would follow the steps described in the flowchart presented in Figure 10.2.

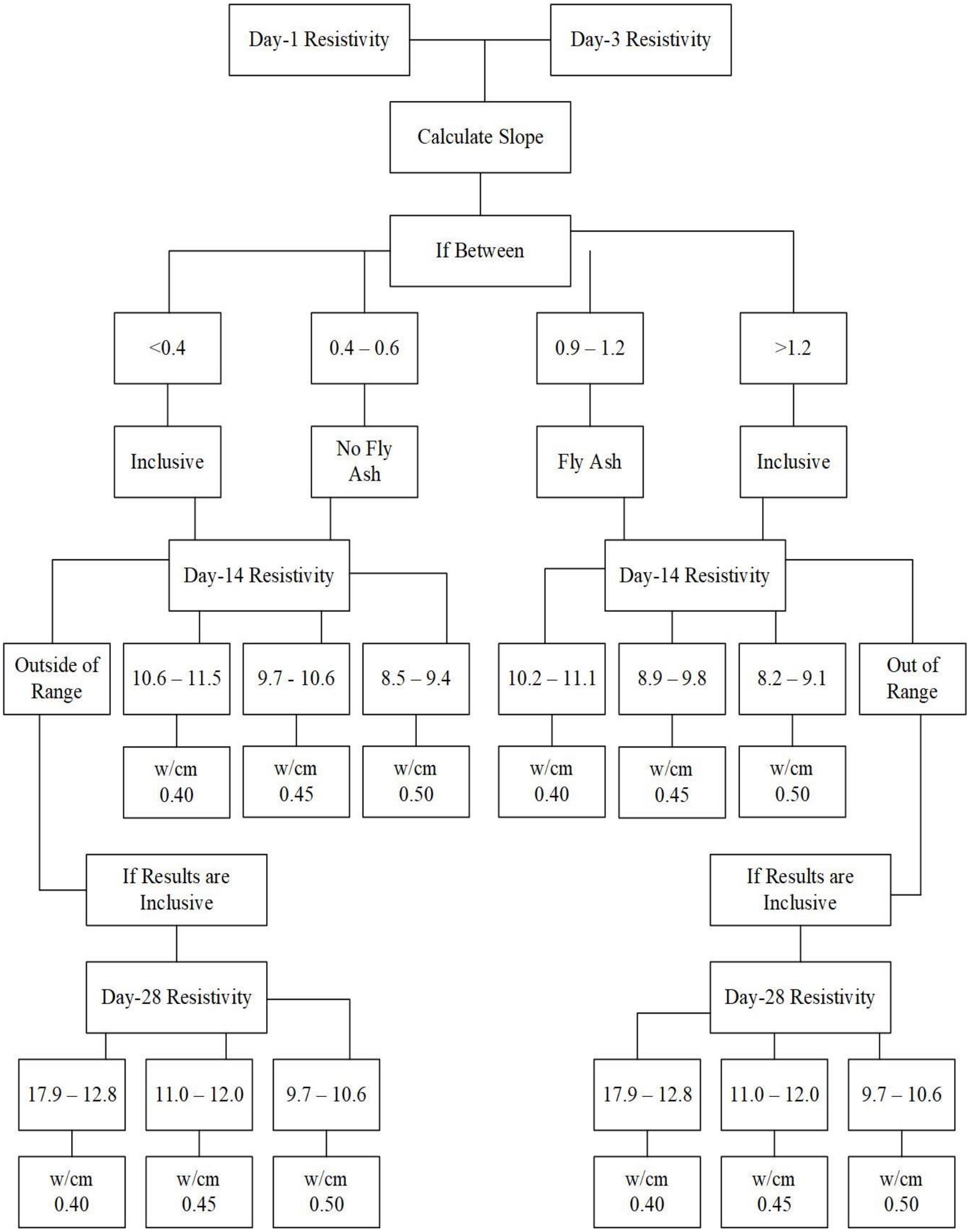

Fig. 10.2 Flowchart of resistivity method for quality control of mixture design parameters

10.3.2 Validation of Mixture Design Control Criteria

To validate the feasibility of the method presented in Figure 10.2, 15 additional concrete mixtures were prepared following the same mixture design proportions; however, other material sources were used to evaluate whether material variability could significantly alter the hypothesis outcome. Two different sources of Class-C fly ash (B and C) and a different aggregate type (dolomitic rock) where used. Surface resistivity measurements were taken on days 1, 3, 14 and 28 days. The average surface resistivity results for six-cylinder replicates are presented in Tables 10.6, 10.7 and 10.8.

Following step one in the flowchart, for each concrete mixture evaluated, the slopes between day-1 and day-3 where calculated using Equation 10.2 (shown in Table 10.6). These slopes were compared to the ranges listed in Table 10.4 to validate whether the criteria can successfully determine the presence of fly ash in the concrete mixture.

Table 10.6 Validation of Fly Ash Content in Concrete Mixtures

Mixture Description	Surface Resistivity (KΩ-cm)		Day 1-3 Slope (KΩ-cm/day)	Validated
	Day 1	Day 3		
10 (0.45 w/cm - 0% Fly Ash)	6.1	7.7	0.78	Unknown
11 (0.45 w/cm - 10% Fly Ash)	5	7.3	1.15	Yes
12 (0.50 w/cm - 0% Fly Ash)	5.1	5.2	0.03	Yes
13 (0.50 w/cm - 20% Fly Ash)	4.7	6.1	0.7	Unknown
14 (0.40 w/cm - 10% Fly Ash)	7.5	9.1	0.82	Unknown
15 (0.40 w/cm - 20% Fly Ash)	5.9	7.7	0.91	Yes
16 (0.45 w/cm - 10% Fly Ash)	5.8	7.1	0.66	Unknown
17 (0.45 w/cm - 20% Fly Ash)	4.4	5.7	0.67	Unknown
18 (0.50 w/cm - 10% Fly Ash)	5.2	6.8	0.78	Unknown
19 (0.40 w/cm - 10% Fly Ash)	4.4	7	1.3	Yes
20 (0.40 w/cm - 20% Fly Ash)	3.2	5.9	1.33	Yes
21 (0.45 w/cm - 10% Fly Ash)	3.7	6.4	1.37	Yes
22 (0.45 w/cm - 20% Fly Ash)	2.2	5	1.42	Yes
23 (0.50 w/cm - 10% Fly Ash)	3	6	1.51	Yes
24 (0.50 w/cm - 20% Fly Ash)	2.7	5.1	1.2	Yes

Out of fifteen mixtures, ten concrete mixtures were correctly identified with respect to Fly Ash content or No Fly Ash. There were five mixtures for which the slope value fell between the upper limit of "No Fly Ash" (0.6 KΩ-cm/day) and lower limit of "Fly Ash" (0.9 KΩ-cm/day). These are identified as "unknown" mixtures in Table 10.6, which means that it was not sure they have fly ash content in them or not. The validation of this statistical approach to determine fly ash content gave an accuracy of 67%, which is low not because the fly ash content was wrongly identified but due to the average values that fall between gaps of upper and lower 95% confidence limits. Further analysis is required to review other procedural or material parameters which may have contributed to outliers' condition. Also, the boundary accuracy could be increase, thus closing the gap, by increasing the confidence limits to 99%. The latter would also help for increasing the upper boundary limit of the Fly Ash class to incorporate mixtures prepared with a dolomitic aggregate. It is noticed that the slope results are, on average, 13% greater for these mixtures.

After the validation of identification of fly ash content criteria, the following step on the flowchart is determination of w/cm. To accomplish such, the day-14 and day-28 mean resistivity values recorded for each mixture were used to determine the potential w/cm. Starting with "No Fly Ash" content and "Unknown" status, Table 10.7 presents the estimated w/cm for days 14 and 28 (based on flowchart ranges) and whether the criteria was effective in validating the design w/cm (Yes, No and Unknown).

Table 10.7 Validation of w/cm with No Fly Ash Content Concrete

Validation of w/cm Ratio with No Fly Ash Content			
Mixture Description	Mean Resistivity	Determined w/cm	Validated
Day-14			
Mixture-10 (0.45 w/cm - unknown)	10.3	0.45	Yes
Mixture-12 (0.50 w/cm - 0% Fly Ash)	9.2	0.5	Yes
Mixture-13 (0.50 w/cm - unknown)	8.7	0.5	Yes
Mixture-16 (0.45 w/cm - unknown)	9.6	0.45/0.5	Unknown
Mixture-17 (0.45 w/cm - unknown)	8.3	0.5	No
Mixture-18 (0.50 w/cm - unknown)	8.8	0.5	Yes
Day-28			
Mixture-10 (0.45 w/cm - unknown)	11.6	0.45	Yes
Mixture-12 (0.50 w/cm - 0% Fly Ash)	9.6	0.5	Yes
Mixture-13 (0.50 w/cm - unknown)	10.6	0.5	Yes
Mixture-16 (0.45 w/cm - unknown)	11.2	0.45	Yes
Mixture-17 (0.45 w/cm - unknown)	11.3	0.45	Yes
Mixture-18 (0.50 w/cm - unknown)	10	0.5	Yes

At day-14, all w/cm mixture designs were correctly identified except for mixtures 17 and 16, the actual w/cm was 0.45 but statistically, they were identified as potentially 0.50 w/cm or greater. So, as indicated in the flowchart, day-28 criteria was verified to validate the w/cm for mixtures 16 and 17, for which the design w/cm was correctly identified. Furthermore, all the recorded resistivity values led to correctly identifying the design w/cm for the concrete mixtures classified as No Fly Ash or Unknown. At day-14, the success rate of identifying the correct w/cm was 67% for six concrete mixtures; whereas, the success rate at day-28, was 100%.

Next, the resistivity results for concrete mixtures classified as “Fly Ash” (containing fly ash) as well as “Unknown” status in Table 10.6 were compared against w/cm criteria developed (Table 10.5). Table 10.8 shows the results of the comparative analysis.

At day-14, out of fourteen concrete mixtures, the design w/cm for eight mixtures were identified correctly and five concrete mixtures were not based on the established range. Mixture 11 identified as 0.45 w/cm or 0.50 w/cm due to the overlapping of confidence limits. The success rate for identifying w/cm at day-14 was 57%. Here the influence of latent hydration of fly ash along with the difference in the percentage of fly ash, calcium and glass content may contribute to the variable results. Therefore, day-14 may be premature for identify w/cm of concrete mixtures containing fly ash. Pursuing the analysis at day-28, the success rate was greater (93%). The design w/cm for thirteen concrete mixtures, out of fourteen, were correctly identified.

Table 10.8 Validation of w/cm with Fly Ash Content Concrete

Validation of w/cm Ratio with Fly Ash Content			
Mixture Description	Mean Resistivity	Determined w/cm	Validated
	Day-14		
10 (0.45 w/cm - unknown)	10.3	0.4	No
11 (0.45 w/cm - Fly Ash)	10	0.40/0.45	Unknown
13 (0.50 w/cm - unknown)	8.7	0.5	Yes
14 (0.40 w/cm - Fly Ash)	12.2	0.4	Yes
15 (0.40 w/cm - Fly Ash)	10.9	0.4	Yes
16 (0.45 w/cm - unknown)	9.6	0.45	Yes
17 (0.45 w/cm - unknown)	8.3	0.5	No
18 (0.50 w/cm - unknown)	8.8	0.5	Yes
19 (0.40 w/cm - Fly Ash)	10.5	0.4	Yes
20 (0.40 w/cm - Fly Ash)	9.1	0.45	No
21 (0.45 w/cm - Fly Ash)	8.8	0.5	No
22 (0.45 w/cm - Fly Ash)	7.7	0.5	No
23 (0.50 w/cm - Fly Ash)	8.6	0.5	Yes
24 (0.50 w/cm - Fly Ash)	7.2	0.5	Yes
	Day-28		
10 (0.45 w/cm - unknown)	11.6	0.45	Yes
11 (0.45 w/cm - Fly Ash)	11.5	0.45	Yes
13 (0.50 w/cm - unknown)	10.6	0.45/0.50	Yes
14 (0.40 w/cm - Fly Ash)	14.2	0.4	Yes
15 (0.40 w/cm - Fly Ash)	13.7	0.4	Yes
16 (0.45 w/cm - unknown)	11.2	0.45	Yes
17 (0.45 w/cm - unknown)	11.3	0.45	Yes
18 (0.50 w/cm - unknown)	10	0.5	Yes
19 (0.40 w/cm - Fly Ash)	12.9	0.4	Yes
20 (0.40 w/cm - Fly Ash)	13.2	0.4	Yes
21 (0.45 w/cm - Fly Ash)	10.6	0.45	Yes
22 (0.45 w/cm - Fly Ash)	10.1	0.5	No
23 (0.50 w/cm - Fly Ash)	10.3	0.5	Yes
24 (0.50 w/cm - Fly Ash)	9.7	0.5	Yes

It needs to be mentioned, that the material sample size for this study is limited. The criteria were develop for a given set of materials and the validation investigated the influence of only two alternative sources of fly ash and one aggregate type available in Oklahoma. It is well known that ionic conductivity is sensitive to slight changes in medium chemistry. Still, positive success rate of the proposed approach, may offer insight on how these changes in chemistry can be beneficially utilized for controlling critical mixture design parameters such as w/cm; thus, further advancing the potential and applications of surface resistivity testing of concrete. The introduction of statistical criteria for quality control and compliance of concrete mixture may be beneficial to strengthen the accountability for the quality of concrete mixture constructed.

10.4 Conclusions and Recommendations

The ANOVA and Tukey's test was successful to establish categories for determining the presence of Class-C fly ash in a concrete mixture based on the gain in resistivity between the ages day-1 and day-3. Furthermore, the statistical method permitted identification of the design w/cm (0.40, 0.45 or 0.50) for concrete mixtures as early as age of day-14; however the accuracy was improved if the validation was performed at day-28. This enabled the development of a flowchart for use as a mixture design quality control tool. The method was trialed for fifteen mixtures of varying mixture design and material source. The method successfully validated 67% percent of mixtures for fly ash content. The validation of concrete mixtures to identify w/cm at day-28 was 100% and 93% accurate and for "No fly ash" and "Fly ash" concrete mixtures respectively.

Finally, these statistical criteria may offer a simple tool to verify the quality of a placed concrete for compliance with the accepted mixture design. Furthermore, it could help control durability problems, repair cost, and increase the service life of concrete structures. However, further investigation is required to validate the statistical criteria against multiple material sources and field trial testing prior to use and implementation. The results presented herein serve as a guiding platform, which may be expanded to incorporate other cementitious materials such as silica fume, blast furnace slag for example.

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CHAPTER 11

CONCLUSIONS AND RECOMMENDATIONS

During construction, the quality control tests are performed in the fresh state and on hardened concrete to determine the quality of concrete mixture and compliance with mixture design. Generally, slump test, unit weight test, and air pressure test are performed on fresh concrete and compression or flexure test is conducted on hardened concrete. These tests do provide information about consistency, workability and air content in the fresh concrete mixture, and strength of the hardened concrete. Even the concrete that has passed the recommended quality control tests, still in some cases the concrete experience the durability issues, for example, cracking, spalling, surface scaling and corrosion during service life. The research presented in this dissertation develops a novel quality control criterion to verify the key concrete mixture parameters, w/cm and fly ash content (class-C), which would help to minimize the durability issues, repair and rehabilitation cost, and an increase in service life of the concrete structure.

The conclusions of the dissertation are highlighted as follows:

11.1 The Effect of Aggregate Type and Size on Surface Resistivity Testing

- Preliminary findings demonstrate a potential marginal difference to no difference between the mixtures prepared with limestone, dolomite and granite aggregate and ordinary Portland cement binder.
- The trends were similar for the development in resistivity over time. However, this was not the case for the same mixture designs with 20% cement replacement with a class-C fly ash. The resistivity behavior in time for the samples changed in comparison to that of the samples containing no fly ash and varied by aggregate type. In this case, the aggregate type may influence the outcome of a test leading to differences in result interpretation in accordance with AASHTO TP95.
- As for the size and gradation of aggregates, small changes in aggregate gradation may not influence the outcome of a resistivity test for a given mortar matrix. However, the sample types studied herein are limited and conclusions are based on materials investigated only. As information is limited on the observed phenomena, further investigation is required to better understand the impact of aggregates on concrete resistivity properties.

11.2 Effect of Water-reducer and Air-entrainer on Surface Resistivity Testing

- The addition of WR and AE in a concrete mixture is a common practice to attain the desired properties of concrete. It was concluded from the study that the addition of WR and AE in a concrete mixture having no fly ash content does not significantly affect the resistivity measurements. Whereas, in the presence of fly ash content, adding WR and AE could be the reason for lower resistivity values. However, these conclusions are based on preliminary results and further investigations are recommended in this research area.

11.3 Effect of Curing Condition and Temperature on Surface Resistivity Measurements

- The effects of curing condition and temperature at the time of test demonstrate the temperature sensitivity of surface resistivity method.
- This study did not corroborate the application of a factor (1.1) to increase the apparent resistivity of a sample cured in limewater tank in order to match the apparent resistivity of a sample cured in a moist room.
- The temperature fluctuations within ASTM range during limewater tank curing did not seem to affect the resistivity measurements significantly on a given day.

11.4 Evaluating the Consistency of Concrete Mixtures Produces in the Field by Comparative Analysis of Surface Resistivity Measurements

- The preliminary results of this study showed that it is required to develop a quality control criterion to determine the consistency in concrete production. The surface resistivity testing can be used to determine the consistency of concrete mixtures produced by a concrete producer. It can help to provide a tool for evaluating the quality of concrete along with compressive strength. This procedure can also be used to develop a long-term credential rating for the concrete producer, which can provide assistance in technical evaluation of a concrete producer.
- The concrete producer-1 has manufactured 22 concrete mixtures, delivered to 6 residencies in Oklahoma are divided into four groups, according to their mixture design. The time-resistivity curves and statistical analysis have shown that concrete producer-1 may not be able to maintain consistency in the reproduction of concrete mixtures. In this case, it is required to develop a quality control criterion to determine the consistency in concrete production.

- The concrete producer-2 have produced 4 concrete mixtures for three different residencies. The producer-2 was not able to maintain the consistency in the reproduction of concrete mixtures having similar mixture design. The reason could be different sources of cement and aggregates that influenced the resistivity of concrete or lack of quality control during concrete production.
- The concrete producer-3 has prepared 3 concrete mixtures for two different residencies. The time-resistivity curves and statistical analysis proved that the concrete producer-3 was successful in maintaining the consistency of concrete reproduction.
- The concrete producer-4 has also manufactured 3 concrete mixtures for a residency in Oklahoma. It is concluded from time-resistivity curves and statistical analysis that the concrete producer-4 has successfully maintained the consistency in the reproduction of concrete mixtures.
- The concrete producers 5, 6, 7 and 8, each manufactured two concrete mixtures for a residency. The concrete producer 6, 7 and 8 successfully produced consistent concrete mixtures both times according to the results obtained from statistical analysis and comparison of time-resistivity behavior. Whereas, concrete producers 5 was not able to maintain consistency in reproduction. In case of concrete producer-8, the time-resistivity curves of both mixtures showed no gain in resistivity with an increase up to 56 days. Therefore, it is concluded that the concrete parameters might have a considerable difference with the approved mixture design.

11.5 Comparative study of Sorptivity, Absorption and Compressive Strength with Surface Resistivity Method

- The concrete mixtures with varying w/cm and fly ash content, the comparison of surface resistivity measurements with sorptivity coefficients, percentage absorption, and compression tests results, did not prove to be well correlated. The linear correlation for all the concrete mixtures, resistivity versus sorptivity gave R^2 of 60%, resistivity versus percentage absorption gave R^2 of 70%, and resistivity versus compressive strength gave R^2 of 22%. However, the percentage absorption shows a better correlation with resistivity. The comparison showed that the sorptivity, percentage absorption, and compressive strength mechanisms may not be evaluated for all concrete mixtures by using surface resistivity method.

- The effect of a change in w/cm of concrete mixtures on surface resistivity can be related to sorptivity coefficients, percentage absorption, and compression tests results. The change in w/cm from 0.40 to 0.50 w/cm resulted in a decrease in resistivity at day 28 and day 56, increase in sorptivity coefficients and percentage absorption and decrease in compressive strength.

- The change in fly ash content from no fly ash to 20% in a concrete mixture showed an increase in resistivity with age depending on the content of fly ash in the concrete mixture; however, at day 28, concrete with 10% fly ash content attained the maximum resistivity. The decrease in sorptivity coefficients and percentage absorption, and no significant difference in compressive strength was observed. The analysis showed that at the age of 28 days, the resistivity measurements could not be correlated with sorptivity coefficients and percentage absorption, and compressive strength methods for varying fly ash content in concrete mixtures because at 28-day age, the resistivity depends on the content of fly ash in the mixture.

- The comparison of fly ash source, having similar chemical properties show good relation between resistivity, percentage absorption, and compressive strength. There was no significant difference found in resistivity, percentage absorption, and compressive strength by changing the source of class-C fly ash. Whereas, sorptivity coefficients showed a significant difference and did not show a good relationship with resistivity. It might be because of high COV, and samples have failed to meet the conditioning requirements of the standard. It is recommended to retest the similar concrete mixtures for the sorptivity test.

- The change in aggregate type, Limestone, Dolomite, and Granite in concrete mixtures was analyzed, and comparison showed that the resistivity did not relate to sorptivity, absorption and compressive strength of concrete. It might be due to their different chemical composition and absorption characteristics, which may affect the pore size and tortuosity, and pore water concentration. Further investigation is recommended in this area.

- The change in aggregate sizes from #56 to #67 presented no significant difference in measured values and showed the comparative relation of resistivity with percentage absorption and compressive strength. The reason could be the similar chemical properties of aggregates and cementitious material that influence of aggregate size was not substantial. It is recommended to repeat the concrete mixtures and test procedures with different aggregate sizes to further verify the correlation.

- The addition of WR and AE in a concrete mixture having fly ash content could cause a reduction in resistivity compared to the resistivity of a concrete mixture having fly ash and no added chemical admixtures. The results of resistivity were found related to sorptivity, the addition of WR and AE in the presence of fly ash resulted in higher sorptivity coefficients and low resistivity, whereas, in case of no-fly ash concrete, there is no significant difference found in resistivity and sorptivity coefficients. The resistivity is found related to percentage absorption, the resistivity decreases and absorption increases in the presence of WR and AE in the fly ash concrete mixture, whereas, there is no significant difference found in resistivity and sorptivity when there is no fly ash content in the concrete mixture. Like resistivity, compressive strength is also affected by the addition of WR and AE in the presence of fly ash content in the mixture.

- The change in paste volume of concrete from 27% to 33% resulted in a decrease of surface resistivity due to increase in a porous structure of concrete. Although, the resistivity of 30% paste volume samples attained higher resistivity at days 28 and 56. However, the change in resistivity due to change in paste fraction can be related to increasing in percentage absorption, but cannot be related to compressive strength because statistical analysis showed no significant difference in compressive strength by increasing the paste content to 6%. It is difficult to correlate resistivity with initial and secondary sorptivity results because of high variation in coefficients. It might be due to improper conditioning or procedural error of samples. Further testing is recommended to verify the correlation of sorptivity with resistivity due to change in paste fraction.

- Based on the preliminary results, this study explains the relationship of surface resistivity with sorptivity, percentage absorption, and compressive strength by varying different parameters in concrete. Further investigation is recommended for change in each parameter and to verify their effects with comparative analysis.

11.6 Predicting Surface Resistivity of Concrete Mixtures with Statistical Models

- The three modeling techniques were investigated, multiple regression (MR), decision trees (DT) and neural networks (NN) by using resistivity data for thirty concrete mixtures. The best predicting models are either MR or NN based on average square error (ASE) values. These two techniques outperformed DT in all days; it means that DT algorithm is not robust enough to predict resistivity values of hardened concrete.

- The various concrete mixtures have a different trend of gain in resistivity over time, and it is because of different proportions of parameters like fly ash and w/cm. Due to this reason, it is possible to predict the resistivity values representing a concrete mixture for a particular day.

- The results showed that by using the prediction intervals, it is not possible to differentiate between components of a concrete mixture due to overlapping of resistivity ranges of various concrete mixtures. However, this analysis introduces a new methodology for data examination in the materials field.

11.7 Development of Statistical Criteria using Surface Resistivity Testing for Quality Control and Compliance of Concrete Mixtures

- The preliminary results of this study offer insight on a new application for surface resistivity testing. The time-resistivity behavior of a given concrete mixture under controlled laboratory conditions seems to be repeatable. And, slight variations in mixture design parameters such as w/cm and class-C fly ash content seem to significantly influence this behavior. Based on these two criteria, it was possible to establish surface resistivity categories one could use to identify with a 95% confidence level whether a mixture contains a class-C fly ash or not and its range in w/cm (0.40, 0.45, 0.50 w/cm).
- A small laboratory trial was conducted to determine whether the tool was successful. A total of 15 mixture designs varying in w/cm, %FA, paste content, air entrainer addition were evaluated. With success above 67% at a confidence of 95%, the tool was deemed successful, and further trial testing is underway in order to refine the tool and incorporate an array of materials commonly used in the construction industry.
- The developed indetification criteria may provide a simple approach to a user to authenticate the quality/compliance of concrete according to the approved mixture

design. In turn, it can help in minimizing potential durability issues, which may arise from increased w/cm of concrete mixtures at the job site or lack of desirable cementitious materials. Overall, improvement of quality control measures at the time of construction is of the essence for improvement of the service life of concrete structures.

11.8 New Method for Quality Control and Compliance of Concrete Mixture Design by Using Surface Resistivity Testing

- The ANOVA and Tukey’s test was successful to establish categories for determining the presence of Class-C fly ash in a concrete mixture based on the gain in resistivity between the age of day-1 and day-3. Furthermore, the statistical method permitted identification of the design w/cm (0.40, 0.45 or 0.50) for concrete mixtures as early as the age of day-14; however, the accuracy was improved if the validation was performed at day-28.
- The method was trialed for twenty-four mixtures of varying mixture design and material source. The method successfully validated 67% percent of mixtures for fly ash content. The validation of concrete mixtures to identify w/cm at day-28 was 100% and 93% accurate and for “No fly ash” and “Fly ash” concrete mixtures.
- This statistical criterion may offer a simple tool to verify the quality of a placed concrete for compliance with the accepted mixture design. Furthermore, it could help control durability problems, repair cost, and increase the service life of concrete structures. However, further investigation is required to validate the statistical criteria against multiple material sources and field trial testing prior to use and implementation. The results presented herein serve as a guiding platform which may be expanded to incorporate other cementitious materials such as silica fume, blast furnace slag for example.

11.9 Future Scope of Work

The conclusions of various studies explained in the dissertation were based on the preliminary results of a limited number of concrete mixtures and specimens, and locally available concrete materials. Further work is recommended in this research area to verify the outcome of this research study.

- It is recommended to use various sources of concrete materials to validate the completed study and further investigate the comparative analysis of influential transport mechanisms with surface resistivity method.
- It is suggested to further investigate the effect of ambient and curing temperature on surface resistivity measurements for different types of cementitious materials available for construction.
- It is proposed to investigate the effect of course aggregates with various chemical compositions and types on surface resistivity measurements.
- It is recommended to validate the quality control criterion to determine the w/cm and fly ash content of the concrete mixtures by making concrete specimen with different aggregate sources and cementitious materials to reevaluate the boundary conditions.

Appendix -A

Mixture Designs

ID	w/cm	Fly Ash (%)	Water (kg/m^3)	Cement (kg/m^3)	Fly Ash (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Paste (%)
40-00-56-0-1-1	0.40	0%	145.4	362.5	0	1097.6	714.9	27.8%
40-05-56-0-1-1	0.40	5%	145.4	344.4	18.1	1097.6	714.9	27.8%
40-10-56-0-1-1	0.40	10%	145.4	326.3	36.3	1097.6	714.9	27.8%
40-15-56-0-1-1	0.40	15%	145.4	308.1	54.4	1097.6	714.9	27.8%
40-20-56-0-1-1	0.40	20%	145.4	290.0	72.5	1097.6	714.9	27.8%
40-25-56-0-1-1	0.40	25%	145.4	271.9	90.6	1097.6	714.9	27.8%
45-00-56-0-1-1	0.45	0%	163.2	362.5	0.0	1097.6	714.9	29.2%
45-05-56-0-1-1	0.45	5%	163.2	344.4	18.1	1097.6	714.9	29.2%
45-10-56-0-1-1	0.45	10%	163.2	326.3	36.3	1097.6	714.9	29.2%
45-15-56-0-1-1	0.45	15%	163.2	308.1	54.4	1097.6	714.9	29.2%
45-20-56-0-1-1	0.45	20%	163.2	290.0	72.5	1097.6	714.9	29.2%
45-25-56-0-1-1	0.45	25%	163.2	271.9	90.6	1097.6	714.9	29.2%
50-00-56-0-1-1	0.50	0%	181.5	362.5	0.0	1097.6	714.9	30.5%
50-05-56-0-1-1	0.50	5%	181.5	344.4	18.1	1097.6	714.9	30.5%
50-10-56-0-1-1	0.50	10%	181.5	326.3	36.3	1097.6	714.9	30.5%
50-15-56-0-1-1	0.50	15%	181.5	308.1	54.4	1097.6	714.9	30.5%
50-20-56-0-1-1	0.50	20%	181.5	290.0	72.5	1097.6	714.9	30.5%
50-25-56-0-1-1	0.50	25%	181.5	271.9	90.6	1097.6	714.9	30.5%
55-00-56-0-1-1	0.55	0%	199.3	362.5	0.0	1097.6	714.9	31.8%
55-05-56-0-1-1	0.55	5%	199.3	344.4	18.1	1097.6	714.9	31.8%
55-10-56-0-1-1	0.55	10%	199.3	326.3	36.3	1097.6	714.9	31.8%
55-15-56-0-1-1	0.55	15%	199.3	308.1	54.4	1097.6	714.9	31.8%
55-20-56-0-1-1	0.55	20%	199.3	290.0	72.5	1097.6	714.9	31.8%
55-25-56-0-1-1	0.55	25%	199.3	271.9	90.6	1097.6	714.9	31.8%
60-00-56-0-1-1	0.60	0%	217.7	362.5	0.0	1097.6	714.9	33.1%
60-05-56-0-1-1	0.60	5%	217.7	344.4	18.1	1097.6	714.9	33.1%
60-10-56-0-1-1	0.60	10%	217.7	326.3	36.3	1097.6	714.9	33.1%
60-15-56-0-1-1	0.60	15%	217.7	308.1	54.4	1097.6	714.9	33.1%
60-20-56-0-1-1	0.60	20%	217.7	290.0	72.5	1097.6	714.9	33.1%
60-25-56-0-1-1	0.60	25%	217.7	271.9	90.6	1097.6	714.9	33.1%
45-10-57-1-1-1	0.45	10%	163.2	326.2	36.2	1088.7	709	29.2%
45-15-57-1-1-1	0.45	15%	163.2	308.1	54.4	1088.7	709	29.2%
45-20-57-1-1-1	0.45	20%	163.2	290	72.5	1088.7	709	29.2%
45-25-57-1-1-1	0.45	25%	163.2	271.9	90.6	1088.7	709	29.2%
45-20-57-1-1-1	0.45	20%	163.2	290	72.5	1088.7	709	29.2%
45-20-57-1-1-1	0.45	20%	163.2	290	72.5	1088.7	709	29.2%
45-20-57-1-1-1	0.45	20%	163.2	290	72.5	1088.7	709	29.2%
40-00-56-3-1-1	0.40	0%	145.4	362.5	0	1097.6	714.9	27.8%
40-05-56-3-1-1	0.40	5%	145.4	344.4	18.1	1097.6	714.9	27.8%
40-10-56-3-1-1	0.40	10%	145.4	326.3	36.3	1097.6	714.9	27.8%
40-15-56-3-1-1	0.40	15%	145.4	308.1	54.4	1097.6	714.9	27.8%
40-20-56-3-1-1	0.40	20%	145.4	290.0	72.5	1097.6	714.9	27.8%
40-25-56-3-1-1	0.40	25%	145.4	271.9	90.6	1097.6	714.9	27.8%

ID	w/cm	Fly Ash (%)	Water (kg/m^3)	Cement (kg/m^3)	Fly Ash (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Paste (%)
45-00-56-3-1-1	0.45	0%	163.2	362.5	0.0	1097.6	714.9	29.2%
45-05-56-3-1-1	0.45	5%	163.2	344.4	18.1	1097.6	714.9	29.2%
45-10-56-3-1-1	0.45	10%	163.2	326.3	36.3	1097.6	714.9	29.2%
45-15-56-3-1-1	0.45	15%	163.2	308.1	54.4	1097.6	714.9	29.2%
45-20-56-3-1-1	0.45	20%	163.2	290.0	72.5	1097.6	714.9	29.2%
45-25-56-3-1-1	0.45	25%	163.2	271.9	90.6	1097.6	714.9	29.2%
50-00-56-3-1-1	0.50	0%	181.5	362.5	0.0	1097.6	714.9	30.5%
50-05-56-3-1-1	0.50	5%	181.5	344.4	18.1	1097.6	714.9	30.5%
50-10-56-3-1-1	0.50	10%	181.5	326.3	36.3	1097.6	714.9	30.5%
50-15-56-3-1-1	0.50	15%	181.5	308.1	54.4	1097.6	714.9	30.5%
50-20-56-3-1-1	0.50	20%	181.5	290.0	72.5	1097.6	714.9	30.5%
50-25-56-3-1-1	0.50	25%	181.5	271.9	90.6	1097.6	714.9	30.5%
55-00-56-3-1-1	0.55	0%	199.3	362.5	0.0	1097.6	714.9	31.8%
55-05-56-3-1-1	0.55	5%	199.3	344.4	18.1	1097.6	714.9	31.8%
55-10-56-3-1-1	0.55	10%	199.3	326.3	36.3	1097.6	714.9	31.8%
55-15-56-3-1-1	0.55	15%	199.3	308.1	54.4	1097.6	714.9	31.8%
55-20-56-3-1-1	0.55	20%	199.3	290.0	72.5	1097.6	714.9	31.8%
55-25-56-3-1-1	0.55	25%	199.3	271.9	90.6	1097.6	714.9	31.8%
60-00-56-3-1-1	0.60	0%	217.7	362.5	0.0	1097.6	714.9	33.1%
60-05-56-3-1-1	0.60	5%	217.7	344.4	18.1	1097.6	714.9	33.1%
60-10-56-3-1-1	0.60	10%	217.7	326.3	36.3	1097.6	714.9	33.1%
60-15-56-3-1-1	0.60	15%	217.7	308.1	54.4	1097.6	714.9	33.1%
60-20-56-3-1-1	0.60	20%	217.7	290.0	72.5	1097.6	714.9	33.1%
60-25-56-3-1-1	0.60	25%	217.7	271.9	90.6	1097.6	714.9	33.1%
40-00-67-0-1-1	0.40	0%	145.35	362.49	0	1097.56	741.60	27%
40-10-67-0-1-1	0.40	10%	145.35	326.24	36.25	1097.56	741.60	27%
40-20-67-0-1-1	0.40	20%	145.35	289.99	72.50	1097.56	741.60	27%
45-00-67-0-1-1	0.45	0%	163.15	362.49	0	1156.89	800.92	27%
45-10-67-0-1-1	0.45	10%	163.15	326.24	36.25	1156.89	800.92	27%
45-20-67-0-1-1	0.45	20%	163.15	289.99	72.50	1156.89	800.92	27%
50-00-67-0-1-1	0.50	0%	181.54	362.49	0	1245.88	845.42	27%
50-10-67-0-1-1	0.50	10%	181.54	326.24	36.25	1245.88	845.42	27%
50-20-67-0-1-1	0.50	20%	181.54	289.99	72.50	1245.88	845.42	27%
40-10-56-0-2-1	0.40	10%	163.15	326.24	36.25	1097.56	714.90	27.8%
45-10-56-0-2-1	0.45	10%	145.35	326.24	36.25	1097.56	714.90	29.2%
50-10-56-0-2-1	0.50	10%	181.54	326.24	36.25	1097.56	714.90	30.5%
40-20-56-0-2-1	0.40	20%	163.15	289.99	72.50	1097.56	714.90	27.8%
45-20-56-0-2-1	0.45	20%	145.35	289.99	72.50	1097.56	714.90	29.2%
50-20-56-0-2-1	0.50	20%	181.54	289.99	72.50	1097.56	714.90	30.5%
40-10-56-0-3-1	0.40	10%	145.35	326.24	36.25	1097.56	741.60	27%
40-20-56-0-3-1	0.40	20%	163.15	289.99	72.50	1156.89	800.92	27%
45-10-56-0-3-1	0.45	10%	181.54	326.24	36.25	1245.88	845.42	27%
45-20-56-0-3-1	0.45	20%	145.35	289.99	72.50	1097.56	741.60	27%

ID	w/cm	Fly Ash (%)	Water (kg/m^3)	Cement (kg/m^3)	Fly Ash (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Paste (%)
50-10-56-0-3-1	0.50	10%	163.15	326.24	36.25	1156.89	800.92	27%
50-20-56-0-3-1	0.50	20%	181.54	289.99	72.50	1245.88	845.42	27%
40-10-56-0-4-1	0.40	10%	145.35	326.24	36.25	1097.56	741.60	27%
40-20-56-0-4-1	0.40	20%	163.15	289.99	72.50	1156.89	800.92	27%
45-10-56-0-4-1	0.45	10%	181.54	326.24	36.25	1245.88	845.42	27%
45-20-56-0-4-1	0.45	20%	145.35	289.99	72.50	1097.56	741.60	27%
50-10-56-0-4-1	0.50	10%	163.15	326.24	36.25	1156.89	800.92	27%
50-20-56-0-4-1	0.50	20%	181.54	289.99	72.50	1245.88	845.42	27%
40-00-56-0-1-2	0.40	0%	145.35	362.49	0	1097.56	741.60	25.8%
40-10-56-0-1-2	0.40	10%	163.15	326.24	36.25	1097.56	741.60	25.8%
40-20-56-0-1-2	0.40	20%	181.54	289.99	72.50	1097.56	741.60	25.8%
45-00-56-0-1-2	0.45	0%	145.35	362.49	0	1156.89	800.92	27.9%
45-10-56-0-1-2	0.45	10%	163.15	326.24	36.25	1156.89	800.92	27.9%
45-20-56-0-1-2	0.45	20%	181.54	289.99	72.50	1156.89	800.92	27.9%
50-00-56-0-1-2	0.50	0%	145.35	362.49	0	1245.88	845.42	29.7%
50-10-56-0-1-2	0.50	10%	163.15	326.24	36.25	1245.88	845.42	29.7%
50-20-56-0-1-2	0.50	20%	181.54	289.99	72.50	1245.88	845.42	29.7%
40-00-56-0-1-3	0.40	0%	145.35	362.49	0	1097.56	741.60	26.1%
40-10-56-0-1-3	0.40	10%	163.15	326.24	36.25	1097.56	741.60	26.1%
40-20-56-0-1-3	0.40	20%	181.54	289.99	72.50	1097.56	741.60	26.1%
45-00-56-0-1-3	0.45	0%	145.35	362.49	0	1156.89	800.92	27.6%
45-10-56-0-1-3	0.45	10%	163.15	326.24	36.25	1156.89	800.92	27.6%
45-20-56-0-1-3	0.45	20%	181.54	289.99	72.50	1156.89	800.92	27.6%
50-00-56-0-1-3	0.50	0%	145.35	362.49	0	1245.88	845.42	29.4%
50-10-56-0-1-3	0.50	10%	163.15	326.24	36.25	1245.88	845.42	29.4%
50-20-56-0-1-3	0.50	20%	181.54	289.99	72.50	1245.88	845.42	29.4%
40-00-56-1-1-1	0.40	0%	145.35	362.49	0	1097.56	1097.56	24%
45-00-56-1-1-1	0.45	0%	163.15	362.49	0	1156.89	1171.72	24%
45-00-56-1-1-1	0.50	0%	181.54	362.49	0	1245.88	1260.71	24%
40-00-56-0-1-1	0.40	0%	145.35	362.49	0	889.91	533.95	33%
45-00-56-0-1-1	0.45	0%	163.15	362.49	0	1127.22	722.02	33%
45-00-56-0-1-1	0.50	0%	181.54	362.49	0	1016.88	605.14	33%

Appendix -B

Resistivity Data

w/cm ratio = 0.45 Aggregate Size = #67 Fly Ash Source = Red Rock
% Fly Ash = 20 Aggregate Type = Limestone Paste Fraction = 27%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
40-20-67-0-1-1-1	4.4	5.9	7.6	8.8	9.7	10.6	12.3	12.8	13.8	14.4
40-20-67-0-1-1-2	4.2	5.5	7.1	8.2	9.3	9.9	11.6	12.1	12.9	13.9
40-20-67-0-1-1-3	4.1	5.6	7.2	8.2	9.5	10.3	11.5	11.8	12.7	13.8
40-20-67-0-1-1-4	4.1	5.6	7.3	8.3	9.8	10.3	-	-	-	-
40-20-67-0-1-1-5	3.9	5.6	7.2	8.1	9.6	10.6	-	-	-	-
40-20-67-0-1-1-6	4.0	5.5	7.2	8.6	10.0	10.6	-	-	-	-
Average	4.1	5.6	7.3	8.4	9.6	10.4	11.8	12.2	13.1	14.0
St. Dev.	0.17	0.14	0.17	0.25	0.23	0.28	0.45	0.53	0.60	0.35
C. Var. (%)	4.12	2.55	2.35	3.02	2.43	2.69	3.82	4.35	4.60	2.50

w/cm ratio = 0.45 Aggregate Size = #57 Fly Ash Source = Red Rock
% Fly Ash = 20 Aggregate Type = Limestone Paste Fraction = 29%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
45-20-57-1-1-1-1	3.8	6.1	7.3	8.0	10.4	10.9	13.0	13.8	13.4	14.3
45-20-57-1-1-1-2	3.6	6.0	7.4	7.7	10.2	10.7	12.0	13.3	12.9	14.2
45-20-57-1-1-1-3	4.1	6.7	8.0	8.6	11.3	11.5	13.4	15.1	14.4	15.3
Average	3.8	6.2	7.6	8.1	10.6	11.0	12.8	14.1	13.5	14.6
St. Dev.	0.25	0.38	0.37	0.49	0.58	0.44	0.74	0.90	0.75	0.60
C. Var. (%)	6.61	6.09	4.88	6.00	5.43	4.03	5.78	6.40	5.52	4.12

w/cm ratio = 0.45 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 20 Aggregate Type = Limestone Paste Fraction = 29%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
45-20-56-0-1-1-1	4.3	5.9	8.2	8.8	9.6	10.5	11.6	11.8	12.6	13.1
45-20-56-0-1-1-2	4.2	6.4	8.5	9.6	10.6	11.6	12.9	13.1	13.7	14.5
45-20-56-0-1-1-3	3.3	5.3	7.2	8.1	9.1	9.8	10.6	11.0	11.6	12.2
45-20-56-0-1-1-4	4.0	6.3	8.3	9.3	10.5	11.3	12.7	13.2	14.0	14.5
45-20-56-0-1-1-5	3.4	6.6	9.1	10.1	11.1	12.2	13.2	13.8	15.0	15.2
45-20-56-0-1-1-6	3.9	6.6	8.8	10.1	11.0	11.7	13.3	13.9	15.0	14.9
Average	3.8	6.2	8.4	9.3	10.3	11.2	12.4	12.8	13.6	14.0
St. Dev.	0.41	0.50	0.65	0.79	0.79	0.90	1.04	1.16	1.34	1.17
C. Var. (%)	10.62	8.13	7.83	8.44	7.69	8.05	8.45	9.10	9.86	8.36

w/cm ratio = 0.40 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 0 Aggregate Type = Limestone Paste Fraction = 27%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
40-00-56-0-1-1-1	5.0	6.2	8.6	10.0	10.7	11.5	12.2	13.0	12.7	13.2
40-00-56-0-1-1-2	5.4	7.1	9.4	11.2	11.8	12.5	13.0	13.7	13.9	14.5
40-00-56-0-1-1-3	5.2	7.0	9.3	11.0	11.6	12.4	13.1	13.5	14.2	14.0
40-00-56-0-1-1-4	5.6	7.2	9.4	11.2	12.0	12.4	13.2	14.1	13.8	14.4
40-00-56-0-1-1-5	5.3	7.0	9.3	11.5	12.1	12.7	13.5	14.2	13.9	14.4
40-00-56-0-1-1-6	5.6	7.3	9.5	11.5	12.3	12.7	13.7	13.9	14.2	14.7
Average	5.3	7.0	9.2	11.0	11.7	12.4	13.1	13.7	13.8	14.2
St. Dev.	0.24	0.38	0.34	0.56	0.55	0.47	0.53	0.41	0.56	0.55
C. Var. (%)	4.48	5.50	3.69	5.08	4.67	3.78	4.06	3.01	4.04	3.87

w/cm ratio = 0.40 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 0 Aggregate Type = Dolomite Paste Fraction = 27%

Sample ID	Day									
	1	7	14	21	28	35	42	49	56	
40-00-56-0-1-2-1-1	5.2	10.0	11.4	12.1	13.1	13.7	14.3	15.3	15.5	
40-00-56-0-1-2-1-2	5.7	10.3	11.8	12.6	14.1	14.3	14.8	15.7	16.1	
40-00-56-0-1-2-1-3	6.0	11.3	13.1	13.9	15.0	15.6	16.1	16.6	17.6	
40-00-56-0-1-2-1-4	5.0	10.2	11.6	12.6	13.6	-	-	-	-	
40-00-56-0-1-2-1-5	5.7	10.8	12.4	13.5	14.5	-	-	-	-	
40-00-56-0-1-2-1-6	5.5	10.4	12.0	13.0	14.2	-	-	-	-	
Average	5.5	10.5	12.0	12.9	14.1	14.5	15.0	15.9	16.4	
St. Dev.	0.37	0.50	0.62	0.64	0.67	0.95	0.92	0.70	1.07	
C. Var. (%)	6.82	4.73	5.16	4.91	4.77	6.54	6.12	4.44	6.54	

w/cm ratio = 0.40 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 0 Aggregate Type = Granite Paste Fraction = 27%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
40-00-56-0-1-3-1-1	5.4	8.7	10.9	12.2	14.5	13.7	14.1	14.1	15.1	14.5
40-00-56-0-1-3-1-2	5.8	9.1	11.0	12.7	13.6	14.1	14.4	14.5	15.4	14.6
40-00-56-0-1-3-1-3	5.0	8.6	10.6	12.4	13.3	13.6	13.8	14.5	15.1	14.8
40-00-56-0-1-3-1-4	5.8	9.1	11.0	12.2	13.2	13.7	-	-	-	-
40-00-56-0-1-3-1-5	5.8	9.0	10.7	12.1	13.4	13.7	-	-	-	-
40-00-56-0-1-3-1-6	5.2	8.5	10.4	11.5	12.5	12.7	-	-	-	-
Average	5.5	8.8	10.7	12.2	13.4	13.6	14.1	14.4	15.2	14.6
St. Dev.	0.33	0.26	0.24	0.38	0.64	0.46	0.34	0.24	0.15	0.19
C. Var. (%)	5.98	2.99	2.27	3.13	4.79	3.43	2.40	1.68	1.00	1.31

Resistivity Data

w/cm ratio = 0.45 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 0 Aggregate Type = Limestone Paste Fraction = 29%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
45-00-56-0-1-1-1-1	6.5	7.0	9.1	10.8	11.5	12.1	12.3	12.9	12.8	13.5
45-00-56-0-1-1-1-2	6.1	6.7	8.9	10.2	10.9	11.6	11.8	12.3	12.6	12.5
45-00-56-0-1-1-1-3	5.2	6.1	8.2	9.3	9.9	10.6	11.0	11.3	11.6	11.8
45-00-56-0-1-1-1-4	6.1	7.0	9.3	10.7	11.5	12.3	13.7	13.1	13.2	13.4
45-00-56-0-1-1-1-5	4.7	6.0	8.2	9.6	10.2	10.7	11.1	11.6	12.7	12.2
45-00-56-0-1-1-1-6	5.4	6.8	9.1	10.5	11.2	12.0	12.4	12.7	12.9	13.2
Average	5.7	6.6	8.8	10.2	10.9	11.5	12.0	12.3	12.6	12.8
St. Dev.	0.67	0.44	0.49	0.61	0.69	0.74	1.01	0.72	0.55	0.70
C. Var. (%)	11.83	6.70	5.57	6.05	6.34	6.43	8.43	5.86	4.32	5.48

w/cm ratio = 0.45 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 0 Aggregate Type = Dolomite Paste Fraction = 27%

Sample ID	Day									
	1	7	14	21	28	35	42	49	56	
45-00-56-0-1-2-1-1	5.2	9.0	10.3	11.4	12.4	12.7	12.9	13.1	13.3	
45-00-56-0-1-2-1-2	5.3	9.8	10.7	12.3	12.6	13.4	13.3	14.4	13.8	
45-00-56-0-1-2-1-3	4.8	9.1	10.2	11.2	11.8	12.5	12.5	13.4	13.0	
45-00-56-0-1-2-1-4	4.4	9.1	10.0	11.1	11.7	-	-	-	-	
45-00-56-0-1-2-1-5	5.0	9.2	10.7	11.2	12.0	-	-	-	-	
45-00-56-0-1-2-1-6	5.4	9.7	10.9	11.7	12.6	-	-	-	-	
Average	5.0	9.3	10.5	11.5	12.2	12.8	12.9	13.6	13.3	
St. Dev.	0.34	0.34	0.34	0.43	0.39	0.48	0.43	0.69	0.43	
C. Var. (%)	6.81	3.69	3.30	3.75	3.22	3.73	3.30	5.11	3.21	

w/cm ratio = 0.45 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 0 Aggregate Type = Granite Paste Fraction = 27%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
45-00-56-0-1-3-1-1	5.4	8.7	10.9	12.2	14.5	13.7	14.1	14.1	15.1	14.5
45-00-56-0-1-3-1-2	5.8	9.1	11.0	12.7	13.6	14.1	14.4	14.5	15.4	14.6
45-00-56-0-1-3-1-3	5.0	8.6	10.6	12.4	13.3	13.6	13.8	14.5	15.1	14.8
45-00-56-0-1-3-1-4	5.8	9.1	11.0	12.2	13.2	13.7	-	-	-	-
45-00-56-0-1-3-1-5	5.8	9.0	10.7	12.1	13.4	13.7	-	-	-	-
45-00-56-0-1-3-1-6	5.2	8.5	10.4	11.5	12.5	12.7	-	-	-	-
Average	5.5	8.8	10.7	12.2	13.4	13.6	14.1	14.4	15.2	14.6
St. Dev.	0.33	0.26	0.24	0.38	0.64	0.46	0.34	0.24	0.15	0.19
C. Var. (%)	5.98	2.99	2.27	3.13	4.79	3.43	2.40	1.68	1.00	1.31

Resistivity Data

w/cm ratio = 0.50 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 0 Aggregate Type = Limestone Paste Fraction = 29%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
50-00-56-0-1-1-1-1	5.0	5.6	7.1	8.3	9.1	9.5	10.1	10.4	10.6	10.8
50-00-56-0-1-1-1-2	4.7	6.1	7.8	9.3	9.9	10.2	11.0	11.1	11.5	11.3
50-00-56-0-1-1-1-3	5.1	6.0	7.4	8.8	9.4	10.0	10.6	11.2	10.8	10.9
50-00-56-0-1-1-1-4	4.5	5.9	7.6	8.9	9.7	10.3	10.7	11.0	11.0	11.4
50-00-56-0-1-1-1-5	5.5	5.9	7.7	9.1	9.8	10.3	10.8	11.6	11.4	11.5
50-00-56-0-1-1-1-6	5.1	6.1	7.8	9.2	9.8	10.7	10.8	10.9	11.3	11.4
Average	5.0	5.9	7.5	8.9	9.6	10.2	10.7	11.0	11.1	11.2
St. Dev.	0.34	0.18	0.28	0.34	0.31	0.40	0.32	0.37	0.35	0.28
C. Var. (%)	6.93	3.02	3.65	3.86	3.22	3.94	3.05	3.33	3.19	2.51

w/cm ratio = 0.50 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 0 Aggregate Type = Dolomite Paste Fraction = 27%

Sample ID	Day									
	1	7	14	21	28	35	42	49	56	
50-00-56-0-1-2-1-1	3.8	7.2	8.3	8.9	9.3	9.8	10.1	10.6	10.2	
50-00-56-0-1-2-1-2	3.5	7.2	8.2	8.7	9.1	9.6	9.9	10.6	10.3	
50-00-56-0-1-2-1-3	3.9	7.8	8.7	9.2	10.2	10.3	10.6	11.5	10.8	
50-00-56-0-1-2-1-4	3.8	7.4	8.4	8.8	9.5	-	-	-	-	
50-00-56-0-1-2-1-5	3.8	8.2	9.3	9.9	10.5	-	-	-	-	
50-00-56-0-1-2-1-6	3.4	7.4	8.2	9.0	9.6	-	-	-	-	
Average	3.7	7.5	8.5	9.1	9.7	9.9	10.2	10.9	10.4	
St. Dev.	0.20	0.41	0.45	0.45	0.54	0.35	0.33	0.51	0.32	
C. Var. (%)	5.26	5.47	5.26	4.95	5.57	3.55	3.25	4.65	3.10	

w/cm ratio = 0.50 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 0 Aggregate Type = Granite Paste Fraction = 27%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
50-00-56-0-1-3-1-1	5.0	6.1	7.2	8.4	8.9	9.1	9.1	9.7	9.8	9.2
50-00-56-0-1-3-1-2	5.0	6.0	7.4	8.1	8.7	8.9	9.0	9.6	9.6	9.1
50-00-56-0-1-3-1-3	6.2	7.7	9.0	10.0	10.6	10.9	11.1	11.5	11.5	11.1
50-00-56-0-1-3-1-4	5.2	6.5	7.7	8.7	9.1	9.3	-	-	-	-
50-00-56-0-1-3-1-5	4.9	6.4	7.9	8.6	9.4	9.6	-	-	-	-
50-00-56-0-1-3-1-6	4.9	6.1	7.3	8.1	8.7	8.9	-	-	-	-
Average	5.2	6.5	7.7	8.6	9.2	9.4	9.7	10.3	10.3	9.8
St. Dev.	0.51	0.62	0.67	0.69	0.73	0.76	1.15	1.03	1.05	1.12
C. Var. (%)	9.74	9.57	8.64	8.04	7.94	8.10	11.81	10.08	10.20	11.47

Resistivity Data

w/cm ratio = 0.40 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 0 Aggregate Type = Limestone Paste Fraction = 24%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
40-00-56-1-1-1-1-1	7.4	12.3	13.9	15.3	16.8	18.0	17.9	19.2	19.8	20.3
40-00-56-1-1-1-1-2	7.0	11.3	13.0	14.0	15.3	16.5	17.0	17.8	18.5	18.5
40-00-56-1-1-1-1-3	6.7	11.6	13.3	14.5	15.5	16.5	17.0	17.3	18.8	19.1
40-00-56-1-1-1-1-4	7.4	11.9	13.8	15.2	16.3	17.6	-	-	-	-
40-00-56-1-1-1-1-5	-	-	-	-	-	-	-	-	-	-
40-00-56-1-1-1-1-6	6.4	11.3	13.0	14.2	14.9	16.2	-	-	-	-
Average	7.0	11.6	13.4	14.6	15.7	17.0	17.3	18.1	19.0	19.3
St. Dev.	0.42	0.41	0.43	0.57	0.76	0.82	0.52	0.97	0.68	0.94
C. Var. (%)	6.01	3.53	3.21	3.91	4.80	4.84	3.00	5.37	3.59	4.86

w/cm ratio = 0.40 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 0 Aggregate Type = Limestone Paste Fraction = 27%

Sample ID	Day									
	1	7	14	21	28	35	42	49	56	
40-00-56-0-1-1-1-1	5.0	6.2	8.6	10.0	10.7	11.5	12.2	13.0	12.7	13.2
40-00-56-0-1-1-1-2	5.4	7.1	9.4	11.2	11.8	12.5	13.0	13.7	13.9	14.5
40-00-56-0-1-1-1-3	5.2	7.0	9.3	11.0	11.6	12.4	13.1	13.5	14.2	14.0
40-00-56-0-1-1-1-4	5.6	7.2	9.4	11.2	12.0	12.4	13.2	14.1	13.8	14.4
40-00-56-0-1-1-1-5	5.3	7.0	9.3	11.5	12.1	12.7	13.5	14.2	13.9	14.4
40-00-56-0-1-1-1-6	5.6	7.3	9.5	11.5	12.3	12.7	13.7	13.9	14.2	14.7
Average	5.3	7.0	9.2	11.0	11.7	12.4	13.1	13.7	13.8	14.2
St. Dev.	0.24	0.38	0.34	0.56	0.55	0.47	0.53	0.41	0.56	0.55
C. Var. (%)	4.48	5.50	3.69	5.08	4.67	3.78	4.06	3.01	4.04	3.87

w/cm ratio = 0.40 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 0 Aggregate Type = Limestone Paste Fraction = 33%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
40-00-56-0-1-1-1-1	4.9	6.0	7.2	7.5	8.2	9.5	9.2	9.3	9.8	9.5
40-00-56-0-1-1-1-2	4.8	6.8	8.0	8.4	9.1	10.1	9.9	9.9	10.4	10.6
40-00-56-0-1-1-1-3	4.4	6.0	6.8	7.5	8.0	9.0	8.9	9.0	9.3	9.3
40-00-56-0-1-1-1-4	4.5	6.0	7.0	7.4	8.1	9.3	-	-	-	-
40-00-56-0-1-1-1-5	4.3	6.1	6.7	7.1	8.1	8.9	-	-	-	-
40-00-56-0-1-1-1-6	5.0	6.6	7.5	8.0	8.9	9.7	-	-	-	-
Average	4.6	6.3	7.2	7.6	8.4	9.4	9.3	9.4	9.8	9.8
St. Dev.	0.28	0.36	0.48	0.48	0.48	0.45	0.51	0.47	0.59	0.68
C. Var. (%)	6.08	5.77	6.62	6.27	5.70	4.76	5.43	5.03	5.98	6.91

Resistivity Data

No Admix w/cm ratio = 0.40 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 20 Aggregate Type = Limestone Paste Fraction = 27%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
40-20-56-0-1-1-1-1	3.8	6.4	8.6	10.2	11.2	12.3	13.3	14.5	14.7	15.7
40-20-56-0-1-1-1-2	4.5	6.8	9.8	11.0	12.4	13.1	14.6	15.8	16.2	17.3
40-20-56-0-1-1-1-3	4.7	7.2	8.2	11.4	12.6	13.4	14.8	16.2	16.7	17.8
40-20-56-0-1-1-1-4	4.1	6.2	9.0	10.0	10.7	11.3	12.8	13.5	14.3	15.1
40-20-56-0-1-1-1-5	4.0	6.6	7.8	10.6	11.4	12.5	13.3	14.7	15.0	16.2
40-20-56-0-1-1-1-6	4.4	6.7	8.0	11.0	11.7	13.2	14.1	15.2	15.8	16.6
Average	4.3	6.6	8.5	10.7	11.6	12.6	13.8	15.0	15.4	16.4
St. Dev.	0.33	0.34	0.73	0.53	0.72	0.77	0.79	0.98	0.93	0.99
C. Var. (%)	7.86	5.20	8.60	4.92	6.16	6.12	5.71	6.58	6.00	6.05

WR/AE w/cm ratio = 0.40 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 0 Aggregate Type = Limestone Paste Fraction = 27%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
40-00-56-3-1-1-1-1	7.7	8.2	9.2	10.9	11.3	11.9	13.4	13.2	14.3	15.3
40-00-56-3-1-1-1-2	6.6	7.9	8.8	10.2	11.3	11.5	12.7	12.5	13.5	13.7
40-00-56-3-1-1-1-3	6.8	7.7	8.4	9.7	10.6	10.0	11.6	11.9	12.9	12.8
40-00-56-3-1-1-1-4	7.3	8.4	9.3	10.8	11.5	12.1	-	-	-	-
40-00-56-3-1-1-1-5	7.5	8.1	9.0	11.9	11.4	11.8	-	-	-	-
40-00-56-3-1-1-1-6	6.9	7.8	8.5	10.0	10.8	11.4	-	-	-	-
Average	7.1	8.0	8.8	10.6	11.1	11.4	12.6	12.5	13.5	13.9
St. Dev.	0.44	0.27	0.38	0.80	0.37	0.76	0.95	0.63	0.70	1.23
C. Var. (%)	6.17	3.39	4.27	7.57	3.36	6.67	7.53	5.01	5.20	8.82

WR/AE w/cm ratio = 0.40 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 20 Aggregate Type = Limestone Paste Fraction = 27%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
40-20-56-3-1-1-1-1	3.8	5.9	7.0	8.0	8.6	9.7	10.8	12.0	13.3	13.6
40-20-56-3-1-1-1-2	4.7	6.6	7.9	8.9	9.7	10.6	12.1	13.2	14.1	14.2
40-20-56-3-1-1-1-3	3.9	6.3	7.3	8.6	9.2	10.2	11.4	12.4	13.8	14.7
40-20-56-3-1-1-1-4	4.0	6.3	7.1	8.3	8.9	9.8	-	-	-	-
40-20-56-3-1-1-1-5	4.1	6.3	7.2	8.4	9.1	10.2	-	-	-	-
40-20-56-3-1-1-1-6	4.2	6.0	7.4	8.5	9.2	10.3	-	-	-	-
Average	4.1	6.2	7.3	8.4	9.1	10.1	11.4	12.5	13.7	14.2
St. Dev.	0.34	0.25	0.34	0.30	0.37	0.34	0.64	0.62	0.37	0.53
C. Var. (%)	8.21	4.02	4.72	3.54	4.08	3.32	5.61	4.97	2.68	3.71

Resistivity Data

Fog room/Tank1/Tank2
w/cm ratio = 0.45 Aggregate Size = #57 Fly Ash Source = Red Rock
% Fly Ash = 10 Aggregate Type = Limestone Paste Fraction = 29%

Sample ID	Day									
	1	2	3	4	5	6	7	9	11	14
45-10-57-1-1-1-1-1	5.9	6.4	7.3	8.0	8.2	8.7	8.8	9.6	9.7	10.0
45-10-57-1-1-1-1-2	6.0	6.8	7.9	8.4	8.9	9.1	9.4	10.0	10.2	10.5
45-10-57-1-1-1-1-3	5.8	6.5	7.5	8.0	8.4	8.7	9.0	9.6	9.9	10.1
Average	5.9	6.6	7.6	8.1	8.5	8.8	9.1	9.7	10.0	10.2
St. Dev.	0.09	0.22	0.28	0.25	0.34	0.25	0.28	0.26	0.25	0.27
C. Var. (%)	1.49	3.28	3.69	3.03	4.02	2.80	3.14	2.67	2.55	2.62
45-10-57-1-1-1-1-1	5.6	6.4	7.0	7.9	8.3	8.2	8.4	9.1	9.7	9.6
45-10-57-1-1-1-1-2	5.3	6.2	7.1	7.7	8.1	8.2	8.2	9.0	9.6	9.6
45-10-57-1-1-1-1-3	5.1	6.2	7.0	7.7	8.3	8.3	8.4	9.3	10.0	9.8
Average	5.3	6.3	7.1	7.7	8.2	8.2	8.3	9.1	9.8	9.6
St. Dev.	0.24	0.12	0.07	0.11	0.11	0.09	0.08	0.14	0.17	0.12
C. Var. (%)	4.55	1.89	0.94	1.41	1.39	1.06	0.97	1.53	1.79	1.28
45-10-57-1-1-1-1-1	4.6	5.6	7.0	7.5	7.9	7.9	8.4	8.9	9.2	9.4
45-10-57-1-1-1-1-2	4.5	5.3	6.6	7.1	7.3	7.3	7.8	8.1	8.5	8.6
45-10-57-1-1-1-1-3	4.9	6.4	7.6	8.0	8.5	8.6	8.8	9.3	9.7	9.8
Average	4.7	5.8	7.1	7.5	7.9	7.9	8.3	8.8	9.1	9.3
St. Dev.	0.24	0.54	0.49	0.43	0.59	0.61	0.52	0.61	0.56	0.60
C. Var. (%)	5.21	9.37	6.98	5.67	7.44	7.75	6.22	6.97	6.19	6.48

Sample ID	Day									
	16	18	21	23	25	28	35	42	49	56
45-10-57-1-1-1-1-1	10.3	10.7	11.1	11.3	11.4	11.9	12.4	12.4	12.7	13.4
45-10-57-1-1-1-1-2	10.8	11.0	11.5	11.8	12.0	12.4	12.8	13.2	14.2	13.8
45-10-57-1-1-1-1-3	10.5	10.8	11.0	11.1	11.5	11.9	12.2	12.8	13.2	13.2
Average	10.5	10.8	11.2	11.4	11.6	12.0	12.5	12.8	13.4	13.4
St. Dev.	0.25	0.18	0.31	0.37	0.29	0.29	0.34	0.41	0.76	0.30
C. Var. (%)	2.34	1.70	2.75	3.23	2.52	2.40	2.72	3.24	5.66	2.23
45-10-57-1-1-1-1-1	9.6	10.3	10.8	10.2	10.4	11.9	12.0	12.7	13.4	12.6
45-10-57-1-1-1-1-2	9.5	10.5	10.7	10.2	10.2	11.7	11.9	12.7	13.2	12.4
45-10-57-1-1-1-1-3	9.8	10.6	10.9	10.5	10.4	12.2	11.9	12.9	13.7	12.9
Average	9.6	10.4	10.8	10.3	10.3	11.9	11.9	12.8	13.4	12.6
St. Dev.	0.15	0.15	0.10	0.16	0.09	0.23	0.08	0.09	0.24	0.26
C. Var. (%)	1.56	1.40	0.94	1.55	0.84	1.92	0.64	0.74	1.81	2.03
45-10-57-1-1-1-1-1	9.8	10.0	10.4	10.3	10.3	12.1	11.7	12.1	12.7	12.7
45-10-57-1-1-1-1-2	9.2	9.4	9.7	9.5	9.6	11.1	10.4	11.2	11.4	11.6
45-10-57-1-1-1-1-3	10.3	10.4	11.1	11.0	10.9	12.5	12.0	12.9	13.3	13.7
Average	9.7	9.9	10.4	10.3	10.2	11.9	11.4	12.1	12.4	12.7
St. Dev.	0.55	0.48	0.70	0.75	0.68	0.70	0.88	0.84	0.95	1.06
C. Var. (%)	5.67	4.83	6.71	7.30	6.60	5.88	7.78	6.95	7.67	8.39

Resistivity Data

Fog room/Tank1/Tank2

w/cm ratio =	0.45	Aggregate Size =	#57	Fly Ash Source =	Red Rock
% Fly Ash =	15	Aggregate Type =	Limestone	Paste Fraction =	29%

Sample ID	Day									
	1	2	3	4	5	6	7	9	11	14
45-15-57-1-1-1-1-1	5.9	6.7	7.9	8.8	8.9	9.2	9.5	9.9	10.7	10.8
45-15-57-1-1-1-1-2	4.8	6.0	6.8	7.9	8.2	8.5	9.0	9.4	9.9	10.3
45-15-57-1-1-1-1-3	6.0	7.0	7.9	8.7	8.6	8.9	9.3	9.6	10.0	10.3
Average	5.6	6.5	7.5	8.5	8.6	8.9	9.3	9.6	10.2	10.5
St. Dev.	0.65	0.49	0.64	0.47	0.33	0.34	0.26	0.23	0.44	0.28
C. Var. (%)	11.66	7.47	8.43	5.56	3.83	3.85	2.85	2.39	4.35	2.63
45-15-57-1-1-1-1-1	4.8	5.8	6.7	7.4	7.7	7.7	8.2	8.8	9.1	9.1
45-15-57-1-1-1-1-2	4.6	6.0	7.2	7.9	8.1	8.0	8.7	9.2	9.4	9.6
45-15-57-1-1-1-1-3	4.5	5.6	6.8	7.4	7.7	7.7	7.8	9.0	9.3	9.3
Average	4.6	5.8	6.9	7.6	7.8	7.8	8.2	9.0	9.3	9.3
St. Dev.	0.14	0.23	0.23	0.28	0.22	0.17	0.44	0.21	0.17	0.28
C. Var. (%)	3.01	3.89	3.37	3.72	2.79	2.21	5.38	2.36	1.79	2.96
45-15-57-1-1-1-1-1	5.1	6.8	7.5	8.1	8.1	8.8	8.9	9.3	9.8	10.1
45-15-57-1-1-1-1-2	4.2	5.4	6.2	6.6	7.1	7.6	7.8	8.1	8.7	9.3
45-15-57-1-1-1-1-3	4.6	6.1	7.0	8.0	8.2	8.7	8.7	9.1	9.9	10.3
Average	4.6	6.1	6.9	7.5	7.8	8.3	8.5	8.8	9.4	9.9
St. Dev.	0.46	0.66	0.64	0.85	0.60	0.69	0.62	0.63	0.67	0.53
C. Var. (%)	10.05	10.88	9.38	11.25	7.68	8.29	7.33	7.18	7.05	5.37

Sample ID	Day									
	16	18	21	23	25	28	35	42	49	56
45-15-57-1-1-1-1-1	11.2	11.9	12.2	12.4	12.8	12.8	13.8	14.6	15.8	15.9
45-15-57-1-1-1-1-2	10.7	11.3	11.3	11.8	12.1	12.2	13.2	13.8	14.5	15.2
45-15-57-1-1-1-1-3	10.6	11.5	11.6	12.1	12.2	12.7	13.0	13.7	14.5	15.3
Average	10.8	11.6	11.7	12.1	12.4	12.6	13.3	14.0	14.9	15.4
St. Dev.	0.33	0.34	0.48	0.29	0.38	0.29	0.43	0.51	0.76	0.39
C. Var. (%)	3.06	2.93	4.06	2.38	3.04	2.31	3.27	3.65	5.09	2.51
45-15-57-1-1-1-1-1	9.9	10.5	10.1	9.9	11.3	10.8	12.6	13.0	13.5	15.2
45-15-57-1-1-1-1-2	10.6	10.9	10.4	10.4	12.1	11.3	13.3	13.8	14.5	15.9
45-15-57-1-1-1-1-3	10.0	10.6	10.2	10.3	11.7	10.8	12.5	13.1	14.0	14.5
Average	10.2	10.6	10.2	10.2	11.7	10.9	12.8	13.3	14.0	15.2
St. Dev.	0.34	0.22	0.15	0.22	0.38	0.28	0.40	0.42	0.49	0.66
C. Var. (%)	3.40	2.03	1.50	2.18	3.22	2.52	3.14	3.13	3.50	4.36
45-15-57-1-1-1-1-1	10.4	11.1	10.9	11.4	13.1	11.9	13.0	13.9	14.4	16.0
45-15-57-1-1-1-1-2	9.7	9.8	9.8	10.5	11.6	10.5	11.7	12.5	13.2	14.5
45-15-57-1-1-1-1-3	10.4	11.0	11.2	11.2	13.0	11.7	13.1	14.1	14.9	15.3
Average	10.2	10.7	10.6	11.0	12.6	11.3	12.6	13.5	14.2	15.3
St. Dev.	0.38	0.72	0.72	0.48	0.87	0.73	0.77	0.89	0.85	0.73
C. Var. (%)	3.76	6.72	6.75	4.32	6.93	6.47	6.16	6.62	5.98	4.75

Resistivity Data

Fog room/Tank1/Tank2
w/cm ratio = 0.45 Aggregate Size = #57 Fly Ash Source = Red Rock
% Fly Ash = 25 Aggregate Type = Limestone Paste Fraction = 29%

Sample ID	Day									
	1	2	3	4	5	6	7	9	11	14
45-25-57-1-1-1-1-1	3.1	4.4	5.4	6.0	6.5	6.7	7.2	7.2	8.2	8.9
45-25-57-1-1-1-1-2	3.0	4.4	5.4	6.2	6.7	6.7	7.1	7.3	8.6	9.0
45-25-57-1-1-1-1-3	3.1	4.3	5.5	6.3	6.6	6.8	7.3	7.5	8.5	8.8
Average	3.0	4.4	5.4	6.2	6.6	6.7	7.2	7.4	8.4	8.9
St. Dev.	0.07	0.07	0.05	0.14	0.10	0.07	0.07	0.16	0.20	0.07
C. Var. (%)	2.19	1.52	0.96	2.23	1.54	1.12	0.92	2.23	2.36	0.75
45-25-57-1-1-1-1-1	3.0	4.5	5.4	5.9	6.1	6.5	7.1	7.4	8.2	8.6
45-25-57-1-1-1-1-2	3.0	4.3	5.3	6.0	6.1	6.4	6.9	7.3	8.2	8.1
45-25-57-1-1-1-1-3	3.6	5.0	5.9	6.5	6.9	7.3	7.8	8.2	8.7	9.0
Average	3.2	4.6	5.5	6.1	6.4	6.7	7.3	7.6	8.4	8.6
St. Dev.	0.33	0.33	0.33	0.34	0.47	0.49	0.48	0.46	0.32	0.48
C. Var. (%)	10.51	7.12	5.88	5.51	7.38	7.33	6.55	6.10	3.81	5.56
45-25-57-1-1-1-1-1	3.2	4.7	5.6	6.3	6.6	7.0	7.3	7.4	8.6	8.6
45-25-57-1-1-1-1-2	3.1	4.6	5.6	6.3	6.5	6.9	7.2	7.5	8.5	8.8
45-25-57-1-1-1-1-3	3.3	4.6	5.7	6.2	6.6	6.9	7.2	7.6	8.5	8.7
Average	3.2	4.6	5.6	6.3	6.6	6.9	7.2	7.5	8.5	8.7
St. Dev.	0.11	0.05	0.08	0.04	0.05	0.04	0.04	0.08	0.03	0.08
C. Var. (%)	3.56	1.08	1.36	0.61	0.76	0.55	0.60	1.02	0.29	0.88

Sample ID	Day									
	16	18	21	23	25	28	35	42	49	56
45-25-57-1-1-1-1-1	9.3	9.8	10.0	11.0	11.4	11.7	13.4	14.9	16.9	17.8
45-25-57-1-1-1-1-2	9.5	10.0	10.5	11.3	11.4	12.2	13.9	15.3	16.3	18.7
45-25-57-1-1-1-1-3	9.4	9.9	10.1	10.8	11.4	12.5	13.8	15.0	17.0	18.7
Average	9.4	9.9	10.2	11.0	11.4	12.1	13.7	15.1	16.7	18.4
St. Dev.	0.08	0.12	0.24	0.25	0.04	0.36	0.28	0.21	0.36	0.50
C. Var. (%)	0.81	1.19	2.36	2.29	0.34	3.01	2.06	1.41	2.15	2.71
45-25-57-1-1-1-1-1	8.4	10.1	9.7	10.4	11.1	12.2	13.9	15.5	16.2	19.1
45-25-57-1-1-1-1-2	8.6	10.2	9.7	10.5	11.2	12.4	14.6	15.5	16.6	19.2
45-25-57-1-1-1-1-3	9.6	11.1	10.7	11.4	12.6	13.7	15.7	17.4	17.9	20.8
Average	8.8	10.5	10.0	10.8	11.6	12.8	14.7	16.1	16.9	19.7
St. Dev.	0.66	0.57	0.60	0.56	0.82	0.81	0.93	1.10	0.88	0.93
C. Var. (%)	7.49	5.40	5.98	5.20	7.03	6.34	6.31	6.86	5.21	4.74
45-25-57-1-1-1-1-1	9.5	11.5	10.4	11.2	12.0	12.4	14.4	16.0	17.4	19.7
45-25-57-1-1-1-1-2	9.6	11.2	10.5	11.3	12.0	12.7	14.9	16.2	17.8	20.1
45-25-57-1-1-1-1-3	9.6	11.2	10.5	11.4	11.9	12.4	14.5	16.0	17.5	19.4
Average	9.5	11.3	10.4	11.3	12.0	12.5	14.6	16.0	17.6	19.7
St. Dev.	0.07	0.16	0.07	0.10	0.05	0.19	0.27	0.10	0.21	0.34
C. Var. (%)	0.76	1.43	0.63	0.90	0.43	1.50	1.83	0.63	1.21	1.71

Resistivity Data

Fog room/Tank1/Tank2
w/cm ratio = 0.45 Aggregate Size = #57 Fly Ash Source = Red Rock
% Fly Ash = 20 Aggregate Type = Limestone Paste Fraction = 29%

Sample ID	Day									
	1	2	3	4	5	6	7	9	11	14
45-20-57-1-1-1-1-1	3.7	4.9	6.1	7.1	7.2	7.4	7.8	8.4	8.5	9.1
45-20-57-1-1-1-1-2	4.0	5.1	6.2	6.7	7.1	7.5	7.6	8.2	8.4	8.9
45-20-57-1-1-1-1-3	4.0	5.1	6.4	6.9	7.4	7.7	7.9	8.5	8.8	9.2
Average	3.9	5.0	6.2	6.9	7.2	7.5	7.8	8.4	8.6	9.0
St. Dev.	0.16	0.09	0.11	0.20	0.16	0.17	0.16	0.16	0.17	0.16
C. Var. (%)	4.14	1.88	1.84	2.97	2.25	2.21	2.09	1.96	1.94	1.80
45-20-57-1-1-1-1-1	3.8	4.8	6.1	6.4	6.6	6.7	7.3	7.9	8.0	8.0
45-20-57-1-1-1-1-2	3.6	4.8	6.0	6.3	6.6	6.8	7.4	7.7	7.9	7.7
45-20-57-1-1-1-1-3	4.1	5.2	6.7	7.0	7.2	7.4	8.0	8.6	8.7	8.6
Average	3.8	4.9	6.2	6.6	6.8	7.0	7.6	8.1	8.2	8.1
St. Dev.	0.25	0.20	0.38	0.40	0.31	0.38	0.37	0.48	0.43	0.49
C. Var. (%)	6.61	3.96	6.09	6.05	4.57	5.41	4.88	5.97	5.24	6.00
45-20-57-1-1-1-1-1	3.7	4.8	6.0	6.4	6.8	7.1	7.5	7.8	8.7	8.6
45-20-57-1-1-1-1-2	3.8	4.9	6.1	6.5	6.7	7.0	7.4	7.8	8.2	8.3
45-20-57-1-1-1-1-3	3.8	4.8	5.7	6.1	6.3	6.8	6.9	7.4	7.8	8.0
Average	3.8	4.8	5.9	6.3	6.6	6.9	7.2	7.7	8.3	8.3
St. Dev.	0.05	0.08	0.23	0.21	0.24	0.19	0.32	0.25	0.46	0.30
C. Var. (%)	1.32	1.58	3.82	3.38	3.58	2.70	4.44	3.19	5.61	3.60

Sample ID	Day									
	16	18	21	23	25	28	35	42	49	56
45-20-57-1-1-1-1-1	9.6	10.3	11.0	11.0	11.2	11.4	12.5	13.5	13.3	16.6
45-20-57-1-1-1-1-2	9.6	9.9	10.4	10.8	11.3	11.2	12.0	12.9	13.0	16.3
45-20-57-1-1-1-1-3	10.0	10.3	10.8	11.1	11.3	11.2	12.5	13.6	13.5	17.1
Average	9.7	10.2	10.7	10.9	11.2	11.3	12.3	13.3	13.3	16.7
St. Dev.	0.23	0.22	0.29	0.19	0.07	0.12	0.28	0.37	0.25	0.41
C. Var. (%)	2.33	2.21	2.72	1.71	0.64	1.09	2.29	2.81	1.91	2.44
45-20-57-1-1-1-1-1	8.8	9.6	10.4	10.6	10.9	10.9	13.0	13.8	13.4	14.3
45-20-57-1-1-1-1-2	9.3	9.4	10.2	10.5	10.6	10.7	12.0	13.3	12.9	14.2
45-20-57-1-1-1-1-3	10.2	10.3	11.3	11.7	11.8	11.5	13.4	15.1	14.4	15.3
Average	9.4	9.8	10.6	10.9	11.1	11.0	12.8	14.1	13.5	14.6
St. Dev.	0.75	0.51	0.58	0.63	0.62	0.44	0.74	0.90	0.75	0.60
C. Var. (%)	7.97	5.19	5.43	5.76	5.59	4.03	5.78	6.40	5.52	4.12
45-20-57-1-1-1-1-1	9.6	9.8	10.5	10.7	11.1	11.5	12.6	15.6	14.4	15.6
45-20-57-1-1-1-1-2	9.3	9.6	10.2	10.4	10.8	11.0	12.2	15.0	13.8	14.6
45-20-57-1-1-1-1-3	9.0	9.2	10.1	10.0	10.2	10.8	11.9	14.6	13.3	14.4
Average	9.3	9.5	10.2	10.3	10.7	11.1	12.2	15.0	13.8	14.9
St. Dev.	0.30	0.30	0.24	0.36	0.46	0.36	0.38	0.50	0.55	0.64
C. Var. (%)	3.23	3.13	2.31	3.53	4.29	3.26	3.08	3.35	3.98	4.33

Resistivity Data

Producer-1

w/cm ratio = 0.44 Aggregate Size = #57

% Fly Ash = 20 Paste Fraction = 28%

	Days							
Sample OSU#	7	14	21	28	35	42	49	56
35-a	-	7.6	9.4	10.9	12.3	12.8	15.1	-
35-b	-	7.5	9.1	10.7	12.2	12.7	15.1	-
35-c	-	7.7	9.5	11.0	12.5	12.8	15.1	-
Average		7.6	9.3	10.9	12.3	12.8	15.1	
St. Dev.	-	0.1	0.2	0.2	0.2	0.1	0.0	-
C. Var. (%)	-	0.02	0.03	0.01	0.01	0.00	0.00	-
43-a	-	-	11.8	11.5	12.6	12.4	15.3	-
43-b	-	-	12.4	12.3	13.5	14.0	16.4	-
43.c	-	-	12.0	12.2	13.3	13.4	16.0	-
Average			12.1	12.0	13.1	13.3	15.9	
St. Dev.	-	-	0.3	0.4	0.5	0.8	0.6	-
C. Var. (%)	-	-	0.02	0.04	0.04	0.06	0.04	-
44-a	-	-	8.9	7.8	10.7	10.6	14.3	-
44-b	-	-	8.8	8.9	10.6	10.3	13.7	-
44-c	-	-	8.6	9.0	10.2	10.2	13.8	-
Average			8.7	8.6	10.5	10.4	13.9	
St. Dev.	-	-	0.1	0.7	0.2	0.2	0.3	-
C. Var. (%)	-	-	0.01	0.08	0.02	0.02	0.02	-
63-a	5.8	6.3	6.3	7.4	-	7.9	8.6	8.4
63-b	5.4	5.9	5.9	7.1	-	7.7	8.0	8.0
63.c	5.8	6.3	6.4	7.5	-	8.2	8.6	8.6
Average	5.6	6.2	6.2	7.3		7.9	8.4	8.3
St. Dev.	0.2	0.2	0.3	0.2	-	0.2	0.3	0.3
C. Var. (%)	0.04	0.04	0.04	0.03	-	0.03	0.04	0.03
64-a	4.8	5.3	5.3	6.1	-	6.7	7.0	7.1
64-b	4.8	5.3	5.3	6.1	-	6.6	7.0	6.8
64-c	4.8	5.3	5.3	6.1	-	6.4	6.8	7.0
Average	4.8	5.3	5.3	6.1		6.6	6.9	7.0
St. Dev.	0.0	0.0	0.0	0.0	-	0.1	0.1	0.2
C. Var. (%)	0.003	0.003	0.003	0.006	-	0.017	0.014	0.022
65-a	5.1	5.6	5.5	6.6	-	7.1	7.6	7.6
65-b	5.4	6.0	6.0	7.1	-	7.7	8.1	8.2
65-c	5.6	6.1	6.0	7.2	-	7.8	8.2	8.2
Average	5.3	5.9	5.8	7.0	-	7.5	8.0	8.0
St. Dev.	0.2	0.2	0.3	0.4	-	0.4	0.4	0.4
C. Var. (%)	0.0	0.0	0.0	0.1	-	0.1	0.0	0.0
65-a	5.1	5.6	5.5	6.6	-	7.1	7.6	7.6
65-b	5.4	6.0	6.0	7.1	-	7.7	8.1	8.2
65-c	5.6	6.1	6.0	7.2	-	7.8	8.2	8.2
Average	5.3	5.9	5.8	7.0		7.5	8.0	8.0
St. Dev.	0.2	0.2	0.3	0.4	-	0.4	0.4	0.4
C. Var. (%)	0.05	0.04	0.05	0.05	-	0.05	0.05	0.04

Resistivity Data

Producer-1 w/cm ratio = 0.44 Aggregate Size = #57
% Fly Ash = 20 Paste Fraction = 24%

Sample OSU#	Days							
	7	14	21	28	35	42	49	56
4-A	7.9	8.7	9.7	10.6	11.2	12.5	13.0	13.7
4-B	8.4	8.8	9.4	10.6	11.2	12.3	13.4	13.7
4-C	8.1	8.5	9.3	10.3	10.8	12.0	12.9	13.2
Average	8.1	8.7	9.4	10.5	11.1	12.2	13.1	13.5
St. Dev.	0.26	0.15	0.20	0.17	0.22	0.24	0.28	0.25
C. Var. (%)	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02
19-A	-	10.7	12.9	15.5	19.4	22.7	25.2	25.7
19-B	-	10.0	11.8	14.1	17.8	21.2	23.8	24.3
19-C	-	10.1	12.5	15.0	19.2	21.8	25.0	25.4
Average		10.3	12.4	14.8	18.8	21.9	24.6	25.1
St. Dev.	-	0.36	0.57	0.69	0.87	0.75	0.76	0.75
C. Var. (%)	-	0.04	0.05	0.05	0.05	0.03	0.03	0.03
29-a	6.6	7.9	8.6	9.8	10.7	11.7	12.7	13.2
29-b	6.8	8.2	9.9	10.0	11.0	12.0	13.1	13.8
29-c	6.6	7.9	8.5	9.6	10.5	11.5	12.2	13.3
Average	6.6	8.0	9.0	9.8	10.8	11.7	12.6	13.4
St. Dev.	0.12	0.16	0.78	0.23	0.25	0.24	0.43	0.30
C. Var. (%)	0.02	0.02	0.09	0.02	0.02	0.02	0.03	0.02
55-a	-	8.8	12.3	14.7	16.9	-	-	25.2
55-b	-	9.7	11.3	13.6	15.9	-	-	24.4
55-c	-	9.8	11.3	13.6	16.5	-	-	25.4
Average		9.4	11.6	14.0	16.4			25.0
St. Dev.	-	0.55	0.55	0.62	0.48	-	-	0.49
C. Var. (%)	-	0.06	0.05	0.04	0.03	-	-	0.02
61-a	-	6.5	8.3	10.1	-	-	18.0	18.7
61-b	-	6.4	8.0	10.0	-	-	18.0	18.6
61-c	-	5.9	7.8	9.8	-	-	17.1	17.8
Average		6.3	8.0	9.9			17.7	18.4
St. Dev.	-	0.29	0.24	0.16	-	-	0.50	0.50
C. Var. (%)	-	0.05	0.03	0.02	-	-	0.03	0.03

Resistivity Data

Producer-1 w/cm ratio = 0.38 Aggregate Size = #57
% Fly Ash = 20 Paste Fraction = 25%

Sample OSU#	Days							
	7	14	21	28	35	42	49	56
18-A	-	-	13.1	16.7	21.0	24.8	29.2	31.5
18-B	-	-	12.5	15.9	20.1	24.1	28.1	30.4
18-C	-	-	12.0	15.5	19.3	23.2	28.8	29.3
Average			12.5	16.0	20.1	24.0	28.7	30.4
St. Dev.	-	-	0.53	0.60	0.88	0.80	0.57	1.10
C. Var. (%)	-	-	0.04	0.04	0.04	0.03	0.02	0.04
33-a	-	-	8.1	8.1	10.6	11.7	12.7	13.8
33-b	-	-	8.3	8.3	10.6	11.8	12.7	13.9
33-c	-	-	8.1	8.1	10.3	11.5	12.4	13.5
Average			8.2	8.2	10.5	11.7	12.6	13.7
St. Dev.	-	-	0.09	0.09	0.15	0.12	0.17	0.20
C. Var. (%)	-	-	0.01	0.01	0.01	0.01	0.01	0.01
38-a	7.1	7.5	8.8	9.9	11.7	11.4	14.2	-
38-b	5.7	5.9	7.0	8.0	9.4	9.2	11.3	-
38-c	6.1	7.0	8.1	9.3	10.7	10.5	13.1	-
Average	6.3	6.8	8.0	9.1	10.6	10.3	12.9	
St. Dev.	0.73	0.82	0.89	0.96	1.15	1.11	1.43	-
C. Var. (%)	0.12	0.12	0.11	0.11	0.11	0.11	0.11	-
45-a	-	7.5	8.8	10.7	10.3	13.2	-	15.2
45-b	-	7.9	9.2	11.0	10.6	13.6	-	15.8
45-c	-	7.9	8.9	11.1	10.7	14.3	-	16.3
Average		7.7	9.0	10.9	10.5	13.7		15.7
St. Dev.	-	0.25	0.18	0.21	0.22	0.59	-	0.56
C. Var. (%)	-	0.03	0.02	0.02	0.02	0.04	-	0.04
46-a	6.6	7.8	9.7	10.2	12.1	-	-	15.8
46-b	6.2	7.9	8.9	9.7	11.0	-	-	14.8
46-c	6.6	8.0	9.2	9.5	11.3	-	-	14.8
Average	6.5	7.9	9.3	9.8	11.4			15.1
St. Dev.	0.22	0.07	0.40	0.33	0.58	-	-	0.59
C. Var. (%)	0.03	0.01	0.04	0.03	0.05	-	-	0.04
47-a	5.8	7.1	8.2	8.6	10.3	-	-	13.4
47-b	6.3	7.8	9.0	9.5	11.1	-	-	14.6
47-c	6.3	8.0	9.5	9.7	11.5	-	-	15.9
Average	6.1	7.6	8.9	9.3	11.0			14.6
St. Dev.	0.29	0.44	0.66	0.57	0.64	-	-	1.28
C. Var. (%)	0.05	0.06	0.07	0.06	0.06	-	-	0.09
48-a	5.3	7.0	8.0	9.3	10.3	-	-	13.5
48-b	5.7	7.4	8.7	9.9	11.1	-	-	14.4
48-c	5.9	7.6	8.9	10.4	11.7	-	-	15.1
Average	5.6	7.3	8.5	9.8	11.0			14.3
St. Dev.	0.29	0.34	0.47	0.55	0.73	-	-	0.80
C. Var. (%)	0.05	0.05	0.06	0.06	0.07	-	-	0.06

Resistivity Data

Producer-1	w/cm ratio =	0.38	Aggregate Size =	#57
	% Fly Ash =	20	Paste Fraction =	25%

Sample OSU#	Days							
	7	14	21	28	35	42	49	56
49-a	5.4	6.8	8.1	9.1	9.9	-	-	13.1
49-b	5.7	7.0	8.5	9.4	10.5	-	-	13.6
49-c	5.6	7.1	8.4	9.2	10.5	-	-	13.7
Average	5.5	7.0	8.3	9.2	10.3			13.5
St. Dev.	0.17	0.14	0.22	0.14	0.36	-	-	0.34
C. Var. (%)	0.03	0.02	0.03	0.02	0.04	-	-	0.03

Resistivity Data

Producer-1

w/cm ratio = 0.38 Aggregate Size = #57

% Fly Ash = 0 Paste Fraction = 25%

	Days							
Sample OSU#	7	14	21	28	35	42	49	56
12-A	10.4	11.5	11.4	12.2	12.7	13.3	13.8	14.4
12-B	11.1	11.1	11.5	12.5	13.1	13.8	14.4	15.0
12-C	9.4	9.8	10.3	11.2	11.6	12.2	12.8	13.2
Average	10.3	10.8	11.1	12.0	12.5	13.1	13.6	14.2
St. Dev.	0.83	0.91	0.67	0.69	0.79	0.81	0.79	0.90
C. Var. (%)	0.08	0.08	0.06	0.06	0.06	0.06	0.06	0.06
22-A	-	11.0	12.0	12.1	12.9	13.5	14.3	15.1
22-B	-	10.9	11.6	11.9	12.4	13.2	14.4	14.8
22-C	-	10.9	11.7	12.3	12.8	13.4	14.0	15.3
Average		10.9	11.7	12.1	12.7	13.4	14.2	15.1
St. Dev.	-	0.04	0.22	0.19	0.24	0.15	0.20	0.25
C. Var. (%)	-	0.00	0.02	0.02	0.02	0.01	0.01	0.02
66-a	7.5	8.2	7.9	9.8	-	10.7	11.4	11.3
66-b	6.9	7.6	7.4	9.1	-	9.7	10.6	10.5
66-c	7.1	7.8	7.6	9.2	-	10.1	10.8	10.8
Average	7.1	7.8	7.6	9.4		10.2	10.9	10.8
St. Dev.	0.29	0.31	0.23	0.37	-	0.47	0.41	0.39
C. Var. (%)	0.04	0.04	0.03	0.04	-	0.05	0.04	0.04

Resistivity Data

Producer-2

w/cm ratio = 0.38 Aggregate Size = #57

% Fly Ash = 20 Paste Fraction = 20%

Sample OSU#	Days							
	7	14	21	28	35	42	49	56
26-a	-	7.7	8.2	8.5	8.9	9.5	9.8	9.9
26-b	-	7.7	8.1	8.6	8.9	9.6	10.0	10.1
26-c	-	7.2	7.6	7.9	8.3	9.0	9.1	9.3
Average		7.5	8.0	8.3	8.7	9.4	9.6	9.8
St. Dev.	-	0.28	0.31	0.35	0.38	0.30	0.47	0.45
C. Var. (%)	-	0.04	0.04	0.04	0.04	0.03	0.05	0.05
30-a	-	-	-	9.3	10.1	10.9	12.0	12.9
30-b	-	-	-	9.3	10.1	10.9	12.0	12.8
30-c	-	-	-	9.4	10.3	11.2	12.4	13.2
Average				9.3	10.1	11.0	12.1	13.0
St. Dev.	-	-	-	0.05	0.11	0.15	0.20	0.21
C. Var. (%)	-	-	-	0.01	0.01	0.01	0.02	0.02
50-a	7.2	8.5	9.4	10.8	12.6	-	-	15.2
50-b	7.1	8.3	9.1	11.0	11.8	-	-	14.9
50-c	7.4	8.7	9.7	11.1	12.4	-	-	15.7
Average	7.2	8.5	9.4	11.0	12.2			15.3
St. Dev.	0.17	0.20	0.29	0.13	0.41	-	-	0.43
C. Var. (%)	0.02	0.02	0.03	0.01	0.03			0.03
56-a	-	10.6	14.6	17.1	21.1	-	-	29.5
56-b	-	11.2	15.3	18.0	22.2	-	-	30.7
56-c	-	10.2	14.0	16.3	21.1	-	-	28.3
Average		10.6	14.6	17.1	21.5			29.5
St. Dev.	-	0.49	0.65	0.86	0.64	-	-	1.24
C. Var. (%)		0.05	0.04	0.05	0.03			0.04

Resistivity Data

Producer-3
w/cm ratio = 0.42 Aggregate Size = #57
% Fly Ash = 15 Paste Fraction = 23%

	Days							
Sample OSU#	7	14	21	28	35	42	49	56
8-A	6.1	7.4	8.3	9.2	9.9	10.4	11.5	12.0
8-B	6.7	7.7	8.4	9.3	10.0	10.8	11.4	12.3
8-C	6.7	7.7	8.3	9.3	9.9	10.7	11.3	12.2
Average	6.5	7.6	8.3	9.3	9.9	10.6	11.4	12.1
St. Dev.	0.35	0.18	0.05	0.05	0.09	0.22	0.10	0.18
C. Var. (%)	0.05	0.02	0.01	0.01	0.01	0.02	0.01	0.01
13-A	7.0	8.2	9.4	10.1	11.5	12.1	12.8	12.6
13-B	7.1	8.5	9.9	10.6	12.2	12.9	13.6	13.3
13-C	7.4	8.8	10.3	11.0	12.4	13.2	14.1	13.7
Average	7.2	8.5	9.9	10.6	12.0	12.7	13.5	13.2
St. Dev.	0.20	0.29	0.41	0.45	0.50	0.55	0.67	0.54
C. Var. (%)	0.03	0.03	0.04	0.04	0.04	0.04	0.05	0.04
14-A	6.7	7.7	9.0	9.5	10.6	11.3	11.8	11.9
14-B	6.9	8.1	9.2	10.0	11.4	12.1	12.4	12.5
14-C	6.5	7.6	9.1	9.6	10.7	11.6	12.0	11.9
Average	6.7	7.8	9.1	9.7	10.9	11.7	12.0	12.1
St. Dev.	0.19	0.27	0.14	0.26	0.40	0.39	0.29	0.35
C. Var. (%)	0.03	0.03	0.02	0.03	0.04	0.03	0.02	0.03
39-a	7.1	7.5	8.8	9.8	11.2	10.6	12.9	-
39-b	6.4	6.8	7.9	8.9	10.0	10.3	11.8	-
39-c	7.0	7.3	8.5	9.4	10.5	10.1	12.4	-
Average	6.8	7.2	8.4	9.4	10.6	10.3	12.4	
St. Dev.	0.37	0.34	0.44	0.46	0.59	0.26	0.54	-
C. Var. (%)	0.05	0.05	0.05	0.05	0.06	0.02	0.04	-

Producer-4	w/cm ratio =	0.44	Aggregate Size =	#57
	% Fly Ash =	20	Paste Fraction =	28%

Sample OSU#	Days							
	7	14	21	28	35	42	49	56
3-A	-	4.5	-	4.9	5.4	5.6	5.9	6.4
3-B	-	4.4	-	4.8	5.2	5.6	6.0	6.4
3-C	-	4.5	-	5.0	5.4	5.8	6.0	6.4
Average		4.5		4.9	5.3	5.7	6.0	6.4
St. Dev.	-	0.05	-	0.09	0.07	0.09	0.05	0.03
C. Var. (%)	-	0.01	-	0.02	0.01	0.02	0.01	0.00
17-A	-	-	4.7	5.2	5.6	5.9	6.1	6.3
17-B	-	-	4.6	5.2	5.5	5.8	5.9	6.2
17-C	-	-	4.7	5.2	5.6	6.0	6.2	6.4
Average			4.7	5.2	5.6	5.9	6.1	6.3
St. Dev.	-	-	0.03	0.03	0.08	0.09	0.14	0.11
C. Var. (%)	-	-	0.01	0.01	0.01	0.02	0.02	0.02
21-A	-	4.8	5.4	5.5	5.7	5.9	6.1	6.5
21-B	-	4.6	5.1	5.4	5.6	5.8	6.0	6.5
22-c	-	4.7	5.3	5.5	6.4	6.0	6.4	6.5
Average		4.7	5.3	5.5	5.9	5.9	6.2	6.5
St. Dev.	-	0.11	0.14	0.05	0.44	0.09	0.19	0.02
C. Var. (%)	-	0.02	0.03	0.01	0.08	0.01	0.03	0.00
53-a	-	-	4.8	5.5	6.1	6.8	-	-
53-b	-	-	4.6	5.0	5.6	6.1	-	-
53.c	-	-	4.9	5.5	6.2	6.7	-	-
Average			4.8	5.3	6.0	6.5		
St. Dev.	-	-	0.19	0.33	0.35	0.39	-	-
C. Var. (%)	-	-	0.04	0.06	0.06	0.06	-	-

Producer-5
w/cm ratio = 0.44 Aggregate Size = #57
% Fly Ash = 20 Paste Fraction = 24%

Sample OSU#	Days							
	7	14	21	28	35	42	49	56
31-a	-	-	-	11.0	13.2	14.5	15.1	16.6
31-b	-	-	-	11.4	13.3	14.5	15.7	16.6
31-c	-	-	-	11.4	13.8	14.3	16.1	17.3
Average				11.2	13.4	14.4	15.6	16.8
St. Dev.	-	-	-	0.25	0.35	0.11	0.50	0.38
C. Var. (%)	-	-	-	0.02	0.03	0.01	0.03	0.02
51-a	6.3	7.8	8.8	10.4	12.0	-	-	15.6
51-b	5.7	7.2	8.3	9.9	11.0	-	-	14.7
51-c	5.4	6.7	7.9	9.1	10.6	-	-	14.1
Average	5.8	7.2	8.3	9.8	11.2			14.8
St. Dev.	0.42	0.53	0.43	0.63	0.76	-	-	0.75
C. Var. (%)	0.07	0.07	0.05	0.06	0.07	-	-	0.05

Producer-6
w/cm ratio = 0.41 Aggregate Size = #57
% Fly Ash = 20 Paste Fraction = 24%

Sample OSU#	Days							
	7	14	21	28	35	42	49	56
1-A	-	8.6	10.0	11.4	12.6	13.6	14.6	15.4
1-B	-	8.4	9.9	11.3	12.3	13.4	14.4	15.4
1-C	-	9.1	10.8	12.1	13.5	14.5	15.3	15.5
Average		8.7	10.2	11.6	12.8	13.8	14.7	15.4
St. Dev.	-	0.36	0.45	0.42	0.62	0.61	0.45	0.03
C. Var. (%)	-	0.04	0.04	0.04	0.05	0.04	0.03	0.00
2-A	-	8.4	10.2	11.7	12.9	14.0	15.5	16.5
2-B	-	8.9	10.7	12.0	13.4	14.5	16.1	17.2
2-C	-	8.4	10.0	11.1	12.6	13.6	15.1	16.2
Average		8.5	10.3	11.6	12.9	14.0	15.5	16.6
St. Dev.	-	0.32	0.37	0.46	0.40	0.44	0.51	0.53
C. Var. (%)	-	0.04	0.04	0.04	0.03	0.03	0.03	0.03

Producer-7

w/cm ratio = 0.41 Aggregate Size = #57
% Fly Ash = 20 Paste Fraction = 27%

Sample OSU#	Days							
	7	14	21	28	35	42	49	56
58-a	4.9	6.3	7.8	9.0	-	-	12.0	11.9
58-b	4.6	6.0	7.4	8.6	-	-	11.4	11.6
58-c	4.9	6.4	7.7	8.8	-	-	11.8	11.9
Average	4.8	6.2	7.6	8.8			11.7	11.8
St. Dev.	0.17	0.19	0.19	0.20	-	-	0.34	0.19
C. Var. (%)	0.03	0.03	0.03	0.02	-	-	0.03	0.02
59-a	4.4	5.9	7.3	8.3	-	-	11.7	11.6
59-b	4.5	6.0	7.3	8.6	-	-	12.2	11.9
59-c	4.7	6.1	7.3	8.5	-	-	11.6	11.8
Average	4.5	6.0	7.3	8.5			11.8	11.8
St. Dev.	0.15	0.08	0.04	0.13	-	-	0.34	0.15
C. Var. (%)	0.03	0.01	0.01	0.02	-	-	0.03	0.01

Producer-8

w/cm ratio = 0.44 Aggregate Size = #57
% Fly Ash = 0 Paste Fraction = 28%

Sample OSU#	Days							
	7	14	21	28	35	42	49	56
10-A	-	9.8	9.4	9.3	9.3	9.5	9.7	9.7
10-B	-	9.8	9.1	9.1	9.2	9.1	9.4	9.4
10-C	-	9.8	9.2	9.2	9.7	9.3	9.5	9.5
Average		9.8	9.2	9.2	9.4	9.3	9.5	9.6
St. Dev.	-	0.04	0.12	0.09	0.26	0.23	0.15	0.16
C. Var. (%)	-	0.00	0.01	0.01	0.03	0.02	0.02	0.02
11-A	-	9.1	8.2	8.1	8.3	8.3	8.3	9.0
11-B	-	9.6	8.7	8.6	8.6	8.7	8.8	8.9
11-C	-	9.9	8.8	8.7	8.5	9.0	8.9	9.3
Average		9.5	8.5	8.5	8.5	8.7	8.7	9.1
St. Dev.	-	0.42	0.30	0.31	0.17	0.33	0.29	0.20
C. Var. (%)	-	0.04	0.03	0.04	0.02	0.04	0.03	0.02

Resistivity Data

w/cm ratio = 0.40 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 0 Aggregate Type = Limestone Paste Fraction = 27%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
40-00-1	5.0	6.2	8.6	10.0	10.7	11.5	12.2	13.0	12.7	13.2
40-00-2	5.4	7.1	9.4	11.2	11.8	12.5	13.0	13.7	13.9	14.5
40-00-3	5.2	7.0	9.3	11.0	11.6	12.4	13.1	13.5	14.2	14.0
40-00-4	5.6	7.2	9.4	11.2	12.0	12.4	13.2	14.1	13.8	14.4
40-00-5	5.3	7.0	9.3	11.5	12.1	12.7	13.5	14.2	13.9	14.4
40-00-6	5.6	7.3	9.5	11.5	12.3	12.7	13.7	13.9	14.2	14.7
Average	5.3	7.0	9.2	11.0	11.7	12.4	13.1	13.7	13.8	14.2
St. Dev.	0.24	0.38	0.34	0.56	0.55	0.47	0.53	0.41	0.56	0.55
C. Var. (%)	4.48	5.50	3.69	5.08	4.67	3.78	4.06	3.01	4.04	3.87

w/cm ratio = 0.40 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 10 Aggregate Type = Limestone Paste Fraction = 27%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
40-10-1	4.3	7.2	10.0	11.9	13.4	13.7	15.0	15.3	15.4	15.8
40-10-2	5.5	7.2	10.4	12.6	13.5	13.6	15.1	15.9	15.5	16.1
40-10-3	4.4	7.0	9.8	11.7	12.8	13.4	14.4	15.0	15.1	15.7
40-10-4	4.4	6.8	9.0	10.9	11.7	12.4	13.3	14.0	14.0	14.8
40-10-5	4.9	8.0	11.3	13.4	14.1	14.3	16.0	16.2	16.5	17.1
40-10-6	4.2	6.6	9.7	11.3	12.6	12.8	13.6	14.4	13.7	15.1
Average	4.6	7.1	10.0	12.0	13.0	13.4	14.6	15.1	15.0	15.7
St. Dev.	0.51	0.46	0.76	0.91	0.83	0.69	1.00	0.85	1.03	0.80
C. Var. (%)	11.17	6.50	7.60	7.57	6.35	5.16	6.87	5.60	6.84	5.11

w/cm ratio = 0.40 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 20 Aggregate Type = Limestone Paste Fraction = 27%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
40-20-1	3.8	6.4	8.6	10.2	11.2	12.3	13.3	14.5	14.7	15.7
40-20-2	4.5	6.8	9.8	11.0	12.4	13.1	14.6	15.8	16.2	17.3
40-20-3	4.7	7.2	8.2	11.4	12.6	13.4	14.8	16.2	16.7	17.8
40-20-4	4.1	6.2	9.0	10.0	10.7	11.3	12.8	13.5	14.3	15.1
40-20-5	4.0	6.6	7.8	10.6	11.4	12.5	13.3	14.7	15.0	16.2
40-20-6	4.4	6.7	8.0	11.0	11.7	13.2	14.1	15.2	15.8	16.6
Average	4.3	6.6	8.5	10.7	11.6	12.6	13.8	15.0	15.4	16.4
St. Dev.	0.33	0.34	0.73	0.53	0.72	0.77	0.79	0.98	0.93	0.99
C. Var. (%)	7.86	5.20	8.60	4.92	6.16	6.12	5.71	6.58	6.00	6.05

Resistivity Data

w/cm ratio = 0.45 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 0 Aggregate Type = Limestone Paste Fraction = 28%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
45-00-1	6.5	7.0	9.1	10.8	11.5	12.1	12.3	12.9	12.8	13.5
45-00-2	6.1	6.7	8.9	10.2	10.9	11.6	11.8	12.3	12.6	12.5
45-00-3	5.2	6.1	8.2	9.3	9.9	10.6	11.0	11.3	11.6	11.8
45-00-4	6.1	7.0	9.3	10.7	11.5	12.3	13.7	13.1	13.2	13.4
45-00-5	4.7	6.0	8.2	9.6	10.2	10.7	11.1	11.6	12.7	12.2
45-00-6	5.4	6.8	9.1	10.5	11.2	12.0	12.4	12.7	12.9	13.2
Average	5.7	6.6	8.8	10.2	10.9	11.5	12.0	12.3	12.6	12.8
St. Dev.	0.67	0.44	0.49	0.61	0.69	0.74	1.01	0.72	0.55	0.70
C. Var. (%)	11.83	6.70	5.57	6.05	6.34	6.43	8.43	5.86	4.32	5.48

w/cm ratio = 0.45 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 10 Aggregate Type = Limestone Paste Fraction = 28%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
45-10-1	5.4	6.5	8.7	10.0	10.7	11.2	12.5	12.3	12.3	12.9
45-10-2	4.7	7.3	9.5	10.8	11.7	12.5	13.3	13.7	13.7	14.4
45-10-3	5.5	6.8	9.3	10.5	11.2	11.9	12.8	13.0	12.9	13.4
45-10-4	4.4	7.1	9.4	11.1	12.2	12.8	13.5	14.0	14.4	14.8
45-10-5	4.9	6.9	9.2	10.5	11.5	12.1	13.0	13.0	13.3	13.6
45-10-6	3.8	6.2	8.4	9.7	10.3	11.1	11.7	12.2	12.1	12.5
Average	4.8	6.8	9.1	10.4	11.2	11.9	12.8	13.0	13.1	13.6
St. Dev.	0.63	0.40	0.43	0.51	0.70	0.69	0.65	0.71	0.87	0.86
C. Var. (%)	13.20	5.93	4.78	4.85	6.22	5.77	5.12	5.42	6.64	6.29

w/cm ratio = 0.45 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 20 Aggregate Type = Limestone Paste Fraction = 28%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
45-20-1	4.3	5.9	8.2	8.8	9.6	10.5	11.6	11.8	12.6	13.1
45-20-2	4.2	6.4	8.5	9.6	10.6	11.6	12.9	13.1	13.7	14.5
45-20-3	3.3	5.3	7.2	8.1	9.1	9.8	10.6	11.0	11.6	12.2
45-20-4	4.0	6.3	8.3	9.3	10.5	11.3	12.7	13.2	14.0	14.5
45-20-5	3.4	6.6	9.1	10.1	11.1	12.2	13.2	13.8	15.0	15.2
45-20-6	3.9	6.6	8.8	10.1	11.0	11.7	13.3	13.9	15.0	14.9
Average	3.8	6.2	8.4	9.3	10.3	11.2	12.4	12.8	13.6	14.0
St. Dev.	0.41	0.50	0.65	0.79	0.79	0.90	1.04	1.16	1.34	1.17
C. Var. (%)	10.62	8.13	7.83	8.44	7.69	8.05	8.45	9.10	9.86	8.36

w/cm ratio = 0.50 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 0 Aggregate Type = Limestone Paste Fraction = 29%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
50-00-1	5.0	5.6	7.1	8.3	9.1	9.5	10.1	10.4	10.6	10.8
50-00-2	4.7	6.1	7.8	9.3	9.9	10.2	11.0	11.1	11.5	11.3
50-00-3	5.1	6.0	7.4	8.8	9.4	10.0	10.6	11.2	10.8	10.9
50-00-4	4.5	5.9	7.6	8.9	9.7	10.3	10.7	11.0	11.0	11.4
50-00-5	5.5	5.9	7.7	9.1	9.8	10.3	10.8	11.6	11.4	11.5
50-00-6	5.1	6.1	7.8	9.2	9.8	10.7	10.8	10.9	11.3	11.4
Average	5.0	5.9	7.5	8.9	9.6	10.2	10.7	11.0	11.1	11.2
St. Dev.	0.34	0.18	0.28	0.34	0.31	0.40	0.32	0.37	0.35	0.28
C. Var. (%)	6.93	3.02	3.65	3.86	3.22	3.94	3.05	3.33	3.19	2.51

w/cm ratio = 0.50 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 10 Aggregate Type = Limestone Paste Fraction = 29%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
50-10-1	3.2	5.3	7.4	8.0	8.6	9.2	9.8	10.6	10.3	10.6
50-10-2	3.2	5.3	7.5	8.3	8.8	9.4	10.1	10.2	10.7	10.9
50-10-3	2.8	5.2	6.9	7.6	8.4	8.9	9.3	10.1	9.8	10.0
50-10-4	2.9	4.9	7.1	7.7	8.3	8.8	9.3	9.4	9.9	10.2
50-10-5	3.0	5.1	7.2	8.0	8.2	8.7	9.3	9.9	10.4	10.1
50-10-6	2.9	5.2	7.1	7.9	8.4	8.9	9.5	9.8	10.3	10.6
Average	3.0	5.2	7.2	7.9	8.4	9.0	9.5	10.0	10.2	10.4
St. Dev.	0.16	0.15	0.22	0.25	0.23	0.25	0.32	0.40	0.31	0.36
C. Var. (%)	5.47	2.87	3.06	3.22	2.75	2.77	3.38	3.97	2.99	3.48

w/cm ratio = 0.50 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 20 Aggregate Type = Limestone Paste Fraction = 29%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
50-20-1	4.4	5.8	7.9	9.3	9.6	10.9	12.4	12.3	13.2	14.0
50-20-2	3.7	6.1	7.7	8.6	10.3	10.3	11.6	12.5	12.9	13.1
50-20-3	2.7	5.3	7.3	8.3	9.0	9.6	10.4	11.4	11.6	12.4
50-20-4	3.1	5.8	7.8	8.6	9.5	10.4	12.0	12.4	12.9	13.0
50-20-5	3.2	5.2	7.2	8.0	8.9	9.5	11.0	11.2	12.2	12.6
50-20-6	3.5	5.8	8.0	9.3	9.9	11.1	12.2	13.7	14.4	14.1
Average	3.4	5.6	7.7	8.7	9.5	10.3	11.6	12.2	12.8	13.2
St. Dev.	0.58	0.33	0.35	0.54	0.54	0.66	0.77	0.92	0.96	0.71
C. Var. (%)	16.79	5.79	4.52	6.20	5.68	6.46	6.63	7.51	7.48	5.38

w/cm ratio = 0.45 Aggregate Size = #56 Fly Ash Source = Muskogee
% Fly Ash = 20 Aggregate Type = Limestone Paste Fraction = 27%

Sample ID	Day									
	1	7	14	21	28	35	42	49	56	
45-20-1	5.5	8.9	10.4	11.5	12.3	13.9	14.2	15.0	15.9	
45-20-2	4.4	7.7	9.0	10.1	10.6	12.1	12.3	13.2	14.0	
45-20-3	5.0	8.3	9.0	11.1	11.7	13.0	13.5	14.2	15.1	
45-20-4	4.9	8.2	9.7	10.9	11.6	-	-	-	-	
45-20-5	5.4	9.1	10.7	12.0	12.3	-	-	-	-	
45-20-6	4.8	8.0	9.4	10.5	11.0	-	-	-	-	
Average	5.0	8.4	9.7	11.0	11.6	13.0	13.3	14.1	15.0	
St. Dev.	0.42	0.53	0.73	0.67	0.69	0.90	0.96	0.91	0.97	
C. Var. (%)	8.37	6.35	7.49	6.09	5.97	6.92	7.17	6.49	6.45	

w/cm ratio = 0.45 Aggregate Size = #56 Fly Ash Source = Nixon
% Fly Ash = 20 Aggregate Type = Limestone Paste Fraction = 27%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
45-20-1	4.1	5.2	6.5	7.9	9.1	10.1	11.4	11.9	13.2	13.7
45-20-2	4.2	5.2	6.5	8.0	9.3	10.6	12.1	12.9	14.2	15.1
45-20-3	4.4	5.6	7.0	7.6	9.7	10.8	12.7	13.4	14.5	15.4
45-20-4	4.6	6.5	7.8	9.3	11.4	13.0	-	-	-	-
45-20-5	4.3	5.6	6.8	7.9	9.5	11.0	-	-	-	-
45-20-6	5.0	6.5	7.3	9.1	10.3	12.3	-	-	-	-
Average	4.4	5.7	7.0	8.3	9.9	11.3	12.1	12.7	14.0	14.7
St. Dev.	0.33	0.59	0.49	0.70	0.83	1.10	0.65	0.76	0.69	0.88
C. Var. (%)	7.39	10.27	7.08	8.50	8.44	9.72	5.41	5.98	4.94	6.00

w/cm ratio = 0.40 Aggregate Size = #67 Fly Ash Source = Red Rock
% Fly Ash = 0 Aggregate Type = Limestone Paste Fraction = 27%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
40-00-1	6.1	8.1	9.6	10.8	12.1	12.3	12.8	13.4	13.3	13.8
40-00-2	6.8	8.9	10.6	12.1	12.6	13.6	13.9	15.1	13.5	14.4
40-00-3	6.0	8.6	9.9	11.1	12.2	13.1	12.9	14.0	13.2	14.0
40-00-4	6.4	8.2	9.8	11.1	12.5	13.0	-	-	-	-
40-00-5	6.4	8.4	10.0	11.3	12.4	13.1	-	-	-	-
40-00-6	6.1	8.5	10.0	11.3	12.1	12.9	-	-	-	-
Average	6.3	8.4	10.0	11.3	12.3	13.0	13.2	14.2	13.3	14.1
St. Dev.	0.30	0.29	0.33	0.45	0.22	0.41	0.62	0.87	0.14	0.29
C. Var. (%)	4.79	3.45	3.33	3.95	1.81	3.17	4.73	6.13	1.03	2.08

w/cm ratio = 0.40 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 5 Aggregate Type = Limestone Paste Fraction = 27%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
40-05-1	5.0	7.1	9.6	11.3	11.8	12.5	13.5	14.5	14.4	13.2
40-05-2	4.5	6.5	8.7	10.4	11.4	11.6	12.3	13.4	13.2	14.5
40-05-3	4.1	6.6	9.0	10.2	11.0	11.8	12.6	12.9	13.0	14.0
40-05-4	4.9	7.6	9.8	11.6	12.4	13.2	13.7	14.5	14.1	14.4
40-05-5	5.3	6.9	9.4	10.7	11.4	12.0	12.9	13.6	13.3	14.4
40-05-6	4.4	6.6	9.2	11.1	11.5	11.8	12.6	13.4	13.3	14.7
Average	4.7	6.9	9.3	10.9	11.6	12.1	12.9	13.7	13.5	14.2
St. Dev.	0.42	0.40	0.42	0.54	0.46	0.59	0.55	0.64	0.55	0.54
C. Var. (%)	9.01	5.86	4.51	4.97	3.95	4.85	4.28	4.69	4.10	3.84

w/cm ratio = 0.40 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 15 Aggregate Type = Limestone Paste Fraction = 27%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
40-00-1	5.5	7.3	10.1	11.9	12.9	13.8	14.9	15.7	15.9	16.6
40-00-2	4.3	6.5	9.0	11.3	10.9	12.3	13.7	14.1	14.6	15.3
40-00-3	4.6	6.7	8.8	10.9	11.6	12.3	13.5	14.4	14.5	15.1
40-00-4	5.2	7.6	9.9	11.9	13.0	13.5	15.0	15.8	16.0	17.0
40-00-5	4.6	6.6	9.2	11.1	11.9	12.5	13.8	14.6	15.4	15.3
40-00-6	4.8	6.4	8.6	10.6	11.2	12.0	13.1	13.7	14.3	14.8
Average	4.8	6.8	9.3	11.3	11.9	12.7	14.0	14.7	15.1	15.7
St. Dev.	0.45	0.49	0.59	0.54	0.87	0.72	0.79	0.85	0.73	0.90
C. Var. (%)	9.39	7.14	6.40	4.75	7.31	5.62	5.66	5.79	4.83	5.76

w/cm ratio = 0.40 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 25 Aggregate Type = Limestone Paste Fraction = 27%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
40-25-1	3.3	5.6	8.8	9.2	10.6	11.7	12.9	14.4	15.3	15.9
40-25-2	3.5	6.1	8.7	9.8	10.9	12.3	13.6	15.0	15.3	16.8
40-25-3	3.4	5.5	7.8	9.3	9.9	11.3	12.7	13.8	14.3	15.7
40-25-4	3.0	5.7	7.8	9.2	10.5	11.7	13.0	14.6	15.2	16.7
40-25-5	3.3	5.2	7.5	8.9	9.9	11.1	11.9	13.3	14.2	15.3
40-25-6	3.4	6.1	8.0	9.6	11.0	11.5	13.5	14.9	15.9	17.0
Average	3.3	5.7	8.1	9.3	10.4	11.6	12.9	14.3	15.0	16.2
St. Dev.	0.17	0.35	0.53	0.32	0.48	0.44	0.61	0.66	0.65	0.70
C. Var. (%)	5.18	6.18	6.60	3.39	4.57	3.81	4.75	4.59	4.35	4.33

w/cm ratio = 0.45 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 5 Aggregate Type = Limestone Paste Fraction = 28%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
45-05-1	5.0	6.6	9.0	10.2	10.9	11.7	12.3	12.8	12.7	13.3
45-05-2	5.6	6.8	9.1	10.6	11.2	11.9	12.8	12.6	13.1	13.5
45-05-3	4.5	6.2	8.4	9.5	10.2	10.8	11.1	11.6	11.8	11.9
45-05-4	5.5	6.6	8.7	10.0	10.6	11.3	12.2	12.5	12.3	12.8
45-05-5	5.9	6.9	9.3	10.6	11.3	12.0	12.6	12.8	12.9	13.3
45-05-6	6.0	7.2	9.5	11.1	12.0	12.4	13.4	13.4	13.8	14.1
Average	5.4	6.7	9.0	10.3	11.0	11.7	12.4	12.6	12.8	13.1
St. Dev.	0.56	0.32	0.41	0.56	0.63	0.58	0.75	0.60	0.68	0.73
C. Var. (%)	10.40	4.80	4.51	5.39	5.72	4.97	6.04	4.76	5.33	5.52

w/cm ratio = 0.45 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 15 Aggregate Type = Limestone Paste Fraction = 28%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
45-15-1	4.3	6.1	8.3	9.5	10.5	10.8	12.0	11.9	12.5	12.7
45-15-2	5.1	7.4	10.0	11.6	12.1	13.4	14.1	14.7	15.2	15.3
45-15-3	4.9	7.2	9.8	10.8	11.9	12.8	13.5	14.3	14.3	14.9
45-15-4	4.8	6.9	9.2	10.4	11.3	12.4	13.1	13.1	14.2	14.3
45-15-5	4.3	7.1	9.7	10.9	12.8	12.9	13.9	13.3	14.6	14.8
45-15-6	4.1	6.8	9.5	11.2	11.5	12.5	12.9	13.9	14.4	14.4
Average	4.6	6.9	9.4	10.7	11.6	12.5	13.2	13.5	14.2	14.4
St. Dev.	0.40	0.44	0.64	0.75	0.79	0.90	0.76	0.99	0.89	0.89
C. Var. (%)	8.74	6.37	6.75	7.01	6.75	7.20	5.73	7.32	6.28	6.22

w/cm ratio = 0.45 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 25 Aggregate Type = Limestone Paste Fraction = 28%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
45-25-1	3.8	6.5	8.8	10.8	11.5	12.9	14.0	15.3	16.0	16.9
45-25-2	4.1	6.2	8.2	9.3	10.4	11.9	12.7	13.6	14.4	15.2
45-25-3	3.7	6.2	8.6	10.0	10.7	12.1	13.1	14.1	15.0	15.7
45-25-4	2.8	5.5	7.7	8.8	9.8	10.7	11.8	12.6	13.4	14.3
45-25-5	3.3	6.4	9.3	10.2	11.5	12.6	14.0	14.8	15.7	16.8
45-25-6	3.4	6.0	8.2	10.0	10.6	12.5	12.9	13.6	15.0	15.8
Average	3.5	6.1	8.4	9.8	10.7	12.1	13.1	14.0	14.9	15.8
St. Dev.	0.48	0.36	0.55	0.71	0.65	0.78	0.85	0.99	0.93	0.97
C. Var. (%)	13.68	5.85	6.48	7.20	6.04	6.45	6.49	7.06	6.25	6.18

Resistivity Data

w/cm ratio = 0.50 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 5 Aggregate Type = Limestone Paste Fraction = 29%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
50-05-1	4.2	5.3	7.3	8.3	9.2	9.6	10.4	11.1	10.6	10.7
50-05-2	3.4	5.2	7.0	8.2	9.0	9.2	9.6	10.3	10.0	10.6
50-05-3	3.6	4.8	6.5	7.4	8.0	8.3	8.8	9.5	9.2	9.3
50-05-4	4.3	5.7	7.6	8.8	9.4	10.0	10.2	10.7	10.7	11.0
50-05-5	3.8	5.5	8.0	8.7	9.1	9.7	10.2	10.8	10.6	10.7
50-05-6	3.9	5.4	7.8	8.6	9.3	9.7	10.3	10.8	10.9	10.9
Average	3.9	5.3	7.3	8.3	9.0	9.4	9.9	10.5	10.3	10.5
St. Dev.	0.33	0.31	0.56	0.52	0.51	0.58	0.60	0.58	0.62	0.64
C. Var. (%)	8.61	5.86	7.57	6.27	5.64	6.18	6.07	5.54	6.04	6.05

w/cm ratio = 0.50 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 15 Aggregate Type = Limestone Paste Fraction = 29%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
50-15-1	3.4	5.7	7.5	8.3	9.3	10.0	10.8	11.1	11.5	11.8
50-15-2	3.3	5.5	7.7	8.2	8.9	9.5	10.4	10.5	11.0	12.0
50-15-3	3.4	5.7	7.7	8.6	9.2	9.7	10.8	12.1	11.5	11.5
50-15-4	3.6	5.6	7.6	8.1	9.2	9.6	10.6	11.6	11.3	11.7
50-15-5	3.1	5.5	6.8	8.1	8.9	9.6	10.3	10.4	10.6	11.2
50-15-6	2.8	4.9	6.4	7.4	8.0	8.8	9.4	10.0	10.2	10.1
Average	3.3	5.5	7.3	8.1	8.9	9.5	10.4	10.9	11.0	11.4
St. Dev.	0.27	0.31	0.57	0.38	0.50	0.39	0.55	0.79	0.52	0.68
C. Var. (%)	8.18	5.71	7.86	4.64	5.60	4.05	5.26	7.18	4.74	5.94

w/cm ratio = 0.50 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 25 Aggregate Type = Limestone Paste Fraction = 29%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
50-25-1	3.1	4.9	6.9	8.1	8.9	10.3	11.5	12.7	13.2	14.0
50-25-2	2.2	3.9	5.5	6.6	6.9	8.0	9.4	9.7	10.6	10.8
50-25-3	2.6	5.0	7.1	7.7	8.9	9.8	11.5	12.4	13.1	13.9
50-25-4	2.6	5.0	6.8	8.1	8.8	10.3	11.9	12.7	13.1	13.6
50-25-5	2.8	5.0	7.0	8.2	9.2	10.6	12.2	12.3	13.6	14.0
50-25-6	2.6	4.0	5.9	6.3	7.2	8.1	8.9	9.9	10.6	11.2
Average	2.6	4.6	6.5	7.5	8.3	9.5	10.9	11.6	12.3	12.9
St. Dev.	0.30	0.53	0.65	0.81	1.00	1.15	1.39	1.43	1.41	1.49
C. Var. (%)	11.40	11.45	9.98	10.85	12.10	12.12	12.78	12.34	11.39	11.52

w/cm ratio = 0.55 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 0 Aggregate Type = Limestone Paste Fraction = 30%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
55-00-1	4.8	4.9	6.4	7.2	7.8	8.4	8.5	9.1	9.4	9.5
55-00-2	4.4	4.9	6.5	7.5	8.0	8.6	8.7	9.0	9.4	9.6
55-00-3	3.8	4.3	6.1	6.9	7.7	8.2	8.3	8.3	8.4	8.7
55-00-4	4.0	5.0	6.8	7.8	8.6	9.0	9.3	9.4	9.4	9.7
55-00-5	4.1	4.9	6.6	7.5	8.4	8.6	8.9	9.2	9.3	9.6
55-00-6	3.9	4.9	6.7	7.7	8.6	8.9	9.2	9.2	9.7	9.9
Average	4.1	4.8	6.5	7.4	8.2	8.6	8.8	9.0	9.3	9.5
St. Dev.	0.37	0.25	0.26	0.35	0.37	0.30	0.37	0.41	0.43	0.41
C. Var. (%)	8.99	5.09	3.93	4.72	4.59	3.49	4.24	4.55	4.67	4.37

w/cm ratio = 0.55 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 5 Aggregate Type = Limestone Paste Fraction = 30%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
55-05-1	4.0	4.8	6.3	7.5	8.4	8.5	9.0	9.5	9.2	9.7
55-05-2	4.6	5.7	7.5	8.9	9.6	10.2	10.4	10.6	10.4	11.5
55-05-3	3.9	4.5	6.1	7.1	7.8	8.3	8.5	8.8	8.7	9.2
55-05-4	4.2	5.3	7.4	8.6	9.3	10.0	10.1	10.3	10.7	11.0
55-05-5	4.2	4.6	6.3	7.6	8.4	8.9	9.0	9.4	9.4	9.6
55-05-6	4.1	5.2	7.2	8.4	9.2	9.7	10.0	10.0	10.5	10.9
Average	4.1	5.0	6.8	8.0	8.8	9.3	9.5	9.8	9.8	10.3
St. Dev.	0.26	0.47	0.62	0.72	0.68	0.82	0.78	0.68	0.81	0.95
C. Var. (%)	6.27	9.32	9.22	8.99	7.77	8.90	8.25	6.97	8.30	9.24

w/cm ratio = 0.55 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 10 Aggregate Type = Limestone Paste Fraction = 30%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
55-10-1	3.7	4.5	6.4	7.6	8.7	9.2	9.1	9.5	9.7	9.7
55-10-2	3.7	5.6	6.9	8.4	9.6	10.0	10.3	10.4	10.7	10.9
55-10-3	3.1	4.4	6.4	7.5	8.1	8.6	8.7	8.9	9.4	9.3
55-10-4	2.9	4.1	5.7	7.0	8.0	8.2	8.1	7.8	8.5	9.0
55-10-5	3.1	4.9	6.9	8.3	9.6	9.8	10.0	10.1	10.4	10.5
55-10-6	3.0	4.6	6.7	7.9	9.0	9.0	9.0	9.4	9.4	9.8
Average	3.2	4.7	6.5	7.8	8.8	9.1	9.2	9.3	9.7	9.9
St. Dev.	0.36	0.53	0.44	0.54	0.71	0.70	0.80	0.92	0.78	0.73
C. Var. (%)	11.02	11.22	6.85	6.93	8.05	7.70	8.71	9.89	8.05	7.43

w/cm ratio = 0.55 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 15 Aggregate Type = Limestone Paste Fraction = 30%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
55-15-1	2.5	4.3	6.1	6.9	7.4	7.9	8.2	8.5	8.7	8.8
55-15-2	2.3	4.0	5.6	6.3	7.1	7.4	7.6	7.9	8.1	8.2
55-15-3	2.7	4.5	6.6	6.9	8.5	8.5	9.0	9.3	9.4	9.7
55-15-4	2.5	4.5	6.5	7.1	8.4	8.5	8.9	9.0	9.3	9.6
55-15-5	2.5	3.9	5.5	6.3	7.6	7.6	7.5	7.6	8.0	8.3
55-15-6	2.8	4.3	5.8	7.5	7.8	8.0	8.0	8.5	8.5	9.0
Average	2.5	4.2	6.0	6.8	7.8	8.0	8.2	8.4	8.7	8.9
St. Dev.	0.16	0.25	0.47	0.47	0.55	0.43	0.63	0.64	0.60	0.60
C. Var. (%)	6.42	5.85	7.85	6.80	7.05	5.38	7.71	7.54	6.91	6.77

w/cm ratio = 0.55 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 20 Aggregate Type = Limestone Paste Fraction = 30%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
55-20-1	3.2	5.3	7.4	8.7	10.0	10.4	10.6	11.4	11.3	12.0
55-20-2	3.6	5.2	7.1	8.1	9.3	9.3	9.7	10.3	11.1	11.2
55-20-3	3.5	5.3	7.3	8.1	9.1	9.2	9.9	10.1	10.9	11.1
55-20-4	2.9	5.0	6.9	7.9	8.4	9.1	9.2	10.1	10.2	10.9
55-20-5	3.0	5.6	7.5	8.4	10.0	10.0	10.5	10.9	11.3	12.1
55-20-6	3.2	5.5	7.4	8.1	9.8	9.8	10.3	10.9	11.5	11.9
Average	3.2	5.3	7.3	8.2	9.4	9.6	10.0	10.6	11.0	11.5
St. Dev.	0.28	0.22	0.24	0.29	0.65	0.51	0.53	0.54	0.48	0.52
C. Var. (%)	8.63	4.25	3.30	3.53	6.91	5.27	5.29	5.07	4.36	4.49

w/cm ratio = 0.55 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 25 Aggregate Type = Limestone Paste Fraction = 30%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
55-25-1	2.7	4.7	6.7	7.1	8.3	8.3	9.1	10.4	10.5	11.2
55-25-2	2.7	4.7	6.6	7.8	9.3	9.6	10.2	12.0	11.4	11.9
55-25-3	2.9	5.4	7.5	8.3	10.0	10.2	10.9	12.6	12.5	12.5
55-25-4	3.0	5.0	7.4	7.8	9.7	10.3	10.3	12.4	12.1	12.7
55-25-5	3.1	5.4	7.5	9.0	10.3	10.5	11.6	12.2	12.8	13.5
55-25-6	3.0	5.3	7.1	8.2	9.7	10.4	11.0	12.0	12.1	12.9
Average	2.9	5.1	7.1	8.0	9.5	9.9	10.5	11.9	11.9	12.4
St. Dev.	0.18	0.33	0.42	0.64	0.71	0.81	0.87	0.78	0.84	0.82
C. Var. (%)	6.14	6.47	5.88	7.98	7.44	8.24	8.25	6.58	7.04	6.59

w/cm ratio = 0.60 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 0 Aggregate Type = Limestone Paste Fraction = 31%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
60-00-1	4.6	4.9	6.6	7.8	8.5	9.0	9.3	9.6	9.9	9.9
60-00-2	4.7	4.8	6.6	7.5	8.3	8.7	8.3	9.2	9.4	9.5
60-00-3	3.9	4.6	6.5	7.5	8.0	8.3	8.5	8.8	9.0	9.1
60-00-4	3.8	4.5	6.0	7.0	7.7	8.2	8.6	8.5	8.8	11.5
60-00-5	5.1	5.5	7.5	8.9	9.7	10.3	10.7	11.1	11.3	8.9
60-00-6	3.8	4.7	6.6	7.8	8.2	8.7	9.0	9.3	9.6	9.4
Average	4.3	4.8	6.6	7.7	8.4	8.9	9.1	9.4	9.7	9.7
St. Dev.	0.54	0.35	0.51	0.64	0.70	0.75	0.88	0.90	0.88	0.94
C. Var. (%)	12.48	7.15	7.74	8.24	8.31	8.48	9.70	9.61	9.13	9.66

w/cm ratio = 0.60 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 5 Aggregate Type = Limestone Paste Fraction = 31%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
60-05-1	2.6	3.9	5.5	6.5	7.2	7.1	7.6	7.8	7.8	7.6
60-05-2	2.6	4.2	5.9	7.0	7.5	7.6	8.2	8.3	8.2	8.1
60-05-3	2.5	3.9	5.5	6.3	6.8	7.2	7.1	7.5	7.4	7.3
60-05-4	2.1	4.0	5.6	6.5	6.8	7.3	7.4	7.7	7.9	7.5
60-05-5	3.3	4.4	6.1	7.3	7.9	8.3	8.6	8.9	9.1	8.7
60-05-6	3.3	4.7	6.5	7.8	8.2	8.5	8.9	9.1	9.3	8.9
Average	2.7	4.2	5.8	6.9	7.4	7.7	7.9	8.2	8.3	8.0
St. Dev.	0.47	0.31	0.43	0.58	0.57	0.61	0.70	0.65	0.76	0.67
C. Var. (%)	17.39	7.32	7.34	8.41	7.66	7.94	8.84	7.95	9.17	8.41

w/cm ratio = 0.60 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 10 Aggregate Type = Limestone Paste Fraction = 31%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
60-10-1	3.0	3.9	5.3	6.2	6.8	7.3	7.3	7.7	7.7	7.5
60-10-2	4.0	4.2	5.8	6.7	7.3	7.8	7.9	8.1	8.2	8.0
60-10-3	2.4	3.8	5.3	6.2	7.2	7.3	7.2	7.5	7.6	7.4
60-10-4	2.7	3.6	5.1	6.1	6.5	7.0	7.0	7.1	7.3	7.1
60-10-5	2.3	4.1	5.4	6.4	7.2	7.4	7.5	7.9	7.9	7.6
60-10-6	2.2	3.5	5.1	5.9	6.4	6.9	6.8	7.1	7.2	7.0
Average	2.8	3.8	5.3	6.2	6.9	7.3	7.3	7.6	7.6	7.4
St. Dev.	0.67	0.26	0.25	0.25	0.41	0.30	0.37	0.41	0.39	0.36
C. Var. (%)	24.11	6.75	4.80	4.08	5.97	4.06	5.11	5.37	5.08	4.86

w/cm ratio = 0.60 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 15 Aggregate Type = Limestone Paste Fraction = 31%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
60-15-1	2.3	3.9	5.2	6.2	6.6	6.9	7.1	7.6	7.7	7.3
60-15-2	2.5	4.2	5.7	6.7	7.2	7.5	7.7	7.8	8.3	7.8
60-15-3	2.9	4.3	6.1	6.6	7.3	7.6	8.4	8.4	8.6	8.2
60-15-4	3.1	4.9	6.4	7.7	8.3	8.7	9.0	9.7	9.8	9.3
60-15-5	2.3	3.6	4.9	5.3	6.1	6.4	6.6	6.8	7.2	6.7
60-15-6	3.2	4.5	5.9	6.5	7.0	7.7	7.8	8.5	8.7	8.1
Average	2.7	4.2	5.7	6.5	7.1	7.4	7.8	8.1	8.4	7.9
St. Dev.	0.39	0.45	0.55	0.76	0.75	0.81	0.87	0.99	0.89	0.88
C. Var. (%)	14.56	10.71	9.73	11.78	10.61	10.84	11.24	12.16	10.65	11.13

w/cm ratio = 0.60 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 20 Aggregate Type = Limestone Paste Fraction = 31%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
60-20-1	2.8	3.8	5.3	6.1	6.4	7.1	7.2	7.3	8.2	7.4
60-20-2	3.4	4.4	6.1	7.2	7.9	8.1	8.4	8.9	9.1	8.6
60-20-3	2.9	4.3	5.7	6.4	7.3	7.6	8.0	8.1	8.9	8.1
60-20-4	3.0	4.2	5.4	6.7	7.1	7.5	7.9	8.4	8.7	8.1
60-20-5	2.6	4.2	5.7	6.8	7.1	7.6	7.6	7.9	8.6	7.9
60-20-6	2.3	4.1	5.2	6.4	6.8	6.9	7.2	7.6	8.0	7.4
Average	2.8	4.2	5.5	6.6	7.1	7.4	7.7	8.0	8.6	7.9
St. Dev.	0.38	0.20	0.33	0.39	0.50	0.41	0.44	0.58	0.42	0.45
C. Var. (%)	13.36	4.71	5.99	5.93	7.09	5.55	5.76	7.21	4.96	5.70

w/cm ratio = 0.60 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 25 Aggregate Type = Limestone Paste Fraction = 31%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
60-25-1	2.4	4.7	6.4	8.3	8.8	9.4	9.6	10.3	10.9	10.1
60-25-2	2.2	3.9	5.2	6.2	7.3	7.5	7.8	8.4	8.6	8.1
60-25-3	3.0	4.9	6.7	7.5	8.7	9.4	10.0	10.9	11.2	10.4
60-25-4	2.3	4.3	5.6	7.1	7.6	8.2	8.7	8.8	9.3	8.8
60-25-5	2.5	4.7	6.4	7.7	8.1	8.9	9.0	9.5	10.2	9.4
60-25-6	2.6	5.1	6.2	7.1	8.1	9.4	9.0	9.4	9.7	9.4
Average	2.5	4.6	6.1	7.3	8.1	8.8	9.0	9.5	10.0	9.3
St. Dev.	0.26	0.43	0.57	0.70	0.59	0.80	0.75	0.94	0.95	0.84
C. Var. (%)	10.61	9.41	9.39	9.59	7.28	9.12	8.28	9.86	9.55	8.96

w/cm ratio = 0.40 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 10 Aggregate Type = Dolomite Paste Fraction = 27%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
40-10-1	4.2	6.6	8.4	9.7	11.7	12.2	13.2	14.0	14.9	15.6
40-10-2	4.1	6.6	8.5	10.1	12.4	12.5	14.3	14.7	15.5	16.4
40-10-3	5.0	8.0	10.4	12.2	14.7	15.2	16.6	17.7	18.9	19.5
40-10-4	4.7	7.5	9.2	10.9	12.5	13.4	-	-	-	-
40-10-5	4.2	7.0	8.5	10.4	12.4	12.7	-	-	-	-
40-10-6	4.0	6.2	7.9	9.4	11.5	11.6	-	-	-	-
Average	4.4	7.0	8.8	10.5	12.5	12.9	14.7	15.5	16.4	17.2
St. Dev.	0.40	0.67	0.89	1.01	1.12	1.26	1.74	1.93	2.14	2.04
C. Var. (%)	9.10	9.60	10.09	9.63	8.95	9.77	11.86	12.50	13.05	11.88

w/cm ratio = 0.40 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 20 Aggregate Type = Dolomite Paste Fraction = 27%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
40-20-1	3.3	6.1	7.7	9.6	11.9	12.8	15.5	16.9	18.7	20.5
40-20-2	2.8	5.9	7.3	8.9	11.0	12.2	14.3	15.7	17.5	19.1
40-20-3	3.4	6.0	7.6	9.5	11.9	13.8	15.6	16.4	18.9	20.5
40-20-4	3.4	5.9	7.5	9.1	12.3	13.8	-	-	-	-
40-20-5	3.1	5.6	7.3	8.8	11.8	13.3	-	-	-	-
40-20-6	3.2	5.7	7.2	9.0	11.4	13.6	-	-	-	-
Average	3.2	5.9	7.4	9.1	11.7	13.2	15.1	16.3	18.4	20.0
St. Dev.	0.23	0.21	0.19	0.31	0.45	0.63	0.72	0.59	0.76	0.82
C. Var. (%)	7.06	3.60	2.59	3.41	3.86	4.80	4.74	3.61	4.16	4.08

w/cm ratio = 0.45 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 10 Aggregate Type = Dolomite Paste Fraction = 27%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
45-10-1	3.5	6.3	7.5	8.8	10.6	10.4	12.6	12.6	13.3	13.9
45-10-2	3.6	6.2	7.4	8.3	9.7	9.9	11.3	11.7	12.9	13.3
45-10-3	3.9	6.7	8.0	9.0	10.8	10.7	12.2	12.8	13.7	14.0
45-10-4	3.6	6.5	7.9	9.2	10.6	11.1	-	-	-	-
45-10-5	3.6	6.1	7.1	8.3	9.8	10.1	-	-	-	-
45-10-6	3.9	6.8	8.4	9.6	11.4	11.6	-	-	-	-
Average	3.7	6.4	7.7	8.8	10.5	10.6	12.0	12.4	13.3	13.7
St. Dev.	0.19	0.31	0.47	0.51	0.63	0.64	0.65	0.57	0.43	0.38
C. Var. (%)	5.27	4.82	6.08	5.80	6.00	6.00	5.38	4.58	3.20	2.79

w/cm ratio = 0.45 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 20 Aggregate Type = Dolomite Paste Fraction = 27%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
45-20-1	2.6	5.5	6.8	8.2	10.3	10.6	12.6	14.0	15.1	16.6
45-20-2	2.4	5.4	6.8	8.3	10.3	10.7	12.6	13.9	15.3	16.9
45-20-3	1.9	4.5	5.8	6.9	9.1	9.2	10.9	11.8	13.0	14.8
45-20-4	2.1	4.7	6.3	7.4	9.3	9.6	-	-	-	-
45-20-5	2.1	5.0	6.4	7.3	9.5	10.1	-	-	-	-
45-20-6	2.2	5.2	6.3	7.8	9.8	10.2	-	-	-	-
Average	2.2	5.0	6.4	7.7	9.7	10.1	12.0	13.2	14.5	16.1
St. Dev.	0.23	0.38	0.36	0.53	0.51	0.60	1.01	1.23	1.26	1.14
C. Var. (%)	10.38	7.57	5.65	6.95	5.25	5.97	8.39	9.27	8.73	7.09

w/cm ratio = 0.50 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 10 Aggregate Type = Dolomite Paste Fraction = 27%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
50-10-1	2.8	6.1	7.6	8.8	10.3	10.3	11.6	12.3	12.5	13.5
50-10-2	3.1	6.1	7.5	8.6	10.3	10.3	11.6	12.2	12.9	13.5
50-10-3	2.7	5.7	7.3	8.5	9.9	10.0	11.1	11.6	12.1	12.9
50-10-4	3.2	6.1	7.9	8.9	11.1	10.7	-	-	-	-
50-10-5	3.0	6.0	7.3	8.3	9.9	9.7	-	-	-	-
50-10-6	3.2	5.9	7.5	8.6	10.7	10.7	-	-	-	-
Average	3.0	6.0	7.5	8.6	10.3	10.3	11.4	12.0	12.5	13.3
St. Dev.	0.22	0.15	0.23	0.22	0.46	0.39	0.30	0.38	0.39	0.35
C. Var. (%)	7.32	2.46	3.11	2.55	4.48	3.79	2.61	3.13	3.10	2.61

w/cm ratio = 0.50 Aggregate Size = #56 Fly Ash Source = Red Rock
% Fly Ash = 20 Aggregate Type = Dolomite Paste Fraction = 27%

Sample ID	Day									
	1	3	7	14	21	28	35	42	49	56
50-20-1	2.6	5.0	5.9	7.3	9.1	9.8	11.5	12.6	13.7	15.2
50-20-2	2.5	4.8	5.8	6.7	8.7	9.0	10.6	11.8	13.1	14.4
50-20-3	2.9	5.5	6.6	7.5	9.8	10.3	11.8	13.2	14.7	16.0
50-20-4	2.7	4.9	5.8	6.9	8.5	9.3	-	-	-	-
50-20-5	2.6	5.0	5.7	6.9	8.7	9.4	-	-	-	-
50-20-6	2.9	5.4	6.3	7.6	9.6	10.2	-	-	-	-
Average	2.7	5.1	6.0	7.1	9.0	9.7	11.3	12.5	13.8	15.2
St. Dev.	0.17	0.28	0.37	0.38	0.53	0.54	0.63	0.70	0.79	0.80
C. Var. (%)	6.36	5.46	6.12	5.25	5.91	5.55	5.62	5.61	5.75	5.28

Appendix -C

Sorptivity Test Sheet

Name: **40- FS (Finished Surl (w/c 0.40, 0%/5%/10% Fly Ash)**

Aggregate Type = Limestone **Fly Ash = Red Rock**

Aggregate Size = #56

Start Date:

Comments:

	Diameter			
Samples	1	2	3	Average
1		102.83	102.5	102.665
2		102.55	102.43	102.49
3		102.67	102.77	102.72

	Diameter			
Samples	1	2	3	Average
4		102.81	102.25	102.53
5		102.14	102.53	102.335
6		102.47	102.72	102.595

	Diameter			
Samples	1	2	3	Average
7		102.7	102.44	102.57
8		102.11	102.93	102.52
9		103.07	102.3	102.685

	Diameter			
Samples	1	2	3	Average
				#DIV/0!
				#DIV/0!
				#DIV/0!

			Measurments																			
	Samples	**Area**	0	60s±2s	5min±10s	10min±2	20min±2	30min±2	60min±2	2hrs±5	3hrs±5	4hrs±5	5hrs±5	6hrs±5	day1±2h	day2±2h	day3±2h	day5±2h	day5±2h	day6±2h	day7±2h	day8±2h
Time (s)	40-00-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.665	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	943.99	945.44	945.89	946.11	946.51	946.7	947.27	947.95	948.39	948.77	949.01	949.29	952.67	954.37	955.57	956.58	957.44	958.1	958.56	958.92
ΔMass (g)		8278.196	0	1.45	1.9	2.12	2.52	2.71	3.28	3.96	4.4	4.78	5.02	5.3	8.68	10.38	11.58	12.59	13.45	14.11	14.57	14.93
Δmass/areaXdensity of water (mm)			0	0.175159	0.229519	0.256094	0.304414	0.327366	0.396222	0.478365	0.531517	0.57742	0.606412	0.640236	1.048538	1.253896	1.398855	1.520863	1.62475	1.704478	1.760045	1.803533
Time (s)	40-00-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.49	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1012.3	1013.92	1014.44	1014.74	1015.14	1015.42	1015.94	1016.58	1017.02	1017.35	1017.65	1017.91	1021.62	1023.52	1024.85	1025.94	1026.83	1027.53	1028.01	1028.41
ΔMass (g)		8249.999	0	1.62	2.14	2.44	2.84	3.12	3.64	4.28	4.72	5.05	5.35	5.61	9.32	11.22	12.55	13.64	14.53	15.23	15.71	16.11
Δmass/areaXdensity of water (mm)			0	0.196364	0.259394	0.295758	0.344242	0.378182	0.441212	0.518788	0.572121	0.612121	0.648485	0.68	1.129697	1.36	1.521212	1.653334	1.761212	1.846061	1.904243	1.952728
Time (s)	40-00-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.72	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1051.35	1052.89	1053.42	1053.79	1054.23	1054.5	1055.08	1055.69	1056.18	1056.53	1056.84	1057.12	1060.76	1062.63	1063.98	1065.08	1065.98	1066.71	1067.27	1067.67
ΔMass (g)		8287.068	0	1.54	2.07	2.44	2.88	3.15	3.73	4.34	4.83	5.18	5.49	5.77	9.41	11.28	12.63	13.73	14.63	15.36	15.92	16.32
Δmass/areaXdensity of water (mm)			0	0.185832	0.249787	0.294435	0.347529	0.38011	0.450099	0.523708	0.582836	0.62507	0.662478	0.696266	1.135504	1.361157	1.524061	1.656798	1.765401	1.85349	1.921065	1.969333
Time (s)			0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of water	Average		0	0.123841	0.162971	0.183951	0.216219	0.235183	0.279145	0.332384	0.367879	0.396514	0.418299	0.440079	0.726078	0.871299	0.973356	1.058065	1.128654	1.183513	1.221429	1.252087
Time (s)	40-05-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.53	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	986.92	988.02	988.38	988.61	988.92	989.14	989.63	990.19	990.63	990.86	991.12	991.34	994.15	995.72	996.83	997.98	998.54	999.18	999.75	1000.32
ΔMass (g)		8256.44	0	1.1	1.46	1.69	2	2.22	2.71	3.27	3.71	3.94	4.2	4.42	7.23	8.8	9.91	11.06	11.62	12.26	12.83	13.4
Δmass/areaXdensity of water (mm)			0	0.133229	0.176832	0.204689	0.242235	0.268881	0.328229	0.396054	0.449346	0.477203	0.508694	0.53534	0.87568	1.065835	1.200275	1.33956	1.407386	1.484902	1.553939	1.622976
Time (s)	40-05-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.335	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1056.45	1057.63	1058	1058.21	1058.48	1058.68	1059.09	1059.65	1060.01	1060.33	1060.6	1060.84	1064.05	1065.69	1066.87	1067.78	1068.66	1069.29	1069.92	1070.35
ΔMass (g)		8225.064	0	1.18	1.55	1.76	2.03	2.23	2.64	3.2	3.56	3.88	4.15	4.39	7.6	9.24	10.42	11.33	12.21	12.84	13.47	13.9
Δmass/areaXdensity of water			0	0.143464	0.188448	0.21398	0.246807	0.271123	0.32097	0.389055	0.432823	0.471729	0.504555	0.533734	0.924005	1.123396	1.266859	1.377497	1.484487	1.561082	1.637677	1.689956
Time (s)	40-05-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.595	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1038.82	1039.99	1040.4	1040.61	1040.99	1041.24	1041.69	1042.35	1042.8	1043.15	1043.45	1043.69	1047.16	1048.96	1050.18	1051.12	1052.06	1052.75	1053.31	1053.74
ΔMass (g)		8266.912	0	1.17	1.58	1.79	2.17	2.42	2.87	3.53	3.98	4.33	4.63	4.87	8.34	10.14	11.36	12.3	13.24	13.93	14.49	14.92
Δmass/areaXdensity of water			0	0.141528	0.191123	0.216526	0.262492	0.292733	0.347167	0.427003	0.481437	0.523775	0.560064	0.589095	1.008841	1.226577	1.374153	1.487859	1.601565	1.685031	1.752771	1.804785
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of water			0	0.139407	0.185468	0.211732	0.250511	0.277579	0.332122	0.404038	0.454536	0.490902	0.524438	0.552723	0.936175	1.138602	1.280429	1.401639	1.497813	1.577005	1.648129	1.705906
Time (s)	40-10-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.57	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1056.61	1057.63	1058.1	1058.31	1058.73	1058.97	1059.55	1060.18	1060.57	1060.96	1061.18	1061.46	1064.87	1066.51	1067.66	1068.7	1069.49	1070.14	1070.73	1071.18
ΔMass (g)		8262.883	0	1.02	1.49	1.7	2.12	2.36	2.94	3.57	3.96	4.35	4.57	4.85	8.26	9.9	11.05	12.09	12.88	13.53	14.12	14.57
Δmass/areaXdensity of water (mm)			0	0.123444	0.180324	0.205739	0.256569	0.285615	0.355808	0.432053	0.479252	0.526451	0.553076	0.586962	0.999651	1.198129	1.337306	1.46317	1.558778	1.637443	1.708847	1.763307
Time (s)	40-10-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.52	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1021.21	1022.03	1022.28	1022.46	1022.76	1022.94	1023.35	1023.91	1024.24	1024.54	1024.77	1024.97	1127.9	1129.44	1130.55	1131.58	1132.38	1133.12	1133.73	1134.2
ΔMass (g)		8254.829	0	0.82	1.07	1.25	1.55	1.73	2.14	2.7	3.03	3.33	3.56	3.76	106.69	108.23	109.34	110.37	111.17	111.91	112.52	112.99
Δmass/areaXdensity of water			0	0.099336	0.129621	0.151427	0.187769	0.209574	0.259242	0.327081	0.367058	0.4034	0.431263	0.455491	12.92456	13.11111	13.24558	13.37036	13.46727	13.55691	13.63081	13.68775
Time (s)	40-10-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.685	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1033.64	1034.98	1035.43	1035.76	1036.14	1036.36	1036.91	1037.45	1037.94	1038.2	1038.49	1038.71	1141.86	1143.61	1144.82	1145.92	1146.82	1147.46	1148.13	1148.59
ΔMass (g)		8281.422	0	1.34	1.79	2.12	2.5	2.72	3.27	3.81	4.3	4.56	4.85	5.07	108.22	109.97	111.18	112.28	113.18	113.82	114.49	114.95
Δmass/areaXdensity of water			0	0.161808	0.216146	0.255995	0.301881	0.328446	0.39486	0.460066	0.519235	0.55063	0.585648	0.612214	13.0678	13.27912	13.42523	13.55806	13.66674	13.74402	13.82492	13.88047
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of water			0	0.142626	0.198235	0.230867	0.279225	0.30703	0.375334	0.446059	0.499243	0.53854	0.569362	0.599588	7.033728	7.238625	7.381268	7.510614	7.612757	7.69073	7.766884	7.821887

Sorptivity Test Sheet

Name: **45- FS (Finished Surl (w/c 0.45, 0%/5%/10% Fly Ash)**

Aggregate Type = **Limestone** **Fly Ash =** **Red Rock**

Aggregate Size = **#56**

Start Date:

Comments:

	Diameter			
Samples	1	2	3	Average
1		102.3	102.39	102.345
2		102.38	102.39	102.385
3		102.52	102.59	102.555

	Diameter			
Samples	1	2	3	Average
4		102.9	102.88	102.89
5		102.23	102.66	102.445
6		102.34	102.48	102.41

	Diameter			
Samples	1	2	3	Average
7		102.45	102.57	102.51
8		102.78	102.44	102.61
9		102.56	102.5	102.53

	Diameter			
Samples	1	2	3	Average
				#DIV/0!
				#DIV/0!
				#DIV/0!

			Measurments																			
	Samples	**Area**	0	60s±2s	5min±10s	10min±2	20min±2	30min±2	60min±2	2hrs±5	3hrs±5	4hrs±5	5hrs±5	6hrs±5	day1±2h	day2±2h	day3±2h	day5±2h	day5±2h	day6±2h	day7±2h	day8±2h
Time (s)	45-00-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.345	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1005.13	1006.31	1006.79	1007.14	1007.59	1007.92	1008.51	1009.23	1009.72	1010.09	1010.42	1010.65	1014.39	1016.29	1017.74	1018.78	1019.87	1020.64	1021.39	1021.94
ΔMass (g)		8226.672	0	1.18	1.66	2.01	2.46	2.79	3.38	4.1	4.59	4.96	5.29	5.52	9.26	11.16	12.61	13.65	14.74	15.51	16.26	16.81
Δmass/areaXdensity of water (mm)			0	0.143436	0.201783	0.244327	0.299027	0.339141	0.410859	0.498379	0.557941	0.602917	0.64303	0.670988	1.125607	1.356563	1.532819	1.659237	1.791733	1.885331	1.976498	2.043354
Time (s)	45-00-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.385	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	938.95	939.98	940.48	940.76	941.18	941.52	942.21	943.01	943.61	944.06	944.46	944.74	949	951.13	952.66	953.77	954.8	955.46	956	956.36
ΔMass (g)		8233.103	0	1.03	1.53	1.81	2.23	2.57	3.26	4.06	4.66	5.11	5.51	5.79	10.05	12.18	13.71	14.82	15.85	16.51	17.05	17.41
Δmass/areaXdensity of water (mm)			0	0.125105	0.185835	0.219844	0.270858	0.312154	0.395962	0.493131	0.566008	0.620665	0.669249	0.703259	1.220682	1.479394	1.665229	1.80005	1.925155	2.005319	2.070908	2.114634
Time (s)	45-00-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.555	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1019.16	1021.19	1022.15	1022.77	1023.55	1024.11	1025.18	1026.49	1027.38	1028.11	1028.74	1029.3	1035.38	1038.02	1039.57	1040.67	1041.31	1041.55	1041.66	1041.79
ΔMass (g)		8260.467	0	2.03	2.99	3.61	4.39	4.95	6.02	7.33	8.22	8.95	9.58	10.14	16.22	18.86	20.41	21.51	22.15	22.39	22.5	22.63
Δmass/areaXdensity of water (mm)			0	0.245749	0.361965	0.437021	0.531447	0.59924	0.728772	0.887359	0.995101	1.083474	1.159741	1.227534	1.963569	2.283164	2.470805	2.603969	2.681447	2.710501	2.723817	2.739555
Time (s)			0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of	Average		0	0.13427	0.193809	0.232086	0.284943	0.325648	0.403411	0.495755	0.561975	0.611791	0.65614	0.687123	1.173144	1.417978	1.599024	1.729644	1.858444	1.945325	2.023703	2.078994
Time (s)	45-05-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.89	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1004.18	1005.03	1006.12	1006.67	1007.15	1007.49	1008.26	1009.03	1009.52	1009.97	1010.3	1010.61	1014.4	1016.38	1017.78	1018.9	1019.92	1020.67	1021.3	1021.82
ΔMass (g)		8314.521	0	0.85	1.94	2.49	2.97	3.31	4.08	4.85	5.34	5.79	6.12	6.43	10.22	12.2	13.6	14.72	15.74	16.49	17.12	17.64
Δmass/areaXdensity of water (mm)			0	0.102231	0.233327	0.299476	0.357206	0.398099	0.490708	0.583317	0.64225	0.696372	0.736062	0.773346	1.229175	1.467312	1.635693	1.770397	1.893074	1.983277	2.059048	2.121589
Time (s)	45-05-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.445	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1078.59	1079.87	1080.36	1080.78	1081.29	1081.62	1082.33	1083.17	1083.78	1084.27	1084.64	1085	1089.11	1091.28	1092.96	1094.18	1095.46	1096.3	1097.11	1097.67
ΔMass (g)		8242.756	0	1.28	1.77	2.19	2.7	3.03	3.74	4.58	5.19	5.68	6.05	6.41	10.52	12.69	14.37	15.59	16.87	17.71	18.52	19.08
Δmass/areaXdensity of water (mm)			0	0.155288	0.214734	0.265688	0.32756	0.367596	0.453732	0.555639	0.629644	0.68909	0.733978	0.777653	1.276272	1.539534	1.743349	1.891358	2.046646	2.148553	2.246821	2.31476
Time (s)	45-05-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.41	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	985.44	986.85	987.54	988.06	988.58	988.96	989.81	990.79	991.38	991.91	992.41	992.81	998.2	1001.29	1003.22	1004.59	1005.59	1006.15	1006.48	1006.66
ΔMass (g)		8237.124	0	1.41	2.1	2.62	3.14	3.52	4.37	5.35	5.94	6.47	6.97	7.37	12.76	15.85	17.78	19.15	20.15	20.71	21.04	21.22
Δmass/areaXdensity of water (mm)			0	0.171176	0.254943	0.318072	0.381201	0.427334	0.530525	0.649499	0.721125	0.785468	0.846169	0.89473	1.549084	1.924215	2.15852	2.32484	2.446242	2.514227	2.554289	2.576142
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of			0	0.128759	0.22403	0.282582	0.342383	0.382847	0.47222	0.569478	0.635947	0.692731	0.73502	0.775499	1.252724	1.503423	1.689521	1.830877	1.96986	2.065915	2.152935	2.218175
Time (s)	45-10-56-0-1-1-S1	Dia.	0	60	300	600	1200	1003.51	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.51	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	931.38	932.61	933.07	933.4	933.81	934.1	934.73	935.44	935.96	936.39	936.68	936.98	941.02	943.18	944.7	945.79	946.74	947.28	947.83	948.17
ΔMass (g)		8253.219	0	1.23	1.69	2.02	2.43	2.72	3.35	4.06	4.58	5.01	5.3	5.6	9.64	11.8	13.32	14.41	15.36	15.9	16.45	16.79
Δmass/areaXdensity of water (mm)			0	0.149033	0.204769	0.244753	0.294431	0.329568	0.405902	0.491929	0.554935	0.607036	0.642174	0.678523	1.168029	1.429745	1.613916	1.745985	1.861092	1.926521	1.993162	2.034358
Time (s)	45-10-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.61	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	1	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	983.19	984.6	985.28	985.5	986.28	986.68	987.43	988.35	989.01	989.47	989.93	990.29	995.04	997.78	999.68	1001.05	1002.16	1002.89	1003.35	1003.61
ΔMass (g)		8269.329	0	1.41	2.09	2.31	3.09	3.49	4.24	5.16	5.82	6.28	6.74	7.1	11.85	14.59	16.49	17.86	18.97	19.7	20.16	20.42
Δmass/areaXdensity of water (mm)			0	0.17051	0.252741	0.279346	0.37367	0.422041	0.512738	0.623993	0.703806	0.759433	0.81506	0.858594	1.433006	1.764351	1.994116	2.159788	2.294019	2.382297	2.437925	2.469366
Time (s)	45-10-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.53	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	954.15	955.53	956.21	956.72	957.3	957.67	958.49	959.46	960.17	960.76	961.2	961.63	967.45	970.74	972.75	973.98	974.85	975.27	975.48	975.64
ΔMass (g)		8256.44	0	1.38	2.06	2.57	3.15	3.52	4.34	5.31	6.02	6.61	7.05	7.48	13.3	16.59	18.6	19.83	20.7	21.12	21.33	21.49
Δmass/areaXdensity of water (mm)			0	0.167142	0.249502	0.311272	0.38152	0.426334	0.52565	0.643134	0.729128	0.800587	0.853879	0.90596	1.610864	2.009341	2.252787	2.401762	2.507134	2.558003	2.583438	2.602817
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of			0	0.168826	0.251122	0.295309	0.377595	0.424188	0.519194	0.633563	0.716467	0.78001	0.83447	0.882277	1.521935	1.886846	2.123451	2.280775	2.400577	2.47015	2.510681	2.536091

Sorptivity Test Sheet

Name: **50- FS (Finished Surf (w/c 0.50, 0%/5%/10% Fly Ash)**

Aggregate Type = **Limestone**

Fly Ash = **Red Rock**

Aggregate Size = **#56**

Start Date:

Comments:

	Diameter			
Samples	1	2	3	Average
1		102.21	102.56	102.385
2		102.51	102.56	102.535
3		102.3	102.69	102.495

	Diameter			
Samples	1	2	3	Average
4		102.58	101.77	102.175
5		102.79	101.6	102.195
6		102.49	101.68	102.085

	Diameter			
Samples	1	2	3	Average
7		102.55	102.29	102.42
8		102.27	102.38	102.325
9		102.4	102.25	102.325

	Diameter			
Samples	1	2	3	Average
10				#DIV/0!
11				#DIV/0!
12				#DIV/0!

			Measurments																			
	Samples	**Area**	0	60s±2s	5min±10s	10min±2	20min±2	30min±2	60min±2	2hrs±5	3hrs±5	4hrs±5	5hrs±5	6hrs±5	day1±2h	day2±2h	day3±2h	day5±2h	day5±2h	day6±2h	day7±2h	day8±2h
Time (s)	50-00-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.385	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1022.43	1024.73	1025.13	1025.83	1026.75	1027.43	1028.69	1030.32	1031.31	1032.14	1032.76	1033.3	1040.11	1043.72	1046.55	1048.45	1049.72	1050.41	1050.6	1050.7
ΔMass (g)		8233.103	0	2.3	2.7	3.4	4.32	5	6.26	7.89	8.88	9.71	10.33	10.87	17.68	21.29	24.12	26.02	27.29	27.98	28.17	28.27
Δmass/areaXdensity of water			0	0.27936	0.327944	0.412967	0.524711	0.607304	0.760345	0.958326	1.078573	1.179385	1.254691	1.32028	2.147428	2.585902	2.929636	3.160412	3.314667	3.398476	3.421553	3.433699
Time (s)	50-00-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.535	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1064.87	1065.78	1066.71	1067.28	1067.9	1068.31	1069.13	1070.07	1070.73	1071.22	1071.7	1072.05	1077.68	1080.78	1083.28	1085.19	1086.59	1087.79	1088.62	1088.96
ΔMass (g)		8257.245	0	0.91	1.84	2.41	3.03	3.44	4.26	5.2	5.86	6.35	6.83	7.18	12.81	15.91	18.41	20.32	21.72	22.92	23.75	24.09
Δmass/areaXdensity of water			0	0.110206	0.222835	0.291865	0.36695	0.416604	0.515911	0.62975	0.70968	0.769022	0.827152	0.869539	1.551365	1.926793	2.229557	2.460869	2.630417	2.775744	2.876262	2.917438
Time (s)	50-00-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.495	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1044.84	1045.91	1046.51	1046.94	1047.49	1047.94	1048.81	1049.87	1050.67	1051.2	1051.66	1052.09	1057.49	1060.66	1063.13	1065.04	1066.52	1067.78	1068.63	1069.07
ΔMass (g)		8250.804	0	1.07	1.67	2.1	2.65	3.1	3.97	5.03	5.83	6.36	6.82	7.25	12.65	15.82	18.29	20.2	21.68	22.94	23.79	24.23
Δmass/areaXdensity of water			0	0.129684	0.202405	0.254521	0.321181	0.375721	0.481165	0.609638	0.706598	0.770834	0.826586	0.878702	1.533184	1.917389	2.216754	2.448246	2.627623	2.780335	2.883355	2.936684
Time (s)			0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of	Average		0	0.119945	0.21262	0.273193	0.344066	0.396162	0.498538	0.619694	0.708139	0.769928	0.826869	0.874121	1.542274	1.922091	2.223155	2.454558	2.62902	2.77804	2.879809	2.927061
Time (s)	50-05-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.175	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1073.61	1074.96	1075.83	1076.4	1077.2	1077.75	1078.93	1080.37	1081.37	1082.21	1082.88	1083.46	1091.88	1096.8	1099.74	1101.3	1101.8	1102.14	1102.16	1102.24
ΔMass (g)		8199.364	0	1.35	2.22	2.79	3.59	4.14	5.32	6.76	7.76	8.6	9.27	9.85	18.27	23.19	26.13	27.69	28.19	28.53	28.55	28.63
Δmass/areaXdensity of water			0	0.164647	0.270753	0.34027	0.437839	0.504917	0.648831	0.824454	0.946415	1.048862	1.130575	1.201313	2.228221	2.828268	3.186832	3.377091	3.438071	3.479538	3.481977	3.491734
Time (s)	50-05-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.195	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1045.4	1047.5	1048.63	1049.33	1050.16	1050.78	1051.9	1053.36	1054.35	1055.18	1055.89	1056.55	1065.5	1070.4	1072.55	1073.23	1073.47	1073.74	1073.72	1073.79
ΔMass (g)		8202.575	0	2.1	3.23	3.93	4.76	5.38	6.5	7.96	8.95	9.78	10.49	11.15	20.1	25	27.15	27.83	28.07	28.34	28.32	28.39
Δmass/areaXdensity of water			0	0.256017	0.393779	0.479118	0.580306	0.655892	0.792434	0.970427	1.091121	1.192309	1.278867	1.359329	2.45045	3.047824	3.309936	3.392837	3.422096	3.455013	3.452574	3.461108
Time (s)	50-05-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.085	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1041.37	1042.6	1043.4	1043.94	1044.66	1045.13	1046.09	1047.29	1048.12	1048.87	1049.51	1050.15	1058.37	1063.12	1066.01	1067.63	1067.99	1068.34	1068.41	1068.4
ΔMass (g)		8184.926	0	1.23	2.03	2.57	3.29	3.76	4.72	5.92	6.75	7.5	8.14	8.78	17	21.75	24.64	26.26	26.62	26.97	27.04	27.03
Δmass/areaXdensity of water			0	0.150276	0.248017	0.313992	0.401958	0.459381	0.57667	0.723281	0.824687	0.916319	0.994511	1.072704	2.076989	2.657324	3.010412	3.208337	3.25232	3.295082	3.303634	3.302412
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x			0	0.190313	0.304183	0.377793	0.473368	0.540063	0.672645	0.839387	0.954074	1.052496	1.134651	1.211115	2.251887	2.844472	3.16906	3.326088	3.370829	3.409877	3.412729	3.418418
Time (s)	50-10-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.42	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1043.7	1044.15	1044.22	1047.87	1048.74	1049.36	1050.51	1051.97	1052.97	1053.69	1054.37	1054.93	1062.47	1066.5	1069.18	1070.76	1071.56	1071.99	1072.1	1072.2
ΔMass (g)		8238.733	0	0.45	0.52	4.17	5.04	5.66	6.81	8.27	9.27	9.99	10.67	11.23	18.77	22.8	25.48	27.06	27.86	28.29	28.4	28.5
Δmass/areaXdensity of water			0	0.05462	0.063116	0.506146	0.611745	0.686999	0.826583	1.003795	1.125173	1.212565	1.295102	1.363074	2.278263	2.767416	3.092708	3.284486	3.381588	3.43378	3.447132	3.45927
Time (s)	50-10-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.325	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1007.46	1009.69	1010.97	1011.76	1012.73	1013.45	1014.74	1016.36	1017.4	1018.28	1018.94	1019.54	1027.41	1031.81	1034.55	1035.75	1036.08	1036.29	1036.32	1036.39
ΔMass (g)		8223.457	0	2.23	3.51	4.3	5.27	5.99	7.28	8.9	9.94	10.82	11.48	12.08	19.95	24.35	27.09	28.29	28.62	28.83	28.86	28.93
Δmass/areaXdensity of water			0	0.271176	0.426828	0.522894	0.64085	0.728404	0.885273	1.08227	1.208737	1.315748	1.396007	1.468969	2.425987	2.961042	3.294235	3.440159	3.480288	3.505825	3.509473	3.517985
Time (s)	50-10-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.325	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1039.46	1041.35	1042.46	1043.17	1043.96	1044.54	1045.66	1047.05	1047.98	1048.71	1049.31	1049.92	1057.02	1061.23	1064.02	1065.75	1066.64	1067.11	1067.24	1067.3
ΔMass (g)		8223.457	0	1.89	3	3.71	4.5	5.08	6.2	7.59	8.52	9.25	9.85	10.46	17.56	21.77	24.56	26.29	27.18	27.65	27.78	27.84
Δmass/areaXdensity of water			0	0.22983	0.36481	0.451148	0.547215	0.617745	0.753941	0.92297	1.036061	1.124831	1.197793	1.271971	2.135355	2.647305	2.986579	3.196952	3.305179	3.362333	3.378142	3.385438
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x			0	0.250503	0.395819	0.487021	0.594032	0.673075	0.819607	1.00262	1.122399	1.22029	1.2969	1.37047	2.280671	2.804174	3.140407	3.318556	3.392734	3.434079	3.443807	3.451712

Sorptivity Test Sheet

Name: **40- FS (Finished Surl (w/c 0.40, 0%/10%/20% Fly Ash)**

Aggregate Type = **Limestone**

Aggregate Size = **#67**

Start Date: June

Fly Ash = **Red Rock**

Comments 40-67-00-1-1

	Diameter			
Samples	1	2	3	Average
1		102.83	102.5	102.665
2		102.55	102.43	102.49
3		102.67	102.77	102.72

	Diameter			
Samples	1	2	3	Average
4		102.81	102.25	102.53
5		102.14	102.53	102.335
6		102.47	102.72	102.595

	Diameter			
Samples	1	2	3	Average
7		102.7	102.44	102.57
8		102.11	102.93	102.52
9		103.07	102.3	102.685

	Diameter			
Samples	1	2	3	Average
				#DIV/0!
				#DIV/0!
				#DIV/0!

			Measurments																			
	Samples	**Area**	0	60s±2s	5min±10s	10min±2	20min±2	30min±2	60min±2	2hrs±5	3hrs±5	4hrs±5	5hrs±5	6hrs±5	day1±2h	day2±2h	day3±2h	day5±2h	day5±2h	day6±2h	day7±2h	day8±2h
Time (s)	40-00-67-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.665	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	949.6	949.64	949.65	949.73	949.79	949.91	949.94	950.03	950.15	950.22	950.24	950.36	950.99	951.39	951.74	951.95	952.22	952.37	952.59	952.71
ΔMass (g)		8278.196	0	0.04	0.05	0.13	0.19	0.31	0.34	0.43	0.55	0.62	0.64	0.76	1.39	1.79	2.14	2.35	2.62	2.77	2.99	3.11
Δmass/areaXdensity of water			0	0.004832	0.00604	0.015704	0.022952	0.037448	0.041072	0.051944	0.06644	0.074896	0.077312	0.091807	0.167911	0.216231	0.25851	0.283878	0.316494	0.334614	0.36119	0.375686
Time (s)	40-00-67-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.49	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	969.6	969.69	969.93	969.93	970.09	970.12	970.13	970.15	970.3	970.38	970.38	970.39	970.94	971.28	971.47	971.69	971.82	971.95	972.08	972.31
ΔMass (g)		8249.999	0	0.09	0.33	0.33	0.49	0.52	0.53	0.55	0.7	0.78	0.78	0.79	1.34	1.68	1.87	2.09	2.22	2.35	2.48	2.71
Δmass/areaXdensity of water			0	0.010909	0.04	0.04	0.059394	0.06303	0.064242	0.066667	0.084848	0.094545	0.094545	0.095758	0.162424	0.203636	0.226667	0.253333	0.269091	0.284849	0.300606	0.328485
Time (s)	40-00-67-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.72	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	934	934	934.07	934.13	934.16	934.18	934.28	934.39	934.53	934.58	934.6	934.73	935.19	935.55	935.78	936.03	936.25	936.34	936.62	936.7
ΔMass (g)		8287.068	0	0	0.07	0.13	0.16	0.18	0.28	0.39	0.53	0.58	0.6	0.73	1.19	1.55	1.78	2.03	2.25	2.34	2.62	2.7
Δmass/areaXdensity of water (mm)			0	0	0.008447	0.015687	0.019307	0.021721	0.033788	0.047061	0.063955	0.069989	0.072402	0.088089	0.143597	0.187038	0.214792	0.24496	0.271507	0.282368	0.316155	0.325809
Time (s)			0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x	Average		0	0.002416	0.007243	0.015695	0.02113	0.029584	0.03743	0.049502	0.065197	0.072442	0.074857	0.089948	0.155754	0.201635	0.236651	0.264419	0.294001	0.308491	0.338673	0.350747

Sorptivity Test Sheet

Name: **40- CS (Casted Surfa (w/c 0.40, 0%/10%/20% Fly Ash)**

Aggregate Type = **Limestone**

Aggregate Size = **#67**

Start Date: June

Fly Ash = **Red Rock**

Comments 40-67-00-1-1

	Diameter			
Samples	1	2	3	Average
1		101.1	101.17	101.135
2		101.09	101.03	101.06
3		101.21	101.37	101.29

	Diameter			
Samples	1	2	3	Average
4		101.37	101	101.185
5		101.14	101.17	101.16
6		101.36	101.2	101.28

	Diameter			
Samples	1	2	3	Average
7		100.98	100.81	100.895
8		101.08	101.03	101.055
9		101.21	101.17	101.19

	Diameter			
Samples	1	2	3	Average
				#DIV/0!
				#DIV/0!
				#DIV/0!

			Measurments																			
	Samples	**Area**	0	60s±2s	5min±10s	10min±2	20min±2	30min±2	60min±2	2hrs±5	3hrs±5	4hrs±5	5hrs±5	6hrs±5	day1±2h	day2±2h	day3±2h	day5±2h	day5±2h	day6±2h	day7±2h	day8±2h
Time (s)	40-00-67-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.135	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	984	984.05	984.17	984.06	984.3	984.37	984.16	984.15	984.26	984.31	984.31	984.32	984.51	984.71	984.86	985.06	985.17	985.34	985.35	985.39
ΔMass (g)		8033.298	0	0.05	0.17	0.06	0.3	0.37	0.16	0.15	0.26	0.31	0.31	0.32	0.51	0.71	0.86	1.06	1.17	1.34	1.35	1.39
Δmass/areaX density of			0	0.006224	0.021162	0.007469	0.037345	0.046058	0.019917	0.018672	0.032365	0.038589	0.038589	0.039834	0.063486	0.088382	0.107054	0.131951	0.145644	0.166806	0.168051	0.17303
Time (s)	40-00-67-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.06	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	956.5	956.55	956.78	956.78	956.81	956.81	956.63	956.72	956.77	956.83	956.83	956.83	957.03	957.31	957.42	957.63	957.76	957.85	958.08	958.1
ΔMass (g)		8021.387	0	0.05	0.28	0.28	0.31	0.31	0.13	0.22	0.27	0.33	0.33	0.33	0.53	0.81	0.92	1.13	1.26	1.35	1.58	1.6
Δmass/areaX density of			0	0.006233	0.034907	0.034907	0.038647	0.038647	0.016207	0.027427	0.03366	0.04114	0.04114	0.04114	0.066073	0.10098	0.114693	0.140873	0.15708	0.1683	0.196973	0.199467
Time (s)	40-00-67-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.29	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1012.9	1012.95	1012.98	1013.02	1013.02	1013.05	1013.06	1013.06	1013.1	1013.12	1013.13	1013.14	1013.28	1013.49	1013.61	1013.78	1013.91	1013.96	1014.26	1014.27
ΔMass (g)		8057.94	0	0.05	0.08	0.12	0.12	0.15	0.16	0.16	0.2	0.22	0.23	0.24	0.38	0.59	0.71	0.88	1.01	1.06	1.36	1.37
Δmass/areaX density of			0	0.006205	0.009928	0.014892	0.014892	0.018615	0.019856	0.019856	0.02482	0.027302	0.028543	0.029784	0.047158	0.07322	0.088112	0.109209	0.125342	0.131547	0.168778	0.170019
Time (s)			0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of	Average		0	0.006219	0.022417	0.024899	0.026769	0.028631	0.018031	0.023641	0.02924	0.034221	0.034842	0.035462	0.056616	0.0871	0.101403	0.125041	0.141211	0.149924	0.182876	0.184743

Sorptivity Test Sheet

Name: **40- FS (Finished Surface)** **(w/cm 0.40, Fly Ash 0% & 20%)**

Start Date:

Comments:

Aggregate Type = **Limestone**
Aggregate Size = **#56**
Fly Ash = **Red Rock**
Chemical Admix = **WR & AE**

	Diameter			
Samples	1	2	3	Average
1				101
2				101
3				101

	Diameter			
Samples	1	2	3	Average
4				101
5				101
6				101

	Diameter			
Samples	1	2	3	Average
7				
8				
9				

	Diameter			
Samples	1	2	3	Average

			Measurments																			
	Samples	**Area**	0	60s±2s	5min±10s	10min±2	20min±2	30min±2	60min±2	2hrs±5	3hrs±5	4hrs±5	5hrs±5	6hrs±5	day1±2h	day2±2h	day3±2h	day5±2h	day5±2h	day6±2h	day7±2h	day8±2h
Time (s)	40-00-56-3-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1013.84	1014.15	1014.28	1014.31	1014.32	1014.36	1014.4	1014.49	1014.63	1014.74	1014.8	1014.93	1015.7	1016.89	1017.51	1017.97	1018.51	1018.81	1019.19	1019.44
ΔMass (g)		8011.865	0	0.31	0.44	0.47	0.48	0.52	0.56	0.65	0.79	0.9	0.96	1.09	1.86	3.05	3.67	4.13	4.67	4.97	5.35	5.6
Δmass/areaXdensity of water (mm)			0	0.038693	0.054919	0.058663	0.059911	0.064904	0.069896	0.08113	0.098604	0.112333	0.119822	0.136048	0.232156	0.380685	0.458071	0.515485	0.582885	0.62033	0.66776	0.698963
Time (s)	40-00-56-3-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area																				
ΔMass (g)		8011.865	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Δmass/areaXdensity of water (mm)			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Time (s)	40-00-56-3-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	980.83	981.25	981.3	981.37	981.47	981.52	981.55	981.69	981.81	981.93	982.02	982.08	983.56	984.48	985.11	985.72	986.12	986.67	986.93	987.43
ΔMass (g)		8011.865	0	0.42	0.47	0.54	0.64	0.69	0.72	0.86	0.98	1.1	1.19	1.25	2.73	3.65	4.28	4.89	5.29	5.84	6.1	6.6
Δmass/areaXdensity of water (mm)			0	0.052422	0.058663	0.0674	0.079882	0.086122	0.089867	0.107341	0.122319	0.137296	0.14853	0.156019	0.340745	0.455574	0.534208	0.610345	0.660271	0.728919	0.761371	0.823778
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of			0	0.045557	0.056791	0.063032	0.069896	0.075513	0.079882	0.094235	0.110461	0.124815	0.134176	0.146033	0.28645	0.41813	0.496139	0.562915	0.621578	0.674624	0.714565	0.761371
Time (s)	40-20-56-3-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	936.18	936.73	936.87	936.94	937.06	937.17	937.44	937.84	938.1	938.37	938.59	938.82	942.24	944.02	945.11	946.16	946.79	947.55	947.88	948.38
ΔMass (g)		8011.865	0	0.55	0.69	0.76	0.88	0.99	1.26	1.66	1.92	2.19	2.41	2.64	6.06	7.84	8.93	9.98	10.61	11.37	11.7	12.2
Δmass/areaXdensity of water (mm)			0	0.068648	0.086122	0.094859	0.109837	0.123567	0.157267	0.207193	0.239645	0.273345	0.300804	0.329511	0.756378	0.978549	1.114597	1.245652	1.324286	1.419145	1.460334	1.522742
Time (s)	40-20-56-3-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	906.68	907.4	907.61	907.79	907.99	908.08	908.34	908.72	909.02	909.3	909.54	909.74	912.92	914.9	916.21	917.42	918.13	918.93	919.29	919.91
ΔMass (g)		8011.865	0	0.72	0.93	1.11	1.31	1.4	1.66	2.04	2.34	2.62	2.86	3.06	6.24	8.22	9.53	10.74	11.45	12.25	12.61	13.23
Δmass/areaXdensity of water (mm)			0	0.089867	0.116078	0.138545	0.163507	0.174741	0.207193	0.254622	0.292067	0.327015	0.356971	0.381934	0.778845	1.025978	1.189486	1.340512	1.42913	1.528982	1.573916	1.651301
Time (s)	40-20-56-3-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1022.65	1023.43	1023.53	1023.67	1023.87	1023.96	1024.11	1024.42	1024.63	1024.93	1025.04	1025.26	1027.74	1029.65	1030.83	1031.65	1032.67	1033.13	1033.91	1034.23
ΔMass (g)		8011.865	0	0.78	0.88	1.02	1.22	1.31	1.46	1.77	1.98	2.28	2.39	2.61	5.09	7	8.18	9	10.02	10.48	11.26	11.58
Δmass/areaXdensity of water (mm)			0	0.097356	0.109837	0.127311	0.152274	0.163507	0.18223	0.220922	0.247133	0.284578	0.298308	0.325767	0.635308	0.873704	1.020986	1.123334	1.250645	1.30806	1.405416	1.445356
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x			0	0.08529	0.104012	0.120238	0.141873	0.153938	0.18223	0.227579	0.259615	0.294979	0.318694	0.345737	0.72351	0.95941	1.108356	1.236499	1.334687	1.418729	1.479888	1.5398

Sorptivity Test Sheet

Name: **40- CS (Casted Surfa (w/c 0.40, 0%/5%/10% Fly Ash)**

Aggregate Type = Limestone

Fly Ash = Red Rock

Aggregate Size = #56

Start Date:

Comments:

	Diameter			
Samples	1	2	3	Average
1		101.1	101.17	101.135
2		101.09	101.03	101.06
3		101.21	101.37	101.29

	Diameter			
Samples	1	2	3	Average
4		101.37	101	101.185
5		101.14	101.17	101.16
6		101.36	101.2	101.28

	Diameter			
Samples	1	2	3	Average
7		100.98	100.81	100.895
8		101.08	101.03	101.055
9		101.21	101.17	101.19

	Diameter			
Samples	1	2	3	Average
				#DIV/0!
				#DIV/0!
				#DIV/0!

			Measurments																			
	Samples	Area	0	60s±2s	5min±10s	10min±2	20min±2	30min±2	60min±2	2hrs±5	3hrs±5	4hrs±5	5hrs±5	6hrs±5	day 1±2h	day 2±2h	day 3±2h	day 5±2h	day 5±2h	day 6±2h	day 7±2h	day 8±2h
Time (s)	40-00-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.135	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1072.69	1073.02	1073.12	1073.18	1073.19	1073.31	1073.44	1073.62	1073.79	1073.94	1073.99	1074.1	1075.81	1076.79	1077.5	1078.11	1078.62	1079.02	1079.32	1079.61
ΔMass (g)		8033.298	0	0.33	0.43	0.49	0.5	0.62	0.75	0.93	1.1	1.25	1.3	1.41	3.12	4.1	4.81	5.42	5.93	6.33	6.63	6.92
Δmass/areaX density of water (mm)			0	0.041079	0.053527	0.060996	0.062241	0.077179	0.093361	0.115768	0.13693	0.155602	0.161826	0.175519	0.388383	0.510376	0.598758	0.674692	0.738178	0.78797	0.825315	0.861415
Time (s)	40-00-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.06	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1077.06	1077.36	1077.52	1077.6	1077.73	1077.76	1077.91	1078.11	1078.25	1078.39	1078.51	1078.65	1080.25	1081.15	1081.81	1082.41	1082.88	1083.28	1083.61	1083.89
ΔMass (g)		8021.387	0	0.3	0.46	0.54	0.67	0.7	0.85	1.05	1.19	1.33	1.45	1.59	3.19	4.09	4.75	5.35	5.82	6.22	6.55	6.83
Δmass/areaX density of water (mm)			0	0.0374	0.057347	0.06732	0.083527	0.087267	0.105967	0.1309	0.148353	0.165807	0.180767	0.19822	0.397687	0.509887	0.592167	0.666967	0.72556	0.775427	0.816567	0.851474
Time (s)	40-00-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.29	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1033.42	1034.11	1034.32	1034.43	1034.63	1034.75	1035.07	1035.49	1035.78	1036.05	1036.26	1036.42	1038.95	1040.22	1041.16	1041.96	1042.6	1043.08	1043.52	1043.92
ΔMass (g)		8057.94	0	0.69	0.9	1.01	1.21	1.33	1.65	2.07	2.36	2.63	2.84	3	5.53	6.8	7.74	8.54	9.18	9.66	10.1	10.5
Δmass/areaX density of water (mm)			0	0.08563	0.111691	0.125342	0.150162	0.165055	0.204767	0.256889	0.292879	0.326386	0.352447	0.372304	0.68628	0.843888	0.960543	1.059824	1.139249	1.198818	1.253422	1.303063
Time (s)			0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of water	Average		0	0.03924	0.055437	0.064158	0.072884	0.082223	0.099664	0.123334	0.142642	0.160705	0.171297	0.18687	0.393035	0.510131	0.595462	0.670829	0.731869	0.781699	0.820941	0.856444
Time (s)	40-05-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.185	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	964.77	966.13	966.76	967.09	967.53	967.81	968.47	969.15	969.61	969.99	970.26	970.52	973.97	975.75	977	977.74	978.75	979.34	979.72	980.11
ΔMass (g)		8041.243	0	1.36	1.99	2.32	2.76	3.04	3.7	4.38	4.84	5.22	5.49	5.75	9.2	10.98	12.23	12.97	13.98	14.57	14.95	15.34
Δmass/areaX density of water (mm)			0	0.169128	0.247474	0.288513	0.343231	0.378051	0.460128	0.544692	0.601897	0.649153	0.68273	0.715064	1.144102	1.365461	1.520909	1.612935	1.738537	1.811909	1.859165	1.907665
Time (s)	40-05-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.155	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1076	1076.33	1076.44	1076.52	1076.59	1076.63	1076.75	1076.97	1077.09	1077.24	1077.33	1077.39	1078.91	1079.87	1080.62	1081.25	1081.8	1082.23	1082.65	1082.95
ΔMass (g)		8036.475	0	0.33	0.44	0.52	0.59	0.63	0.75	0.97	1.09	1.24	1.33	1.39	2.91	3.87	4.62	5.25	5.8	6.23	6.65	6.95
Δmass/areaX density of			0	0.041063	0.05475	0.064705	0.073415	0.078393	0.093324	0.1207	0.135632	0.154297	0.165495	0.172961	0.362099	0.481554	0.574879	0.653271	0.721709	0.775215	0.827477	0.864807
Time (s)	40-05-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.28	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1045.4	1045.97	1046.18	1046.33	1046.53	1046.65	1046.97	1047.43	1047.7	1047.98	1048.18	1048.32	1050.66	1051.92	1052.8	1053.54	1054.22	1054.71	1055.16	1055.49
ΔMass (g)		8056.349	0	0.57	0.78	0.93	1.13	1.25	1.57	2.03	2.3	2.58	2.78	2.92	5.26	6.52	7.4	8.14	8.82	9.31	9.76	10.09
Δmass/areaX density of			0	0.070752	0.096818	0.115437	0.140262	0.155157	0.194877	0.251975	0.285489	0.320244	0.345069	0.362447	0.652901	0.8093	0.91853	1.010383	1.094789	1.15561	1.211467	1.252428
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of water			0	0.093648	0.133014	0.156218	0.185636	0.203867	0.249443	0.305789	0.341006	0.374565	0.397765	0.416824	0.719701	0.885438	1.004773	1.092196	1.185012	1.247578	1.29937	1.341634
Time (s)	40-10-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		100.895	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1056.57	1056.88	1056.91	1056.94	1056.97	1057.07	1057.19	1057.34	1057.44	1057.58	1057.63	1057.71	1059.14	1059.97	1060.6	1061.16	1061.62	1061.98	1062.29	1062.54
ΔMass (g)		7995.216	0	0.31	0.34	0.37	0.4	0.5	0.62	0.77	0.87	1.01	1.06	1.14	2.57	3.4	4.03	4.59	5.05	5.41	5.72	5.97
Δmass/areaX density of water (mm)			0	0.038773	0.042525	0.046278	0.05003	0.062537	0.077546	0.096308	0.108815	0.126326	0.132579	0.142585	0.321442	0.425254	0.504051	0.574093	0.631628	0.676655	0.715428	0.746697
Time (s)	40-10-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.055	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1030.37	1030.71	1030.92	1031.02	1031.22	1031.32	1031.63	1032.05	1032.34	1032.55	1032.73	1032.92	1035.22	1036.42	1037.27	1038.04	1038.62	1039.12	1039.56	1039.93
ΔMass (g)		8020.594	0	0.34	0.55	0.65	0.85	0.95	1.26	1.68	1.97	2.18	2.36	2.55	4.85	6.05	6.9	7.67	8.25	8.75	9.19	9.56
Δmass/areaX density of			0	0.042391	0.068573	0.081041	0.105977	0.118445	0.157096	0.209461	0.245618	0.2718	0.294243	0.317932	0.604693	0.754308	0.860285	0.956288	1.028602	1.090942	1.1458	1.191932
Time (s)	40-10-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.19	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1081.71	1082.21	1082.28	1082.33	1082.41	1082.47	1082.58	1082.81	1083	1083.12	1083.24	1083.36	1085.25	1086.36	1087.18	1087.86	1088.45	1088.93	1089.32	1089.64
ΔMass (g)		8042.037	0	0.5	0.57	0.62	0.7	0.76	0.87	1.1	1.29	1.41	1.53	1.65	3.54	4.65	5.47	6.15	6.74	7.22	7.61	7.93
Δmass/areaX density of			0	0.062173	0.070878	0.077095	0.087043	0.094503	0.108182	0.136781	0.160407	0.175329	0.19025	0.205172	0.440187	0.578212	0.680176	0.764732	0.838096	0.897782	0.946278	0.986069
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of water			0	0.050473	0.056701	0.061686	0.068536	0.07852	0.092864	0.116544	0.134611	0.150827	0.161415	0.173879	0.380815	0.501733	0.592114	0.669412	0.734862	0.787219	0.830853	0.866383

Sorptivity Test Sheet

Name: **45- CS (Casted Surfa (w/c 0.45, 0%/5%/10% Fly Ash)**

Aggregate Type = **Limestone**

Fly Ash = **Red Rock**

Aggregate Size = **#56**

Start Date:

Comments:

	Diameter			
Samples	1	2	3	Average
1		101.41	101.27	101.34
2		101.04	101.24	101.14
3		101.03	101.3	101.17

	Diameter			
Samples	1	2	3	Average
4		101.08	101.21	101.145
5		101.29	101.37	101.33
6		101.14	101.14	101.14

	Diameter			
Samples	1	2	3	Average
7		101.07	101.19	101.13
8		101.06	101.07	101.065
9		101.09	101.16	101.125

	Diameter			
Samples	1	2	3	Average
				#DIV/0!
				#DIV/0!
				#DIV/0!

			Measurments																			
	Samples	**Area**	0	60s±2s	5min±10s	10min±2	20min±2	30min±2	60min±2	2hrs±5	3hrs±5	4hrs±5	5hrs±5	6hrs±5	day1±2h	day2±2h	day3±2h	day5±2h	day5±2h	day6±2h	day7±2h	day8±2h
Time (s)	45-00-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.34	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	928.77	929.34	929.4	929.44	929.5	929.55	929.72	929.9	930.06	930.19	930.3	930.41	932.67	934.18	935.28	936.23	937.09	937.88	938.59	939.15
ΔMass (g)		8065.897	0	0.57	0.63	0.67	0.73	0.78	0.95	1.13	1.29	1.42	1.53	1.64	3.9	5.41	6.51	7.46	8.32	9.11	9.82	10.38
Δmass/areaX density of water (mm)			0	0.070668	0.078107	0.083066	0.090504	0.096703	0.11778	0.140096	0.159933	0.17605	0.189688	0.203325	0.483517	0.670725	0.807102	0.924882	1.031503	1.129447	1.217471	1.2869
Time (s)	45-00-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.14	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1104.39	1104.81	1104.88	1104.93	1105.02	1105.08	1105.26	1105.46	1105.64	1105.81	1105.93	1106.06	1108.16	1109.42	1110.34	1111.1	1111.83	1112.36	1112.92	1113.41
ΔMass (g)		8034.092	0	0.42	0.49	0.54	0.63	0.69	0.87	1.07	1.25	1.42	1.54	1.67	3.77	5.03	5.95	6.71	7.44	7.97	8.53	9.02
Δmass/areaX density of water (mm)			0	0.052277	0.06099	0.067214	0.078416	0.085884	0.108289	0.133182	0.155587	0.176747	0.191683	0.207864	0.46925	0.626082	0.740594	0.835191	0.926054	0.992023	1.061725	1.122716
Time (s)	45-00-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.165	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1070.38	1070.9	1071	1071.08	1071.18	1071.27	1071.45	1071.68	1071.9	1072.1	1072.26	1072.37	1074.83	1076.36	1077.48	1078.44	1079.35	1080.19	1080.9	1081.53
ΔMass (g)		8038.064	0	0.52	0.62	0.7	0.8	0.89	1.07	1.3	1.52	1.72	1.88	1.99	4.45	5.98	7.1	8.06	8.97	9.81	10.52	11.15
Δmass/areaX density of water (mm)			0	0.064692	0.077133	0.087086	0.099526	0.110723	0.133117	0.16173	0.1891	0.213982	0.233887	0.247572	0.553616	0.74396	0.883297	1.002729	1.11594	1.220443	1.308773	1.38715
Time (s)			0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of water	Average		0	0.058485	0.069062	0.07715	0.088971	0.098304	0.120703	0.147456	0.172344	0.195364	0.212785	0.227718	0.511433	0.685021	0.811946	0.91896	1.020997	1.106233	1.185249	1.254933
Time (s)	45-05-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.145	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1002.2	1002.71	1002.82	1002.87	1002.98	1003.04	1003.24	1003.57	1003.82	1004.08	1004.27	1004.45	1007.68	1009.67	1011.04	1012.22	1013.28	1014.2	1015.02	1015.69
ΔMass (g)		8034.886	0	0.51	0.62	0.67	0.78	0.84	1.04	1.37	1.62	1.88	2.07	2.25	5.48	7.47	8.84	10.02	11.08	12	12.82	13.49
Δmass/areaX density of water (mm)			0	0.063473	0.077164	0.083386	0.097077	0.104544	0.129436	0.170506	0.201621	0.23398	0.257627	0.280029	0.682026	0.929696	1.100202	1.247062	1.378987	1.493487	1.595542	1.678929
Time (s)	45-05-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.33	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	946.05	946.54	946.6	946.62	946.71	946.72	946.8	947.05	947.18	947.35	947.42	947.55	949.31	950.45	951.26	951.9	952.55	953	953.47	953.89
ΔMass (g)		8064.306	0	0.49	0.55	0.57	0.66	0.67	0.75	1	1.13	1.3	1.37	1.5	3.26	4.4	5.21	5.85	6.5	6.95	7.42	7.84
Δmass/areaX density of water (mm)			0	0.060762	0.068202	0.070682	0.081842	0.083082	0.093002	0.124003	0.140124	0.161204	0.169884	0.186005	0.404251	0.545614	0.646057	0.725419	0.806021	0.861822	0.920104	0.972185
Time (s)	45-05-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.14	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	979.24	979.69	979.78	979.82	979.94	980.01	980.16	980.41	980.64	980.83	980.98	981.16	983.93	985.76	987.07	988.13	989.15	990	990.77	991.43
ΔMass (g)		8034.092	0	0.45	0.54	0.58	0.7	0.77	0.92	1.17	1.4	1.59	1.74	1.92	4.69	6.52	7.83	8.89	9.91	10.76	11.53	12.19
Δmass/areaX density of water (mm)			0	0.056011	0.067214	0.072192	0.087129	0.095842	0.114512	0.145629	0.174257	0.197907	0.216577	0.238982	0.583762	0.811542	0.974597	1.106535	1.233493	1.339293	1.435134	1.517284
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of water			0	0.060082	0.07086	0.07542	0.088683	0.094489	0.112317	0.146713	0.172001	0.197697	0.214696	0.235005	0.55668	0.762284	0.906952	1.026338	1.1395	1.231534	1.316927	1.389466
Time (s)	45-10-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.13	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1024.69	1025.11	1025.18	1025.2	1025.25	1025.27	1025.35	1025.44	1025.55	1025.63	1025.72	1025.84	1027.21	1028.15	1028.82	1029.44	1030.04	1030.51	1030.92	1031.32
ΔMass (g)		8032.503	0	0.42	0.49	0.51	0.56	0.58	0.66	0.75	0.86	0.94	1.03	1.15	2.52	3.46	4.13	4.75	5.35	5.82	6.23	6.63
Δmass/areaX density of water (mm)			0	0.052288	0.061002	0.063492	0.069717	0.072207	0.082166	0.093371	0.107065	0.117025	0.128229	0.143168	0.313725	0.43075	0.514161	0.591347	0.666044	0.724556	0.775599	0.825396
Time (s)	45-10-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.065	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	951.22	951.71	951.78	951.84	951.9	951.93	952.01	952.21	952.38	952.46	952.61	952.74	954.77	955.99	956.92	957.59	958.33	958.86	959.4	959.87
ΔMass (g)		8022.181	0	0.49	0.56	0.62	0.68	0.71	0.79	0.99	1.16	1.24	1.39	1.52	3.55	4.77	5.7	6.37	7.11	7.64	8.18	8.65
Δmass/areaX density of water (mm)			0	0.061081	0.069806	0.077286	0.084765	0.088505	0.098477	0.123408	0.144599	0.154571	0.17327	0.189475	0.442523	0.594601	0.71053	0.794048	0.886293	0.952359	1.019673	1.07826
Time (s)	45-10-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.125	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	987.11	987.64	987.74	987.76	987.81	987.85	988.01	988.21	988.42	988.55	988.69	988.84	991.01	992.38	993.42	994.2	994.97	995.58	996.13	996.62
ΔMass (g)		8031.709	0	0.53	0.63	0.65	0.7	0.74	0.9	1.1	1.31	1.44	1.58	1.73	3.9	5.27	6.31	7.09	7.86	8.47	9.02	9.51
Δmass/areaX density of water (mm)			0	0.065988	0.078439	0.080929	0.087155	0.092135	0.112056	0.136957	0.163104	0.179289	0.19672	0.215396	0.485575	0.656149	0.785636	0.882751	0.978621	1.05457	1.123049	1.184057
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of water			0	0.063535	0.074123	0.079107	0.08596	0.09032	0.105266	0.130182	0.153851	0.16693	0.184995	0.202435	0.464049	0.625375	0.748083	0.8384	0.932457	1.003465	1.071361	1.131159

Sorptivity Test Sheet

Name: **50- CS (Casted Surfa (w/c 0.50, 0%/5%/10% Fly Ash)**

Aggregate Type = **Limestone**

Fly Ash = **Red Rock**

Aggregate Size = **#56**

Start Date:

Comments:

	Diameter			
Samples	1	2	3	Average
1		101.12	101.15	101.135
2		101.09	101.38	101.235
3		101.22	101.2	101.21

	Diameter			
Samples	1	2	3	Average
4		101.77	101.18	101.475
5		101.13	101.06	101.10
6		100.88	100.89	100.885

	Diameter			
Samples	1	2	3	Average
7		101.33	101.24	101.285
8		102.31	102.25	102.28
9		101.52	102.46	101.99

	Diameter			
Samples	1	2	3	Average
10				#DIV/0!
11				#DIV/0!
12				#DIV/0!

			Measurments																			
	Samples	**Area**	0	60s±2s	5min±10s	10min±2	20min±2	30min±2	60min±2	2hrs±5	3hrs±5	4hrs±5	5hrs±5	6hrs±5	day1±2h	day2±2h	day3±2h	day5±2h	day5±2h	day6±2h	day7±2h	day8±2h
Time (s)	50-00-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		101.135	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1096.47	1096.96	1097.08	1097.17	1097.26	1097.37	1097.55	1097.85	1098.11	1098.34	1098.53	1098.77	1101.77	1103.69	1105.22	1106.45	1107.43	1108.39	1109.25	1109.96
ΔMass (g)		8033.298	0	0.49	0.61	0.7	0.79	0.9	1.08	1.38	1.64	1.87	2.06	2.3	5.3	7.22	8.75	9.98	10.96	11.92	12.78	13.49
Δmass/areaX density of			0	0.060996	0.075934	0.087137	0.098341	0.112034	0.13444	0.171785	0.20415	0.232781	0.256433	0.286308	0.659754	0.898759	1.089216	1.242329	1.364321	1.483824	1.590878	1.679261
Time (s)	50-00-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		101.235	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1046.76	1047.4	1047.5	1047.51	1047.57	1047.58	1047.69	1047.91	1048.08	1048.22	1048.32	1048.5	1050.82	1052.34	1053.58	1054.58	1055.36	1056.16	1056.89	1057.5
ΔMass (g)		8049.192	0	0.64	0.74	0.75	0.81	0.82	0.93	1.15	1.32	1.46	1.56	1.74	4.06	5.58	6.82	7.82	8.6	9.4	10.13	10.74
Δmass/areaX density of			0	0.079511	0.091935	0.093177	0.100631	0.101874	0.11554	0.142871	0.163992	0.181385	0.193808	0.216171	0.504398	0.693237	0.84729	0.971526	1.06843	1.167819	1.258511	1.334295
Time (s)	50-00-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		101.21	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1102.97	1103.32	1103.33	1103.36	1103.4	1103.45	1103.54	1103.68	1103.8	1103.92	1103.99	1104.1	1105.71	1106.81	1107.63	1108.31	1108.79	1109.29	1109.73	1110.05
ΔMass (g)		8045.217	0	0.35	0.36	0.39	0.43	0.48	0.57	0.71	0.83	0.95	1.02	1.13	2.74	3.84	4.66	5.34	5.82	6.32	6.76	7.08
Δmass/areaX density of			0	0.043504	0.044747	0.048476	0.053448	0.059663	0.07085	0.088251	0.103167	0.118083	0.126783	0.140456	0.340575	0.477302	0.579226	0.663748	0.723411	0.78556	0.840251	0.880026
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of water			0	0.070254	0.083934	0.090157	0.099486	0.106954	0.12499	0.157328	0.184071	0.207083	0.22512	0.25124	0.582076	0.795998	0.968253	1.106928	1.216376	1.325822	1.424695	1.506778
√Time ($s^{½}$)	50-05-56-0-1-1-S1	101.475	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1111.96	1112.53	1112.67	1112.74	1112.88	1112.96	1113.23	1113.56	1113.9	1114.24	1114.46	1114.75	1119.27	1122.19	1124.23	1126.28	1127.97	1129.64	1130.89	1131.96
ΔMass (g)		8087.402	0	0.57	0.71	0.78	0.92	1	1.27	1.6	1.94	2.28	2.5	2.79	7.31	10.23	12.27	14.32	16.01	17.68	18.93	20
Δmass/areaX density of			0	0.07048	0.087791	0.096446	0.113757	0.123649	0.157034	0.197839	0.239879	0.28192	0.309123	0.344981	0.903875	1.26493	1.517175	1.770655	1.979622	2.186116	2.340678	2.472982
Time (s)	50-05-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		101.095	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1082.78	1083.22	1083.31	1083.36	1083.43	1083.45	1083.58	1083.8	1083.98	1084.12	1084.25	1084.36	1086.61	1088.11	1089.38	1090.35	1091.15	1091.94	1092.68	1093.31
ΔMass (g)		8026.944	0	0.44	0.53	0.58	0.65	0.67	0.8	1.02	1.2	1.34	1.47	1.58	3.83	5.33	6.6	7.57	8.37	9.16	9.9	10.53
Δmass/areaX density of			0	0.054815	0.066028	0.072257	0.080977	0.083469	0.099664	0.127072	0.149496	0.166938	0.183133	0.196837	0.477143	0.664014	0.822231	0.943074	1.042738	1.141157	1.233346	1.311832
Time (s)	50-05-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		100.885	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1063.41	1065.79	1065.84	1065.89	1065.94	1066.02	1066.14	1066.31	1066.47	1066.61	1066.76	1066.89	1069.18	1070.75	1072	1072.89	1073.73	1074.53	1075.23	1075.82
ΔMass (g)		7993.631	0	2.38	2.43	2.48	2.53	2.61	2.73	2.9	3.06	3.2	3.35	3.48	5.77	7.34	8.59	9.48	10.32	11.12	11.82	12.41
Δmass/areaX density of			0	0.297737	0.303992	0.310247	0.316502	0.32651	0.341522	0.362789	0.382805	0.400319	0.419084	0.435347	0.721825	0.918231	1.074606	1.185944	1.291028	1.391108	1.478677	1.552486
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of			0	0.141011	0.152603	0.15965	0.170412	0.177876	0.199407	0.229233	0.257394	0.283059	0.30378	0.325722	0.700948	0.949058	1.138004	1.299891	1.437796	1.572793	1.684234	1.7791
Time (s)	50-10-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		101.285	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1081.89	1082.33	1082.5	1082.58	1082.75	1082.82	1083.04	1083.47	1083.75	1084.02	1084.27	1084.5	1087.89	1090.02	1091.63	1092.92	1093.97	1094.99	1095.89	1096.6
ΔMass (g)		8057.145	0	0.44	0.61	0.69	0.86	0.93	1.15	1.58	1.86	2.13	2.38	2.61	6	8.13	9.74	11.03	12.08	13.1	14	14.71
Δmass/areaX density of			0	0.05461	0.075709	0.085638	0.106738	0.115426	0.14273	0.196099	0.230851	0.264362	0.29539	0.323936	0.744681	1.009042	1.208865	1.368971	1.49929	1.625886	1.737588	1.825709
Time (s)	50-10-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		102.28	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1065.1	1065.51	1065.7	1065.81	1066.02	1066.16	1066.51	1067	1067.47	1067.86	1068.19	1068.54	1073.75	1076.98	1079.14	1081.18	1082.79	1084.12	1085.23	1085.98
ΔMass (g)		8216.225	0	0.41	0.6	0.71	0.92	1.06	1.41	1.9	2.37	2.76	3.09	3.44	8.65	11.88	14.04	16.08	17.69	19.02	20.13	20.88
Δmass/areaX density of			0	0.049901	0.073026	0.086414	0.111974	0.129013	0.171612	0.23125	0.288454	0.335921	0.376085	0.418684	1.052795	1.445919	1.708814	1.957103	2.153057	2.314932	2.45003	2.541313
Time (s)	50-10-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		101.99	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1060.62	1061.03	1061.17	1061.25	1061.32	1061.39	1061.6	1061.98	1062.25	1062.49	1062.72	1062.97	1066.85	1069.6	1071.45	1073.26	1074.79	1076.18	1077.37	1078.3
ΔMass (g)		8169.699	0	0.41	0.55	0.63	0.7	0.77	0.98	1.36	1.63	1.87	2.1	2.35	6.23	8.98	10.83	12.64	14.17	15.56	16.75	17.68
Δmass/areaX density of			0	0.050185	0.067322	0.077114	0.085682	0.094251	0.119955	0.166469	0.199518	0.228895	0.257047	0.287648	0.762574	1.099184	1.32563	1.547181	1.734458	1.904599	2.050259	2.164094
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of			0	0.052256	0.074368	0.086026	0.109356	0.122219	0.157171	0.213674	0.259652	0.300141	0.335738	0.37131	0.898738	1.227481	1.458839	1.663037	1.826174	1.970409	2.093809	2.183511

Sorptivity Test Sheet

Name: **40- FS (Finished Surface)** **Fly Ash Type**

Aggregate Type = **Limestone**

Aggregate Size = **#56**

Start Date:

Fly Ash = **Sources I-II-III**

Comments:

	Diameter			
Samples	1	2	3	Average
1		102.83	102.5	102.665
2		102.55	102.43	102.49
3		102.67	102.77	102.72

	Diameter			
Samples	1	2	3	Average
4		102.81	102.25	102.53
5		102.14	102.53	102.335
6		102.47	102.72	102.595

	Diameter			
Samples	1	2	3	Average
7		102.7	102.44	102.57
8		102.11	102.93	102.52
9		103.07	102.3	102.685

	Diameter			
Samples	1	2	3	Average
				#DIV/0!
				#DIV/0!
				#DIV/0!

			Measurments																			
	Samples	**Area**	0	60s±2s	5min±10s	10min±2	20min±2	30min±2	60min±2	2hrs±5	3hrs±5	4hrs±5	5hrs±5	6hrs±5	day1±2h	day2±2h	day3±2h	day5±2h	day5±2h	day6±2h	day7±2h	day8±2h
Time (s)	40-00-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		102.665	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	943.99	945.44	945.89	946.11	946.51	946.7	947.27	947.95	948.39	948.77	949.01	949.29	952.67	954.37	955.57	956.58	957.44	958.1	958.56	958.92
ΔMass (g)		8278.196	0	1.45	1.9	2.12	2.52	2.71	3.28	3.96	4.4	4.78	5.02	5.3	8.68	10.38	11.58	12.59	13.45	14.11	14.57	14.93
Δmass/areaXdensity of water			0	0.175159	0.229519	0.256094	0.304414	0.327366	0.396222	0.478365	0.531517	0.57742	0.606412	0.640236	1.048538	1.253896	1.398855	1.520863	1.62475	1.704478	1.760045	1.803533
Time (s)	40-00-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		102.49	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1012.3	1013.92	1014.44	1014.74	1015.14	1015.42	1015.94	1016.58	1017.02	1017.35	1017.65	1017.91	1021.62	1023.52	1024.85	1025.94	1026.83	1027.53	1028.01	1028.41
ΔMass (g)		8249.999	0	1.62	2.14	2.44	2.84	3.12	3.64	4.28	4.72	5.05	5.35	5.61	9.32	11.22	12.55	13.64	14.53	15.23	15.71	16.11
Δmass/areaXdensity of water			0	0.196364	0.259394	0.295758	0.344242	0.378182	0.441212	0.518788	0.572121	0.612121	0.648485	0.68	1.129697	1.36	1.521212	1.653334	1.761212	1.846061	1.904243	1.952728
Time (s)	40-00-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		102.72	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1051.35	1052.89	1053.42	1053.79	1054.23	1054.5	1055.08	1055.69	1056.18	1056.53	1056.84	1057.12	1060.76	1062.63	1063.98	1065.08	1065.98	1066.71	1067.27	1067.67
ΔMass (g)		8287.068	0	1.54	2.07	2.44	2.88	3.15	3.73	4.34	4.83	5.18	5.49	5.77	9.41	11.28	12.63	13.73	14.63	15.36	15.92	16.32
Δmass/areaXdensity of water (mm)			0	0.185832	0.249787	0.294435	0.347529	0.38011	0.450099	0.523708	0.582836	0.62507	0.662478	0.696266	1.135504	1.361157	1.524061	1.656798	1.765401	1.85349	1.921065	1.969333
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x			0	0.180495	0.239653	0.275265	0.325972	0.353738	0.42316	0.501036	0.557176	0.601245	0.634445	0.668251	1.092021	1.307527	1.461458	1.58883	1.695076	1.778984	1.840555	1.886433
Time (s)	40-00-56-0-3-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		102.53	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1110.25	1110.92	1112.92	1113.22	1113.87	1114.35	1115.2	1116.42	1117.06	1117.91	1118.3	1118.83	1125.49	1127.75	1129.3	1131.12	1131.38	1133.18	1134.02	1134.49
ΔMass (g)		8256.44	0	0.67	2.67	2.97	3.62	4.1	4.95	6.17	6.81	7.66	8.05	8.58	15.24	17.5	19.05	20.87	21.13	22.93	23.77	24.24
Δmass/areaXdensity of water			0	0.081149	0.323384	0.359719	0.438446	0.496582	0.599532	0.747295	0.824811	0.927761	0.974997	1.039189	1.845832	2.119558	2.30729	2.527724	2.559214	2.777226	2.878965	2.93589
Time (s)	40-00-56-0-3-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		102.335	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	970.52	971.84	973.03	973.8	974.79	975.4	976.65	978.24	979.22	980.11	980.76	981.31	989.26	992.46	994.36	996.32	996.56	998.02	998.58	998.69
ΔMass (g)		8225.064	0	1.32	2.51	3.28	4.27	4.88	6.13	7.72	8.7	9.59	10.24	10.79	18.74	21.94	23.84	25.8	26.04	27.5	28.06	28.17
Δmass/areaXdensity of water			0	0.160485	0.305165	0.398781	0.519145	0.593308	0.745283	0.938595	1.057743	1.165948	1.244975	1.311844	2.278402	2.667456	2.898458	3.136754	3.165933	3.343439	3.411524	3.424897
Time (s)	40-00-56-0-3-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		102.595	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1079.15	1082.07	1082.64	1083.11	1083.56	1083.89	1084.65	1085.64	1086.29	1086.89	1087.38	1087.89	1094.56	1097.26	1099.09	1101.1	1101.39	1103.11	1103.87	1104.28
ΔMass (g)		8266.912	0	2.92	3.49	3.96	4.41	4.74	5.5	6.49	7.14	7.74	8.23	8.74	15.41	18.11	19.94	21.95	22.24	23.96	24.72	25.13
Δmass/areaXd			0	0.353215	0.422165	0.479018	0.533452	0.57337	0.665303	0.785057	0.863684	0.936263	0.995535	1.057227	1.864058	2.190661	2.412025	2.655163	2.690243	2.898301	2.990234	3.039829
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x			0	0.198283	0.350238	0.412506	0.497014	0.55442	0.670039	0.823649	0.915412	1.009991	1.071836	1.136086	1.996097	2.325892	2.539258	2.773214	2.80513	3.006322	3.093574	3.133539
Time (s)	40-00-56-0-4-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		102.57	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1003.67	1005.03	1006.01	1006.66	1006.99	1007.95	1009.1	1010.48	1011.42	1012.33	1013.78	1013.79	1020.8	1023.3	1024.64	1026.45	1026.46	1028.02	1028.72	1029.07
ΔMass (g)		8262.883	0	1.36	2.34	2.99	3.32	4.28	5.43	6.81	7.75	8.66	10.11	10.12	17.13	19.63	20.97	22.78	22.79	24.35	25.05	25.4
Δmass/areaXdensity of water (mm)			0	0.164591	0.283194	0.361859	0.401797	0.517979	0.657156	0.824168	0.937929	1.04806	1.223544	1.224754	2.073126	2.375684	2.537855	2.756907	2.758117	2.946913	3.031629	3.073988
Time (s)	40-00-56-0-4-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		102.52	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1030.11	1031.41	1032.96	1033.03	1033.98	1034.61	1036.04	1037.88	1039.24	1040.3	1041.3	1041.79	1052.26	1056.01	1057.91	1059.69	1059.69	1060.64	1060.87	1060.9
ΔMass (g)		8254.829	0	1.3	2.85	2.92	3.87	4.5	5.93	7.77	9.13	10.19	11.19	11.68	22.15	25.9	27.8	29.58	29.58	30.53	30.76	30.79
Δmass/areaXdensity of water			0	0.157484	0.345252	0.353732	0.468816	0.545135	0.718367	0.941267	1.106019	1.234429	1.35557	1.414929	2.683278	3.137557	3.367726	3.583357	3.583357	3.698441	3.726304	3.729938
Time (s)	40-00-56-0-4-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		102.685	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1025.09	1026.46	1027.27	1027.97	1028.81	1029.46	1030.68	1032.26	1033.37	1034.26	1034.96	1035.57	1043.19	1045.38	1046.66	1048.38	1048.38	1049.71	1050.23	1050.49
ΔMass (g)		8281.422	0	1.37	2.18	2.88	3.72	4.37	5.59	7.17	8.28	9.17	9.87	10.48	18.1	20.29	21.57	23.29	23.29	24.62	25.14	25.4
Δmass/areaXdensity of water			0	0.165431	0.26324	0.347766	0.449198	0.527687	0.675005	0.865793	0.999828	1.107298	1.191824	1.265483	2.185615	2.450062	2.604625	2.812319	2.812319	2.972919	3.035711	3.067106
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x			0	0.161038	0.314223	0.357796	0.435307	0.531557	0.687761	0.882717	1.021974	1.141245	1.289557	1.319842	2.378202	2.756621	2.95279	3.170132	3.170737	3.322677	3.378967	3.401963

Sorptivity Test Sheet

Name: **40- CS (Casted Surface)** **(w/cm 0.40, Fly Ash 0% & 20%)**

Start Date:

Comments:

Aggregate Type = **Limestone**
Aggregate Size = **#56**
Fly Ash = **Red Rock**
Chemical Admix = **WR & AE**

	Diameter			
Samples	1	2	3	Average
1				101
2				101
3				101

	Diameter			
Samples	1	2	3	Average
4				101
5				101
6				101

	Diameter			
Samples	1	2	3	Average
7				
8				
9				

	Diameter			
Samples	1	2	3	Average

			Measurments																			
	Samples	**Area**	0	60s±2s	5min±10s	10min±2	20min±2	30min±2	60min±2	2hrs±5	3hrs±5	4hrs±5	5hrs±5	6hrs±5	day1±2h	day2±2h	day3±2h	day5±2h	day5±2h	day6±2h	day7±2h	day8±2h
Time (s)	40-00-56-3-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	926.07	926.22	926.3	926.26	926.3	926.36	926.4	926.4	926.35	926.36	926.42	926.49	926.69	927.06	927.38	927.53	927.77	927.86	928.05	928.13
ΔMass (g)		8011.865	0	0.15	0.23	0.19	0.23	0.29	0.33	0.33	0.28	0.29	0.35	0.42	0.62	0.99	1.31	1.46	1.7	1.79	1.98	2.06
Δmass/areaX density of water (mm)			0	0.018722	0.028707	0.023715	0.028707	0.036196	0.041189	0.041189	0.034948	0.036196	0.043685	0.052422	0.077385	0.123567	0.163507	0.18223	0.212185	0.223419	0.247133	0.257119
Time (s)	40-00-56-3-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	967.25	967.4	967.43	967.5	967.51	967.53	967.56	967.58	967.59	967.6	967.65	967.67	967.99	968.29	968.44	968.62	968.72	968.91	969.01	969.14
ΔMass (g)		8011.865	0	0.15	0.18	0.25	0.26	0.28	0.31	0.33	0.34	0.35	0.4	0.42	0.74	1.04	1.19	1.37	1.47	1.66	1.76	1.89
Δmass/areaX density of water (mm)			0	0.018722	0.022467	0.031204	0.032452	0.034948	0.038693	0.041189	0.042437	0.043685	0.049926	0.052422	0.092363	0.129807	0.14853	0.170996	0.183478	0.207193	0.219674	0.2359
Time (s)	40-00-56-3-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	971.27	971.35	971.39	971.42	971.47	971.55	971.5	971.51	971.55	971.55	971.55	971.5	971.67	971.92	972.08	972.23	972.37	972.48	972.68	972.76
ΔMass (g)		8011.865	0	0.08	0.12	0.15	0.2	0.28	0.23	0.24	0.28	0.28	0.28	0.23	0.4	0.65	0.81	0.96	1.1	1.21	1.41	1.49
Δmass/areaX density of water (mm)			0	0.009985	0.014978	0.018722	0.024963	0.034948	0.028707	0.029956	0.034948	0.034948	0.034948	0.028707	0.049926	0.08113	0.1011	0.119822	0.137296	0.151026	0.175989	0.185974
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of water			0	0.018722	0.022467	0.031204	0.032452	0.034948	0.038693	0.041189	0.042437	0.043685	0.049926	0.052422	0.092363	0.129807	0.14853	0.170996	0.183478	0.207193	0.219674	0.2359
Time (s)	40-20-56-3-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	984.23	984.45	984.46	984.47	984.48	984.49	984.52	984.53	984.57	984.58	984.64	984.66	985.08	985.4	985.63	985.81	985.91	986.11	986.16	986.4
ΔMass (g)		8011.865	0	0.22	0.23	0.24	0.25	0.26	0.29	0.3	0.34	0.35	0.41	0.43	0.85	1.17	1.4	1.58	1.68	1.88	1.93	2.17
Δmass/areaX density of water (mm)			0	0.027459	0.028707	0.029956	0.031204	0.032452	0.036196	0.037444	0.042437	0.043685	0.051174	0.05367	0.106093	0.146033	0.174741	0.197208	0.209689	0.234652	0.240893	0.270848
Time (s)	40-20-56-3-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	969.76	969.96	970	970.02	970.03	970.04	970.06	970.08	970.13	970.14	970.16	970.25	970.85	971.25	971.48	971.68	971.83	972.1	972.14	972.37
ΔMass (g)		8011.865	0	0.2	0.24	0.26	0.27	0.28	0.3	0.32	0.37	0.38	0.4	0.49	1.09	1.49	1.72	1.92	2.07	2.34	2.38	2.61
Δmass/areaX density of water (mm)			0	0.024963	0.029956	0.032452	0.0337	0.034948	0.037444	0.039941	0.046182	0.04743	0.049926	0.061159	0.136048	0.185974	0.214682	0.239645	0.258367	0.292067	0.297059	0.325767
Time (s)	40-20-56-3-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1010.52	1010.72	1010.72	1010.72	1010.7	1010.71	1010.71	1010.76	1010.75	1010.85	1010.86	1010.89	1011.21	1011.6	1011.9	1012	1012.29	1012.39	1012.57	1012.69
ΔMass (g)		8011.865	0	0.2	0.2	0.2	0.18	0.19	0.19	0.24	0.23	0.33	0.34	0.37	0.69	1.08	1.38	1.48	1.77	1.87	2.05	2.17
Δmass/areaX density of water (mm)			0	0.024963	0.024963	0.024963	0.022467	0.023715	0.023715	0.029956	0.028707	0.041189	0.042437	0.046182	0.086122	0.1348	0.172245	0.184726	0.220922	0.233404	0.25587	0.270848
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of			0	0.026211	0.029331	0.031204	0.032452	0.0337	0.03682	0.038693	0.044309	0.045557	0.05055	0.057415	0.12107	0.166004	0.194711	0.218426	0.234028	0.263359	0.268976	0.298308

Sorptivity Test Sheet

Name: **40- FS (Finished Surl (w/c 0.40, 15%/20%/25% Fly Ash)**

Aggregate Type = Limestone

Fly Ash = Red Rock

Aggregate Size = #56

Start Date:

Comments:

	Diameter			
Samples	1	2	3	Average
1		102.28	102.48	102.38
2		101.97	102.44	102.205
3		102.59	102.39	102.49

	Diameter			
Samples	1	2	3	Average
4		101.96	102.72	102.34
5		102.67	102.82	102.745
6		103.55	102.41	102.98

	Diameter			
Samples	1	2	3	Average
7		102.34	102.36	102.35
8		102.58	102.42	102.5
9		102.31	102.41	102.36

	Diameter			
Samples	1	2	3	Average
10				#DIV/0!
11				#DIV/0!
12				#DIV/0!

			Measurments																			
	Samples	**Area**	0	60s±2s	5min±10s	10min±2	20min±2	30min±2	60min±2	2hrs±5	3hrs±5	4hrs±5	5hrs±5	6hrs±5	day1±2h	day2±2h	day3±2h	day5±2h	day5±2h	day6±2h	day7±2h	day8±2h
Time (s)	40-15-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.38	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1069.04	1070.33	1070.61	1070.79	1071.05	1071.3	1071.73	1072.28	1072.67	1072.92	1073.18	1073.42	1076.35	1077.9	1079	1079.93	1080.68	1081.34	1081.8	1082.23
ΔMass (g)		8232.299	0	1.29	1.57	1.75	2.01	2.26	2.69	3.24	3.63	3.88	4.14	4.38	7.31	8.86	9.96	10.89	11.64	12.3	12.76	13.19
Δmass/areaXdensity of water (mm)			0	0.1567	0.190712	0.212577	0.24416	0.274528	0.326762	0.393572	0.440946	0.471314	0.502897	0.532051	0.887966	1.076249	1.209869	1.322838	1.413943	1.494115	1.549992	1.602226
Time (s)	40-15-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.205	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1087.67	1089.26	1089.57	1089.76	1090.02	1090.27	1090.68	1091.31	1091.68	1091.97	1092.25	1092.46	1095.38	1096.91	1097.96	1098.9	1099.6	1100.2	1100.73	1101.11
ΔMass (g)		8204.18	0	1.59	1.9	2.09	2.35	2.6	3.01	3.64	4.01	4.3	4.58	4.79	7.71	9.24	10.29	11.23	11.93	12.53	13.06	13.44
Δmass/areaXdensity of water (mm)			0	0.193804	0.231589	0.254748	0.286439	0.316912	0.366886	0.443676	0.488775	0.524123	0.558252	0.583849	0.939765	1.126255	1.254239	1.368814	1.454137	1.52727	1.591871	1.638189
Time (s)	40-15-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.49	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1016.84	1017.95	1018.28	1018.49	1018.81	1019.02	1019.41	1019.98	1020.3	1020.57	1020.77	1020.97	1023.48	1024.89	1025.87	1026.68	1027.36	1027.92	1028.34	1028.74
ΔMass (g)		8249.999	0	1.11	1.44	1.65	1.97	2.18	2.57	3.14	3.46	3.73	3.93	4.13	6.64	8.05	9.03	9.84	10.52	11.08	11.5	11.9
Δmass/areaXdensity of water (mm)			0	0.134545	0.174545	0.2	0.238788	0.264242	0.311515	0.380606	0.419394	0.452121	0.476364	0.500606	0.804849	0.975758	1.094546	1.192727	1.275152	1.343031	1.39394	1.442424
Time (s)			0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of water	Average		0	0.161683	0.198949	0.222442	0.256462	0.285227	0.335054	0.405951	0.449705	0.48252	0.512504	0.538835	0.877526	1.05942	1.186218	1.294793	1.381077	1.454805	1.511934	1.560946
Time (s)	40-20-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.34	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1075.89	1076.98	1077.31	1077.4	1077.65	1077.83	1078.19	1078.68	1079.05	1079.3	1079.58	1079.75	1082.32	1083.6	1084.58	1085.32	1086	1086.54	1087	1087.42
ΔMass (g)		8225.868	0	1.09	1.42	1.51	1.76	1.94	2.3	2.79	3.16	3.41	3.69	3.86	6.43	7.71	8.69	9.43	10.11	10.65	11.11	11.53
Δmass/areaXdensity of water (mm)			0	0.132509	0.172626	0.183567	0.213959	0.235841	0.279606	0.339174	0.384154	0.414546	0.448585	0.469251	0.78168	0.937287	1.056424	1.146384	1.22905	1.294696	1.350617	1.401676
Time (s)	40-20-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.745	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1076.28	1077.51	1077.87	1078.07	1078.39	1078.61	1079.06	1079.66	1080.1	1080.38	1080.62	1080.85	1083.77	1085.24	1086.26	1087	1087.76	1088.28	1088.82	1089.19
ΔMass (g)		8291.103	0	1.23	1.59	1.79	2.11	2.33	2.78	3.38	3.82	4.1	4.34	4.57	7.49	8.96	9.98	10.72	11.48	12	12.54	12.91
Δmass/areaXdensity of water			0	0.148352	0.191772	0.215894	0.25449	0.281024	0.335299	0.407666	0.460735	0.494506	0.523453	0.551193	0.903378	1.080677	1.2037	1.292952	1.384617	1.447335	1.512465	1.557091
Time (s)	40-20-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.98	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1134.44	1135.53	1135.89	1136.17	1136.3	1136.56	1136.96	1137.46	1137.75	1138.05	1138.22	1138.46	1140.9	1142.12	1142.98	1143.61	1144.28	1144.73	1145.13	1145.54
ΔMass (g)		8329.073	0	1.09	1.45	1.73	1.86	2.12	2.52	3.02	3.31	3.61	3.78	4.02	6.46	7.68	8.54	9.17	9.84	10.29	10.69	11.1
Δmass/areaXdensity of water			0	0.130867	0.174089	0.207706	0.223314	0.25453	0.302555	0.362585	0.397403	0.433422	0.453832	0.482647	0.775597	0.922071	1.025324	1.100963	1.181404	1.235432	1.283456	1.332681
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of water			0	0.131688	0.173358	0.195637	0.218637	0.245186	0.29108	0.35088	0.390779	0.423984	0.451208	0.475949	0.778638	0.929679	1.040874	1.123673	1.205227	1.265064	1.317037	1.367179
Time (s)	40-25-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.35	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1098.64	1099.93	1100.26	1100.52	1100.83	1101.04	1101.55	1102.17	1102.57	1102.92	1103.16	1103.39	1106.46	1107.96	1109	1109.78	1110.53	1111.07	1111.48	1111.88
ΔMass (g)		8227.475	0	1.29	1.62	1.88	2.19	2.4	2.91	3.53	3.93	4.28	4.52	4.75	7.82	9.32	10.36	11.14	11.89	12.43	12.84	13.24
Δmass/areaXdensity of water (mm)			0	0.156792	0.196901	0.228503	0.266181	0.291706	0.353693	0.42905	0.477668	0.520208	0.549379	0.577334	0.950474	1.13279	1.259196	1.354	1.445158	1.510792	1.560625	1.609242
Time (s)	40-25-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.5	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1071.5	1072.96	1073.39	1073.66	1074.02	1074.27	1074.84	1075.49	1076.03	1076.39	1076.72	1077.01	1080.2	1081.72	1082.82	1083.62	1084.37	1084.94	1085.39	1085.77
ΔMass (g)		8251.609	0	1.46	1.89	2.16	2.52	2.77	3.34	3.99	4.53	4.89	5.22	5.51	8.7	10.22	11.32	12.12	12.87	13.44	13.89	14.27
Δmass/areaXdensity of water			0	0.176935	0.229046	0.261767	0.305395	0.335692	0.40477	0.483542	0.548984	0.592612	0.632604	0.667749	1.05434	1.238546	1.371854	1.468804	1.559696	1.628773	1.683308	1.72936
Time (s)	40-25-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.36	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1106.97	1108.14	1108.45	1108.66	1108.96	1109.18	1109.63	1110.13	1110.54	1110.82	1111.07	1111.28	1113.99	1115.24	1116.28	1117.06	1117.76	1118.34	1118.76	1119.25
ΔMass (g)		8229.083	0	1.17	1.48	1.69	1.99	2.21	2.66	3.16	3.57	3.85	4.1	4.31	7.02	8.27	9.31	10.09	10.79	11.37	11.79	12.28
Δmass/areaXdensity of water			0	0.142179	0.17985	0.205369	0.241825	0.26856	0.323244	0.384004	0.433827	0.467853	0.498233	0.523752	0.853072	1.004972	1.131353	1.226139	1.311203	1.381685	1.432723	1.492268
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of water			0	0.166863	0.212974	0.245135	0.285788	0.313699	0.379231	0.456296	0.513326	0.55641	0.590991	0.622541	1.002407	1.185668	1.315525	1.411402	1.502427	1.569782	1.621966	1.669301

Sorptivity Test Sheet

Name: **45- FS (Finished Surl (w/c 0.45, 15%/20%/25% Fly Ash)**

Aggregate Type = **Limestone** **Fly Ash =** **Red Rock**

Aggregate Size = **#56**

Start Date:

Comments:

	Diameter			
Samples	1	2	3	Average
1		101.18	101.21	101.195
2		101.26	101.27	101.265
3		101.45	101.24	101.345

	Diameter			
Samples	1	2	3	Average
4		101.24	101.25	101.245
5		101.17	101.18	101.175
6		101.32	101.07	101.195

	Diameter			
Samples	1	2	3	Average
7		101.14	101.16	101.15
8		101.34	101.4	101.37
9		101.08	101.3	101.19

	Diameter			
Samples	1	2	3	Average
10				#DIV/0!
11				#DIV/0!
12				#DIV/0!

			Measurments																			
	Samples	**Area**	0	60s±2s	5min±10s	10min±2	20min±2	30min±2	60min±2	2hrs±5	3hrs±5	4hrs±5	5hrs±5	6hrs±5	day1±2h	day2±2h	day3±2h	day5±2h	day5±2h	day6±2h	day7±2h	day8±2h
Time (s)	45-15-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.195	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	956.13	957.61	956.27	958.73	959.34	959.82	960.73	961.8	962.58	963.17	963.71	964.08	968.68	971.3	973.02	974.25	975.11	975.59	975.81	975.97
ΔMass (g)		8042.832	0	1.48	0.14	2.6	3.21	3.69	4.6	5.67	6.45	7.04	7.58	7.95	12.55	15.17	16.89	18.12	18.98	19.46	19.68	19.84
Δmass/areaXdensity of water (mm)			0	0.184015	0.017407	0.323269	0.399113	0.458794	0.571938	0.704976	0.801956	0.875314	0.942454	0.988458	1.560396	1.886152	2.100007	2.252938	2.359865	2.419546	2.446899	2.466793
Time (s)	45-15-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.265	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1023.26	1024.9	1025.62	1026.68	1026.71	1027.15	1028.05	1029.09	1029.83	1030.39	1030.93	1031.36	1036.73	1039.84	1041.81	1043.11	1044.05	1044.58	1044.86	1045.05
ΔMass (g)		8053.963	0	1.64	2.36	3.42	3.45	3.89	4.79	5.83	6.57	7.13	7.67	8.1	13.47	16.58	18.55	19.85	20.79	21.32	21.6	21.79
Δmass/areaXdensity of water (mm)			0	0.203626	0.293023	0.424636	0.428361	0.482992	0.594738	0.723867	0.815747	0.885278	0.952326	1.005716	1.672469	2.058614	2.303214	2.464625	2.581338	2.647144	2.68191	2.7055
Time (s)	45-15-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.345	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1049.53	1051.32	1052.03	1052.56	1053.17	1053.64	1054.55	1055.6	1056.23	1056.71	1057.2	1057.39	1062.48	1065.29	1067.05	1068.34	1069.24	1069.77	1070.06	1070.26
ΔMass (g)		8066.693	0	1.79	2.5	3.03	3.64	4.11	5.02	6.07	6.7	7.18	7.67	7.86	12.95	15.76	17.52	18.81	19.71	20.24	20.53	20.73
Δmass/areaXdensity of water (mm)			0	0.2219	0.309916	0.375619	0.451238	0.509502	0.622312	0.752477	0.830576	0.89008	0.950823	0.974377	1.605367	1.953713	2.171894	2.33181	2.44338	2.509083	2.545033	2.569826
Time (s)			0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of	Average		0	0.202957	0.163662	0.349444	0.425176	0.484148	0.597125	0.728726	0.816266	0.882697	0.946639	0.981417	1.582881	1.919932	2.13595	2.292374	2.401623	2.464314	2.495966	2.518309
Time (s)	45-20-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.245	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	996.19	997.77	998.15	998.46	998.92	999.27	1000.05	1000.92	1001.55	1001.99	1002.4	1002.73	1007.36	1009.89	1011.66	1013	1014.1	1014.79	1015.36	1015.73
ΔMass (g)		8050.782	0	1.58	1.96	2.27	2.73	3.08	3.86	4.73	5.36	5.8	6.21	6.54	11.17	13.7	15.47	16.81	17.91	18.6	19.17	19.54
Δmass/areaXdensity of water (mm)			0	0.196254	0.243455	0.28196	0.339097	0.382572	0.479457	0.587521	0.665774	0.720427	0.771354	0.812343	1.387443	1.701698	1.921552	2.087996	2.224629	2.310335	2.381135	2.427093
Time (s)	45-20-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.175	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1027.7	1029.31	1029.82	1030.23	1030.71	1031.11	1031.83	1032.63	1033.27	1033.68	1034.05	1034.35	1038.48	1040.71	1042.28	1043.46	1044.49	1045.25	1045.8	1046.33
ΔMass (g)		8039.653	0	1.61	2.12	2.53	3.01	3.41	4.13	4.93	5.57	5.98	6.35	6.65	10.78	13.01	14.58	15.76	16.79	17.55	18.1	18.63
Δmass/areaXdensity of water (mm)			0	0.200257	0.263693	0.31469	0.374394	0.424148	0.513704	0.613211	0.692816	0.743813	0.789835	0.82715	1.340854	1.618229	1.813511	1.960284	2.088399	2.18293	2.251341	2.317264
Time (s)	45-20-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.195	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1048	1050	1050.8	1051.22	1051.88	1052.27	1053.17	1054.17	1054.87	1055.41	1055.88	1056.33	1061.39	1064.3	1066.27	1067.84	1069.04	1069.98	1070.66	1071.05
ΔMass (g)		8042.832	0	2	2.8	3.22	3.88	4.27	5.17	6.17	6.87	7.41	7.88	8.33	13.39	16.3	18.27	19.84	21.04	21.98	22.66	23.05
Δmass/areaXdensity of water (mm)			0	0.248669	0.348136	0.400356	0.482417	0.530908	0.642808	0.767143	0.854177	0.921317	0.979754	1.035705	1.664836	2.026649	2.271588	2.466793	2.615994	2.732868	2.817415	2.865906
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of			0	0.198256	0.253574	0.298325	0.356746	0.40336	0.49658	0.600366	0.679295	0.73212	0.780594	0.819747	1.364148	1.659964	1.867532	2.02414	2.156514	2.246632	2.316238	2.372179
Time (s)	45-25-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.15	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1022.87	1024.86	1025.51	1026.02	1026.61	1027.05	1027.86	1028.82	1029.5	1030.09	1030.51	1030.86	1035.77	1038.29	1039.87	1040.97	1041.77	1042.22	1042.6	1042.8
ΔMass (g)		8035.681	0	1.99	2.64	3.15	3.74	4.18	4.99	5.95	6.63	7.22	7.64	7.99	12.9	15.42	17	18.1	18.9	19.35	19.73	19.93
Δmass/areaXdensity of water (mm)			0	0.247645	0.328535	0.392002	0.465424	0.52018	0.62098	0.740448	0.82507	0.898493	0.95076	0.994315	1.60534	1.918941	2.115564	2.252454	2.35201	2.40801	2.455299	2.480188
Time (s)	45-25-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.37	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1057.33	1059.43	1060.22	1060.77	1061.46	1061.89	1062.82	1063.88	1064.63	1065.17	1065.63	1066.01	1070.84	1073.48	1075.18	1076.41	1077.21	1077.81	1078.25	1078.59
ΔMass (g)		8070.674	0	2.1	2.89	3.44	4.13	4.56	5.49	6.55	7.3	7.84	8.3	8.68	13.51	16.15	17.85	19.08	19.88	20.48	20.92	21.26
Δmass/areaXdensity of water (mm)			0	0.260201	0.358087	0.426235	0.511729	0.565009	0.680241	0.81158	0.904509	0.971418	1.028415	1.075499	1.673962	2.001072	2.211711	2.364115	2.463239	2.537582	2.592101	2.634229
Time (s)	45-25-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.19	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	956.87	958.7	959.27	959.69	960.23	960.61	961.43	962.34	962.95	963.42	963.84	964.17	968.86	971.72	973.54	974.83	975.6	976.14	976.44	976.64
ΔMass (g)		8042.037	0	1.83	2.4	2.82	3.36	3.74	4.56	5.47	6.08	6.55	6.97	7.3	11.99	14.85	16.67	17.96	18.73	19.27	19.57	19.77
Δmass/areaXdensity of water (mm)			0	0.227554	0.298432	0.350657	0.417805	0.465056	0.56702	0.680176	0.756027	0.81447	0.866696	0.90773	1.490916	1.846547	2.072858	2.233265	2.329012	2.396159	2.433463	2.458332
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of			0	0.253923	0.343311	0.409118	0.488577	0.542594	0.65061	0.776014	0.86479	0.934955	0.989587	1.034907	1.639651	1.960007	2.163638	2.308284	2.407625	2.472796	2.5237	2.557208

Sorptivity Test Sheet

Name: **50- FS (Finished Surl (w/c 0.50, 15%/20%/25% Fly Ash)**

Aggregate Type = Limestone

Fly Ash = Red Rock

Aggregate Size = #56

Start Date:

Comments:

	Diameter			
Samples	1	2	3	Average
1		102.35	102.73	102.54
2		102.62	102.24	102.43
3		102.78	102.58	102.68

	Diameter			
Samples	1	2	3	Average
4		102.54	102.26	102.4
5		102.92	102.33	102.625
6		102.59	102.59	102.59

	Diameter			
Samples	1	2	3	Average
7		101.43	101.99	101.71
8		102.33	102.27	102.3
9		101.32	101.66	101.49

	Diameter			
Samples	1	2	3	Average
10				#DIV/0!
11				#DIV/0!
12				#DIV/0!

			Measurments																			
	Samples	Area	0	60s±2s	5min±10s	10min±2	20min±2	30min±2	60min±2	2hrs±5	3hrs±5	4hrs±5	5hrs±5	6hrs±5	day1±2h	day2±2h	day3±2h	day5±2h	day5±2h	day6±2h	day7±2h	day8±2h
Time (s)	50-15-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		102.54	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1041.67	1043.27	1044.04	1044.59	1045.31	1045.84	1046.84	1048.08	1048.87	1049.55	1050.08	1050.53	1056.87	1060.11	1062.5	1064.27	1065.57	1066.53	1067.09	1067.37
ΔMass (g)		8258.05	0	1.6	2.37	2.92	3.64	4.17	5.17	6.41	7.2	7.88	8.41	8.86	15.2	18.44	20.83	22.6	23.9	24.86	25.42	25.7
Δmass/areaXdensity of water			0	0.19375	0.286993	0.353594	0.440782	0.504962	0.626056	0.776212	0.871877	0.95422	1.0184	1.072892	1.840628	2.232973	2.522387	2.736723	2.894146	3.010396	3.078208	3.112115
Time (s)	50-15-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		102.43	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1048.54	1050.83	1051.83	1052.53	1053.42	1053.97	1055.07	1056.34	1057.3	1058.02	1058.59	1059.1	1066.02	1069.66	1072.04	1073.57	1074.41	1074.9	1075.06	1075.13
ΔMass (g)		8240.342	0	2.29	3.29	3.99	4.88	5.43	6.53	7.8	8.76	9.48	10.05	10.56	17.48	21.12	23.5	25.03	25.87	26.36	26.52	26.59
Δmass/areaXdensity of water			0	0.277901	0.399255	0.484203	0.592208	0.658953	0.792443	0.946563	1.063063	1.150438	1.21961	1.2815	2.121271	2.563	2.851823	3.037495	3.139433	3.198896	3.218313	3.226808
Time (s)	50-15-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		102.68	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	964.11	966.16	967.2	967.76	968.51	968.97	969.95	971.21	972.09	972.8	973.36	973.91	980.6	984.1	986.17	987.26	987.67	987.93	987.99	988.06
ΔMass (g)		8280.615	0	2.05	3.09	3.65	4.4	4.86	5.84	7.1	7.98	8.69	9.25	9.8	16.49	19.99	22.06	23.15	23.56	23.82	23.88	23.95
Δmass/areaXdensity of water			0	0.247566	0.373161	0.440788	0.531361	0.586913	0.705262	0.857424	0.963696	1.049439	1.117067	1.183487	1.991398	2.414072	2.664053	2.795686	2.845199	2.876598	2.883844	2.892297
Time (s)			0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of	Average		0	0.220658	0.330077	0.397191	0.486072	0.545937	0.665659	0.816818	0.917786	1.00183	1.067733	1.12819	1.916013	2.323522	2.59322	2.766205	2.869672	2.943497	2.981026	3.002206
Time (s)	50-20-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		102.4	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1050.07	1052.46	1053.42	1054.08	1054.87	1055.44	1056.58	1057.98	1058.94	1059.63	1060.21	1060.77	1067.47	1070.93	1073.1	1074.49	1075.25	1075.79	1075.98	1076.07
ΔMass (g)		8235.516	0	2.39	3.35	4.01	4.8	5.37	6.51	7.91	8.87	9.56	10.14	10.7	17.4	20.86	23.03	24.42	25.18	25.72	25.91	26
Δmass/areaXdensity of water			0	0.290206	0.406775	0.486915	0.582841	0.652054	0.790479	0.960474	1.077042	1.160826	1.231253	1.299251	2.1128	2.532932	2.796425	2.965206	3.057489	3.123059	3.14613	3.157058
Time (s)	50-20-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		102.625	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1057.91	1060.09	1060.91	1061.45	1062.32	1062.98	1064.18	1065.61	1066.58	1067.28	1067.84	1068.38	1074.68	1078.04	1080.41	1082.08	1083.15	1084.03	1084.42	1084.62
ΔMass (g)		8271.747	0	2.18	3	3.54	4.41	5.07	6.27	7.7	8.67	9.37	9.93	10.47	16.77	20.13	22.5	24.17	25.24	26.12	26.51	26.71
Δmass/areaXdensity of water			0	0.263548	0.36268	0.427963	0.53314	0.61293	0.758002	0.93088	1.048146	1.132772	1.200472	1.265754	2.027383	2.433585	2.720103	2.921995	3.051351	3.157737	3.204885	3.229064
Time (s)	50-20-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		102.59	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1004.66	1007.12	1008.26	1009.05	1009.99	1010.57	1011.83	1013.24	1014.28	1014.99	1015.63	1016.17	1023.39	1027.02	1028.84	1029.69	1030.05	1030.29	1030.33	1030.41
ΔMass (g)		8266.106	0	2.46	3.6	4.39	5.33	5.91	7.17	8.58	9.62	10.33	10.97	11.51	18.73	22.36	24.18	25.03	25.39	25.63	25.67	25.75
Δmass/areaXdensity of water			0	0.297601	0.435513	0.531084	0.644802	0.714968	0.867398	1.037974	1.163789	1.249682	1.327106	1.392433	2.26588	2.705022	2.925198	3.028028	3.071579	3.100614	3.105453	3.115131
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x			0	0.280574	0.399097	0.479524	0.588971	0.663949	0.8127	0.984427	1.105967	1.191227	1.263789	1.329094	2.146631	2.569304	2.822651	2.975011	3.061465	3.129175	3.155169	3.172097
Time (s)	50-25-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		101.71	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1051.82	1054.3	1055.69	1056.6	1057.7	1058.48	1059.99	1061.78	1063.06	1064.05	1064.92	1065.69	1075.87	1080.18	1080.6	1080.93	1080.99	1081.2	1081.41	1081.39
ΔMass (g)		8124.903	0	2.48	3.87	4.78	5.88	6.66	8.17	9.96	11.24	12.23	13.1	13.87	24.05	28.36	28.78	29.11	29.17	29.38	29.59	29.57
Δmass/areaXdensity of water			0	0.305234	0.476313	0.588315	0.723701	0.819702	1.00555	1.225861	1.383401	1.505249	1.612327	1.707097	2.960035	3.490503	3.542196	3.582812	3.590197	3.616043	3.641889	3.639428
Time (s)	50-25-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		102.3	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1074.7	1076.8	1077.79	1078.49	1079.32	1079.85	1080.91	1082.2	1082.99	1083.59	1084.1	1084.59	1090.77	1094.3	1096.71	1098.32	1099.27	1099.9	1100.15	1100.29
ΔMass (g)		8219.439	0	2.1	3.09	3.79	4.62	5.15	6.21	7.5	8.29	8.89	9.4	9.89	16.07	19.6	22.01	23.62	24.57	25.2	25.45	25.59
Δmass/areaXdensity of water			0	0.255492	0.375938	0.461102	0.562082	0.626563	0.755526	0.912471	1.008585	1.081582	1.14363	1.203245	1.955121	2.384591	2.677798	2.873676	2.989255	3.065903	3.096318	3.113351
Time (s)	50-25-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		101.49	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1040.45	1042.64	1043.62	1044.26	1045.06	1045.64	1046.66	1047.91	1048.71	1049.36	1049.94	1050.43	1057.12	1060.88	1063.38	1064.94	1065.66	1066.01	1066.11	1066.22
ΔMass (g)		8089.793	0	2.19	3.17	3.81	4.61	5.19	6.21	7.46	8.26	8.91	9.49	9.98	16.67	20.43	22.93	24.49	25.21	25.56	25.66	25.77
Δmass/areaXdensity of water			0	0.270712	0.391852	0.470964	0.569854	0.641549	0.767634	0.92215	1.02104	1.101388	1.173083	1.233653	2.060621	2.525405	2.834436	3.027272	3.116273	3.159537	3.171898	3.185496
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x			0	0.280363	0.426126	0.524708	0.642892	0.723133	0.880538	1.069166	1.195993	1.293416	1.377979	1.455171	2.457578	2.937547	3.109997	3.228244	3.289726	3.340973	3.369104	3.37639

Sorptivity Test Sheet

Name: **40- CS (Casted Surface)** **Fly Ash Type**

Aggregate Type = **Limestone**
Aggregate Size = **#56**
Fly Ash = **Sources I-II-III**

Start Date:

Comments:

	Diameter			
Samples	1	2	3	Average
1		101.1	101.17	101.135
2		101.09	101.03	101.06
3		101.21	101.37	101.29

	Diameter			
Samples	1	2	3	Average
4		101.37	101	101.185
5		101.14	101.17	101.16
6		101.36	101.2	101.28

	Diameter			
Samples	1	2	3	Average
7		100.98	100.81	100.895
8		101.08	101.03	101.055
9		101.21	101.17	101.19

	Diameter			
Samples	1	2	3	Average
				#DIV/0!
				#DIV/0!
				#DIV/0!

			Measurments																			
	Samples	**Area**	0	60s±2s	5min±10s	10min±2	20min±2	30min±2	60min±2	2hrs±5	3hrs±5	4hrs±5	5hrs±5	6hrs±5	day1±2h	day2±2h	day3±2h	day5±2h	day5±2h	day6±2h	day7±2h	day8±2h
Time (s)	40-00-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		101.135	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1072.69	1073.02	1073.12	1073.18	1073.19	1073.31	1073.44	1073.62	1073.79	1073.94	1073.99	1074.1	1075.81	1076.79	1077.5	1078.11	1078.62	1079.02	1079.32	1079.61
ΔMass (g)		8033.298	0	0.33	0.43	0.49	0.5	0.62	0.75	0.93	1.1	1.25	1.3	1.41	3.12	4.1	4.81	5.42	5.93	6.33	6.63	6.92
Δmass/areaX density of			0	0.041079	0.053527	0.060996	0.062241	0.077179	0.093361	0.115768	0.13693	0.155602	0.161826	0.175519	0.388383	0.510376	0.598758	0.674692	0.738178	0.78797	0.825315	0.861415
Time (s)	40-00-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		101.06	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1077.06	1077.36	1077.52	1077.6	1077.73	1077.76	1077.91	1078.11	1078.25	1078.39	1078.51	1078.65	1080.25	1081.15	1081.81	1082.41	1082.88	1083.28	1083.61	1083.89
ΔMass (g)		8021.387	0	0.3	0.46	0.54	0.67	0.7	0.85	1.05	1.19	1.33	1.45	1.59	3.19	4.09	4.75	5.35	5.82	6.22	6.55	6.83
Δmass/areaX density of			0	0.0374	0.057347	0.06732	0.083527	0.087267	0.105967	0.1309	0.148353	0.165807	0.180767	0.19822	0.397687	0.509887	0.592167	0.666967	0.72556	0.775427	0.816567	0.851474
Time (s)	40-00-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		101.29	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1033.42	1034.11	1034.32	1034.43	1034.63	1034.75	1035.07	1035.49	1035.78	1036.05	1036.26	1036.42	1038.95	1040.22	1041.16	1041.96	1042.6	1043.08	1043.52	1043.92
ΔMass (g)		8057.94	0	0.69	0.9	1.01	1.21	1.33	1.65	2.07	2.36	2.63	2.84	3	5.53	6.8	7.74	8.54	9.18	9.66	10.1	10.5
Δmass/areaX density of water (mm)			0	0.08563	0.111691	0.125342	0.150162	0.165055	0.204767	0.256889	0.292879	0.326386	0.352447	0.372304	0.68628	0.843888	0.960543	1.059824	1.139249	1.198818	1.253422	1.303063
Time (s)			0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of	Average		0	0.03924	0.055437	0.064158	0.072884	0.082223	0.099664	0.123334	0.142642	0.160705	0.171297	0.18687	0.393035	0.510131	0.595462	0.670829	0.731869	0.781699	0.820941	0.856444
Time (s)	40-00-56-0-3-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		101.185	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1054.65	1055.47	1056.35	1056.44	1056.7	1056.87	1057.35	1058.05	1058.32	1058.85	1059.17	1059.38	1063.5	1064.74	1065.52	1066.79	1066.79	1068	1068.44	1068.8
ΔMass (g)		8041.243	0	0.82	1.7	1.79	2.05	2.22	2.7	3.4	3.67	4.2	4.52	4.73	8.85	10.09	10.87	12.14	12.14	13.35	13.79	14.15
Δmass/areaX density of			0	0.101974	0.21141	0.222602	0.254936	0.276077	0.335769	0.42282	0.456397	0.522307	0.562102	0.588218	1.100576	1.254781	1.351781	1.509717	1.509717	1.660191	1.714909	1.759678
Time (s)	40-00-56-0-3-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		101.155	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1158.22	1158.91	1159.03	1159.29	1159.39	1159.54	1159.91	1160.68	1161.12	1161.76	1162.07	1162.42	1166.64	1167.95	1168.64	1169.88	1169.88	1170.99	1171.48	1171.71
ΔMass (g)		8036.475	0	0.69	0.81	1.07	1.17	1.32	1.69	2.46	2.9	3.54	3.85	4.2	8.42	9.73	10.42	11.66	11.66	12.77	13.26	13.49
Δmass/areaX density of			0	0.085859	0.10079	0.133143	0.145586	0.164251	0.210291	0.306104	0.360855	0.440492	0.479066	0.522617	1.047723	1.21073	1.296588	1.450885	1.450885	1.589005	1.649977	1.678597
Time (s)	40-00-56-0-3-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		101.28	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1014.41	1015.15	1015.37	1015.59	1015.99	1016.44	1017	1018	1018.42	1019.05	1019.45	1019.83	1025.26	1027.04	1028.32	1030.09	1030.17	1031.75	1032.53	1032.9
ΔMass (g)		8056.349	0	0.74	0.96	1.18	1.58	2.03	2.59	3.59	4.01	4.64	5.04	5.42	10.85	12.63	13.91	15.68	15.76	17.34	18.12	18.49
Δmass/areaX			0	0.091853	0.119161	0.146468	0.196119	0.251975	0.321486	0.445611	0.497744	0.575943	0.625594	0.672761	1.346764	1.567708	1.726589	1.946291	1.956221	2.15234	2.249158	2.295084
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of			0	0.093229	0.143787	0.167405	0.19888	0.230768	0.289182	0.391512	0.438332	0.512914	0.555587	0.594532	1.165021	1.344406	1.458319	1.635631	1.638941	1.800512	1.871348	1.91112
Time (s)	40-00-56-0-4-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		100.895	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1007.02	1008.05	1008.33	1008.6	1009.02	1009.27	1009.93	1010.12	1011.32	1011.95	1012.31	1012.76	1017.3	1018.39	1018.97	1019.99	1019.99	1020.65	1020.92	1021.09
ΔMass (g)		7995.216	0	1.03	1.31	1.58	2	2.25	2.91	3.1	4.3	4.93	5.29	5.74	10.28	11.37	11.95	12.97	12.97	13.63	13.9	14.07
Δmass/areaX density of water (mm)			0	0.128827	0.163848	0.197618	0.25015	0.281418	0.363968	0.387732	0.537822	0.616619	0.661646	0.717929	1.285769	1.4221	1.494644	1.62222	1.62222	1.70477	1.73854	1.759802
Time (s)	40-00-56-0-4-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		101.055	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1003.43	1004.26	1004.5	1004.87	1005.23	1005.44	1006.21	1007.31	1008.21	1008.89	1009.39	1010.14	1017.17	1019.58	1021	1022.71	1022.78	1024.32	1025.18	1025.64
ΔMass (g)		8020.594	0	0.83	1.07	1.44	1.8	2.01	2.78	3.88	4.78	5.46	5.96	6.71	13.74	16.15	17.57	19.28	19.35	20.89	21.75	22.21
Δmass/areaX density of			0	0.103484	0.133407	0.179538	0.224422	0.250605	0.346608	0.483755	0.595966	0.680748	0.743087	0.836596	1.71309	2.013567	2.190611	2.403812	2.41254	2.604545	2.711769	2.769122
Time (s)	40-00-56-0-4-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		101.19	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	998.43	999.09	999.29	999.64	999.93	1000.22	1000.8	1001.82	1002.4	1003.14	1003.34	1003.93	1008.91	1010.01	1010.63	1011.79	1011.79	1012.41	1012.75	1012.85
ΔMass (g)		8042.037	0	0.66	0.86	1.21	1.5	1.79	2.37	3.39	3.97	4.71	4.91	5.5	10.48	11.58	12.2	13.36	13.36	13.98	14.32	14.42
Δmass/areaX density of			0	0.082069	0.106938	0.150459	0.18652	0.22258	0.294701	0.421535	0.493656	0.585672	0.610542	0.683906	1.303152	1.439934	1.517029	1.661271	1.661271	1.738365	1.780643	1.793078
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of			0	0.116155	0.148627	0.188578	0.237286	0.266012	0.355288	0.435743	0.566894	0.648683	0.702366	0.777263	1.49943	1.717834	1.842627	2.013016	2.01738	2.154657	2.225155	2.264462

Sorptivity Test Sheet

Name: **40- CS (Casted Surfa (w/c 0.40, 0%/10%/20% Fly Ash)**

Aggregate Type = **Dolomite-Granite** **Fly Ash =** **Red Rock**

Aggregate Size = **#56 & #57**

Start Date:

Comments:

	Diameter			
Samples	1	2	3	Average
1		101.1	101.17	101.135
2		101.09	101.03	101.06
3		101.21	101.37	101.29

	Diameter			
Samples	1	2	3	Average
4		101.1	101.17	101.135
5		101.09	101.03	101.06
6		101.21	101.37	101.29

	Diameter			
Samples	1	2	3	Average
7				#DIV/0!
8				#DIV/0!
9				#DIV/0!

	Diameter			
Samples	1	2	3	Average
				#DIV/0!
				#DIV/0!
				#DIV/0!

			Measurments																			
	Samples	**Area**	0	60s±2s	5min±10s	10min±2	20min±2	30min±2	60min±2	2hrs±5	3hrs±5	4hrs±5	5hrs±5	6hrs±5	day1±2h	day2±2h	day3±2h	day5±2h	day5±2h	day6±2h	day7±2h	day8±2h
Time (s)	40-00-S1 (Dolomite)	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		101.135	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1054.65	1055.47	1056.35	1056.44	1056.7	1056.87	1057.35	1058.05	1058.32	1058.85	1059.17	1059.38	1063.5	1064.74	1065.52	1066.79	1066.79	1068	1068.44	1068.8
ΔMass (g)		8033.298	0	0.82	1.7	1.79	2.05	2.22	2.7	3.4	3.67	4.2	4.52	4.73	8.85	10.09	10.87	12.14	12.14	13.35	13.79	14.15
Δmass/areaX density of water (mm)			0	0.102075	0.211619	0.222823	0.255188	0.27635	0.336101	0.423238	0.456849	0.522824	0.562658	0.588799	1.101665	1.256022	1.353118	1.51121	1.51121	1.661833	1.716605	1.761419
Time (s)	40-00-S2 (Dolomite)	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		101.06	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1158.22	1158.91	1159.03	1159.29	1159.39	1159.54	1159.91	1160.68	1161.12	1161.76	1162.07	1162.42	1166.64	1167.95	1168.64	1169.88	1169.88	1170.99	1171.48	1171.71
ΔMass (g)		8021.387	0	0.69	0.81	1.07	1.17	1.32	1.69	2.46	2.9	3.54	3.85	4.2	8.42	9.73	10.42	11.66	11.66	12.77	13.26	13.49
Δmass/areaX density of water (mm)			0	0.08602	0.10098	0.133393	0.14586	0.16456	0.210687	0.30668	0.361533	0.44132	0.479967	0.5236	1.049694	1.213007	1.299027	1.453614	1.453614	1.591994	1.653081	1.681754
Time (s)	40-00-S3 (Dolomite)	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		101.29	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1014.41	1015.15	1015.37	1015.59	1015.99	1016.44	1017	1018	1018.42	1019.05	1019.45	1019.83	1025.26	1027.04	1028.32	1030.09	1030.17	1031.75	1032.53	1032.9
ΔMass (g)		8057.94	0	0.74	0.96	1.18	1.58	2.03	2.59	3.59	4.01	4.64	5.04	5.42	10.85	12.63	13.91	15.68	15.76	17.34	18.12	18.49
Δmass/areaX density of water (mm)			0	0.091835	0.119137	0.146439	0.19608	0.251925	0.321422	0.445523	0.497646	0.57583	0.62547	0.672628	1.346498	1.567398	1.726248	1.945907	1.955835	2.151915	2.248714	2.294631
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of water			0	0.094048	0.1563	0.178108	0.200524	0.220455	0.273394	0.364959	0.409191	0.482072	0.521312	0.5562	1.075679	1.234515	1.326073	1.482412	1.482412	1.626914	1.684843	1.721586
Time (s)	40-00-S1 (Granite)	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		7.745967	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1007.02	1008.05	1008.33	1008.6	1009.02	1009.27	1009.93	1010.12	1011.32	1011.95	1012.31	1012.76	1017.3	1018.39	1018.97	1019.99	1019.99	1020.65	1020.92	1021.09
ΔMass (g)		47.124	0	1.03	1.31	1.58	2	2.25	2.91	3.1	4.3	4.93	5.29	5.74	10.28	11.37	11.95	12.97	12.97	13.63	13.9	14.07
Δmass/areaX density of water (mm)			0	0.128216	0.163071	0.196681	0.248964	0.280084	0.362242	0.385894	0.535272	0.613696	0.658509	0.714526	1.279674	1.415359	1.487558	1.61453	1.61453	1.696688	1.730298	1.75146
Time (s)	40-00-S2 (Granite)	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		1015.15	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1003.43	1004.26	1004.5	1004.87	1005.23	1005.44	1006.21	1007.31	1008.21	1008.89	1009.39	1010.14	1017.17	1019.58	1021	1022.71	1022.78	1024.32	1025.18	1025.64
ΔMass (g)		809377.9	0	0.83	1.07	1.44	1.8	2.01	2.78	3.88	4.78	5.46	5.96	6.71	13.74	16.15	17.57	19.28	19.35	20.89	21.75	22.21
Δmass/areaX density of water (mm)			0	0.103473	0.133393	0.17952	0.2244	0.25058	0.346573	0.483707	0.595907	0.68068	0.743014	0.836514	1.712921	2.013367	2.190394	2.403574	2.412301	2.604288	2.711501	2.768848
Time (s)	40-00-S3 (Granite)	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		0.74	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	998.43	999.09	999.29	999.64	999.93	1000.22	1000.8	1001.82	1002.4	1003.14	1003.34	1003.93	1008.91	1010.01	1010.63	1011.79	1011.79	1012.41	1012.75	1012.85
ΔMass (g)		0.430085	0	0.66	0.86	1.21	1.5	1.79	2.37	3.39	3.97	4.71	4.91	5.5	10.48	11.58	12.2	13.36	13.36	13.98	14.32	14.42
Δmass/areaX density of water (mm)			0	0.081907	0.106727	0.150162	0.186152	0.222141	0.29412	0.420703	0.492682	0.584517	0.609337	0.682557	1.300581	1.437092	1.514035	1.657992	1.657992	1.734935	1.777129	1.789539
Time (s)			0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of	Average		0	0.105062	0.134899	0.173422	0.217558	0.251113	0.328181	0.403298	0.513977	0.599106	0.633923	0.698541	1.290127	1.426225	1.500797	1.636261	1.636261	1.715811	1.753714	1.7705

Sorptivity Test Sheet

Name: **40- CS (Casted Surfa (w/c 0.40, 15%/20%/25% Fly Ash)** Equipment:

Start Date:

Comments:

	Diameter			
Samples	1	2	3	Average
1		101.19	101.23	101.21
2		101.03	101.1	101.065
3		101.11	101.17	101.14

	Diameter			
Samples	1	2	3	Average
4		101.08	101.04	101.06
5		101.04	101.15	101.10
6		100.97	100.8	100.885

	Diameter			
Samples	1	2	3	Average
7		101.12	101.08	101.1
8		101.15	101.38	101.265
9		100.91	100.97	100.94

	Diameter			
Samples	1	2	3	Average
				#DIV/0!
				#DIV/0!
				#DIV/0!

			Measurments																			
	Samples	**Area**	0	60s±2s	5min±10s	10min±2	20min±2	30min±2	60min±2	2hrs±5	3hrs±5	4hrs±5	5hrs±5	6hrs±5	day1±2h	day2±2h	day3±2h	day5±2h	day5±2h	day6±2h	day7±2h	day8±2h
Time (s)	40-15-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.21	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1065.58	1065.95	1066.06	1066.13	1066.22	1066.23	1066.4	1066.58	1066.72	1066.88	1066.97	1067.04	1068.5	1069.24	1069.82	1070.35	1070.69	1070.98	1071.22	1071.46
ΔMass (g)		8045.217	0	0.37	0.48	0.55	0.64	0.65	0.82	1	1.14	1.3	1.39	1.46	2.92	3.66	4.24	4.77	5.11	5.4	5.64	5.88
Δmass/areaX density of water (mm)			0	0.04599	0.059663	0.068364	0.07955	0.080793	0.101924	0.124297	0.141699	0.161587	0.172773	0.181474	0.362949	0.454929	0.527021	0.592899	0.63516	0.671206	0.701038	0.730869
Time (s)	40-15-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.065	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1067.39	1067.88	1067.9	1067.96	1068.04	1068.1	1068.22	1068.43	1068.57	1068.72	1068.83	1068.91	1070.34	1071.14	1071.72	1072.25	1072.61	1072.95	1073.22	1073.44
ΔMass (g)		8022.181	0	0.49	0.51	0.57	0.65	0.71	0.83	1.04	1.18	1.33	1.44	1.52	2.95	3.75	4.33	4.86	5.22	5.56	5.83	6.05
Δmass/areaX density of water (mm)			0	0.061081	0.063574	0.071053	0.081025	0.088505	0.103463	0.129641	0.147092	0.16579	0.179502	0.189475	0.36773	0.467454	0.539753	0.60582	0.650696	0.693078	0.726735	0.754159
Time (s)	40-15-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.14	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1075.58	1075.97	1076.04	1076.06	1076.08	1076.1	1076.18	1076.31	1076.35	1076.45	1076.51	1076.58	1077.59	1078.28	1078.8	1079.26	1079.59	1079.86	1080.09	1080.31
ΔMass (g)		8034.092	0	0.39	0.46	0.48	0.5	0.52	0.6	0.73	0.77	0.87	0.93	1	2.01	2.7	3.22	3.68	4.01	4.28	4.51	4.73
Δmass/areaX density of water (mm)			0	0.048543	0.057256	0.059745	0.062235	0.064724	0.074682	0.090863	0.095842	0.108289	0.115757	0.12447	0.250184	0.336068	0.400792	0.458048	0.499123	0.53273	0.561358	0.588741
Time (s)			0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of water	Average		0	0.053535	0.061618	0.069708	0.080288	0.084649	0.102694	0.126969	0.144396	0.163689	0.176138	0.185474	0.36534	0.461191	0.533387	0.59936	0.642928	0.682142	0.713886	0.742514
Time (s)	40-20-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.06	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1063.01	1063.38	1063.44	1063.51	1063.59	1063.62	1063.92	1064.2	1064.47	1064.67	1064.88	1064.99	1066.97	1067.95	1068.65	1069.18	1069.68	1070.05	1070.38	1070.68
ΔMass (g)		8021.387	0	0.37	0.43	0.5	0.58	0.61	0.91	1.19	1.46	1.66	1.87	1.98	3.96	4.94	5.64	6.17	6.67	7.04	7.37	7.67
Δmass/areaX density of water (mm)			0	0.046127	0.053607	0.062333	0.072307	0.076047	0.113447	0.148353	0.182013	0.206947	0.233127	0.24684	0.49368	0.615854	0.70312	0.769194	0.831527	0.877654	0.918794	0.956194
Time (s)	40-20-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.095	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1081.52	1081.92	1082.06	1082.14	1082.26	1082.34	1082.62	1082.86	1083.07	1083.25	1083.43	1083.57	1085.39	1086.28	1086.93	1087.39	1087.84	1088.17	1088.48	1088.71
ΔMass (g)		8026.944	0	0.4	0.54	0.62	0.74	0.82	1.1	1.34	1.55	1.73	1.91	2.05	3.87	4.76	5.41	5.87	6.32	6.65	6.96	7.19
Δmass/areaX density of			0	0.049832	0.067273	0.07724	0.09219	0.102156	0.137038	0.166938	0.1931	0.215524	0.237949	0.25539	0.482126	0.593003	0.67398	0.731287	0.787348	0.82846	0.86708	0.895733
Time (s)	40-20-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		100.885	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1088.41	1088.73	1088.86	1088.88	1088.98	1089.02	1089.12	1089.35	1089.45	1089.62	1089.7	1089.82	1091.11	1091.76	1092.37	1092.74	1093.15	1093.4	1093.65	1093.86
ΔMass (g)		7993.631	0	0.32	0.45	0.47	0.57	0.61	0.71	0.94	1.04	1.21	1.29	1.41	2.7	3.35	3.96	4.33	4.74	4.99	5.24	5.45
Δmass/areaX density of			0	0.040032	0.056295	0.058797	0.071307	0.076311	0.088821	0.117594	0.130104	0.151371	0.161378	0.17639	0.337769	0.419084	0.495394	0.541681	0.592972	0.624247	0.655522	0.681793
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of water			0	0.047979	0.06044	0.069787	0.082248	0.089101	0.125243	0.157646	0.187557	0.211235	0.235538	0.251115	0.487903	0.604428	0.68855	0.75024	0.809438	0.853057	0.892937	0.925963
Time (s)	40-25-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.1	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1064.22	1064.63	1064.71	1064.77	1064.8	1064.87	1064.93	1065.14	1065.23	1065.37	1065.46	1065.58	1066.95	1067.63	1068.11	1068.48	1068.82	1069.05	1069.24	1069.42
ΔMass (g)		8027.738	0	0.41	0.49	0.55	0.58	0.65	0.71	0.92	1.01	1.15	1.24	1.36	2.73	3.41	3.89	4.26	4.6	4.83	5.02	5.2
Δmass/areaX density of water (mm)			0	0.051073	0.061038	0.068512	0.072249	0.080969	0.088443	0.114603	0.125814	0.143253	0.154464	0.169413	0.340071	0.424777	0.48457	0.53066	0.573013	0.601664	0.625332	0.647754
Time (s)	40-25-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.265	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1086.09	1086.52	1086.61	1086.64	1086.65	1086.69	1086.8	1086.88	1087	1087.05	1087.14	1087.16	1088.16	1088.69	1089.07	1089.4	1089.67	1089.9	1090.03	1090.2
ΔMass (g)		8053.963	0	0.43	0.52	0.55	0.56	0.6	0.71	0.79	0.91	0.96	1.05	1.07	2.07	2.6	2.98	3.31	3.58	3.81	3.94	4.11
Δmass/areaX density of			0	0.05339	0.064564	0.068289	0.069531	0.074497	0.088155	0.098088	0.112988	0.119196	0.130371	0.132854	0.257016	0.322822	0.370004	0.410978	0.444502	0.473059	0.4892	0.510308
Time (s)	40-25-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		100.94	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1091.74	1092.14	1092.2	1092.23	1092.27	1092.3	1092.38	1092.52	1092.66	1092.73	1092.79	1092.87	1094.03	1094.63	1095.15	1095.52	1095.85	1096.08	1096.29	1096.42
ΔMass (g)		8002.349	0	0.4	0.46	0.49	0.53	0.56	0.64	0.78	0.92	0.99	1.05	1.13	2.29	2.89	3.41	3.78	4.11	4.34	4.55	4.68
Δmass/areaX density of			0	0.049985	0.057483	0.061232	0.066231	0.069979	0.079977	0.097471	0.114966	0.123714	0.131211	0.141209	0.286166	0.361144	0.426125	0.472361	0.513599	0.542341	0.568583	0.584828
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of water			0	0.052231	0.062801	0.068401	0.07089	0.077733	0.088299	0.106345	0.119401	0.131225	0.142418	0.151133	0.298544	0.3738	0.427287	0.470819	0.508757	0.537361	0.557266	0.579031

Sorptivity Test Sheet

Name: **45- CS (Casted Surfa (w/c 0.45, 15%/20%/25% Fly Ash)** Equipment: ____________

Start Date: ____________ ____________

Comments: ____________

	Diameter			
Samples	1	2	3	Average
1		101.18	101.21	101.195
2		101.26	101.27	101.265
3		101.45	101.24	101.35

	Diameter			
Samples	1	2	3	Average
4		101.24	101.25	101.245
5		101.17	101.18	101.18
6		101.32	101.07	101.195

	Diameter			
Samples	1	2	3	Average
7		101.14	101.16	101.15
8		101.34	101.4	101.37
9		101.08	101.3	101.19

	Diameter			
Samples	1	2	3	Average
				#DIV/0!
				#DIV/0!
				#DIV/0!

			Measurments																			
	Samples	Area	0	60s±2s	5min±10s	10min±2	20min±2	30min±2	60min±2	2hrs±5	3hrs±5	4hrs±5	5hrs±5	6hrs±5	day 1±2h	day 2±2h	day 3±2h	day 5±2h	day 5±2h	day 6±2h	day 7±2h	day 8±2h
Time (s)	45-15-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.195	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1011.17	1011.67	1011.75	1011.79	1011.84	1011.89	1012.07	1012.29	1012.47	1012.62	1012.79	1012.9	1015.08	1016.52	1017.47	1018.32	1019.12	1019.74	1020.36	1020.83
ΔMass (g)		8042.832	0	0.5	0.58	0.62	0.67	0.72	0.9	1.12	1.3	1.45	1.62	1.73	3.91	5.35	6.3	7.15	7.95	8.57	9.19	9.66
Δmass/areaX density of water (mm)			0	0.062167	0.072114	0.077087	0.083304	0.089521	0.111901	0.139254	0.161635	0.180285	0.201422	0.215098	0.486147	0.665189	0.783306	0.88899	0.988458	1.065545	1.142632	1.201069
Time (s)	45-15-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.265	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	982.99	983.53	983.59	983.63	983.64	983.69	983.84	984.02	984.2	984.33	984.48	984.57	986.72	988.11	989.09	989.82	990.57	991.15	991.61	992.08
ΔMass (g)		8053.963	0	0.54	0.6	0.64	0.65	0.7	0.85	1.03	1.21	1.34	1.49	1.58	3.73	5.12	6.1	6.83	7.58	8.16	8.62	9.09
Δmass/areaX density of water (mm)			0	0.067048	0.074497	0.079464	0.080706	0.086914	0.105538	0.127887	0.150237	0.166378	0.185002	0.196177	0.463126	0.635712	0.757391	0.84803	0.941152	1.013166	1.070281	1.128637
Time (s)	45-15-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.345	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1040.69	1041.21	1041.32	1041.38	1041.51	1041.63	1041.85	1042.23	1042.58	1042.88	1043.11	1043.35	1047.06	1049.27	1050.69	1051.9	1052.97	1053.9	1054.75	1055.46
ΔMass (g)		8066.693	0	0.52	0.63	0.69	0.82	0.94	1.16	1.54	1.89	2.19	2.42	2.66	6.37	8.58	10	11.21	12.28	13.21	14.06	14.77
Δmass/areaX density of water (mm)			0	0.064463	0.078099	0.085537	0.101653	0.116529	0.143801	0.190908	0.234297	0.271487	0.299999	0.329751	0.789667	1.063633	1.239665	1.389665	1.522309	1.637598	1.742969	1.830986
Time (s)			0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of water	Average		0	0.064607	0.073306	0.078276	0.082005	0.088217	0.108719	0.133571	0.155936	0.173331	0.193212	0.205638	0.474637	0.65045	0.770349	0.86851	0.964805	1.039355	1.106456	1.164853
Time (s)	45-20-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.245	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1014.77	1015.24	1015.3	1015.34	1015.39	1015.45	1015.59	1015.75	1015.87	1016.02	1016.14	1016.26	1018.3	1019.6	1020.45	1021.19	1021.88	1022.43	1023.02	1023.45
ΔMass (g)		8050.782	0	0.47	0.53	0.57	0.62	0.68	0.82	0.98	1.1	1.25	1.37	1.49	3.53	4.83	5.68	6.42	7.11	7.66	8.25	8.68
Δmass/areaX density of water (mm)			0	0.058379	0.065832	0.070801	0.077011	0.084464	0.101853	0.121727	0.136633	0.155264	0.17017	0.185075	0.438467	0.599942	0.705522	0.797438	0.883144	0.95146	1.024745	1.078156
Time (s)	45-20-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.175	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1009.76	1010.36	1010.42	1010.43	1010.49	1010.52	1010.64	1010.81	1010.97	1011.08	1011.22	1011.35	1013.26	1014.49	1015.38	1016.04	1016.73	1017.15	1017.54	1017.97
ΔMass (g)		8039.653	0	0.6	0.66	0.67	0.73	0.76	0.88	1.05	1.21	1.32	1.46	1.59	3.5	4.73	5.62	6.28	6.97	7.39	7.78	8.21
Δmass/areaX density of water (mm)			0	0.07463	0.082093	0.083337	0.0908	0.094531	0.109457	0.130603	0.150504	0.164186	0.1816	0.19777	0.435342	0.588334	0.699035	0.781128	0.866953	0.919194	0.967703	1.021188
Time (s)	45-20-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.195	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1026.47	1026.92	1026.99	1027.06	1027.07	1027.14	1027.27	1027.45	1027.67	1027.81	1027.96	1028.11	1030.55	1032.15	1033.29	1034.24	1035.08	1035.77	1036.43	1036.95
ΔMass (g)		8042.832	0	0.45	0.52	0.59	0.6	0.67	0.8	0.98	1.2	1.34	1.49	1.64	4.08	5.68	6.82	7.77	8.61	9.3	9.96	10.48
Δmass/areaX density of water (mm)			0	0.05595	0.064654	0.073357	0.074601	0.083304	0.099467	0.121848	0.149201	0.166608	0.185258	0.203908	0.507284	0.706219	0.84796	0.966078	1.070518	1.156309	1.23837	1.303024
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of water			0	0.066505	0.073963	0.077069	0.083906	0.089498	0.105655	0.126165	0.143568	0.159725	0.175885	0.191422	0.436904	0.594138	0.702278	0.789283	0.875048	0.935327	0.996224	1.049672
Time (s)	45-25-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.15	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1013.02	1013.33	1013.4	1013.46	1013.54	1013.59	1013.75	1013.96	1014.16	1014.34	1014.49	1014.61	1016.87	1018.16	1019.08	1019.8	1020.48	1021	1021.47	1021.86
ΔMass (g)		8035.681	0	0.31	0.38	0.44	0.52	0.57	0.73	0.94	1.14	1.32	1.47	1.59	3.85	5.14	6.06	6.78	7.46	7.98	8.45	8.84
Δmass/areaX density of water (mm)			0	0.038578	0.047289	0.054756	0.064711	0.070934	0.090845	0.116978	0.141867	0.164267	0.182934	0.197867	0.479113	0.639647	0.754136	0.843737	0.928359	0.993071	1.05156	1.100093
Time (s)	45-25-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.37	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1062.73	1063.2	1063.27	1063.32	1063.39	1063.49	1063.63	1063.84	1064.03	1064.18	1064.35	1064.47	1066.55	1067.78	1068.66	1069.41	1070.01	1070.54	1070.98	1071.41
ΔMass (g)		8070.674	0	0.47	0.54	0.59	0.66	0.76	0.9	1.11	1.3	1.45	1.62	1.74	3.82	5.05	5.93	6.68	7.28	7.81	8.25	8.68
Δmass/areaX density of water (mm)			0	0.058236	0.066909	0.073104	0.081778	0.094168	0.111515	0.137535	0.161077	0.179663	0.200727	0.215595	0.473319	0.625722	0.734759	0.827688	0.902031	0.967701	1.022219	1.075499
Time (s)	45-25-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		101.19	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1030.06	1030.6	1030.65	1030.7	1030.74	1030.81	1030.87	1031.03	1031.16	1031.25	1031.41	1031.48	1033.12	1034.11	1034.76	1035.35	1035.76	1036.18	1036.52	1036.83
ΔMass (g)		8042.037	0	0.54	0.59	0.64	0.68	0.75	0.81	0.97	1.1	1.19	1.35	1.42	3.06	4.05	4.7	5.29	5.7	6.12	6.46	6.77
Δmass/areaX density of water (mm)			0	0.067147	0.073364	0.079582	0.084556	0.09326	0.100721	0.120616	0.136781	0.147972	0.167868	0.176572	0.380501	0.503604	0.584429	0.657794	0.708776	0.761001	0.803279	0.841826
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of water			0	0.048407	0.057099	0.06393	0.073244	0.082551	0.10118	0.127257	0.151472	0.171965	0.19183	0.206731	0.476216	0.632685	0.744448	0.835712	0.915195	0.980386	1.03689	1.087796

Sorptivity Test Sheet

Name: **50- CS (Casted Surfa (w/c 0.50, 15%/20%/25% Fly Ash)**
Aggregate Type = **Limestone**
Fly Ash = **Red Rock**
Aggregate Size = **#56**
Start Date:
Comments:

	Diameter			
Samples	1	2	3	Average
1		101.55	101.18	101.365
2		101.16	101.19	101.175
3		101.69	102.29	101.99

	Diameter			
Samples	1	2	3	Average
4		102.07	102.3	102.185
5		101.96	102.41	102.19
6		101.13	101.38	101.255

	Diameter			
Samples	1	2	3	Average
7		101.06	101.2	101.13
8		102	102.49	102.245
9		101.11	101.15	101.13

	Diameter			
Samples	1	2	3	Average
10				#DIV/0!
11				#DIV/0!
12				#DIV/0!

			Measurments																			
	Samples	**Area**	0	60s±2s	5min±10s	10min±2	20min±2	30min±2	60min±2	2hrs±5	3hrs±5	4hrs±5	5hrs±5	6hrs±5	day1±2h	day2±2h	day3±2h	day5±2h	day5±2h	day6±2h	day7±2h	day8±2h
Time (s)	50-15-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		101.365	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1073.2	1073.71	1073.9	1073.98	1074.1	1074.23	1074.52	1074.91	1075.34	1075.68	1075.99	1076.3	1081.5	1085.04	1087.41	1089.68	1091.58	1093.08	1094.37	1094.96
ΔMass (g)		8069.878	0	0.51	0.7	0.78	0.9	1.03	1.32	1.71	2.14	2.48	2.79	3.1	8.3	11.84	14.21	16.48	18.38	19.88	21.17	21.76
Δmass/areaX density of			0	0.063198	0.086742	0.096656	0.111526	0.127635	0.163571	0.211899	0.265184	0.307316	0.34573	0.384145	1.028516	1.467185	1.760869	2.042162	2.277606	2.463482	2.623336	2.696447
Time (s)	50-15-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		101.175	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1043.03	1043.41	1043.5	1043.62	1043.71	1043.81	1044.01	1044.32	1044.56	1044.76	1045.02	1045.16	1048.43	1050.53	1052.12	1053.45	1054.53	1055.56	1056.46	1057.16
ΔMass (g)		8039.653	0	0.38	0.47	0.59	0.68	0.78	0.98	1.29	1.53	1.73	1.99	2.13	5.4	7.5	9.09	10.42	11.5	12.53	13.43	14.13
Δmass/areaX density of			0	0.047266	0.05846	0.073386	0.084581	0.097019	0.121896	0.160455	0.190307	0.215183	0.247523	0.264937	0.671671	0.932876	1.130646	1.296076	1.43041	1.558525	1.67047	1.757538
Time (s)	50-15-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		101.99	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1077.81	1078.31	1078.47	1078.55	1078.71	1078.87	1079.11	1079.54	1079.97	1080.34	1080.65	1080.97	1086.28	1089.85	1092.29	1094.51	1096.2	1097.65	1098.79	1099.47
ΔMass (g)		8169.699	0	0.5	0.66	0.74	0.9	1.06	1.3	1.73	2.16	2.53	2.84	3.16	8.47	12.04	14.48	16.7	18.39	19.84	20.98	21.66
Δmass/areaX density of			0	0.061202	0.080786	0.090579	0.110163	0.129748	0.159125	0.211758	0.264392	0.309681	0.347626	0.386795	1.036758	1.473738	1.772403	2.044139	2.251001	2.428486	2.568026	2.65126
Time (s)			0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of water	Average		0	0.055232	0.072601	0.085021	0.098053	0.112327	0.142734	0.186177	0.227745	0.26125	0.296627	0.324541	0.850093	1.20003	1.445758	1.669119	1.854008	2.011004	2.146903	2.226993
Time (s)	50-20-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		102.185	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1047.52	1047.9	1048.02	1048.1	1048.22	1048.28	1048.48	1048.8	1049.12	1049.36	1049.62	1049.87	1053.63	1056.21	1057.93	1059.58	1060.96	1062.18	1063.26	1063.97
ΔMass (g)		8200.969	0	0.38	0.5	0.58	0.7	0.76	0.96	1.28	1.6	1.84	2.1	2.35	6.11	8.69	10.41	12.06	13.44	14.66	15.74	16.45
Δmass/areaX density of			0	0.046336	0.060968	0.070723	0.085356	0.092672	0.117059	0.156079	0.195099	0.224364	0.256067	0.286551	0.745034	1.059631	1.269362	1.470558	1.638831	1.787594	1.919285	2.00586
Time (s)	50-20-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		102.185	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1054.92	1055.44	1055.55	1055.57	1055.76	1055.82	1056.13	1056.49	1056.81	1057.07	1057.33	1057.55	1061.15	1063.66	1065.44	1067.08	1068.49	1069.88	1071.05	1071.92
ΔMass (g)		8200.969	0	0.52	0.63	0.65	0.84	0.9	1.21	1.57	1.89	2.15	2.41	2.63	6.23	8.74	10.52	12.16	13.57	14.96	16.13	17
Δmass/areaX density of			0	0.063407	0.07682	0.079259	0.102427	0.109743	0.147544	0.191441	0.230461	0.262164	0.293868	0.320694	0.759666	1.065728	1.282775	1.482752	1.654682	1.824175	1.966841	2.072926
Time (s)	50-20-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		101.255	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1090.78	1091.2	1091.34	1091.43	1091.53	1091.67	1091.93	1092.32	1092.62	1092.92	1093.14	1093.36	1096.72	1098.76	1100.26	1101.58	1102.62	1103.61	1104.5	1105.21
ΔMass (g)		8052.372	0	0.42	0.56	0.65	0.75	0.89	1.15	1.54	1.84	2.14	2.36	2.58	5.94	7.98	9.48	10.8	11.84	12.83	13.72	14.43
Δmass/areaX density of			0	0.052159	0.069545	0.080722	0.09314	0.110526	0.142815	0.191248	0.228504	0.26576	0.293081	0.320402	0.737671	0.991012	1.177293	1.34122	1.470374	1.593319	1.703846	1.792018
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of			0	0.054872	0.068894	0.074991	0.093891	0.101208	0.132301	0.17376	0.21278	0.243264	0.274967	0.303623	0.75235	1.062679	1.276069	1.476655	1.646757	1.805884	1.943063	2.039393
Time (s)	50-25-56-0-1-1-S1	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		101.13	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1083.54	1084.02	1084.17	1084.25	1084.39	1084.48	1084.7	1085.06	1085.36	1085.59	1085.93	1086.08	1089.52	1091.56	1093.08	1094.31	1095.35	1096.32	1097.18	1097.82
ΔMass (g)		8032.503	0	0.48	0.63	0.71	0.85	0.94	1.16	1.52	1.82	2.05	2.39	2.54	5.98	8.02	9.54	10.77	11.81	12.78	13.64	14.28
Δmass/areaX density of			0	0.059757	0.078431	0.088391	0.10582	0.117025	0.144413	0.189231	0.226579	0.255213	0.297541	0.316215	0.744475	0.998443	1.187675	1.340802	1.470276	1.591036	1.698101	1.777777
Time (s)	50-25-56-0-1-1-S2	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		102.245	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1065.35	1066.01	1066.21	1066.3	1066.53	1066.71	1067.05	1067.75	1068.25	1068.68	1069.07	1069.44	1074.95	1078.58	1080.98	1083.06	1084.5	1085.38	1085.8	1086
ΔMass (g)		8210.603	0	0.66	0.86	0.95	1.18	1.36	1.7	2.4	2.9	3.33	3.72	4.09	9.6	13.23	15.63	17.71	19.15	20.03	20.45	20.65
Δmass/areaX density of			0	0.080384	0.104743	0.115704	0.143717	0.165639	0.207049	0.292305	0.353202	0.405573	0.453073	0.498136	1.16922	1.611331	1.903636	2.156967	2.33235	2.439528	2.490682	2.515041
Time (s)	50-25-56-0-1-1-S3	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)		101.13	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1096.25	1096.63	1096.75	1096.88	1096.98	1097.08	1097.29	1097.66	1097.9	1098.08	1098.29	1098.48	1101.03	1102.54	1103.66	1104.67	1105.38	1106.12	1106.73	1107.25
ΔMass (g)		8032.503	0	0.38	0.5	0.63	0.73	0.83	1.04	1.41	1.65	1.83	2.04	2.23	4.78	6.29	7.41	8.42	9.13	9.87	10.48	11
Δmass/areaX density of			0	0.047308	0.062247	0.078431	0.090881	0.10333	0.129474	0.175537	0.205415	0.227824	0.253968	0.277622	0.595082	0.783068	0.922502	1.048241	1.136632	1.228758	1.304699	1.369436
Time (s)	Average		0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{½}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of			0	0.070071	0.091587	0.102047	0.124768	0.141332	0.175731	0.240768	0.289891	0.330393	0.375307	0.407176	0.956848	1.304887	1.545655	1.748885	1.901313	2.015282	2.094391	2.146409

Sorptivity Test Sheet

Name: **40- FS (Finished Surface)**

Aggregate Type = Dolomite-Granite

Fly Ash = Red Rock

Aggregate Size = #56 & #57

Start Date:

Comments:

	Diameter			
Samples	1	2	3	Average
1		102.83	102.5	102.665
2		102.55	102.43	102.49
3		102.67	102.77	102.72

	Diameter			
Samples	1	2	3	Average
4		102.83	102.5	102.665
5		102.55	102.43	102.49
6		102.67	102.77	102.72

	Diameter			
Samples	1	2	3	Average
7				#DIV/0!
8				#DIV/0!
9				#DIV/0!

	Diameter			
Samples	1	2	3	Average
				#DIV/0!
				#DIV/0!
				#DIV/0!

			Measurments																			
	Samples	**Area**	0	60s±2s	5min±10s	10min±2	20min±2	30min±2	60min±2	2hrs±5	3hrs±5	4hrs±5	5hrs±5	6hrs±5	day1±2h	day2±2h	day3±2h	day5±2h	day5±2h	day6±2h	day7±2h	day8±2h
Time (s)	40-00-S1 (Dolomite)	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.665	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1110.25	1110.92	1112.92	1113.22	1113.87	1114.35	1115.2	1116.42	1117.06	1117.91	1118.3	1118.83	1125.49	1127.75	1129.3	1131.12	1131.38	1133.18	1134.02	1134.49
ΔMass (g)		8278.196	0	0.67	2.67	2.97	3.62	4.1	4.95	6.17	6.81	7.66	8.05	8.58	15.24	17.5	19.05	20.87	21.13	22.93	23.77	24.24
Δmass/areaXd ensity of water			0	0.080936	0.322534	0.358774	0.437293	0.495277	0.597956	0.745331	0.822643	0.925322	0.972434	1.036458	1.840981	2.113987	2.301226	2.521081	2.552488	2.769927	2.871398	2.928174
Time (s)	40-00-S2 (Dolomite)	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.49	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	970.52	971.84	973.03	973.8	974.79	975.4	976.65	978.24	979.22	980.11	980.76	981.31	989.26	992.46	994.36	996.32	996.56	998.02	998.58	998.69
ΔMass (g)		8249.999	0	1.32	2.51	3.28	4.27	4.88	6.13	7.72	8.7	9.59	10.24	10.79	18.74	21.94	23.84	25.8	26.04	27.5	28.06	28.17
Δmass/areaXd ensity of water			0	0.16	0.304242	0.397576	0.517576	0.591515	0.74303	0.935758	1.054546	1.162424	1.241212	1.307879	2.271515	2.659394	2.889697	3.127273	3.156364	3.333334	3.401213	3.414546
Time (s)	40-00-S3 (Dolomite)	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		102.72	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1079.15	1082.07	1082.64	1083.11	1083.56	1083.89	1084.65	1085.64	1086.29	1086.89	1087.38	1087.89	1094.56	1097.26	1099.09	1101.1	1101.39	1103.11	1103.87	1104.28
ΔMass (g)		8287.068	0	2.92	3.49	3.96	4.41	4.74	5.5	6.49	7.14	7.74	8.23	8.74	15.41	18.11	19.94	21.95	22.24	23.96	24.72	25.13
Δmass/areaXd ensity of water (mm)			0	0.352356	0.421138	0.477853	0.532154	0.571975	0.663685	0.783148	0.861583	0.933985	0.993114	1.054655	1.859524	2.185333	2.406159	2.648705	2.683699	2.891252	2.982961	3.032435
Time (s)			0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x	Average		0	0.216646	0.371836	0.418313	0.484724	0.533626	0.63082	0.76424	0.842113	0.929654	0.982774	1.045556	1.850252	2.14966	2.353692	2.584893	2.618094	2.830589	2.92718	2.980305
Time (s)	40-00-S1 (Granite)	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		7.745967	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1003.67	1005.03	1006.01	1006.66	1006.99	1007.95	1009.1	1010.48	1011.42	1012.33	1013.78	1013.79	1020.8	1023.3	1024.64	1026.45	1026.46	1028.02	1028.72	1029.07
ΔMass (g)		47.124	0	1.36	2.34	2.99	3.32	4.28	5.43	6.81	7.75	8.66	10.11	10.12	17.13	19.63	20.97	22.78	22.79	24.35	25.05	25.4
Δmass/areaXd ensity of water			0	0.164287	0.28267	0.36119	0.401054	0.517021	0.65594	0.822643	0.936194	1.046122	1.221281	1.222489	2.069291	2.37129	2.533161	2.751807	2.753015	2.941462	3.026022	3.068301
Time (s)	40-00-S2 (Granite)	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		1082.07	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1030.11	1031.41	1032.96	1033.03	1033.98	1034.61	1036.04	1037.88	1039.24	1040.3	1041.3	1041.79	1052.26	1056.01	1057.91	1059.69	1059.69	1060.64	1060.87	1060.9
ΔMass (g)		919605.6	0	1.3	2.85	2.92	3.87	4.5	5.93	7.77	9.13	10.19	11.19	11.68	22.15	25.9	27.8	29.58	29.58	30.53	30.76	30.79
Δmass/areaXd ensity of water			0	0.157576	0.345455	0.353939	0.469091	0.545455	0.718788	0.941818	1.106667	1.235152	1.356364	1.415758	2.684849	3.139394	3.369697	3.585455	3.585455	3.700607	3.728485	3.732122
Time (s)	40-00-S3 (Granite)	Dia.	0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)		2.92	0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Mass (g)		Area	1025.09	1026.46	1027.27	1027.97	1028.81	1029.46	1030.68	1032.26	1033.37	1034.26	1034.96	1035.57	1043.19	1045.38	1046.66	1048.38	1048.38	1049.71	1050.23	1050.49
ΔMass (g)		6.696635	0	1.37	2.18	2.88	3.72	4.37	5.59	7.17	8.28	9.17	9.87	10.48	18.1	20.29	21.57	23.29	23.29	24.62	25.14	25.4
Δmass/areaXd ensity of water			0	0.165318	0.26306	0.347529	0.448892	0.527328	0.674545	0.865203	0.999147	1.106543	1.191012	1.264621	2.184126	2.448393	2.602851	2.810403	2.810403	2.970894	3.033642	3.065016
Time (s)			0	60	300	600	1200	1800	3600	7200	10800	14400	18000	21600	86400	172800	259200	345600	432000	518400	604800	691200
√Time ($s^{1/2}$)			0	7.745967	17.32051	24.4949	34.64102	42.42641	60	84.85281	103.923	120	134.1641	146.9694	293.9388	415.6922	509.1169	587.8775	657.2671	720	777.6889	831.3844
Δmass/area x density of	Average		0	0.164802	0.272865	0.35436	0.424973	0.522174	0.665242	0.843923	0.967671	1.076332	1.206146	1.243555	2.126709	2.409841	2.568006	2.781105	2.781709	2.956178	3.029832	3.066659

Appendix -D

Percentage Absorption Data

Aggregate Size = #56 Fly Ash = Red Rock
Aggregate Type = Limestone No Admix

Sample Surface	Sample ID	w/cm	Fly Ash	Oven dry mass (g)	Saturated mass after immersion (g)	Absorption after immersion (%)
Finished Surface	40-00-56-0-1-1	0.40	0%	926.68	971.58	4.8
	45-00-56-0-1-1	0.45	0%	811.97	859.18	5.8
	50-00-56-0-1-1	0.50	0%	822.5	872.58	6.1
Casted Surface	40-00-56-0-1-1	0.40	0%	861.1	898.02	4.3
	45-00-56-0-1-1	0.45	0%	902.24	942.69	4.5
	50-00-56-0-1-1	0.50	0%	927.93	974.35	5.0

Aggregate Size = #56 Fly Ash = Red Rock
Aggregate Type = Limestone No Admix

Sample Surface	Sample ID	w/cm	Fly Ash	Oven dry mass (g)	Saturated mass after immersion (g)	Absorption after immersion (%)
Finished Surface	40-00-56-0-1-1	0.40	0%	926.68	971.58	4.8
	40-10-56-0-1-1	0.40	10%	892.4	935.36	4.8
	40-20-56-0-1-1	0.40	20%	911.6	952.65	4.5
Casted Surface	40-00-56-0-1-1	0.40	0%	861.1	898.02	4.3
	40-10-56-0-1-1	0.40	10%	897.8	936.43	4.3
	40-20-56-0-1-1	0.40	20%	894.29	929.87	4.0

Aggregate Size = #56 Fly Ash = Red Rock
Aggregate Type = Limestone No Admix

Sample Surface	Sample ID	w/cm	Fly Ash	Paste Fraction	Oven dry mass (g)	Saturated mass after immersion (g)	Absorption after immersion (%)
Finished Surface	40-00-56-0-1-1	0.40	0%	27%	926.68	971.58	4.8
	40-00-56-0-1-1	0.40	0%	33%	866.06	909.9	5.1
Casted Surface	40-00-56-0-1-1	0.40	0%	27%	861.1	898.0	4.3
	40-00-56-0-1-1	0.40	0%	33%	874.51	935.9	7.0

Percentage Absorption Data

Aggregate Size =	#56	Fly Ash =	Multiple
Aggregate Type =	Limestone	No Admix	

Sample Surface	Sample ID	Fly Ash Source	w/cm	Fly Ash	Oven dry mass (g)	Saturated mass after immersion (g)	Absorption after immersion (%)
Finished Surface	40-20-56-0-1-1	Red Rock	0.40	20%	911.6	952.65	4.5
	40-20-56-3-1-1	Muskogee	0.40	20%	925.11	972	5.1
	40-20-56-3-1-1	Muskogee	0.40	20%	812.8	853.35	5.0
	40-20-56-3-1-1	Muskogee	0.40	20%	855.78	900.42	5.2
	40-20-56-4-1-1	Nixon	0.40	20%	822.35	868.0	5.5
	40-20-56-4-1-1	Nixon	0.40	20%	812.03	855.4	5.3
	40-20-56-4-1-1	Nixon	0.40	20%	824.07	861.7	4.6
Casted Surface	40-20-56-0-1-1	Red Rock	0.40	20%	894.29	929.9	4.0
	40-20-56-3-1-1	Muskogee	0.40	20%	864.9	902.1	4.3
	40-20-56-3-1-1	Muskogee	0.40	20%	827.23	864.0	4.4
	40-20-56-3-1-1	Muskogee	0.40	20%	861.9	898.0	4.2
	40-20-56-4-1-1	Nixon	0.40	20%	835.62	869.41	4.0
	40-20-56-4-1-1	Nixon	0.40	20%	823.35	859.6	4.4
	40-20-56-4-1-1	Nixon	0.40	20%	805.18	839.6	4.3

Aggregate Size =	#56 & #67	Fly Ash =	Red Rock
Aggregate Type =	Limestone	No Admix	

Sample Surface	Sample ID	Aggregate Size	w/cm	Fly Ash	Oven dry mass (g)	Saturated mass after immersion (g)	Absorption after immersion (%)
Finished Surface	40-00-56-0-1-1	#56	0.40	0%	926.68	971.58	4.8
	40-00-67-0-1-1	#67	0.40	0%	859.6	895.89	4.2
	40-00-67-0-1-1	#67	0.40	0%	886.4	898.49	1.4
	40-00-67-0-1-1	#67	0.40	0%	862.1	925.4	7.3
Casted Surface	40-00-56-0-1-1	#56	0.40	0%	861.1	898.0	4.3
	40-00-67-0-1-1	#67	0.40	0%	871.2	916.4	5.2
	40-00-67-0-1-1	#67	0.40	0%	893.9	899.6	0.6
	40-00-67-0-1-1	#67	0.40	0%	858.8	937.34	9.1

Percentage Absorption Data

Aggregate Size =	#56 & #57	Fly Ash =	Red Rock
Aggregate Type =	Limestone	No Admix	

Sample Surface	Sample ID	Aggregate Type	w/cm	Fly Ash	Oven dry mass (g)	Saturated mass after immersion (g)	Absorption after immersion (%)
Finished Surface	40-00-56-0-1-1	Limestone	0.40	0%	926.68	971.58	4.8
	40-00-56-0-1-2	Dolomite	0.40	0%	915.35	957.44	4.6
	40-00-56-0-1-2	Dolomite	0.40	0%	830.28	873.16	5.2
	40-00-56-0-1-2	Dolomite	0.40	0%	893.06	934.4	4.6
	40-00-56-0-1-3	Granite	0.40	0%	931.64	975.0	4.6
	40-00-56-0-1-3	Granite	0.40	0%	854.92	897.3	5.0
	40-00-56-0-1-3	Granite	0.40	0%	822.21	861.1	4.7
Casted Surface	40-00-56-0-1-1	Limestone	0.40	0%	861.1	898.0	4.3
	40-00-56-0-1-2	Dolomite	0.40	0%	852.65	886.8	4.0
	40-00-56-0-1-2	Dolomite	0.40	0%	854.47	889.3	4.1
	40-00-56-0-1-2	Dolomite	0.40	0%	842.18	875.64	4.0
	40-00-56-0-1-3	Granite	0.40	0%	903.14	939.38	4.0
	40-00-56-0-1-3	Granite	0.40	0%	847.82	886.22	4.5
	40-00-56-0-1-3	Granite	0.40	0%	892.01	930.13	4.3

Aggregate Size =	#56	Fly Ash =	Red Rock
Aggregate Type =	Limestone		

Sample Surface	Sample ID	Chemical Admixture	w/cm	Fly Ash	Oven dry mass (g)	Saturated mass after immersion (g)	Absorption after immersion (%)
Finished Surface	40-00-56-0-1-1	No Admix	0.40	0%	926.68	971.58	4.8
	40-20-56-0-1-1	No Admix	0.40	20%	911.6	953.22	4.6
	40-00-56-3-1-1	WR & AE	0.40	0%	852.36	894.55	4.9
	40-20-56-3-1-1	WR & AE	0.40	20%	798.99	843.91	5.6
Casted Surface	40-00-56-0-1-1	No Admix	0.40	0%	861.08	898.12	4.3
	40-20-56-0-1-1	No Admix	0.40	20%	894.29	930.51	4.1
	40-00-56-3-1-1	WR & AE	0.40	0%	815.66	850.83	4.3
	40-20-56-3-1-1	WR & AE	0.40	20%	870.53	910.62	4.6

Appendix -E

Compressive Strength Data

Aggregate Size = #56
w/cm = 0.40 to 0.60
Aggregate Type = Limestone
Fly Ash = Red Reck

Sample ID	Load (lb)	f'c (Psi)
40-00-56-0-1-1-C1	82910	6334
40-00-56-0-1-1-C2	95225	7275
40-05-56-0-1-1-C1	91755	7010
40-05-56-0-1-1-C2	82950	6337
40-10-56-0-1-1-C1	86195	6585
40-10-56-0-1-1-C2	69220	6288
40-15-56-0-1-1-C1	98665	7537
40-15-56-0-1-1-C2	96490	7371
40-20-56-0-1-1-C1	95605	7304
40-20-56-0-1-1-C2	95205	7273
40-25-56-0-1-1-C1	92850	7093
40-25-56-0-1-1-C2	94090	7188
45-00-56-0-1-1-C1	6531	6273
45-00-56-0-1-1-C2	6378	6147
45-05-56-0-1-1-C1	6190	5742
45-05-56-0-1-1-C2	6606	6285
45-10-56-0-1-1-C1	5967	5742
45-10-56-0-1-1-C2	4101	3955
45-15-56-0-1-1-C1	5940	5720
45-15-56-0-1-1-C2	6627	6369
45-20-56-0-1-1-C1	6839	6583
45-20-56-0-1-1-C2	7390	7120
45-25-56-0-1-1-C1	6958	6718
45-25-56-0-1-1-C2	6986	6742
50-00-56-0-1-1-C1	59195	4710
50-00-56-0-1-1-C2	55225	4395
50-05-56-0-1-1-C1	73740	5868
50-05-56-0-1-1-C2	72305	5754
50-10-56-0-1-1-C1	71480	5688
50-10-56-0-1-1-C2	73950	5885
50-15-56-0-1-1-C1	76060	6053
50-15-56-0-1-1-C2	71190	5665
50-20-56-0-1-1-C1	51825	4124
50-20-56-0-1-1-C2	55000	4377
50-25-56-0-1-1-C1	54400	4329
50-25-56-0-1-1-C2	28480	2266
55-00-56-0-1-1-C1	56935	4531
55-00-56-0-1-1-C2	65760	5523
55-05-56-0-1-1-C1	47760	3801
55-05-56-0-1-1-C2	44025	3504
55-10-56-0-1-1-C1	45565	3626
55-10-56-0-1-1-C2	41555	3307
55-15-56-0-1-1-C1	55800	4441
55-15-56-0-1-1-C2	55905	4449

Compressive Strength Data

Aggregate Size = #56 w/cm = 0.40 to 0.60
Aggregate Type = Limestone Fly Ash = Red Reck

Sample ID	Load (lb)	f'c (Psi)
55-20-56-0-1-1-C1	46235	3679
55-20-56-0-1-1-C2	42220	3360
55-25-56-0-1-1-C1	47410	3773
55-25-56-0-1-1-C2	51185	4073
60-00-56-0-1-1-C1	37035	2947
60-00-56-0-1-1-C2	39930	3178
60-05-56-0-1-1-C1	50320	4005
60-05-56-0-1-1-C2	47605	3788
60-10-56-0-1-1-C1	39689	3172
60-10-56-0-1-1-C2	39689	3172
60-15-56-0-1-1-C1	57240	4555
60-15-56-0-1-1-C2	60430	4809
60-20-56-0-1-1-C1	54000	4297
60-20-56-0-1-1-C2	56060	4461
60-25-56-0-1-1-C1	31560	2512
60-25-56-0-1-1-C2	41725	3320

Aggregate Size = #56 w/cm = 0.40 & 0.45 Paste = 33%
Aggregate Type = Limestone Fly Ash = Red Reck (0%,10%,20%)

Sample ID	Load (lb)	f'c (Psi)
40-00-56-0-1-1-C1	83320	6583
40-00-56-0-1-1-C2	83460	6578
40-10-56-0-1-1-C1	86590	6868
40-10-56-0-1-1-C2	89925	7164
40-20-56-0-1-1-C1	92405	7398
40-20-56-0-1-1-C2	91030	7121
45-00-56-0-1-1-C1	86275	6788
45-00-56-0-1-1-C2	90000	7160
45-10-56-0-1-1-C1	88115	6971
45-10-56-0-1-1-C2	91350	7180
45-20-56-0-1-1-C1	93525	7384
45-20-56-0-1-1-C2	97250	7675

Aggregate Size = #56 w/cm = 0.40 Paste = 27%
Aggregate Type = Limestone Fly Ash = Red Reck

Fly Ash	Chemical Admixtures	f'c (Psi)
40-00-56-0-1-1-C1	No Admix	6805
40-00-56-0-1-1-C2	WR & AE	7268
40-20-56-0-1-1-C1	No Admix	7289
40-20-56-0-1-1-C2	WR & AE	7669

Aggregate Size = #67 w/cm = 0.40 to 0.50 Paste = 27%
Aggregate Type = Limestone Fly Ash = Red Reck (0%,10%,20%)

Sample ID	Load (lb)	f'c (Psi)
40-00-67-0-1-1-C1	-	7152
40-00-67-0-1-1-C2	-	7387
40-10-67-0-1-1-C1	-	7340
40-10-67-0-1-1-C2	-	7970
40-20-67-0-1-1-C1	-	8288
40-20-67-0-1-1-C2	-	8124
45-00-67-0-1-1-C1	-	6533
45-00-67-0-1-1-C2	-	6596
45-10-67-0-1-1-C1	-	7338
45-10-67-0-1-1-C2	-	7035
45-20-67-0-1-1-C1	-	7340
45-20-67-0-1-1-C2	-	7970
50-00-67-0-1-1-C1	-	6554
50-00-67-0-1-1-C2	-	6391
50-10-67-0-1-1-C1	-	6837
50-10-67-0-1-1-C2	-	6712
50-20-67-0-1-1-C1	-	7187
50-20-67-0-1-1-C2	-	6711

Aggregate Size = #56 w/cm = 0.40 Paste = 27%
Aggregate Type = Limestone Fly Ash = 20%

Fly Ash Source	Sample ID	Load (lb)	f'c (Psi)
Muskogee	40-20-56-0-3-1-C1	94685	7535
Muskogee	40-20-56-0-3-1-C2	91310	7266
Nixon	40-20-56-0-4-1-C1	100850	8025
Nixon	40-20-56-0-4-1-C2	97165	7732

Aggregate Size = #56 w/cm = 0.40
Paste = 27% Fly Ash = 20%

Aggregate Type	Sample ID	Load (lb)	f'c (Psi)
Dolomite	40-20-56-0-1-2-C1	97065	7724
Dolomite	40-20-56-0-1-2-C2	102515	8158
Granite	40-20-56-0-1-3-C1	101620	8087
Granite	40-20-56-0-1-3-C2	101375	8067

Appendix -F

The City of Stillwater
OKLAHOMA

Water Resources
723 S. Lewis Street
Stillwater, Oklahoma 74074

Office: (405) 742-8325
Fax: (405) 742-8324
Web: stillwater.org

2015 Annual Water Quality Report
Public Water Supply ID OK1021220

The 2015 Annual Water Quality Report provides information about the quality of your drinking water; the efforts being made to improve the water treatment process; and how we protect our water resources. Our goal is to make sure you have a safe and dependable supply of drinking water. This report is also known as the *Consumer Confidence Report (CCR)*.

Stillwater's water source is Kaw Lake, which is located approximately 10 miles east of Ponca City in Kay County. Kaw Lake surface water is transported to the City's treatment facility located at 1022 West Yost Road. In 2015, the facility supplied more than 2.4 billion gallons of clean drinking water to the Stillwater citizens, five rural water districts, and several mobile home communities in Payne and Noble Counties.

The City of Stillwater routinely monitors your drinking water for constituents according to federal (EPA) and state (ODEQ) rules and regulations. The tables in this report show the results for Jan. 1, 2015 to Dec. 31, 2015. All drinking water, including bottled drinking water, may be reasonably expected to contain at least small amounts of some constituents. These constituents may be microbes, organic chemicals, radioactive or other materials. It's important to remember that the presence of these constituents does not necessarily pose a health risk.

If you have any questions about this report or concerns about your water utility, please contact Water Resources Department Director William Millis at (405) 742-8325 or the Water Treatment Plant Superintendent at (405) 743-4580. You may also contact your mayor and city councilors.

To view a copy of the *2015 Stillwater Rural Water System Annual Water Quality Report*, go online to stillwater.org or contact the Operations-Water Distribution staff at (405) 533-8048 or by email at khitch@stillwater.org.

DEFINITIONS:

Action Level (AL) – The concentration of a contaminant which, if exceeded, triggers treatment or other requirements which a water system must follow.

Below Practical Quantitation Limits (BPQL) – The method detection limit (MDL) adjusted for any dilutions or other changes made to the sample to deal with interferences/matrix effects.

Maximum Contaminant Level (MCL) – The highest level of a contaminant that is allowed in drinking water. MCLs are set as close to the MCLGs as feasible using the best available treatment technology.

Maximum Contaminant Level Goal (MCLG) – The level of a contaminant in drinking water below which there is no known or expected risk to health. MCLGs allow for a margin of safety.

MRL – Minimum Reporting Level.

MPN/100 ml – Most Probable Number of colonies per 100 ml of sample.

Nephelometric Turbidity Unit (NTU) – Nephelometric turbidity unit is a measure of the clarity of water. Turbidity in excess of 5 NTU is just noticeable to the average person.

Parts per billion (ppb) or Micrograms per liter (ug/L) – One part of contaminant per billion parts of water.

Parts per million (ppm) or Milligrams per liter (mg/L) – One part of contaminant per million parts of water.

Picocuries per liter (pCi/L) – Picocuries per liter is a measure of the radioactivity in water.

Treatment Technique (TT) – A treatment technique is a required process intended to reduce the level of a contaminant in drinking water.

No Detection (ND) – No organisms detected in the sample.

WATER QUALITY DATA

Microbiological Contaminants

Parameter	MCL	Maximum Level Detected	Lowest Monthly Percentage	Violations	Sources of Contaminant
Turbidity in treated water	0.3 NTU in 95 % of all samples taken within one month	0.57 NTU in a single sample	< 0.3 NTU in 99.4 % of all samples taken within one month	None	Soil Runoff

Radionuclides

Parameter	MCL	Level Detected	Range of Detections	Violations	Sources of Contaminant
Gross Alpha	15 pCi/L	1.05 pCi/L	1.05 – 1.05 pCi/L	None	Erosion of natural deposits
Gross Beta	4 mrem/Year	5.0 pCi/L	5.0 – 5.0 pCi/L	None	Erosion of natural deposits
Radium 226 + 228	5 pCi/L	0.079 pCi/L	0.079 – 0.079 pCi/L	None	Erosion of natural deposits
Uranium	30.0 ug/L	BPQL ug/L	< 1.0 ug/L – < 1.0 ug/L	None	Erosion of natural deposits

Disinfection By-products Rule Stage 2

Parameter	MCL	Maximum Level Detected	Range of Detections	Violations	Sources of Contaminant
Total Trihalomethanes	80 ppb	23.10 ppb	10.60 ppb – 23.10 ppb	None	By-product of drinking water chlorination
HAA5	60 ppb	22.20 ppb	3.12 ppb – 22.20 ppb	None	By-product of drinking water chlorination
BROMATE	10 ppb (running annual average)	< 5.0 ppb	< 5.0 ppb – < 5.0 ppb	None	By-product of drinking water ozonation

Lead and Copper (Regulated at Customer's Tap)

Parameter	Action Level *	90% Sample Detected	Violations	Sources of Contaminant
Lead	15 ppb	< BPQL ppb	None	Corrosion of household plumbing systems
Copper	1.3 ppm	0.029 ppm	None	Corrosion of household plumbing systems

* Action Level – 90 % of samples must be below this level.

Organic Carbon

Parameter	MCL	MCLG	Date Sampled	2015 Removal Avg.	Removal Range (Low – High)	Violations	Sources of Contaminant
Total Organic Carbon	TT removal < 1.0% (running avg.)	N/A	Jan. – Dec. 2015 (monthly)	1.40 %	0.93 % – 2.27 %	None	Naturally present in the environment

Bacteriological Contaminants

Parameter	MCL	Maximum Level Detected	Number of Positive E. Coliforms	MCLG	Violations	Likely Source of Contaminant
Coliform (TCR)	5 % of monthly samples are positive	0	0	0	None	Naturally present in the environment

Inorganic Contaminants

Parameter	MCL	Maximum Level Detected	Range of Detections	Date Sampled	MCLG	Violations	Sources of Contaminant
Antimony	6 ppb	BPQL	< 0.005 ppm	10/22/15	6 ppb	None	Discharge from Petroleum refineries; Fire retardants; Ceramics; Electronics; Solder
Arsenic	10 ppb	BPQL	< 0.005 ppm	10/22/15	N/A	None	Erosion of natural deposits; Runoff from orchards; Runoff from glass and electronics production wastes
Barium	2 ppm	0.032 ppm	0.032 ppm	10/22/15	2 ppm	None	Discharge of drilling wastes; Discharge from metal refineries; Erosion of natural deposits
Fluoride	4 ppm	0.92 ppm	0.44 – 0.92 ppm	Monthly	4 ppm	None	Erosion of natural deposits; Water additive which promotes strong teeth; Discharge from fertilizer and aluminum factories
Nitrate + Nitrite	10 ppm	0.56 ppm	0.56 ppm	10/22/15	10 ppm	None	Runoff from fertilizer use; Leaching from septic tanks, sewage; Erosion of natural deposits
Selenium	.05 ppm	BPQL	< 0.005 ppm	10/22/15	.05 ppm	None	Discharge from petroleum refineries; Erosion of natural deposits; Discharge from mines
Beryllium	.004 ppm	BPQL	< 0.001 ppm	10/22/15	.004 ppm	None	Discharge from metal refineries and coal burning factories; Discharge from electrical, aerospace, and defense industries
Cadmium	.005 ppm	BPQL	< 0.0010 ppm	10/22/15	.0010 ppm	None	Corrosion of galvanized pipes; Erosion of natural deposits; Discharge from metal refineries; Runoff from waste batteries and paints
Chromium	.10 ppm	BPQL	< 0.01 ppm	10/22/15	.10 ppm	None	Discharge from steel and pulp mills; Erosion from natural deposits
Mercury	.002 ppm	BPQL	< 0.0002 ppm	10/22/15	.002 ppm	None	Erosion from natural deposits; Discharge from refineries and factories; Runoff from landfills and crop lands
Nickel	N/A	BPQL	< 0.010 ppm	10/22/15	N/A	None	Discharge from steel mills and; Erosion from natural deposits
Thallium	.002 ppm	BPQL	< 0.0010 ppm	10/22/15	.0005 ppm	None	Leaching from ore-processing sites; Discharge from electronics, glass, and drug factories
Sodium	N/A	64.7 ppm	64.7 ppm	10/22/15	N/A	None	Erosion from natural deposits

Long Term 2 Enhanced Surface Water Treatment Rule (Raw water Testing)

Analyte	Results (10-14-15)	Results (11-11-15)	Results (12-9-15)
Crypto	ND oocysts/L	ND oocysts/L	ND oocysts/L
Giardia	ND cysts/L	ND cysts/L	ND cysts/L
E-Coli	< 1.0 MPN/100 ml	2.0 MPN/100ml	13.2 MPN/100ml
Turbidity	6.30 NTU's	9.22 NTU's	12.3 NTU's

In our continuing efforts to maintain a safe and dependable water supply it may be necessary to make improvements to the water system. The costs of these improvements may be reflected in the rate structure. Water rate adjustments may be necessary in order to address these improvements.

Important Health Information

Some people may be more vulnerable to contaminants in drinking water than the general population. Immuno-compromised persons such as persons with cancer undergoing chemotherapy, persons who have undergone organ transplants, people with HIV/AIDS or other immune system disorders, some elderly, and infants can be particularly at risk from infections. These people should seek advice about drinking water from their health care providers. Environmental Protection Agency/Center for Disease Control guidelines on appropriate means to lessen the risk of infection by Cryptosporidium and other microbiological contaminants are available from the Safe Drinking Water Hotline (800) 426-4791.

Call the Water Resources office at (405) 742-8325 or email shall@stillwater.org, if you have any questions.

STILLWATER MUNICIPAL WATER SYSTEM
2016 Annual Water Quality Report
Public Water Supply ID OK1021220

Water Resources
723 S. Lewis Street
Stillwater, Oklahoma 74074

Office: (405) 742-8325
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The City of Stillwater routinely monitors your drinking water for constituents according to federal (EPA) and state (ODEQ) rules and regulations. The tables in this report show the results for Jan. 1, 2016 to Dec. 31, 2016. Some constituents are analyzed less frequently than once per year, according to the required sampling schedule. The most recent data is reported for those. All drinking water, including bottled drinking water, may be reasonably expected to contain at least small amounts of some constituents. These constituents may be microbes, organic chemicals, radioactive or other materials. It's important to remember that the presence of these constituents does not necessarily pose a health risk.

If you have any questions about this report or concerns about your water utility, please contact Water Resources Department Director William Millis at (405) 742-8325 or the Water Treatment Plant Superintendent Doug Carothers at (405) 533-8492. You may also contact your mayor and city councilors.

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Maximum Contaminant Level Goal (MCLG) – The level of a contaminant in drinking water below which there is no known or expected risk to health. MCLGs allow for a margin of safety.

MRL – Minimum Reporting Level.

MPN/100 ml – Most Probable Number of colonies per 100 mL of sample.

Neohelometric Turbidity Unit (NTU) – NTU is a measure of the clarity of water. Turbidity in excess of 5 NTU is just noticeable to the average person.

Parts per billion (ppb) or Micrograms per Liter (ug/L) – One part of contaminant per billion parts of water.

Parts per million (ppm) or Milligrams per Liter (ug/L) – One part of contaminant per million parts of water.

Picocuries per Liter (pCi/L) – Picocuries per liter is a measure of the radioactivity in water.

Treatment Technique (TT) – A treatment technique is a required process intended to reduce the level of a contaminant in drinking water.

No Detection (ND) – No organisms detected in the sample.

WATER QUALITY DATA

Microbial Contaminants

Parameter	MCL	Maximum Level Detected	Lowest Monthly Percentage	Violations	Sources of Contaminant
Turbidity	0.3 NTU in 95% of all samples taken within one month	0.64 NTU in a single sample	< 0.3 NTU in 99.4% of all samples taken within one month	None	Soil runoff

Radionuclides

Parameter	MCL	Level Detected	Range Detected	Violations	Source of Contaminant
Gross Alpha	15 pCi/L	1.05 pCi/L	1.05 - 1.05 pCi/L	None	Erosion of natural deposits
Gross Beta	4 mrem/Year	5.0 pCi/L	5.0 - 5.0 pCi/L	None	Erosion of natural deposits
Radium 226 + 228	5 pCi/L	0.158 pCi/L	0.158 - 0.158 pCi/L	None	Erosion of natural deposits
Uranium	30.0 ug/L	BPQL	< 1.0 - < 1.0 ug/L	None	Erosion of natural deposits

Disinfection By-Products Rules Stage 2

Parameter	MCL	Level Detected	Range Detected	Violations	Source of Contaminant
Total Trihalomethanes	80 ppb	28.1 ppb	8.18 - 28.1 ppb	None	By-product of water chlorination
Haloacetic Acids 5	60 ppb	32.1 ppb	4.94 - 32.1 ppb	None	By-product of water chlorination
Bromate	10 ppb (RAA)	< 2.06 ppb	< 2.06 - < 2.06 ppb	None	By-product of water ozonation

Lead and Copper (Regulated at Customer's Tap)

Parameter	Action Level*	90% Sample Detected	Violations	Source of Contaminant
Lead	15 ppb	BPQL (< 0.005 ppb)	None	Corrosion of household plumbing systems
Copper	1.3 ppm	0.029 ppm	None	Corrosion of household plumbing systems

*Action Level – 90% of samples must be below this level

Organic Carbon

Parameter	MCL	MCLG	Date Sampled	2016 Removal Average	Removal Range (Low-High)	Violations	Source of Contaminant
Total Organic Carbon	TT removal < 1.0 (running avg.)	N/A	Jan. - Dec. 2016 (monthly)	1.12	0.66% - 1.66	None	Naturally present in the environment.

Bacteriological Contaminants

Parameter	MCL	Maximum Level Detected	Number of Positive E. Coli	MCLG	Violations	Likely Source of Contaminant
Coliform (TCR)	< 5% of monthly Samples positive	0	0	0	None	Naturally present in the environment.

Inorganic Contaminants

Parameter	MCL	Maximum Level Detected	Range of Detections	Date Sampled	MCLG	Violations	Possible Sources of Contaminant
Antimony	6 ppb	BPQL	< 0.002 ppm	10/22/15	6 ppb	None	Discharge from petroleum refineries; Fire retardants; Ceramics; Electronics; Solder.
Arsenic	10 ppb	BPQL	< 0.005 ppm	10/22/15	10 ppb	None	Erosion of natural deposits; Runoff from orchards; Runoff from glass and electronics production wastes.
Barium	2 ppm	0.032 ppm	0.032 ppm	10/22/15	2 ppm	None	Erosion of natural deposits; Discharge of drilling wastes or metal refineries.
Fluoride	4 ppm	0.92 ppm	0.44 – 0.92 ppm	10/22/15	4 ppm	None	Erosion of natural deposits; Water additive; Discharge from fertilizer and aluminum factories.
Nitrate +Nitrite	10 ppm	0.56 ppm	0.56 ppm	10/22/15	10 ppm	None	Erosion of natural deposits; Runoff from fertilizer use; Leaching from sewage sources.
Selenium	0.05 ppm	BPQL	< 0.005 ppm	10/22/15	0.05 ppm	None	Erosion of natural deposits; Discharge from mines, or petroleum refineries.
Beryllium	0.004 ppm	BPQL	< 0.001 ppm	10/22/15	0.004 ppm	None	Discharge from metal refineries, coal burning factories, electrical, aerospace, and defense industries.
Cadmium	0.005 ppm	BPQL	< 0.0010 ppm	10/22/15	0.005 ppm	None	Erosion of natural deposits; Corrosion of galvanized pipes; Discharge from metal refineries; Runoff from waste batteries, paint.
Chromium	0.10 ppm	BPQL	< 0.01 ppm	10/22/15	0.10 ppm	None	Erosion of natural deposits; Discharge from steel and pulp mills.
Mercury	0.002 ppm	BPQL	< 0.0002 ppm	10/22/15	0.002 ppm	None	Erosion of natural deposits; Discharge from factories and refineries; Runoff from landfills and crop lands.
Nickel	N/A	BPQL	< 0.010 ppm	10/22/15	N/A	None	Erosion of natural deposits; Discharge from steel mills.
Thallium	0.002 ppm	BPQL	< 0.0010 ppm	10/22/15	0.002 ppm	None	Leaching from ore-processing sites; Discharge from electronics, glass, and drug factories.
Sodium	N/A	64.7 ppm	64.7 ppm	10/22/15	N/A	None	Erosion of natural deposits.

Long Term 2 Enhanced Surface Water Treatment Rule (Raw Water Testing)

Analyte \ Results	Jan 13	Feb 10	Mar 9	Apr 13	May 11	Jun 8	Jul 14	Aug 10	Sep 14	Oct 12	Nov 9	Dec 14
Cryptosporidium, oocysts/L	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Giardia, cysts/L	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
E. Coli, MPD/100 mL	2.0	3.0	12.1	2.0	4.1	35.0	< 1	< 1	40.4	7.4	7.4	60.5
Turbidity, NTUs	19.1	19.9	11.0	7.12	10.8	63.5	40.2	24.3	128	44.1	19.6	8.1

Violations – Not all of the required water quality samples were collected and analyzed.

Violation Type	Begin	End	Violation Explanation
Nitrate and Nitrite [measured as Nitrogen] Monitoring, Routine Major	1/1/2016	12/31/2016	We failed to test our drinking water for nitrate-nitrite during 2016. Because of this, we cannot be sure of the quality of our water for this parameter during this period.
Infants below the age of six months who drink water containing nitrate and nitrite in excess of the MCL could become seriously ill and, if untreated, may die. Symptoms include shortness of breath and blue-baby syndrome. In past years, nitrate-nitrite has measured well below the MCL. Additionally, in 2017 nitrate-nitrite has measured well below the MCL.			
Total Organic Carbon Monitoring, Routine Major	8/1/2016 11/1/2016	9/30/2016 12/31/2016	We failed to test our drinking water for total organic carbon during the months indicated. Because of this, we cannot be sure of the quality of our water for this parameter during this period.
Total organic carbon has no known health effects. However, total organic carbon provides a medium for the formation of disinfection by-products. These byproducts include Trihalomethanes (THMs) and haloacetic acids (HAAs). Drinking water containing these byproducts in excess of the MCL may lead to adverse health problems. For the other months of the 2016 year, as well as past years and in 2017, our TOC removal and byproducts test results were well below the MCLs.			

In our continuing efforts to maintain a safe and dependable water supply it may be necessary to make improvements to the water system. The cost of these improvements may be reflected in the rate structure. Water rate adjustments may be necessary in order to address these improvements.

Important Health Information

Some people may be more vulnerable to contaminants in drinking water than the general population. Immuno-compromised persons such as persons with cancer undergoing chemotherapy, persons who have undergone organ transplants, people with HIV/AIDS or other immune system disorders, some elderly, and infants can be particularly at risk from infections. These people should seek advice about drinking water from their health care providers. Environmental Protection Agency / Center for Disease Control guidelines on appropriate means to lessen the risk of infection by Cryptosporidium and other microbiological contaminants are available from the Safe Drinking Water Hotline (800) 426-4791.

Additional Information about Lead

If present, elevated levels of lead can cause serious health problems, especially for pregnant women and young children. Lead in drinking water is primarily from materials and components associated with service lines and home plumbing. We are responsible for providing high quality drinking water, but cannot control the variety of materials used in plumbing components. When your water has been sitting for several hours, you can minimize the potential for lead exposure by flushing your tap for 30 seconds to 2 minutes before using water for drinking or cooking. If you are concerned about lead in your water, you may wish to have your water tested. Information on lead in drinking water, testing methods, and steps you can take to minimize exposure is available from the Safe Drinking Water Hotline or at http://www.epa.gov/safewater/lead.

Call the Water Resources office at (405) 742-8325 or email shall@stillwater.org, if you have any questions.

VITA

Wassay Gulrez

Candidate for the Degree of

Doctor of Philosophy

Thesis: INVESTIGATING RESISTIVITY TESTING AS A METHOD FOR QUALITY CONTROL OF CONCRETE MIXTURES

Major Field: Civil Engineering

Biographical: Wassay Gulrez was born in Lahore, Pakistan on November 11, 1980.

Education:

- Completed the requirements for the Doctor of Philosophy in Civil Engineering at Oklahoma State University, Stillwater, Oklahoma in May, 2018.
- Completed the requirements for the Master of Science in Water Resources Management at University of Engineering and Technology, Lahore, Pakistan in 2006.
- Completed the requirements for the Bachelor of Science in Civil Engineering at National University of Sciences and Technology, Islamabad, Pakistan in 2002.

Experience:

- Graduate Research Assistant, Oklahoma State University, Stillwater, OK, U.S. 2013-2017.
- Senior Engineer, Water & Power Development Authority, Lahore, Pakistan 2008-2012.
- Junior Engineer, Water & Power Development Authority, Lahore, Pakistan 2003-2008.
- Site Engineer, Hassan Zaman Private Limited Company, Lahore, Pakistan 2002-2003.

Professional Memberships:

- Transportation Research Board (TRB) – since 2017
- American Society of Nondestructive Testing (ASNT) – since 2016.
- American Society of Civil Engineers (ASCE) – since 2015.
- American Concrete Institute (ACI) – since 2013.
- Institute of Engineers Pakistan (IEP) – since 2005.
- Pakistan Engineering Council (PEC) – since 2002.