COMPARING CONCRETE PERFORMANCE USING CONVENTIONAL AND ALTERNATIVE COAL ASH

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COMPARING CONCRETE PERFORMANCE USING CONVENTIONAL AND ALTERNATIVE COAL ASH

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Abstract: Fly ash is widely used as a supplementary cementitious material in concrete as it can contribute to strength gain and increased durability of the concrete. In 2019, the coal ash production volume decreased by 23% from the previous year, according to the American Coal Ash Association [3]. This is due to most coal combustion energy use being converted to natural gas. One solution to this is to use alternative coal ash such as reclaimed coal ash and bottom coal ash. This research aims to investigate the performance of different fly ash materials at both 20% and 40% replacement so that it can be used to develop performance-based testing. This work investigated concrete's slump, compressive strength, and electrical resistivity to compare the performance of traditional, reclaimed, blended, and bottom coal ash sources.

TABLE OF CONTENTS

Chapter **Page**

I. IMPORTANCE OF PERFORMANCE-BASED TESTING FOR RECLAIMED COAL ASH....1

1.1 INTRODUCTION 1

1.1.1 Types of Ashes from Coal Combustion....2

1.1.2 Conventional Ash Classification....4

1.1.3 Performance of Coal Combustion Ash in Concrete....4

1.2 PERFORMANCE BASED TESTING OF CONCRETE 4

1.3 OBJECTIVE....5

II. PERFORMANCE COMPARISON OF CONCRETE USING CONVENTIONAL AND UNCONVENTIONAL TYPES OF COAL ASH....6

2.1 AIM OF THIS RESEARCH....6

2.2 EXPERIMENTAL METHODS....6

2.2.1 Laboratory Materials 6

2.2.2 Isothermal Calorimetry Testing.... 11

2.2.3 Calculations for Isothermal Calorimetry Testing 12

2.2.4 Concrete Mixture Design.... 13

2.2.5 Concrete Mixing Procedure.... 13

2.2.6 Testing Procedure 14

2.2.7 Statistical Analysis.... 15

Chapter **Page**

2.3 RESULTS AND DISCUSSION ... 16

2.3.1 Overview ... 16

2.3.2 Isothermal Calorimetry Test ... 16

2.3.3 Slump Test ... 17

2.3.4 Compressive Strength ... 19

2.3.5 Electrical Resistivity ... 22

2.3.6 Statistical Analysis ... 26

2.3.6.1 Statistical Comparison of Coal Production in Concrete Using T-Test ... 26

2.3.6.2 Performance Classification of Coal Ash in Concrete ... 28

III. CONCLUSION ... 35

3.1 Summary ... 35

REFERENCES ... 39

APPENDICES ... 44

APPENDIX A: TABLES AND FIGURES ... 44

APPENDIX B: ANALYSIS OF THE VARIABILITY IN SLUMP PERFORMANCE BETWEEN DIFFERENT COAL ASH SOURCES ... 90

LIST OF TABLES

Table **Page**

1-1. Types of Ash..2

1-2. Performance Based Testing 5

2-1. Coal Ash Types and Number of Sources..7

2-2. Bulk Oxide Analysis Using ASEM 8

2-3. Particle Size Distribution Using ASEM 9

2-4. Type I Cement Oxide Analysis and Bogue Calculations 11

2-5. Isothermal Calorimetry Paste Design 11

2-6. Concrete Mixture Design per Cubic Yard 13

2-7. Statistical Analysis of Coal Ash Concrete Performance Using
T-Test – Green = statistical significance, yellow = somewhat significant but
inconclusive, red = not significant 27

2-8. Performance Classification of Coal Ash 29

2-9A. Average Performance of Coal Ash by Type...31

2-9B. Average Performance of Coal Ash by Type 32

3-1. Impact of Class F Fly Ash on Properties of Concrete 37

3-2. Impact of Coal Ash on Properties of Concrete..38

A1-1. Statistical Summary of the 48-hr heat of hydration of each coal ash source...........44

A1-2. Statistical Summary of the Slump Performance of Coal ash at 20% and 40%
Replacement 45

Table **Page**

A1-3. Compressive Strength Data and T-Test Analysis of Coal Ash at 20% Replacement at 3-, 7-, and 14-day Ages 49

A1-4. Compressive Strength Data and T-Test Analysis of Coal Ash at 20% Replacement at 28-, 56-, and 90-day Ages 51

A1-5. Compressive Strength Data and T-Test Analysis of Coal Ash at 20% Replacement at 180-day Age 53

A1-6. Compressive Stregnth Data Classification of Coal Ash at 20% Replacement for 3-, 7-, and 14-day Ages 55

A1-7. Compressive Strength Data Classification of Coal Ash at 20% Replacement for 28-, 56-, and 90-day Ages 57

A1-8. Compressive Strength Data Classification of Coal Ash at 20% Replacement for 180-day Ages....................59

A1-9. Compressive Strength Data and T-Test Analysis of Coal Ash at 40% Replacement for 3-, 7-, and 14-day Ages 61

A1-10. Compressive Strength Data and T-Test Analysis of Coal Ash at 40% Replacement for 28-, 56-, and 90-day Ages 62

A1-11. Compressive Strength Data and T-Test Analysis of Coal Ash at 40% Replacement for 180-day Ages....................63

A1-12. Compressive Strength Data Classification of Coal Ash at 40% Replacement at 3-, 7-, and 14-day Ages....................65

A1-13. Compressive Strength Data Classification of Coal Ash at 40% Replacement at 28-, 56-, and 90-day Ages....................66

Table	Page

A1-14. Compressive Strength Data Classification of Coal Ash at 40% Replacement at 180-day Age 67

A1-15. Electrical Resistivity Data and T-Test Analysis of Coal Ash at 20% Replacement at 3-, 7-, and 14-day Ages 69

A1-16. Electrical Resistivity Data and T-Test Analysis of Coal Ash at 20% Replacement at 28-, 56-, and 90-day Ages 71

A1-17. Electrical Resistivity Data Classificaiton of Coal Ash at 20% Replacement for 3-, 7-, and 14-day Ages 73

A1-18. Electrical Resistivity Data Classification of Coal Ash at 20% Replacement for 28-, 56-, and 90-day Ages 74

A1-19. Electrical Resistivity Data Classification of Coal Ash at 20% Replacement for 180-day Age 76

A1-20. Electrical Resistivity Data and T-Test Analysis of Coal Ash at 40% Replacement for 3-, 7-, an d14-day Ages 78

A1-21. Electrical Resistivity Data Classificaiton of Coal Ash at 40% Replacement for 28-, 56-, and 90-day Ages 80

A1-22. Electrical Resistivity Data Classification of Coal Ash at 40% Replacement for 180-day Age 81

A1-23. Electrical Resistivity Data Classification of Coal Ash at 40% Replacement for 3-, 7-, and 14-day Ages 83

A1-24. Electrical Resistivity Data Classification of Coal Ash at 40% Replacement for 28-, 56-, and 90-day Ages 85

Table **Page**

A1-25. Electrical Resistivity Data Classificaiton of Coal Ash at 40% Replacement for 180-day Age 86

A1-26. T-Test Analysis of Conventional and Non-Traditional Coal Ash Average Performance 88

A1-27. Performance Classificaiton of Class F Coal Ash....88

A1-28. Performance Classification of Class C Coal Ash 89

A2-1. Coal Ash Types and Number of Sources....95

A2-2. Bulk Oxide Analysis Using ASEM 95

A2-3. Particle Size Distribution Using ASEM 97

A2-4. OPC Type I Cement Oxide Analysis and Bogue Calculations....99

A2-5. Concrete Mixture Design per cubic yard....99

LIST OF FIGURES

Figure **Page**

2-1. Average 48-hr Heat of Hydration....16

2-2. Average Performance of Concrete in Slump Test....18

2-3. Compressive Strength of Concrete over 180-days with 20% Coal Ash Substitution....19

2-4. Compressive Strength of Concrete over 180-days with 40% Coal Ash Substitution....20

2-5. Compressive Strength of Concrete with 20% Coal Ash Substitution....21

2-6. Compressive Strength of Concrete with 40% Coal Ash Substitution....22

2-7. Electrical Resistivity of Concrete over 180-days with 20% Coal Ash Substitution....23

2-8. Electrical Resistivity of Concrete over 180-days with 40% Coal Ash Substitution....23

2-9. Electrical Resistivity of Concrete with 20% Coal Ash Substitution....25

2-10. Electrical Resistivity of Concrete with 40% Coal Ash Substitution....25

A2-1. Correlation of Coal Ash Fineness to Slump Performance at 20% Replacement....91

Figure **Page**

A2-2. Correlation of Coal Ash Fineness to Slump Performance at 20% Replacement.....92

A2-3. Correlation of Coal Ash Fineness to Slump Performance at 40% Replacement.....93

A2-4. Correlation of Coal Ash Fineness to Slump Performance at 40% Replacement.....94

A2-5. Average Slump Performance of Each Coal Ash at 20% Replacement 102

A2-6. Average Slump Performance of Each Coal Ash at 40% Replacement 102

A2-7. Slump Performance in Relation to Coal Ash Fineness..103

A2-8. Slump Performance Comparison of Low Fineness Coal Ash 105

A2-9. Compressive Strength Comparison of Low Fineness Coal Ash at 20% 105

A2-10. Compressive Strength Comparison of Low Fineness coal Ash at 40% 106

A2-11. Resistivity Comparison of Low Fineness Coal Ash at 20%................................106

A2-12. Resistivity Comparison of Low Fineness Coal Ash at 40%................................107

CHAPTER I

IMPORTANCE OF PERFORMANCE-BASED TESTING FOR RECLAIMED COAL ASH

1.1 INTRODUCTION

The use of concrete as a construction material is highly sought after due to the economic advantages and ability of this composite material to withstand environmental conditions. However, the harmful effects that cement production has on the environment are driving researchers to search for alternatives to lower CO_2 emissions. For each ton of cement produced, roughly 2000 lbs. of CO_2 are released into the atmosphere [18]. One method for reducing cement content in a concrete mixture is by partially replacing the cement with coal ash. The reuse of coal ash improves the sustainability of a concrete mixture by reducing the percentage of cement in concrete [27].

Coal ash is a useful supplementary cementitious material (SCM) and has been shown to improve concrete's durability, workability, and lower cost. Coal ash is a waste material from the coal combustion process that is typically sent to a landfill if another purpose is not identified. In 2019, the coal ash production volume decreased by 23% from the previous year, according to the American Coal Ash Association [3]. As coal combustion energy plants are being converted to natural gas, the tons of coal ash produced in the United States has dramatically decreased. On the other hand, other types of ash are available in abundance to be used in concrete. However, guidelines for the use of these materials need to be developed.

1.1.1 TYPES OF ASHES FROM COAL COMBUSTION

Coal combustion ash (CCA) is the byproduct produced by the combustion of pulverized coal. This ash is carried by the exhaust gasses and then collected by electrostatic precipitators or bag filters as a finely divided powder. This ash is classified into multiple types in Table 1-1 below. The most common types used are Class C and Class F coal ash, which are byproduct materials produced by coal-fired power plants. ASTM C618 [16] covers coal fly ash and raw or calcinated natural pozzolans for use in concrete. This specification has multiple requirements for coal ash to be used in a concrete mixture, such as chemical composition and physical requirements. Materials that don't meet this specification are not currently accepted. This research compares the performance of concrete using coal ash that does not meet ASTM C618 and examines the performance in various test methods that are important to using these materials in concrete.

Table 1-1 Types of Coal Ash

Type of Ash	Standard	Description of Ash
Conventional Ash	ASTM C 618	Solids removed from the exhaust of the combustion chamber of a coal-fired power plant.
Reclaimed Ash	ASTM E 3183	Waste product from a coal-fired power plant that has been stored in a landfill or storage pond. It is typically made of a blend of conventional ash and bottom ash.
Unrefined Reclaimed Ash	----	Waste product from a coal-fired power plant that has been stored in a landfill or storage

Type of Ash	Standard	Description of Ash
		pond. It is typically made of a blend of conventional ash and bottom ash.
Blended Ash	----	A combination of at least two coal ashes
Bottom Ash	----	Solids collected in the combustion chamber of a coal-fired power plant.

Reclaimed coal ashes are collected from the disposal sites of coal power plants. These materials may have been land-filled because they did not meet current requirements, or there may not be a demand for the material when it was available, so it was placed in a landfill. While these materials have been exposed to moisture and contamination, they can still be collected and used in concrete [5, 19, 20, 29]. One guideline for collecting these materials is ASTM E 3183 [17]. This specification provides guidance for harvesting coal combustion products placed in active and inactive storage areas. The specification does not include information on how to determine what storage areas to harvest from or provide information on processing harvested coal combustion products. Reclaimed coal ash is not typically used in current construction practices, but its use has the potential to address shortages caused by the loss of traditional coal ash supplies. Developing a better understanding of these reclaimed coal ashes in terms of their chemical composition, fineness, specific gravity, LOI, moisture content, and performance in concrete can help promote their use.

In this work, unrefined coal ash or unprocessed coal ash is material collected from a disposal site that is used without meeting the guidelines outlined in ASTM E 3183. This means the material was not processed in any way, so it often contains material that is lightly cemented and contains pieces greater than 0.2 in or a #4 sieve. For this study, the unprocessed coal ash was heated to remove moisture and sieved through a number 4 sieve to remove large conglomerates.

Blended coal ash is a combination of two types of coal ash to achieve a certain property. The blended coal ash used in this study was a combination of one coal ash that does not meet current specifications with one that does meet ASTM C 618. The bottom ash for this study has been ground to meet the fineness requirements of ASTM C 618.

1.1.2 PERFORMANCE OF COAL COMBUSTION ASH IN CONCRETE

The improvements of coal combustion ash in concrete are dependent on the chemical composition and the particle size distribution of the coal ash. One method that ASTM C618 uses to separate coal ash into classification categories is based on the elemental oxide content. A Class C coal ash has a calcium oxide at or above 18%, and a Class F coal ash has a calcium oxide content of less than 18% [16]. This work uses this same requirement to classify ash that does not meet ASTM C 618. The coal ash particle size can make hydration reactions occur more rapidly [24]. Chapters II and III of this paper will include the oxide content analysis and particle size distribution. Both parameters will be important to characterize both traditional and non-traditional coal combustion ash.

1.2 PERFORMANCE-BASED TESTING OF CONCRETE

Performance-based testing has become very popular because the results provide insight into how the material performs in concrete. This work uses the following tests: slump, the heat of hydration, compressive strength, and resistivity. Each of these tests provides valuable insights into how the concrete will perform in the field. For example, the slump test gives insight into how easy it is to move and finish the concrete. This is important for many applications, and the slump is the most widely recognized way to measure this in practice. A summary of all the tests used and what they measure is given in Table 1-2. These materials are also characterized by measuring the bulk oxide content, fineness, and particle size distribution.

Table 1-2: Performance-Based Testing of Coal Ash

Test	Method	Provides
Heat of Hydration	ASTM C311	Amount of heat given off over 48 h of hydration. When initially mixed, Portland cement and water react exothermically and give off heat. This test measures the release of heat over time.
Slump	ASTM C143	Measure consistency of workability between fresh concrete samples.
Air Content Testing	ASTM C231	Measures the air content of freshly mixed concrete.
Unit Weight	ASTM C138	Measures the density of the concrete.
Compressive Strength	ASTM C39/39M	Measures concrete's ability to withstand an axial load. The compressive strength of concrete is a fundamental physical property used in the design calculations for structures using the material.
Electrical Resistivity	AASHTO T 358	Concrete's ability to resist the movement of electrons under a constant current. It can be used to predict the permeability of the concrete.

1.3 OBJECTIVE

This work aims to present performance-based testing of traditional, reclaimed coal ash, and unrefined reclaimed coal ash and compare their performance. This will allow the performance of traditional and untraditional coal ash materials at either 0%, 20%, or 40% replacement to be compared. The statistical difference in the performance will be compared.

CHAPTER II

PERFORMANCE COMPARISON OF CONCRETE USING CONVENTIONAL AND UNCONVENTIONAL TYPES OF COAL ASH

2.1 AIM OF THIS RESEARCH

This chapter aims to gather the performance data for a variety of different coal ashes, both reclaimed and conventional coal ashes. A general evaluation will be made to compare the performance of the various ashes used at different replacement levels in concrete mixtures. The chapter will compare the performance of traditional and non-traditional coal ash sources.

2.2 EXPERIMENTAL METHODS

2.2.1 Laboratory Materials

Multiple types and sources of coal ash were used in this study and are listed in Table 2-1. Each coal ash was given an identification label. The letters are used as identifiers for the type of coal ash and are as follows: Class F coal ash is denoted with an “F”, Class C coal ash is denoted with a “C”, reclaimed coal ash is denoted with an “R”, unprocessed coal ash is denoted with a “U”, blended Class F coal ash is denoted by a “BF”, blended Class C coal ash is denoted with a “BC”, and bottom Class F coal ash is denoted by “BTF”.

Each label is then followed by a number to serve as a unique label for the coal ash. If two shipments from the samples from the same source were obtained at separate times, then the sources were labeled “-1” and “-2”, respectively. Limited numbers of reclaimed, unprocessed, blended, and bottom ashes are reported because they were all that could be obtained in enough quantity to complete the testing.

Table 2-1: Coal Ash Types and Number of Sources

Coal Ash Type	ID	Number of Sources
Class F	F #	16
Class C	C #	17
Reclaimed Class F	R #	8
Unprocessed Class F	U #	4
Blended Class F	BF #	1
Blended Class C	BC #	1
Bottom Class F	BTF #	1

Each coal ash source's physical and chemical characteristics were measured using an automated scanning electron microscopy (ASEM). The technique used allowed for the rapid measurement of thousands of individual particles within each sample of the coal ash. [1, 23, 30-33] These measurements are provided in Table2-2 and Table 2-3. Table 2-2 shows the proportion of 11 chemical oxides (SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, SO_3, Na_2O, K_2O, TiO_2, P_2O_5, SrO) found in each coal ash sample as a percentage of the total. The performance of coal ash in concrete is strongly influenced by its chemical composition. One example is as the calcium content in coal ash increases, the coal ash becomes more hydraulic.

Table 2-2: Bulk Oxide Analysis of Coal Ash Using ASEM

Coal Ash Source	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TiO_2	P_2O_5	SrO
F1	48.76	23.79	7.39	12.53	2.97	0.48	0.86	2.05	0.78	0.09	0.29
F2	50.40	20.91	3.89	17.09	3.69	0.54	1.04	1.37	0.70	0.05	0.32
F3	48.81	26.62	6.65	9.30	1.95	0.28	1.75	1.93	1.46	0.14	1.10
F4	45.34	27.39	4.00	14.61	3.59	0.70	1.48	0.65	1.09	0.37	0.76
F5	53.18	25.36	11.21	2.06	0.19	0.89	0.97	4.43	0.71	0.03	0.96
F6	51.87	25.71	12.32	2.50	0.32	0.67	1.61	4.13	0.66	0.05	0.16
F9	48.27	25.01	5.86	12.59	3.32	0.49	1.33	1.77	1.12	0.18	0.06
F10	53.59	27.76	2.79	10.53	2.50	0.47	0.33	1.27	0.45	0.28	0.02
F11	58.33	21.87	6.87	3.67	1.42	0.59	2.17	4.25	0.22	0.36	0.24
F12	59.18	25.01	9.54	1.59	0.24	0.12	0.05	3.62	0.51	0.02	0.11
F15-1	57.14	23.42	10.16	1.94	0.41	0.58	1.24	3.74	0.84	0.10	0.43
F15-2	57.02	18.62	13.77	3.86	0.44	0.78	0.60	3.57	0.80	0.16	0.12
F16	59.95	21.16	6.46	7.37	1.91	0.21	0.31	1.72	0.67	0.08	0.13
F17	60.46	18.65	3.97	5.64	0.41	0.28	5.62	2.62	0.55	0.00	1.80
F27	52.88	23.86	12.25	5.26	0.39	0.61	0.40	3.36	0.47	0.12	0.39
C1	36.20	21.72	5.35	23.15	5.38	0.67	3.58	1.01	0.80	1.90	0.23
C2	35.82	19.18	5.60	26.88	5.49	0.98	3.00	0.88	0.73	1.25	0.18
C3	25.32	19.26	5.22	32.50	7.76	2.60	3.42	0.63	1.08	1.89	0.32
C4	36.70	22.82	4.53	22.45	4.33	1.19	3.44	0.95	1.28	1.09	1.22
C5	31.25	22.46	5.38	26.06	5.95	0.56	4.30	0.84	0.84	2.11	0.23
C6	27.66	22.88	4.23	21.54	4.52	2.55	12.61	0.76	1.27	0.67	1.32
C7	35.28	20.61	4.74	24.72	4.93	0.74	4.26	1.23	1.64	0.82	1.00
C8	40.11	22.61	4.54	19.45	5.72	0.76	3.74	0.91	0.64	1.42	0.10
C9	31.49	24.02	5.96	25.71	5.35	0.99	3.72	0.61	0.94	1.12	0.10
C10	36.04	19.30	5.06	22.70	7.77	1.97	4.78	0.57	1.03	0.32	0.47
C11	30.96	20.77	6.38	27.15	7.14	1.59	3.45	0.73	0.78	0.83	0.23
C12	31.82	22.87	5.68	28.24	5.52	1.08	2.28	1.02	0.78	0.46	0.25
C13	25.15	21.20	6.22	30.47	7.78	1.04	4.02	0.56	1.22	2.18	0.15
C14	29.66	21.03	5.92	30.29	5.35	1.87	2.22	0.55	1.04	1.61	0.46
C15	29.85	17.66	4.73	31.75	9.32	1.19	2.57	0.76	0.83	1.08	0.24
C16	37.07	22.64	5.20	25.60	4.38	1.02	1.95	0.87	0.55	0.54	0.16
C17	36.93	22.94	6.17	24.02	3.78	0.72	2.71	0.63	1.50	0.44	0.13
C18	28.80	18.37	5.69	32.08	7.29	2.72	2.59	0.38	0.78	0.88	0.32
C19	35.30	24.08	4.52	23.82	5.27	1.01	3.67	0.60	0.93	0.59	0.16
RF2	57.55	30.47	5.15	1.45	0.26	0.07	0.03	3.43	1.05	0.06	0.49
RF3	54.53	30.54	7.33	2.94	0.15	0.13	0.02	3.61	0.63	0.02	0.10
RF4	53.50	26.22	9.91	4.62	0.70	0.35	0.08	3.53	0.51	0.14	0.42

Coal Ash Source	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TiO_2	P_2O_5	SrO
RF5	57.88	27.51	6.62	2.37	0.24	0.17	0.13	4.08	0.59	0.03	0.38
RF6-1	56.30	26.90	9.32	1.45	0.64	0.11	0.01	4.20	0.75	0.21	0.08
RF6-2	53.01	27.42	10.24	4.07	0.41	0.49	0.37	3.12	0.74	0.10	0.03
RF7-1	59.12	20.68	5.95	9.07	1.90	0.56	0.25	1.67	0.42	0.00	0.38
RF11	57.56	17.93	5.20	12.79	2.35	0.36	0.17	2.29	1.00	0.19	0.13
UF1	53.04	25.31	11.45	3.36	0.52	0.93	0.35	4.39	0.41	0.18	0.03
UF2	57.57	23.51	10.12	2.82	0.49	0.48	0.21	3.85	0.67	0.19	0.05
UF3	52.39	22.24	11.18	4.98	0.45	3.94	0.18	3.80	0.78	0.01	0.06
UF4	61.59	19.64	11.25	1.98	0.38	0.64	0.22	3.32	0.77	0.03	0.19
BF9	44.85	15.74	11.02	17.48	3.50	1.94	2.14	1.48	0.87	0.80	0.12
BC3	31.40	19.63	5.25	29.27	6.56	1.39	3.69	0.79	0.91	0.93	0.12
BTF1	60.37	14.88	5.99	13.20	1.70	0.82	0.06	1.26	1.43	0.01	0.26

Table 2-3: Particle Size Distribution Using ASEM

Coal Ash Source	ASEM				#325 Sieve
	D50	D90	Average	STDEV	% Retained
F1	1.68	4.14	2.19	1.74	20.45%
F2	2.15	5.10	2.73	2.11	13.00%
F3	2.24	4.45	2.67	1.65	23.10%
F4	1.68	4.57	2.33	2.06	21.80%
F5	2.07	5.21	2.71	2.20	18.71%
F6	2.03	4.96	2.62	2.00	30.24%
F9	2.09	4.48	2.18	1.70	32.00%
F10	2.05	4.29	2.39	1.61	15.00%
F11	1.71	3.96	3.26	2.77	25.00%
F12	2.06	3.93	3.32	2.93	25.18%
F15-1	2.45	6.48	3.56	2.89	19.07%
F15-2	2.37	6.80	3.10	2.27	---
F16	2.48	6.38	2.64	2.31	44.80%
F17	2.45	6.71	3.59	2.92	22.14%
C1	1.49	3.68	1.97	1.64	15.22%
C2	1.6	3.91	2.09	1.67	20.42%
C3	1.3	3.09	1.69	1.32	51.91%
C4	1.71	4.31	2.30	1.85	17.82%
C5	1.63	4.08	2.17	1.80	14.90%
C6	1.48	4.55	2.17	2.09	12.03%

Coal Ash Source	ASEM				#325 Sieve
	D50	D90	Average	STDEV	% Retained
C7	1.67	3.53	2.05	1.42	18.58%
C8	1.73	3.61	2.10	1.46	24.21%
C9	1.44	3.54	1.91	1.59	---
C10	3.08	9.72	4.34	4.00	---
C11	1.62	4.09	2.14	1.72	14.29%
C12	1.35	4.75	2.14	2.15	15.49%
C13	1.76	4.26	2.23	1.78	12.57%
C14	1.64	3.73	2.40	2.29	27.82%
C15	1.59	4.15	2.11	1.75	24.52%
C16	1.37	3.68	1.90	1.68	30.75%
C17	1.36	3.82	1.96	1.95	16.96%
C18	1.39	3.79	1.93	1.71	16.56%
C19	1.43	3.72	1.93	1.68	23.72%
RF2	2.37	6.15	3.11	2.45	29.50%
RF3	1.83	5.09	2.56	2.29	36.75%
RF4	2.23	6.95	3.19	2.83	30.50%
RF5	2.32	6.11	3.09	2.65	54.37%
RF6-1	1.90	4.89	2.58	2.34	50.60%
RF6-2	2.36	6.76	3.29	2.82	26.79%
RF7-1	2.78	7.00	3.57	2.95	---
RF11	2.09	4.46	2.54	1.68	---
UF1	2.20	5.52	2.90	2.41	---
UF2	2.61	6.89	3.51	2.97	21.47%
UF3	2.02	5.88	2.90	2.81	27.69%
UF4	1.87	4.60	2.54	2.32	28.61%
BF9	1.68	4.05	2.18	1.74	19.77%
BC3	1.76	4.50	2.32	1.78	17.99%
BTF1	3.07	7.37	3.99	3.05	11.89%

All the laboratory concrete mixtures in this research used an Ordinary Portland Cement (OPC) Type I that met the requirements of ASTM C150. The oxide analysis and Bogue calculations for this OPC are shown in Table 2-4. The aggregates used were locally available #57 crushed limestone as coarse aggregate and natural sand as fine aggregate used in commercial concrete. The crushed limestone had a maximum nominal aggregate size of 3/4 in. Both the crushed limestone and the sand met ASTM C33 specifications. No chemical admixtures were used in this study. The concrete mixture design yielded enough workability that there was no need for water-reducing admixtures. An air-entraining admixture was not used to minimize the number of variables used in the testing.

Table 2-4: OPC Type I Cement Oxide Analysis and Bogue Calculations

Oxide %								Bogue Calculation			
CaO	SiO_2	Al_2O_3	Fe_2O_3	Na_2O	MgO	SO_3	K_2O	C3S	C2S	C3A	C4AF
62.1	21.1	4.7	2.6	0.2	2.4	3.2	0.3	56.7	17.8	8.2	7.8

2.2.2 Isothermal Calorimetry Testing

Isothermal calorimetry experiments were performed to determine the heat of hydration for a paste mixture. All tests were performed per ASTM C1702 [9] and used a TAM Air 8-channel isothermal calorimeter with glass ampoules. Each coal ash was tested at 20% and 40% replacement with a w/cm ratio of 0.45. A mixture was also used with no coal ash. These paste designs are provided in Table 2-5 below. The heat evolution was measured at 48 hours, and the average and standard deviation between each type of coal ash were found.

Table 2-5: Isothermal Calorimetry Paste Design

Mixture	w/cm	OPC (lbs(x10^3))	Coal Ash (lbs(x10^3))	Water (lbs(x10^3))	Paste (%)
0% Coal Ash	0.45	4.409	0	1.984	100
20% Coal Ash	0.45	3.527	0.882	1.984	100
40% Coal Ash	0.45	2.645	1.764	1.984	100

A glass ampoule was prepared for each test using the paste designs provided in Table 2-5. Each glass ampoule was then lowered into its respective chamber within the instrument. This process disturbs the temperature of the chamber, causing the initial rate of heat evolution data to start at different magnitudes. To account for this, the ASTM C1702 [9] requires a thirty-minute baseline to be established at the start of the test. The minimum starting point for OPC was found to be at 1.66 h and 0.318 milliwatts per gram of paste. Each ash was adjusted so that the minimum was at this same point. This allowed all the materials to be compared while removing the initial warming period of the sample.

2.2.3 Calculations for Isothermal Calorimetry Testing

The measurements taken from the Isothermal Calorimetry Testing can be summarized with the total heat of hydration measured in Joules per gram of cement and coal ash. The rate of heat evolution in milliwatts per gram of cement and coal ash (Joules per gram per second) is obtained by taking the first derivative of the total heat of hydration. The second derivative of the total heat of hydration provides the maximum value on the rate of heat evolution in milliwatts per second per gram (Joules per second per second per gram).

To evaluate how each coal ash effected the heat of hydration in concrete, each sample of coal ash was measured for the point at which the maximum heat of hydration was achieved and for the total heat of hydration. The total heat of hydration represents the amount of heat given off by the sample over a 48-hr time interval. The higher total heat of hydration represents an increase in potential temperature rise in a concrete element. For most concrete elements, less concern is created by this rise in heat, but for elements considered mass concrete or have high cement content, the amount of heat created is critical. For these elements, after hardening, elevated temperatures may create tensile stresses and result in thermal cracking or may increase the potential for delayed ettringite formation (DEF) [24].

2.2.4 Concrete Mixture Design

Coal ash samples were tested at 20% and 40% substitution rates and compared to a conventional concrete mixture using 100% OPC. The mixture design maintained a 29% paste content and a water-cement ratio of 0.45. These mixture designs are provided in Table 2-6. The paste volume and water-cement ratio of the concrete mixture design allowed for adequate workability of the concrete.

Table 2-6: Concrete Mixture Design per Cubic Yard

Mixture	w/cm	OPC (lbs)	Coal Ash (lbs)	Water (lbs)	Paste (%)	Coarse (lbs)	Fine (lbs)
0% Coal ash	0.45	625	0	281	28.8	1903	1243
20% Coal Ash	0.45	500	125	281	28.9	1900	1240
40% Coal Ash	0.45	375	250	281	29.0	1892	1228

2.2.5 Concrete Mixing Procedure

Aggregates were collected from outside storage piles and brought into a temperature-controlled room at 73.4°F for at least 24 hours before mixing. Aggregates were placed in the mixer and spun, and a representative sample was taken for moisture correction. At the time of mixing, all aggregate was loaded into the mixer along with approximately one-half of the mixing water. This combination was mixed for three minutes to allow the aggregates to approach the saturated surface dry (SSD) condition and ensure that the aggregates were evenly distributed.

Next, the cement, coal ash, and the remaining water were added and mixed for three minutes. The resulting mixture rested for two minutes while the sides of the mixing drum were scraped. After the rest period, the mixer was started, and the concrete was mixed for three minutes.

2.2.6 Testing Procedure

Slump measurements were taken from each wheelbarrow following ASTM C143[7] and averaged. The air content was measured using an ASTM C231[11] Type B air pressure meter. Unit weight was collected according to ASTM C138 [6], and a Phoenix Test was conducted following the test methods to measure the actual water-to-cementitious material ratio (w/cm) in the fresh concrete [27].

The concrete was then used to mold and cure 66 samples of 4”x8” cylinders according to ASTM C192 [10]. These cylinders were then placed in a controlled environment chamber at 70 ˚F and 100% RH until the day of testing.   The samples were left in the cylinder molds until they were tested. While cylinders being left in the molds during curing does not conform to ASTM C192, this was carried out to prevent leaching from the surface of the cylinder. However, to meet the moist condition for test standards of compressive strength ASTM C39 and electrical resistivity AASHTO T358 [1], the surface of the samples was lightly sprayed with water. The compressive strength (ASTM C39) and electrical resistivity (AASHTO T 358) testing were completed at 3, 7, 14, 28, 56, 90, and 180 days.

2.2.7 Statistical Analysis

A statistical analysis was conducted to determine if there was a significant correlation between the properties of concrete comparing traditional and non-traditional ash. For this study, a Student’s t-test was performed. Previous studies have used Student’s t-test analysis to compare the performance of concrete [21,26].

A Student’s t-test is a statistical hypothesis test that measures the difference between groups. As the performance of unconventional coal ash could be greater or less than conventional fly ash, a two-tailed t-test was performed. A type 3 t-test was performed due to the data sets having unequal variance. The test is used to obtain a T-score, which is the ratio between the difference between two groups and the difference within a group. The test's null hypothesis states that there is no statistical difference between the two data sets. The T-score is compared to a T-critical value that is found using a T-table and is based on the α value or probability factor. The null hypothesis is accepted if the t-score is less than the t-critical value. A p-value is then found and is used to support the rejection of the null hypothesis. The p-value is the probability that the results from the sample data occurred by chance or at random. The p-value is compared to the α-value, which is the confidence level you require for the analysis. For example, if the confidence level required for the t-test is 95% or an α-value of 0.05, a p-value of less than 0.05 would indicate a high probability of results. This showing high evidence that the null hypothesis is rejected or the comparison is statistically different.

2.3.0 RESULTS & DISCUSSION

2.3.1 Overview

The following results were obtained from coal ash samples collected for this study. Coal Ash samples of each type of coal ash outlined in this report were subjected to fresh and hardened property testing. The average performance of each type of coal ash is evaluated in this chapter and analyzed using a T-Test.

2.3.2 Isothermal Calorimetry Test

Figure 2-1 shows the average 48-hr heat of hydration for each coal ash type at 20% and 40% replacement and the standard deviation. The 100% OPC paste mixture was tested 16 times, and the average was found to be 162.7 mW/g with a standard deviation of 2.50.

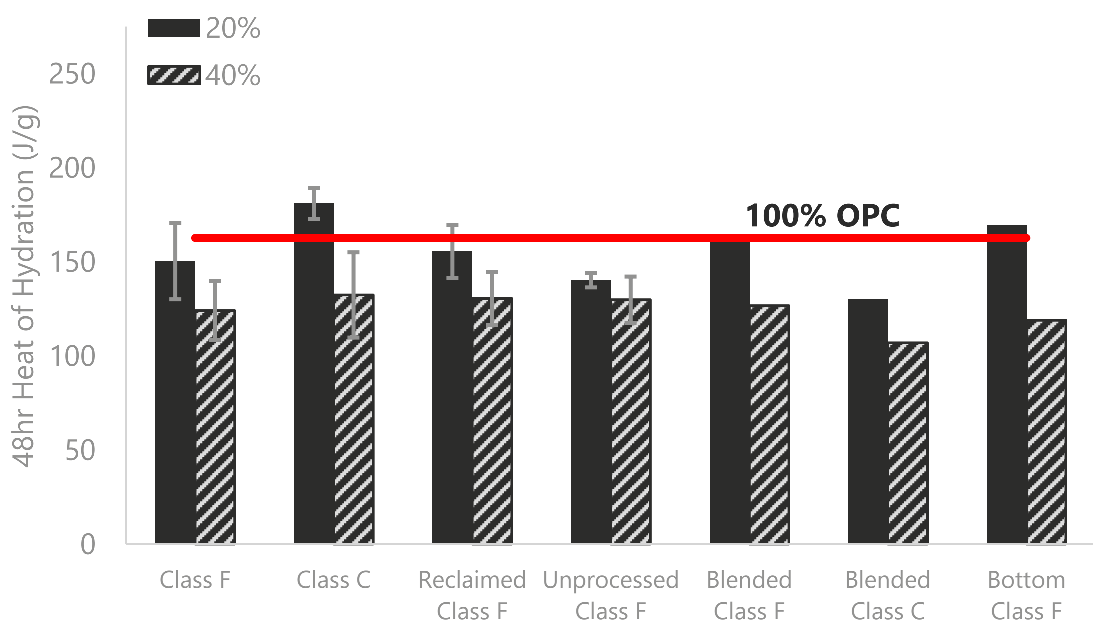

Figure 2-1: Average 48-hr Heat of Hydration

Each conventional and reclaimed coal ash was shown to have decreased heat of hydration when their content was increased from 20% to 40% replacement. When compared to 100% OPC, Class C conventional coal ash and bottom Class F coal ash were shown to have increased 48-hr heat of hydration when used at 20% replacement. Each other coal ash type shown to have an average heat below that of 100% OPC when used at 20% replacement. At 40% replacement, each coal ash shown to have decreased 48-hr heat of hydration when compared to 100% OPC. Each non-traditional Class F coal ash shown to fall within the standard deviation of the 48-hr heat of hydration of conventional Class F coal ash. Blended Class C coal ash at 20% shown to not fall within the standard deviation of the average heat of hydration measured of conventional Class C coal ash sources.

2.3.3 Slump Test

Three slump tests were performed for each mixture as per ASTM C143[7]. The average of these was taken as the slump value for a mixture. These measurements are provided in Appendix 1. This test provides a quantitative understanding of the change in workability of flowable concrete. Figure 2-1 provides a comparison between the average slump of concrete using only OPC and the slump achieved when substituting 20% and 40% OPC for each type of coal ash.

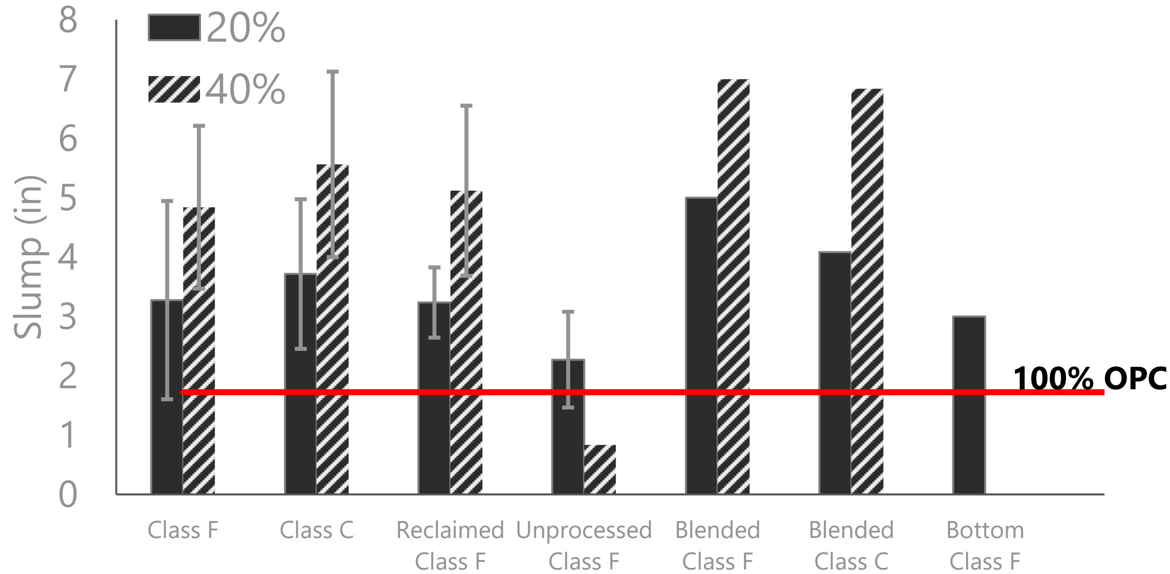

Figure 2-2: Average Performance of Concrete in Slump Test

Graph depicts the average slump performance of each type of coal ash when used in concrete. Concrete using 100% OPC is depicted as a linear line on the graph.

Typically, the mixtures that used coal ash achieved a higher slump than that of concrete using 100% OPC. Unprocessed Class F coal ash used at 40% substitution shown to decrease slump performance from 100% OPC concrete. Aside from Unprocessed Class F coal ash, each coal ash source also shown to increase slump performance when the substitution rate was increased from 20% to 40%. Conventional fly ash had a similar performance to reclaimed Class F and Bottom Class F. The Blended Class F and C showed better performance than traditional Class F and C ash.

A large standard deviation in slump performance was observed between the coal ash used in this study. The fineness of each coal ash could be one reason for this. Appendix II provides an analysis of each coal ashes slump performance in relation to their fineness.

2.3.4 Compressive Strength

Each coal ash was subjected to compressive strength testing following ASTM C39 [14] at 20% and 40% substitution rates. Measurements were taken at 3, 7, 14, 28, 56, 90, and 180 days. The average strength development of each type of coal ash at 20% and 40% substitution is depicted in Figure 2-4 and Figure 2-5 below. The average performance for each coal ash is provided in Appendix I.

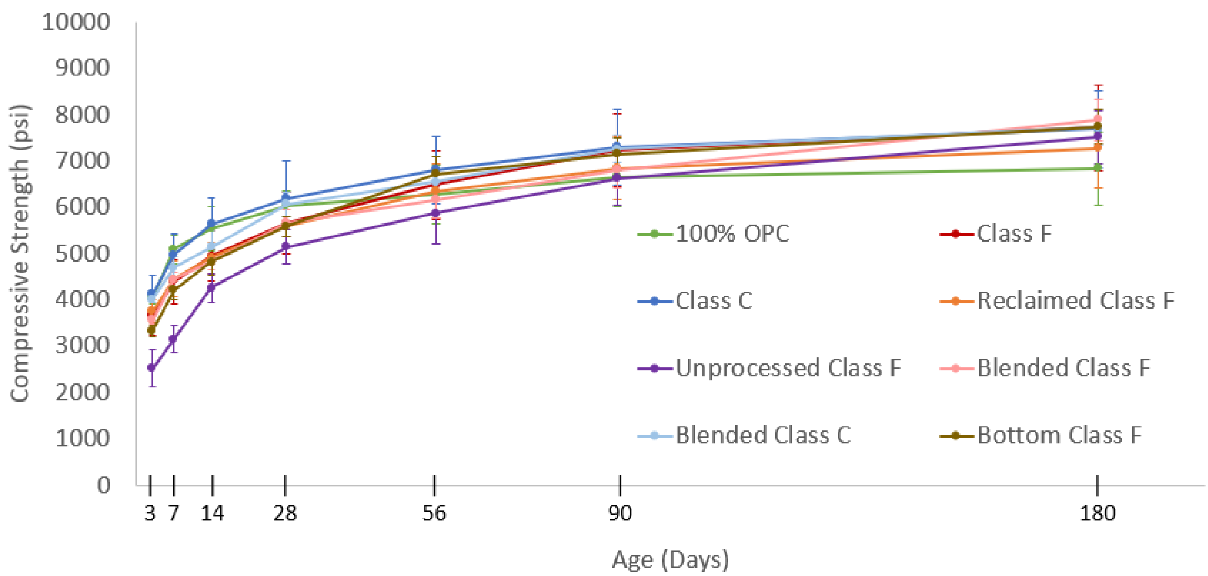

Figure 2-3: Compressive Strength of Concrete over 180-days with 20% Coal Ash Substitution

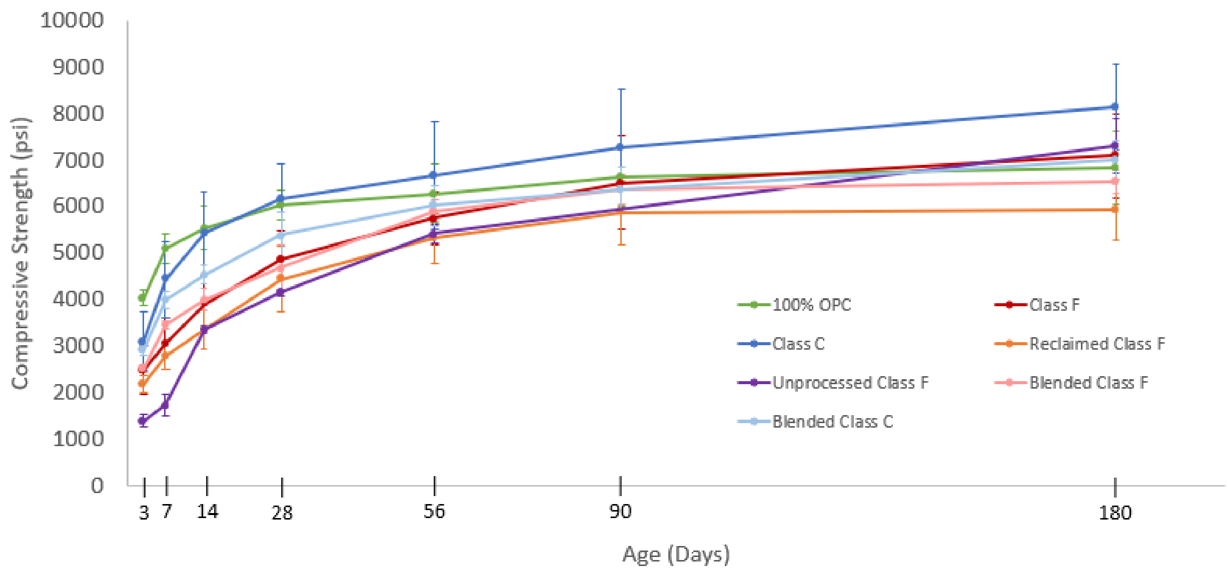

Figure 2-4: Compressive Strength of Concrete over 180-days with 40% Coal Ash Substitution

Concrete having 100% OPC content had a higher 3- and 7-day strength than all CCA investigated at both 20% and 40% replacement except conventional Class C coal ash at 20% replacement level. This can be seen in Figure 3-4 through Figure 3-7. However, at 180 days, all of the mixtures that contained CCA at 20% and 40% replacement have higher strengths than a mixture with 100% OPC except for the reclaimed Class F coal ash at 40% replacement and the Blended Class F coal ash at 40% replacement. Increasing the CCA replacement from 20% to 40% reduces the initial and long-term compressive strength for all types of coal ash except Conventional Class C coal ash at 180-day age. At 20% replacement, Reclaimed Class F coal ash increased the initial compressive strength and reduced the long-term strength performance when compared to Conventional Class F coal ash. The strength achieved using Reclaimed Class F coal ash at both 20%, and 40% replacement falls within the standard deviation of the strength achieved by Conventional Class F coal ash. This means that their performance may be similar. Unprocessed coal ash reduced the compressive strength when compared to Conventional Class F coal ash at both 20% and 40% replacement. When compared to Reclaimed Class F coal ash, Unprocessed coal ash shown to have reduced early age strength and higher long-term strength. Blended Class F coal ash has a similar performance at 20% replacement when compared to 100% OPC but reduced performance when increased to 40% replacement. Blended Class C coal ash reduced performance at 20% and 40% replacement compared to Conventional Coal Ash. Bottom Class F coal ash shown to have a similar performance to Conventional Class F coal ash.

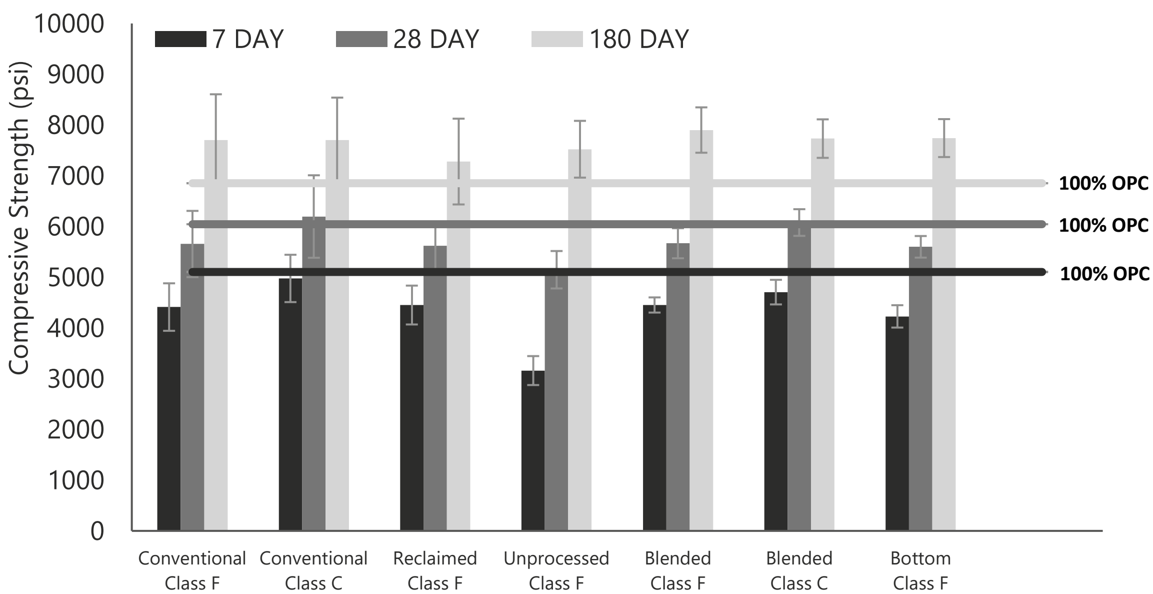

Figure 2-5: Compressive Strength of Concrete with 20% Coal Ash Substitution

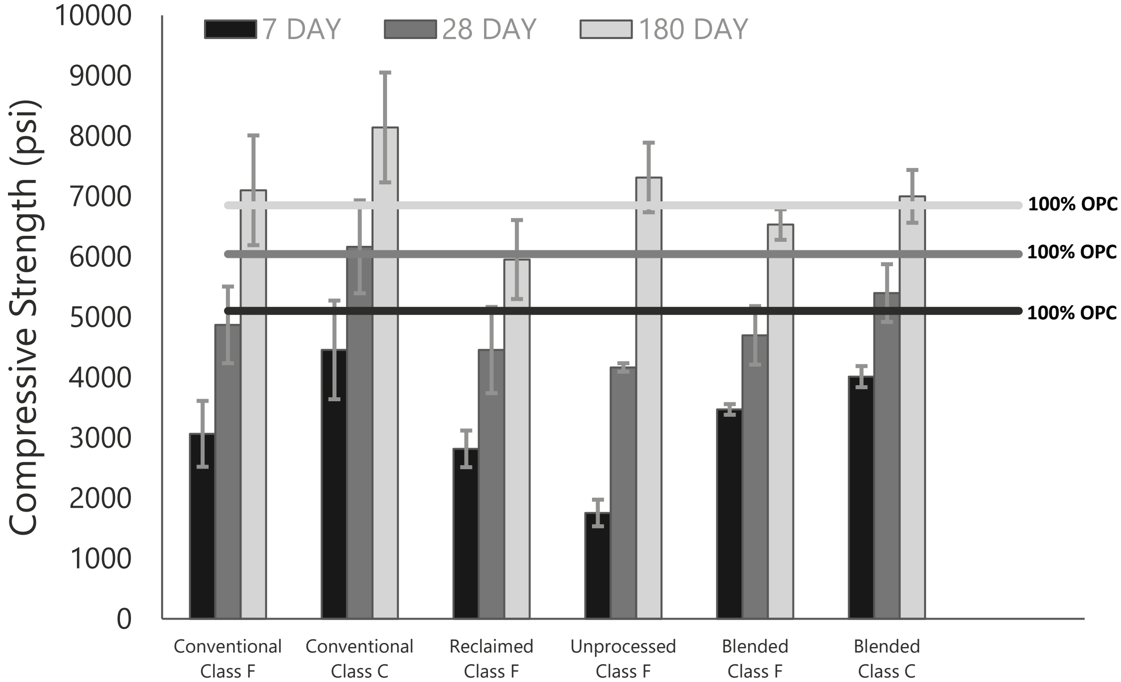

Figure 2-6: Compressive Strength of Concrete with 40% Coal Ash Substitution

2.3.5 Electrical Resistivity

The electrical resistivity of concrete measures the resistance to passing an electrical charge through the concrete. It has been reported that this can also provide insight into the resistance of the concrete to penetration by chloride ions [22]. Coal ash samples were tested at both 20% and 40% at 3, 7, 14, 28, 56, 90, and 180-day age. The electrical resistivity of 100% OPC concrete was also tested. The results of these tests are depicted in Figure 2-8 and Figure 2-9.

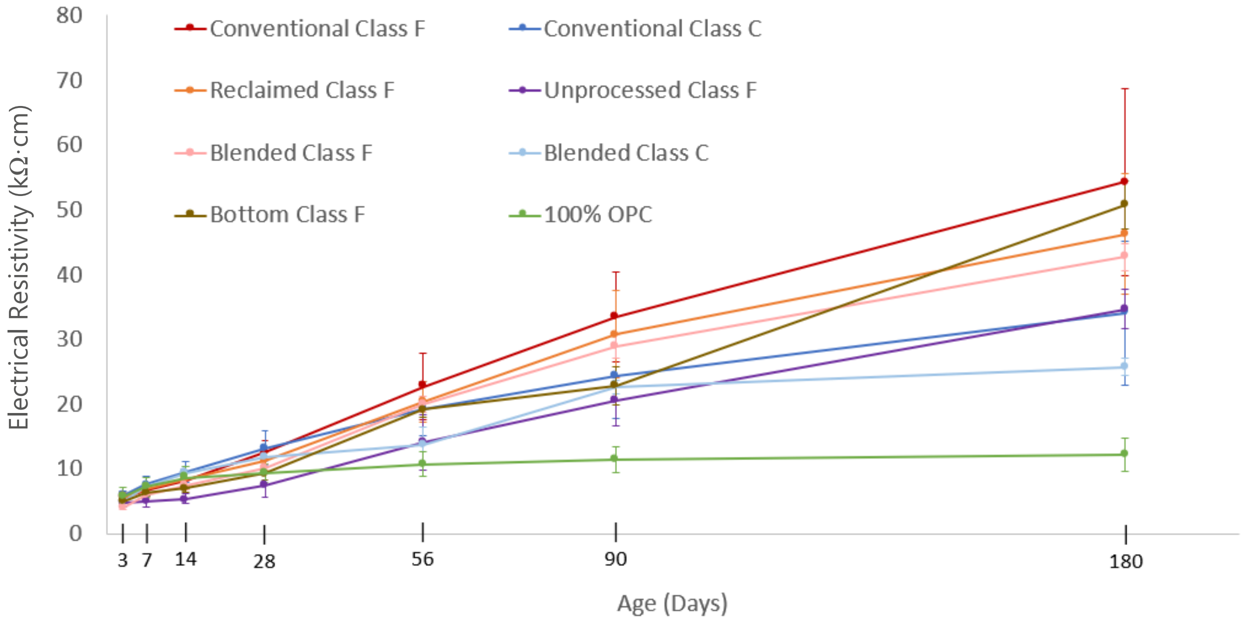

Figure 2-7: Electrical Resistivity of Concrete over 180-days with 20% Coal Ash Substitution

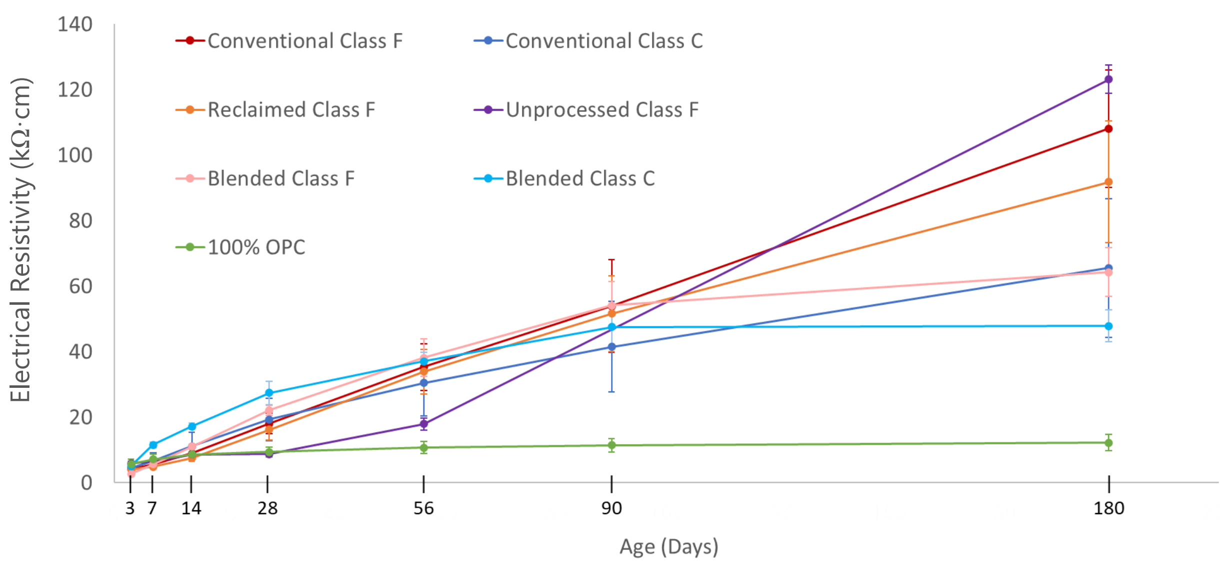

Figure 2-8: Electrical Resistivity of Concrete over 180-days with 40% Coal Ash Substitution

Concrete using coal ash substitution shown to have reduced initial electrical resistivity development compared to concrete using 100% OPC, except for Conventional Class C coal ash used at 20% replacement and Unprocessed Class F coal ash used at 40% replacement. Concrete using coal ash replacement at both 20% and 40% exceeds the long-term electrical resistivity performance of 100% OPC concrete. The average performance of each coal ash type shown to be more than double the average electrical resistivity performance of 100% OPC at 180-day testing. Increasing the coal ash content increases the long-term electrical resistivity development when compared to concrete using 100% OPC. Reclaimed coal ash shown to have similar but reduced electrical resistivity performance when compared to Conventional coal ash at both 20% and 40% replacement. Unprocessed coal ash has a reduced electrical resistivity performance at 20% replacement but increased early age electrical resistivity at 40% replacement when compared to conventional coal ash. This can be seen in Figure 2-10 and Figure 2-11. Each type of blended coal ash shown to have reduced performance from conventional ash at 20% replacement but mostly increased performance when used at 40% replacement. Bottom coal ash shown to have similar electrical resistivity performance when compared to conventional coal ash at 20% replacement, as seen in Figure 2-10.

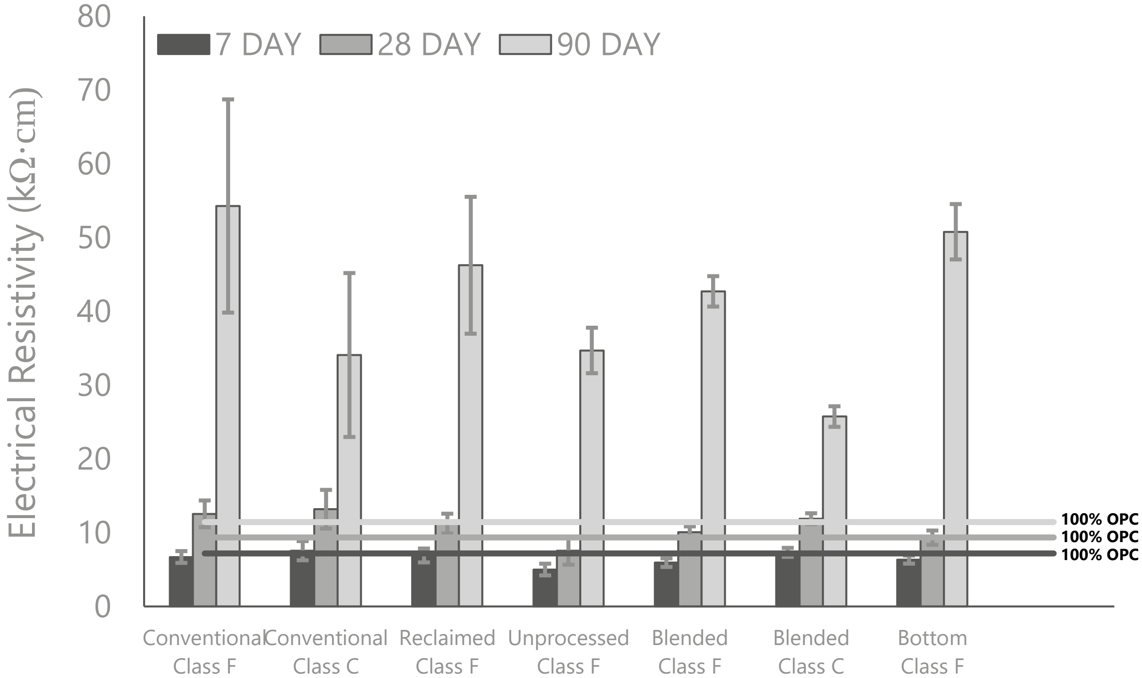

Figure 2-9: Electrical Resistivity of Concrete with 20% Coal Ash Substitution

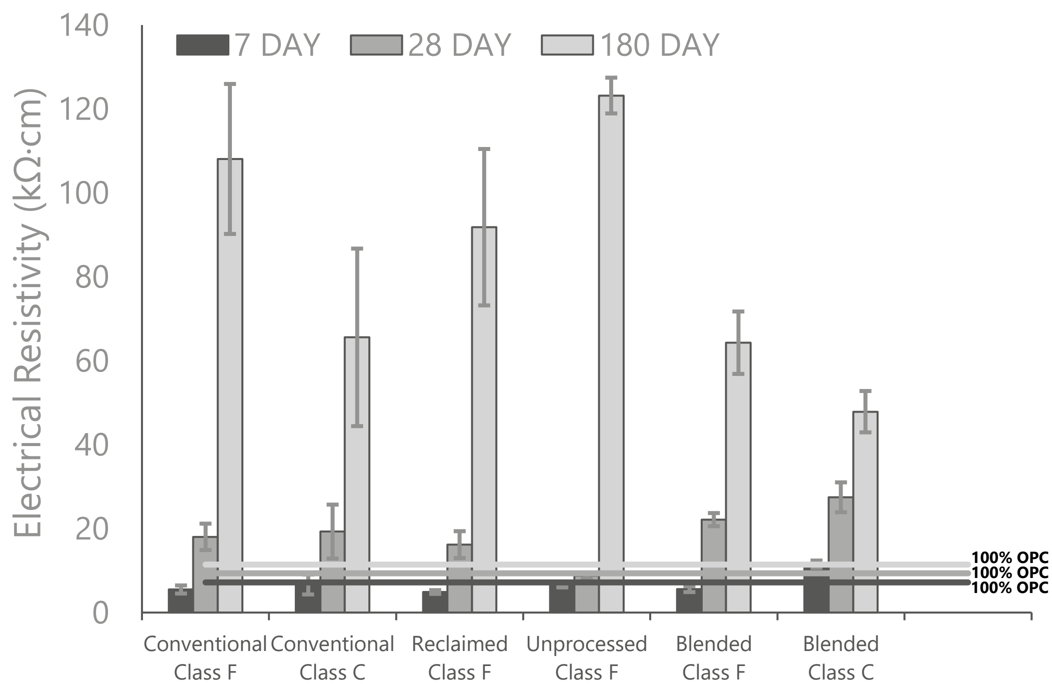

Figure 2-10: Electrical Resistivity of Concrete with 40% Coal Ash Substitution

2.3.6 Statistical Analysis

2.3.6.1 Statistical Comparison of Coal Products in Concrete using T-Test

The goal of this work is to make a statistical comparison of conventional and unconventional coal ash. Table 2-7 shows a statistical comparison of how different properties of unconventional coal ash compare to conventional coal ash. These were determined by comparing the p-value for each group of coal ash to the performance of traditional coal ash. When the results were similar with a 95% confidence interval (p-value ≤ 0.05), then the box is green. This means the results are statistically similar. When the results were somewhat significant but inconclusive ($0.05 <$ p-value ≤ 0.10), then the box is shown in yellow. When the results were not statistically similar (p-value > 0.10), then the box is shown in red. The p-value for each comparison is shown in the appendix.

Table 2-7: Statistical Analysis of Coal Ash Concrete Performance Using T-test – Green = statical significance, yellow = somewhat significant but inconclusive, red = not significant.

		Reclaimed F to Conventional Class F		Unprocessed F to Conventional Class F		Blended F to Conventional Class F		Bottom F to Conventional Class F	Blended C to Conventional Class C	
		20%	40%	20%	40%	20%	40%	20%	20%	40%
48-HR HEAT OF HYDRATION		Green	Green	Red	Green	Green	Yellow	Red	Green	Red
Slump		Green	Green	Red	Red	Red	Red	Yellow	Green	Green
Compressive Strength	3d	Green	Red	Red	Red	Yellow	Green	Red	Red	Yellow
	7d	Green	Red	Red	Red	Green	Red	Green	Yellow	Red
	14d	Green	Red	Red	Red	Green	Green	Green	Red	Red
	28d	Green	Red	Red	Red	Green	Green	Green	Green	Red
	56d	Green	Red	Red	Red	Green	Green	Green	Red	Red
	90d	Red	Red	Red	Yellow	Yellow	Green	Green	Green	Red
	180d	Red	Red	Green	Green	Green	Red	Green	Green	Red
Electrical Resistivity	3d	Green	Green	Red	Red	Red	Red	Red	Red	Red
	7d	Green	Red	Red	Red	Red	Green	Green	Green	Red
	14d	Green	Red	Red	Green	Yellow	Red	Red	Green	Red
	28d	Red	Red	Red	Red	Red	Red	Red	Red	Red
	56d	Red	Green	Red	Red	Red	Green	Red	Green	Red
	90d	Red	Green	Red	Green	Red	Yellow	Red	Red	Yellow
	180d ,	Red	Red	Red	Green	Red	Red	Yellow	Red	Red

Table 2-7 provides the statistical analysis of the data acquired in this study. Each non-traditional coal ash was compared to the data set of the conventional coal ash of its same class (class F or class C). A p-score was found and is provided in Appendix 1 of this document. The average performance of each coal ash was evaluated and classified based on the following:

- (Green) Statistical significance – P-value at or greater than 0.05.
- (Yellow) Somewhat significant, but inconclusive – P-value between 0.05 and 0.01.
- (Red) No statistical significance – P-value below 0.01.

Heat of Hydration

Each non-traditional coal ash shown to have similar 48-hr heat of hydration compared to conventional coal ash, aside from 20% unprocessed class F, bottom class F, and blended Class C.

Slump

The analysis shows Reclaimed Class F and Blended Class C as the only non-traditional coal ash to have statistically similar results to conventional coal ash at both 20% and 40% replacement. Each other non-traditional coal ash shown not to have statistical similarity between their average slump performance and the average performance of conventional coal ash.

Compressive Strength

The average compressive strength of reclaimed Class F coal ash at 20%, bottom Class F at 20%, and blended Class F coal ash at both 20% and 40% replacement, shown to be statistically similar to their conventional coal ash counterpart, respectively.

Electrical Resistivity

Overall, no non-traditional coal ash shown to have similar average electrical resistivity performance.

2.3.6.2 Performance Classification System for Coal Ash in Concrete

Another approach for comparing the performance of concrete using each type of coal ash is through classifying each ash's performance based on the results with the CCA in comparison to a mixture with only OPC. To achieve this, a ranking classification was developed that groups the material into three performance categories: high, moderate, and low. These limits were found by using all the data gathered in this work and establishing limits based on the 33% and 66% performance levels. These limits were found by making a histogram of all of the materials' performance and choosing these limits. This means that these limits are based on the dataset investigated; however, since the research encompasses 48 CCA sources, then this should be a meaningful set of limits. It should be noted that these limits are based on the testing methods and the materials investigated; however, these results are still helpful as they are normalized by the performance of a mixture with only OPC.

Table 2-8: Performance Classification of Coal Ash

Parameter	Calculation	Performance Classification		
Total Heat at 48-hr from isothermal calorimetry		Low Total Heat	Moderate Total Heat	High Total Heat
	$\frac{CCP\ Substitution}{100\%\ OPC}$	< 0.80	0.80 – 1.00	> 1.00
		Low Slump	Moderate Slump	High Slump
20% CCP Slump	$\frac{20\%\ Substituion}{100\%\ OPC}$	< 1.55	1.55 - 2.30	> 2.30
40% CCP Slump	$\frac{40\%\ Substituion}{100\%\ OPC}$	< 2.75	2.75 - 3.70	> 3.70
		Decreased Strength	Moderate Strength	Increased Strength
20% CCP Compressive Strength (3d, 7d, 14d, 28d, 56d, 90d, and 180d)	$\frac{20\%\ Substituion}{100\%\ OPC}$ (Done at each age)	< 0.95	0.95 – 1.10	> 1.10
40% CCP Compressive Strength	$\frac{40\%\ Substituion}{100\%\ OPC}$ (Done at each age)	< 0.80	0.80 – 1.00	> 1.00

Parameter	Calculation	Performance Classification		
(3d, 7d, 14d, 28d, 56d, 90d, and 180d)				
		Decreased Resistivity	Moderate Resistivity	Increased Resistivity
20% CCP Electrical Resistivity (3d, 7d, 14d, 28d, 56d, 90d, and 180d)	$\frac{20\%\ Substituion}{100\%\ OPC}$ (Done at each age)	< 1.00	1.00 – 1.70	> 1.70
40% CCP Electrical Resistivity (3d, 7d, 14d, 28d, 56d, 90d, and 180d)	$\frac{40\%\ Substituion}{100\%\ OPC}$ (Done at each age)	< 1.00	1.00 – 3.00	> 3.00

To give the reader an example of how these results could be used, the average CCA performance for each material is shown in Table 2-9. The performance is shown with a color chart where the highest performance is yellow, the medium performance is orange, and the lowest performance is red.

Table 2-9A: Average Performance of Coal Ash by Type

		Conventional Class F		Conventional Class C		Reclaimed Class F		Unprocessed Class F		Blended Class F		Blended Class C		Bottom Class F
		20%	40%	20%	40%	20%	40%	20%	40%	20 %	40 %	20 %	40 %	20%
Heat of Hydration		Moderate	Low	High	Moderate	Moderate	Moderate	Moderate	Low	Moderate	High	Moderate	High	High
Slump		Moderate	High	Moderate	High	Moderate	High	Low	Low	High	High	High	High	Moderate
Compressive Strength	3 Day	Low	Low	Moderate	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
	7 Day	Low	Low	Moderate	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
	14 Day	Low	Low	Moderate	Moderate	Low	Low	Low	Low	Low	Low	Low	Moderate	Low
	28 Day	Moderate	Moderate	Moderate	High	Low	Low	Low	Low	Low	Low	Moderate	Moderate	Low
	56 Day	Moderate	Moderate	High	High	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
	90 Day	Moderate	Moderate	High	High	Moderate	Moderate	Moderate	---	Moderate	Moderate	Moderate	Moderate	Moderate
	180 Day	Moderate	Moderate	High	High	Moderate	Moderate	Moderate	High	Moderate	Moderate	Moderate	Moderate	Moderate
Electrical Resistivity	3 Day	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
	7 Day	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Moderate	Low
	14 Day	Low	Low	Moderate	Moderate	Low	Low	Low	Low	Low	Moderate	Moderate	Moderate	Low
	28 Day	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Low	Low	Moderate	Moderate	Moderate	Moderate	Low
	56 Day	High	High	High	Moderate	High	High	Moderate	Low	High	High	Moderate	High	High
	90 Day	High	High	High	High	High	High	High	---	High	High	High	High	High
	180 Day	High	High	High	High	High	High	High	High	High	High	High	High	---

This table provides the classification of the average performance of each coal ash type based on the data collected in this study. The classification used is outlined in TABLE 2-8 The color system is depicted below:

- High Performance
- Moderate Performance
- Low Performance

Table 2-9B: Average Performance of Coal Ash by Type

		Conventional Class F		Conventional Class C		Reclaimed Class F		Unprocessed Class F		Blended Class F		Blended Class C		Bottom Class F
		20%	40%	20%	40%	20%	40%	20%	40%	20 %	40 %	20 %	40 %	20%
Heat of Hydration		↔	↓	↑	↔	↔	↔	↔	↓	↔	↑	↔	↑	↑
Slump		↔	↑	↔	↑	↔	↑	↓	↓	↑	↑	↑	↑	↔
Compressive Strength	3 Day	↓	↓	↔	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
	7 Day	↓	↓	↔	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
	14 Day	↓	↓	↔	↔	↓	↓	↓	↓	↓	↓	↓	↔	↓
	28 Day	↔	↔	↔	↑	↓	↓	↓	↓	↓	↓	↔	↔	↓
	56 Day	↔	↔	↑	↑	↔	↔	↔	↔	↔	↔	↔	↔	↔
	90 Day	↔	↔	↑	↑	↔	↔	↔	---	↔	↔	↔	↔	↔
	180 Day	↔	↔	↑	↑	↔	↔	↔	↑	↔	↔	↔	↔	↔
Electrical Resistivity	3 Day	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
	7 Day	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓		↔	↓
	14 Day	↓	↓	↔	↔	↓	↓	↓	↓	↓	↔	↔	↔	↓
	28 Day	↔	↔	↔	↔	↔	↔	↓	↓	↔	↔	↔	↔	↓
	56 Day	↑	↑	↑	↔	↑	↑	↔	↓	↑	↑	↔	↑	↑
	90 Day	↑	↑	↑	↑	↑	↑	↑	---	↑	↑	↑	↑	↑
	180 Day	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	---

This table provides the classification of the average performance of each coal ash type based on the data collected in this study. The classification used is outlined in TABLE 2-8 The color system is depicted below:

↑ High Performance

↔ Moderate Performance

↓ Low Performance

Heat of hydration

Based on this classification system, the average 48-hour heat of hydration for most coal ash types was found to be moderate. The only low performance was 40% conventional class F, and 40% unprocessed class F. Concrete made with coal ash typically has a lower heat of hydration than portland cement concrete. Typically, the contribution to the heat of hydration by Class F coal ash is 50% of that of Portland cement, while Class C coal ash provides a heat of hydration that is higher than that of Class F [24].

Slump

The average performance of most coal ash types shown to be moderate at 20% replacement and high at 40% replacement. Blended coal ash shows high slump performance at both 20% and 40% replacement, while unprocessed coal ash shows low performance at both 20% and 40% replacement. Generally, the use of fly ash will increase the workability of concrete. Coal ash with high percentages of coarse particles (retained on No. 325 sieve) or high carbon content can increase the water demand and lower the workability of the concrete [24].

Compressive Strength

Each coal ash shown to be low for the first 14d except for conventional Class C. Most of the samples had moderate strength between 28d and 180d except for 40% conventional C ash. This result was expected as fly ash typically aids in long-term strength development. Coal ash commonly requires 28 to 90 days to exceed control strength, depending on the fineness and proportions used. Higher reactive coal ashes, such as high-calcium Class C ashes, can equal or exceed the strength of 100% OPC concrete in 1 to 28 days [24].

Electrical Resistivity

The average performance of most coal ash types was found to be low for the first 14 d, moderate at 28 d, and high at 56d and larger. Coal ash generally reduces the permeability of concrete [24].

CHAPTER III

CONCLUSION

3.1 SUMMARY

This thesis compares the concrete performance achieved by using traditional and non-traditional coal ash samples. A total of 33 traditional coal ash sources and 15 non-traditional coal ash sources were used in this study.

The overall study has shown promising results for the use of non-traditional coal ash in concrete. Some non-traditional coal ash sources used in this study shown to outperform coal ash currently used in the industry. Due to the limited availability of Unprocessed Coal Ash, Blended Coal Ash, and Bottom Coal ash, further testing is needed to better understand their performance ability in concrete. Using performance-based specifications, these non-traditional coal ash sources can provide an adequate supply of reliable coal ash to the industry.

The following conclusions can be drawn:

- There is no statistical difference in the heat of hydration between traditional and non-traditional Class F coal ash.
- Concrete with traditional and non-traditional coal ash increases the slump of the concrete over mixtures with 100% OPC concrete at 20% and 40% replacement.

- Concrete with traditional and non-traditional coal ash at 20% and 40% replacement have a lower average 7-day compressive strength than mixtures with 100% OPC.
- All coal ash had a 180-day compressive strength that is higher than mixtures with 100% OPC, except for reclaimed and blended coal ash at 40% replacement.
- Each coal ash source has a lower average 3-day electrical resistivity measurement when compared to mixtures with 100% OPC.
- Each coal ash has an electrical resistivity that is more than double mixtures with 100% OPC.
- The following are the findings from the T-Test:
    - At 20% replacement, Reclaimed and Blended coal ash have statistically similar heat of hydration to conventional coal ash.
    - At 40% replacement, Reclaimed and Unprocessed coal ash shown to statistically similar heat of hydration to Conventional coal ash.
    - Slump performance of Reclaimed Class F and Blended Class C coal ash shown to be statistically similar to conventional coal ash.
    - Processed coal ash sources are shown to have statistically similar performance to conventional coal ash when used at 20% replacement for 10 of the 16 average performance comparisons.
    - Unprocessed coal ash does not have a statistically similar performance for strength measurements compared to conventional coal ash at 20% replacement.

- The statistical similarity of unconventional and conventional coal ash in terms of electrical resistivity is inconsistent between the age and type of unconventional coal ash used.

- The Design and Control of Concrete Mixtures [24] provides tables that outline the typical impact of SCMs on concrete fresh and hardened properties. Based on those tables, Table 3-1 provides the typical performance for Class F fly ash for slump, heat of hydration, compressive strength, and corrosion resistance. In an effort to compare the reclaimed and unprocessed coal ash used in this study, Table 3-1 and Table 3-2 provide the classification for the average performance of conventional, reclaimed, and unprocessed coal ash. As there was only 1 sample of each blended and bottom ash used in this study, additional testing is needed to determine how each type relates to conventional coal ash. Appendix I provides a table that outlines the classification of each coal ash with regard to the properties listed in Table 3-2.

Table 3-1: Impact of Class F Fly Ash on Properties of Concrete

Coal Ash	Workability	Heat of Hydration	Early Strength	Long Term Strength	Corrosion Resistance
Class F Fly Ash	↑	↓	↓	↑	↑

This table is based on Table 3-6 and Table 3-10 of Design and Control of Concrete Mixtures. These tables were adapted from Thomas and Wilson 2002, and Omran and others 2018.

Table 3-2: Impact of Coal Ash on Properties of Concrete Based

Coal Ash	Content	Workability	Heat of Hydration	Early Strength	Long Term Strength	Electrical Resistivity
Conventional	20%	↔	↔	↓	↔	↑
	40%	↑	↓	↓	↔	↑
Reclaimed	20%	↔	↔	↓	↔	↑
	40%	↑	↔	↓	↔	↑
Unprocessed	20%	↓	↔	↓	↔	↑
	40%	↓	↓	↓	↔	↑

Both reclaimed and unprocessed coal ash shown to have the same performance classifications as conventional coal ash for each property, aside for two. At 40% replacement, reclaimed coal ash shown to have a moderate heat of hydration, while the average heat of hydration of conventional coal ash was classified as low. At 20% replacement, unprocessed coal ash shown to have low workability, while conventional coal ash had moderate workability on average.

This work makes an important contribution by comparing large data sets of conventional and unconventional coal ashes in relevant testing protocols. This information will help build confidence in practitioners in the use of these non-traditional coal ashes in practical concrete mixtures.

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APPENDICES

APPENDIX A

TABLES AND FIGURES

TABLE A1-1: STATISTICAL SUMMARY OF THE 48-HR HEAT OF HYDRATION OF EACH COAL ASH SOURCE

FA ID	20% Coal Ash				40% Coal Ash			
	20% (J/g)	TTEST	SCORE	RATING	40% (J/g)	TTEST	SCORE	RATING
C1	178	---	1.09	HIGH	119	---	0.73	LOW
C2	170	---	1.05	HIGH	107	---	0.66	LOW
C3	---	---	---	---	124	---	0.76	LOW
C4	182	---	1.12	HIGH	---	---	---	---
C5	---	---	---	---	---	---	---	---
C6	---	---	---	---	---	---	---	---
C7	166	---	1.02	HIGH	---	---	---	---
C8	179	---	1.10	HIGH	---	---	---	---
C11	188	---	1.15	HIGH	---	---	---	---
C12	---	---	---	---	101	---	0.62	LOW
C13	---	---	---	---	---	---	---	---
C14	176	---	1.08	HIGH	147	---	0.90	MODERATE
C15	189	---	1.16	HIGH	---	---	---	---
C16	180	---	1.11	HIGH	153	---	0.94	MODERATE
C17	---	---	---	---	---	---	---	---
C18	190	---	1.17	HIGH	---	---	---	---
C19	180	---	1.10	HIGH	---	---	---	---
F1	145	---	0.89	MODERATE	109	---	0.67	LOW
F2	154	---	0.95	MODERATE	141	---	0.87	MODERATE
F3	145	---	0.89	MODERATE	109	---	0.67	LOW
F4	184	---	1.13	HIGH	141	---	0.87	MODERATE
F5	143	---	0.88	MODERATE	112	---	0.69	LOW
F6	143	---	0.88	MODERATE	119	---	0.73	LOW
F9	175	---	1.08	HIGH	142	---	0.87	MODERATE
F10	177	---	1.09	HIGH	---	---	---	---

FA ID	20% Coal Ash				40% Coal Ash			
	20% (J/g)	TTEST	SCORE	RATING	40% (J/g)	TTEST	SCORE	RATING
F11	---	---	---	---	---	---	---	---
F12	175	---	1.07	HIGH	142	---	0.87	MODERATE
F15-1	---	---	---	---	---	---	---	---
F15-2	135	---	0.83	MODERATE	138	---	0.85	MODERATE
F16	182	---	1.12	HIGH	128	---	0.79	LOW
F17	177	---	1.09	HIGH	135	---	0.83	MODERATE
F27	155	---	0.95	MODERATE	104	---	0.64	LOW
RF2	155	0.168	0.95	MODERATE	134	0.026	0.83	MODERATE
RF3	142	0.011	0.87	MODERATE	---	---	---	---
RF4-2	150	0.947	0.92	MODERATE	114	0.000	0.70	
RF5	150	0.839	0.92	MODERATE	---	---	---	---
RF6-1	---	---	---	---	---	---	---	---
RF6-2	---	---	---	---	122	0.329	0.75	LOW
RF7-1	151	0.822	0.93	MODERATE	151	0.000	0.93	MODERATE
RF11	136	0.000	0.84	MODERATE	---	---	---	---
UF1	141	0.005	0.86	MODERATE	151	0.000	0.93	MODERATE
UF2	146	0.188	0.90	MODERATE	127	0.207	0.78	LOW
UF3	138	0.000	0.85	MODERATE	121	0.215	0.74	LOW
UF4	136	0.000	0.84	MODERATE	121	0.215	0.74	LOW
BF9	161	0.049	0.99	MODERATE	123	0.470	0.76	LOW
BC3	130	0.268	0.80	MODERATE	107	0.001	0.66	LOW
BTF1	169	0.000	1.04	HIGH	119	0.000	0.73	LOW

TABLE A1-2: Statistical Summary of the Slump Performance of Coal ash at 20% and 40% Replacement

ID	% Coal Ash	AVG (in.)	STD	TTEST	SCORE	RATING
100% OPC	0%	1.00	0.00	---	---	---
100% OPC	0%	1.50	0.00	---	---	---
100% OPC	0%	2.67	0.12	---	---	---
C1	20%	4.25	0.20	---	2.47	HIGH
C1	20%	2.25	0.00	---	1.31	LOW
C2	20%	1.75	0.00	---	1.02	LOW
C3	20%	4.08	0.24	---	2.37	HIGH
C3	20%	1.25	0.00	---	0.73	LOW
C3	20%	4.00	0.00	---	2.32	HIGH
C3	20%	7.00	0.00	---	4.06	HIGH

ID	% Coal Ash	AVG (in.)	STD	TTEST	SCORE	RATING
C4	20%	1.92	0.12	---	1.11	LOW
C4	20%	2.50	0.00	---	1.45	LOW
C5	20%	1.75	0.20	---	1.02	LOW
C5	20%	4.25	0.00	---	2.47	HIGH
C6	20%	4.42	0.12	---	2.56	HIGH
C6	20%	2.75	0.00	---	1.60	MODERATE
C7	20%	2.58	0.42	---	1.50	LOW
C7	20%	3.75	0.00	---	2.18	MODERATE
C7	20%	6.00	0.00	---	3.48	HIGH
C7	20%	3.25	0.00	---	1.89	MODERATE
C7	20%	2.00	0.00	---	1.16	LOW
C8	20%	5.04	0.16	---	2.93	HIGH
C8	20%	4.00	0.20	---	2.32	HIGH
C11	20%	4.25	0.00	---	2.47	HIGH
C12	20%	3.58	0.31	---	2.08	MODERATE
C12	20%	3.50	0.00	---	2.03	MODERATE
C13	20%	3.92	0.12	---	2.27	MODERATE
C13	20%	6.50	0.00	---	3.77	HIGH
C14	20%	4.42	0.42	---	2.56	HIGH
C14	20%	4.25	0.00	---	2.47	HIGH
C15	20%	5.58	0.31	---	3.24	HIGH
C15	20%	5.00	0.00	---	2.90	HIGH
C16	20%	3.97	0.24	---	2.31	HIGH
C17	20%	2.63	0.32	---	1.53	LOW
C18	20%	2.25	0.20	---	1.31	LOW
C19	20%	3.92	0.42	---	2.27	MODERATE
F1	20%	2.42	0.24	---	1.40	LOW
F1	20%	2.50	0.00	---	1.45	LOW
F2	20%	2.00	0.00	---	1.16	LOW
F3	20%	2.33	0.24	---	1.35	LOW
F3	20%	1.50	0.00	---	0.87	LOW
F4	20%	1.67	0.31	---	0.97	LOW
F4	20%	3.75	0.00	---	2.18	MODERATE
F4	20%	1.75	0.00	---	1.02	LOW
F5	20%	3.75	0.35	---	2.18	MODERATE
F5	20%	3.42	0.12	---	1.98	MODERATE
F5	20%	1.50	0.00	---	0.87	LOW
F6	20%	3.50	0.00	---	2.03	MODERATE
F6	20%	4.00	0.00	---	2.32	HIGH
F9	20%	2.92	0.24	---	1.69	MODERATE
F10	20%	2.08	0.12	---	1.21	LOW

ID	% Coal Ash	AVG (in.)	STD	TTEST	SCORE	RATING
F11	20%	4.92	0.12	---	2.85	HIGH
F11	20%	3.75	0.00	---	2.18	MODERATE
F12	20%	6.67	0.42	---	3.87	HIGH
F15-1	20%	2.25	0.20	---	1.31	LOW
F 15-2	20%	5.08	0.12	---	2.95	HIGH
F16	20%	3.00	0.20	---	1.74	MODERATE
F17	20%	7.28	0.21	---	4.23	HIGH
F27	20%	3.08	0.12	---	1.79	MODERATE
RF2	20%	3.50	0.00	0.89	2.03	MODERATE
RF3	20%	2.33	0.31	0.01	1.35	LOW
RF4	20%	3.17	0.12	0.22	1.84	MODERATE
RF5	20%	2.75	0.20	0.02	1.60	MODERATE
RF6-1	20%	3.08	0.12	0.12	1.79	MODERATE
RF6-2	20%	4.17	0.31	0.06	2.42	HIGH
RF7-1	20%	3.47	0.33	0.99	2.01	MODERATE
RF11	20%	3.33	0.12	0.59	1.94	MODERATE
UF1	20%	1.17	0.31	0.00	0.68	LOW
UF2	20%	2.00	0.20	0.00	1.16	LOW
UF3	20%	3.25	0.20	0.43	1.89	MODERATE
UF4	20%	2.67	0.12	0.00	1.55	LOW
BC3	20%	4.08	0.47	0.35	2.37	HIGH
BF9	20%	5.00	0.35	0.00	2.90	HIGH
BTF1	20%	3.00	0.00	0.05	1.74	MODERATE
C1	40%	4.75	0.00	---	2.76	MODERATE
C2	40%	4.75	0.00	---	2.76	MODERATE
C3	40%	6.50	0.00	---	3.77	HIGH
C4	40%	5.00	0.00	---	2.90	MODERATE
C4	40%	6.50	0.00	---	3.77	HIGH
C5	40%	4.25	0.00	---	2.47	LOW
C6	40%	6.00	0.00	---	3.48	MODERATE
C6	40%	6.17	0.47	---	3.58	MODERATE
C7	40%	6.50	2.16	---	3.77	HIGH
C7	40%	6.00	0.00	---	3.48	MODERATE
C7	40%	4.25	0.00	---	2.47	LOW
C8	40%	7.17	0.12	---	4.16	HIGH
C11	40%	5.25	0.00	---	3.05	MODERATE
C12	40%	6.75	0.00	---	3.92	HIGH
C12	40%	5.42	1.53	---	3.15	MODERATE
C13	40%	6.92	0.42	---	4.02	HIGH
C13	40%	4.25	0.00	---	2.47	LOW
C14	40%	5.25	0.00	---	3.05	MODERATE

ID	% Coal Ash	AVG (in.)	STD	TTEST	SCORE	RATING
C14	40%	2.75	0.00	---	1.60	LOW
C15	40%	4.85	0.46	---	2.81	MODERATE
C15	40%	2.50	0.00	---	1.45	LOW
C15	40%	8.25	0.00	---	4.79	HIGH
C16	40%	7.92	0.59	---	4.60	HIGH
F1	40%	6.50	0.00	---	3.77	HIGH
F2	40%	6.50	0.00	---	3.77	HIGH
F3	40%	3.25	0.00	---	1.89	LOW
F4	40%	4.25	0.41	---	2.47	LOW
F4	40%	4.50	0.00	---	2.61	LOW
F5	40%	4.50	0.00	---	2.61	LOW
F5	40%	2.25	0.00	---	1.31	LOW
F6	40%	3.50	0.00	---	2.03	LOW
F11	40%	7.00	0.00	---	4.06	HIGH
F11	40%	5.33	0.24	---	3.10	MODERATE
F12	40%	6.58	1.18	---	3.82	HIGH
F15-2	40%	5.25	0.20	---	3.05	MODERATE
F27	40%	3.50	0.20	---	2.03	LOW
RF2	40%	6.33	0.24	0.00	3.68	MODERATE
RF3	40%	4.83	0.62	0.90	2.81	MODERATE
RF4	40%	3.67	0.12	0.00	2.13	LOW
RF5	40%	4.25	0.20	0.06	2.47	LOW
RF6-1	40%	3.67	0.31	0.01	2.13	LOW
RF6-2	40%	7.08	0.31	0.00	4.11	HIGH
RF11	40%	5.42	0.72	0.44	3.15	MODERATE
UF1	40%	0.83	0.12	0.00	0.48	LOW
BC3	40%	6.83	0.62	0.15	3.97	HIGH
BF9	40%	7.00	0.74	0.03	4.06	HIGH

TABLE A1-3: Compressive Strength Data and T-Test Analysis of Coal Ash at 20% Replacement at 3-, 7-, and 14-day Ages

Days of hydration	3 DAY			7 DAY			14 DAY		
Sample#	AVG (psi)	STD	T Test	AVG (psi)	STD	T Test	AVG (psi)	STD	T Test
100% OPC	3960	168	---	5040	61	---	5770	71	---
100% OPC	4060	44	---	4740	105	---	5040	284	---
100% OPC	4090	153	---	5240	293	---	5650	488	---
C1	3770	137	---	4630	125	---	5300	122	---
C1	4280	166	---	5300	197	---	6260	77	---
C2	4330	143	---	5440	38	---	6050	137	---
C3	4120	86	---	4760	82	---	5380	162	---
C3	4310	42	---	5290	111	---	6160	85	---
C4	4480	381	---	5270	463	---	6010	272	---
C4	3630	127	---	4850	22	---	5840	125	---
C5	3960	161	---	4480	204	---	5090	290	---
C5	4470	17	---	5630	126	---	6590	74	---
C6	4340	281	---	4840	119	---	5280	203	---
C6	4190	33	---	5240	80	---	5860	173	---
C7	4270	241	---	5460	396	---	5850	421	---
C7	4240	62	---	5330	49	---	6100	35	---
C8	3440	137	---	4430	280	---	4600	145	---
C11	4400	33	---	5720	12	---	6550	130	---
C12	4040	143	---	4750	207	---	5300	203	---
C12	3630	173	---	4540	38	---	5370	23	---
C13	4130	150	---	4960	202	---	6240	628	---
C13	3860	78	---	4580	120	---	5620	271	---
C14	4020	147	---	4500	38	---	5570	123	---
C14	4160	261	---	5170	437	---	6100	450	---
C15	3970	297	---	5080	219	---	5390	360	---
C15	4040	41	---	4870	125	---	5260	11	---
C16	5000	263	---	5590	544	---	6160	631	---
C17	4180	273	---	5050	398	---	5540	408	---
C18	4030	182	---	4820	230	---	5400	152	---
C19	3780	195	---	4470	145	---	5460	129	---
F1	3600	114	---	4530	191	---	4950	284	---
F1	3530	69	---	4360	177	---	5180	98	---
F2	3790	59	---	4590	13	---	5320	90	---
F3	4280	271	---	5050	254	---	5560	309	---
F3	3590	92	---	4640	67	---	5350	119	---

Days of hydration	3 DAY			7 DAY			14 DAY		
F4	4630	335	---	5460	381	---	5790	456	---
F4	3600	67	---	4460	77	---	5380	61	---
F4	3600	57	---	4550	85	---	5190	91	---
F5	3430	134	---	4440	187	---	4930	156	---
F5	3600	133	---	4510	98	---	5060	46	---
F6	3650	69	---	4700	107	---	5250	35	---
F6	3430	136	---	4250	97	---	4810	245	---
F9	3920	179	---	4360	188	---	4870	136	---
F10	3390	109	---	4200	123	---	4690	133	---
F11	3310	58	---	4170	136	---	4700	106	---
F11	3220	85	---	3840	65	---	4420	88	---
F12	3350	167	---	---	---	---	3860	277	---
F15-1	4020	302	---	4530	176	---	5470	296	---
F15-2	4050	149	---	4440	228	---	4760	417	---
F16	3400	194	---	3980	363	---	5200	328	---
F17	3350	174	---	3780	123	---	4530	219	---
F27	3560	146	---	4490	226	---	5220	373	---
RF2	3930	165	0.002	4670	214	0.009	5330	235	0.002
RF3	3810	177	0.072	4540	233	0.182	4890	274	0.548
RF4	3420	246	0.023	5040	76	0.000	5150	218	0.041
RF5	3990	139	0.000	4510	241	0.339	5020	276	0.545
RF6-1	3730	175	0.428	4560	228	0.118	4660	282	0.020
RF6-2	3770	245	0.309	4220	185	0.026	4730	240	0.037
RF7-1	3640	171	0.676	4040	263	0.004	---	---	---
RF11	3750	116	0.175	4020	169	0.000	4630	169	0.000
UF1	2150	226	0.000	2740	189	0.000	4020	364	0.000
UF2	2680	213	0.000	3020	97	0.000	4240	241	0.000
UF3	1950	168	0.000	2500	271	0.000	3800	165	0.000
UF4	2010	269	0.000	2840	255	0.000	4130	210	0.000
BC3	4030	88	0.040	4710	242	0.014	5150	345	0.003
BF9	3570	70	0.016	4450	149	0.541	4820	163	0.074
BTF1	3350	124	0.000	4230	220	0.056	4820	270	0.238

TABLE A1-4: Compressive Strength Data and T-Test Analysis of Coal Ash at 20% Replacement at 28-, 56-, and 90-day Ages

Days of hydration	**28 DAY**			**56 DAY**			**90 DAY**		
Sample#	AVG (psi)	STD	T Test	AVG (psi)	STD	T Test	AVG (psi)	STD	T Test
100% OPC	6320	165	---	6560	160	---	7240	24	---
100% OPC	5600	118	---	6020	158	---	6260	181	---
100% OPC	6100	253	---	6290	777	---	6600	706	---
C1	5930	211	---	6570	190	---	6520	263	---
C1	7280	12	---	8070	177	---	8070	201	---
C2	6970	103	---	8000	307	---	8410	175	---
C3	6090	308	---	6600	158	---	7620	119	---
C3	6740	148	---	7240	76	---	7790	109	---
C4	6780	696	---	6860	395	---	7640	228	---
C4	6520	30	---	7350	109	---	8100	320	---
C5	5670	386	---	6370	185	---	6910	115	---
C5	7420	62	---	8360	183	---	9100	38	---
C6	5690	443	---	6350	638	---	6030	444	---
C6	6500	6	---	6960	90	---	7220	276	---
C7	6930	515	---	6700	457	---	8010	743	---
C7	7130	62	---	7970	164	---	8370	199	---
C8	4770	703	---	6000	673	---	6580	424	---
C11	7510	231	---	8550	163	---	8910	109	---
C12	5920	198	---	6550	314	---	7100	336	---
C12	5750	61	---	6750	196	---	7130	395	---
C13	6520	971	---	6810	306	---	7110	470	---
C13	6210	167	---	6470	76	---	6810	323	---
C14	6070	215	---	7010	140	---	7220	242	---
C14	6200	815	---	7380	228	---	7370	578	---
C15	5760	218	---	6720	474	---	6920	351	---
C15	5910	69	---	6470	210	---	6660	240	---
C16	6540	357	---	7590	861	---	8370	710	---
C17	6580	491	---	6680	273	---	7290	302	---
C18	5840	225	---	6240	358	---	7050	175	---
C19	5960	224	---	6300	199	---	6810	145	---
F1	5640	303	---	5990	227	---	6800	315	---
F1	5920	160	---	7090	59	---	8020	183	---
F2	6310	102	---	7250	166	---	8010	228	---
F3	6300	549	---	7280	573	---	8130	680	---
F3	6240	36	---	7610	229	---	8140	276	---

Days of hydration	28 DAY			56 DAY			90 DAY		
F4	6710	640	---	7380	665	---	8420	513	---
F4	6180	115	---	7210	74	---	7920	99	---
F4	5740	272	---	6240	105	---	6500	229	---
F5	5560	184	---	6500	536	---	7550	407	---
F5	5810	115	---	7290	125	---	7770	133	---
F6	6270	65	---	7370	123	---	8220	178	---
F6	5220	87	---	6170	60	---	6680	193	---
F9	6110	276	---	6760	196	---	7280	457	---
F10	5550	141	---	5900	486	---	7130	177	---
F11	5350	66	---	6080	75	---	6520	167	---
F11	5130	166	---	5820	214	---	6340	725	---
F12	4730	282	---	5180	144	---	5870	211	---
F15-1	5800	336	---	6460	228	---	6800	218	---
F15-2	---	---	---	6700	412	---	7410	471	---
F16	5520	294	---	6600	141	---	7090	439	---
F17	4580	157	---	6000	419	---	6620	496	---
F27	6010	346	---	6830	506	---	7110	292	---
RF2	5800	219	0.145	6600	733	0.672	7250	658	0.917
RF3	5920	716	0.297	6430	507	0.794	6720	447	0.014
RF4	6170	299	0.001	6990	517	0.026	7810	653	0.036
RF5	5470	393	0.236	6260	380	0.178	6780	784	0.159
RF6-1	5420	147	0.004	---	---	---	6350	196	0.000
RF6-2	5280	172	0.000	6160	418	0.066	6720	432	0.012
RF7-1	5620	246	0.754	6260	253	0.050	6600	356	0.001
RF11	5200	186	0.000	5760	272	0.000	6620	252	0.000
UF1	5090	233	0.000	5980	512	0.025	6720	517	0.028
UF2	5100	457	0.008	5780	426	0.001	6480	417	0.002
UF3	4660	279	0.000	5490	757	0.006	6330	406	0.000
UF4	4810	256	0.000	5540	771	0.009	6340	763	0.012
BC3	6080	263	0.312	6550	181	0.006	7270	291	0.757
BF9	5670	296	0.901	6170	394	0.084	6820	396	0.023
BTF1	5600	213	0.558	6730	369	0.168	7160	360	0.695

TABLE A1-5: Compressive Strength Data and T-Test Analysis of Coal Ash at 20% Replacement at 180-day Age

Days of hydration	180 DAY		
Sample#	AVG (psi)	STD	T Test
100% OPC	7830	75	---
100% OPC	6200	630	---
100% OPC	6730	629	---
C1	7690	328	---
C1	9200	200	---
C2	9050	49	---
C3	7480	326	---
C3	8630	123	---
C4	7850	558	---
C4	8450	269	---
C5	7550	294	---
C5	9750	226	---
C6	7100	733	---
C6	8190	78	---
C7	7820	813	---
C7	8790	109	---
C8	7100	584	---
C11	9360	43	---
C12	7840	309	---
C12	7540	118	---
C13	8070	584	---
C13	7220	150	---
C14	7410	158	---
C14	8300	395	---
C15	7430	135	---
C15	7030	117	---
C16	8040	789	---
C17	7030	345	---
C18	7210	308	---
C19	6760	255	---
F1	7250	484	---
F1	8660	141	---
F2	8660	234	---
F3	8550	518	---
F3	8610	231	---

Days of hydration	180 DAY		
F4	8580	966	---
F4	8630	179	---
F4	7270	202	---
F5	8460	513	---
F5	8480	129	---
F6	8940	130	---
F6	7380	162	---
F9	7220	721	---
F10	7530	650	---
F11	7070	78	---
F11	6830	416	---
F12	6360	444	---
F15-1	7080	322	---
F15-2	7990	696	---
F16	7010	357	---
F17	7490	670	---
F27	7990	400	---
RF2	8350	654	0.024
RF3	7260	608	0.080
RF4	8010	715	0.282
RF5	7220	665	0.081
RF6-1	6560	532	0.000
RF6-2	7010	799	0.041
RF7-1	6760	557	0.001
RF11	7030	252	0.000
UF1	7730	308	0.868
UF2	7610	240	0.508
UF3	7050	469	0.004
UF4	7530	714	0.523
BC3	7730	380	0.861
BF9	7900	447	0.292
BTF1	7740	374	0.865

TABLE A1-6: Compressive Strength Data Classification of Coal Ash at 20% Replacement for 3-, 7-, and 14-day Ages

Days of hydration	3 DAY			7 DAY			14 DAY		
Sample#	AVG	SCORE	RATING	AVG	SCORE	RATING	AVG	SCORE	RATING
C1	3770	0.94	LOW	4630	0.92	LOW	5300	0.97	MODERATE
C1	4280	1.06	MODERATE	5300	1.06	MODERATE	6260	1.14	HIGH
C2	4330	1.07	MODERATE	5440	1.09	MODERATE	6050	1.10	HIGH
C3	4120	1.02	MODERATE	4760	0.95	MODERATE	5380	0.98	MODERATE
C3	4310	1.07	MODERATE	5290	1.06	MODERATE	6160	1.12	HIGH
C4	4480	1.11	HIGH	5270	1.05	MODERATE	6010	1.10	MODERATE
C4	3630	0.90	LOW	4850	0.97	MODERATE	5840	1.06	MODERATE
C5	3960	0.98	MODERATE	4480	0.90	LOW	5090	0.93	LOW
C5	4470	1.11	HIGH	5630	1.12	HIGH	6590	1.20	HIGH
C6	4340	1.08	MODERATE	4840	0.97	MODERATE	5280	0.96	MODERATE
C6	4190	1.04	MODERATE	5240	1.05	MODERATE	5860	1.07	MODERATE
C7	4270	1.06	MODERATE	5460	1.09	MODERATE	5850	1.07	MODERATE
C7	4240	1.05	MODERATE	5330	1.06	MODERATE	6100	1.11	HIGH
C8	3440	0.85	LOW	4430	0.88	LOW	4600	0.84	LOW
C11	4400	1.09	MODERATE	5720	1.14	HIGH	6550	1.19	HIGH
C12	4040	1.00	MODERATE	4750	0.95	LOW	5300	0.96	MODERATE
C12	3630	0.90	LOW	4540	0.91	LOW	5370	0.98	MODERATE
C13	4130	1.02	MODERATE	4960	0.99	MODERATE	6240	1.14	HIGH
C13	3860	0.96	MODERATE	4580	0.91	LOW	5620	1.02	MODERATE
C14	4020	1.00	MODERATE	4500	0.90	LOW	5570	1.01	MODERATE
C14	4160	1.03	MODERATE	5170	1.03	MODERATE	6100	1.11	HIGH
C15	3970	0.98	MODERATE	5080	1.01	MODERATE	5390	0.98	MODERATE
C15	4040	1.00	MODERATE	4870	0.97	MODERATE	5260	0.96	MODERATE
C16	5000	1.24	HIGH	5590	1.12	HIGH	6160	1.12	HIGH
C17	4180	1.03	MODERATE	5050	1.01	MODERATE	5540	1.01	MODERATE
C18	4030	1.00	MODERATE	4820	0.96	MODERATE	5400	0.98	MODERATE
C19	3780	0.94	LOW	4470	0.89	LOW	5460	1.00	MODERATE
F1	3600	0.89	LOW	4530	0.91	LOW	4950	0.90	LOW
F1	3530	0.88	LOW	4360	0.87	LOW	5180	0.94	LOW
F2	3790	0.94	LOW	4590	0.92	LOW	5320	0.97	MODERATE
F3	4280	1.06	MODERATE	5050	1.01	MODERATE	5560	1.01	MODERATE
F3	3590	0.89	LOW	4640	0.93	LOW	5350	0.97	MODERATE
F4	4630	1.15	HIGH	5460	1.09	MODERATE	5790	1.06	MODERATE
F4	3600	0.89	LOW	4460	0.89	LOW	5380	0.98	MODERATE

Days of hydration	3 DAY			7 DAY			14 DAY		
F4	3600	0.89	LOW	4550	0.91	LOW	5190	0.95	LOW
F5	3430	0.85	LOW	4440	0.89	LOW	4930	0.90	LOW
F5	3600	0.89	LOW	4510	0.90	LOW	5060	0.92	LOW
F6	3650	0.90	LOW	4700	0.94	LOW	5250	0.96	MODERATE
F6	3430	0.85	LOW	4250	0.85	LOW	4810	0.88	LOW
F9	3920	0.97	MODERATE	4360	0.87	LOW	4870	0.89	LOW
F10	3390	0.84	LOW	4200	0.84	LOW	4690	0.85	LOW
F11	3310	0.82	LOW	4170	0.83	LOW	4700	0.86	LOW
F11	3220	0.80	LOW	3840	0.77	LOW	4420	0.81	LOW
F12	3350	0.83	LOW	---	0.00	LOW	3860	0.70	LOW
F15-1	4020	1.00	MODERATE	4530	0.90	LOW	5470	1.00	MODERATE
F15-2	4050	1.00	MODERATE	4440	0.89	LOW	4760	0.87	LOW
F16	3400	0.84	LOW	3980	0.79	LOW	5200	0.95	LOW
F17	3350	0.83	LOW	3780	0.75	LOW	4530	0.82	LOW
F27	3560	0.88	LOW	4490	0.90	LOW	5220	0.95	MODERATE
F28	3370	0.83	LOW	3890	0.78	LOW	4370	0.80	LOW
RF2	3930	0.97	MODERATE	4670	0.93	LOW	5330	0.97	MODERATE
RF3	3810	0.94	LOW	4540	0.91	LOW	4890	0.89	LOW
RF4	3420	0.85	LOW	5040	1.01	MODERATE	5150	0.94	LOW
RF5	3990	0.99	MODERATE	4510	0.90	LOW	5020	0.92	LOW
RF6-1	3730	0.92	LOW	4560	0.91	LOW	4660	0.85	LOW
RF6-2	3770	0.93	LOW	4220	0.84	LOW	4730	0.86	LOW
RF7-1	3640	0.90	LOW	4040	0.81	LOW	---	0.00	LOW
RF11	3750	0.93	LOW	4020	0.80	LOW	4630	0.84	LOW
UF1	2150	0.53	LOW	2740	0.55	LOW	4020	0.73	LOW
UF2	2680	0.66	LOW	3020	0.60	LOW	4240	0.77	LOW
UF3	1950	0.48	LOW	2500	0.50	LOW	3800	0.69	LOW
UF4	2010	0.50	LOW	2840	0.57	LOW	4130	0.75	LOW
BC3	4030	1.00	MODERATE	4710	0.94	LOW	5150	0.94	LOW
BF9	3570	0.88	LOW	4450	0.89	LOW	4820	0.88	LOW
BTF1	3350	0.83	LOW	4230	0.84	LOW	4820	0.88	LOW

TABLE A1-7: Compressive Strength Data Classification of Coal Ash at 20% Replacement for 28-, 56-, and 90-day Ages

Days of hydration	28 DAY			56 DAY			90 DAY		
Sample#	AVG	SCORE	RATING	AVG	SCORE	RATING	AVG	SCORE	RATING
C1	5930	0.99	MODERATE	6570	1.04	MODERATE	6520	0.97	MODERATE
C1	7280	1.21	HIGH	8070	1.28	HIGH	8070	1.20	HIGH
C2	6970	1.16	HIGH	8000	1.27	HIGH	8410	1.26	HIGH
C3	6090	1.01	MODERATE	6600	1.05	MODERATE	7620	1.14	HIGH
C3	6740	1.12	HIGH	7240	1.15	HIGH	7790	1.16	HIGH
C4	6780	1.13	HIGH	6860	1.09	MODERATE	7640	1.14	HIGH
C4	6520	1.08	MODERATE	7350	1.17	HIGH	8100	1.21	HIGH
C5	5670	0.94	LOW	6370	1.01	MODERATE	6910	1.03	MODERATE
C5	7420	1.24	HIGH	8360	1.33	HIGH	9100	1.36	HIGH
C6	5690	0.95	LOW	6350	1.01	MODERATE	6030	0.90	LOW
C6	6500	1.08	MODERATE	6960	1.11	HIGH	7220	1.08	MODERATE
C7	6930	1.15	HIGH	6700	1.06	MODERATE	8010	1.20	HIGH
C7	7130	1.19	HIGH	7970	1.27	HIGH	8370	1.25	HIGH
C8	4770	0.79	LOW	6000	0.95	MODERATE	6580	0.98	MODERATE
C11	7510	1.25	HIGH	8550	1.36	HIGH	8910	1.33	HIGH
C12	5920	0.99	MODERATE	6550	1.04	MODERATE	7100	1.06	MODERATE
C12	5750	0.96	MODERATE	6750	1.07	MODERATE	7130	1.06	MODERATE
C13	6520	1.09	MODERATE	6810	1.08	MODERATE	7110	1.06	MODERATE
C13	6210	1.03	MODERATE	6470	1.03	MODERATE	6810	1.02	MODERATE
C14	6070	1.01	MODERATE	7010	1.11	HIGH	7220	1.08	MODERATE
C14	6200	1.03	MODERATE	7380	1.17	HIGH	7370	1.10	MODERATE
C15	5760	0.96	MODERATE	6720	1.07	MODERATE	6920	1.03	MODERATE
C15	5910	0.98	MODERATE	6470	1.03	MODERATE	6660	0.99	MODERATE
C16	6540	1.09	MODERATE	7590	1.21	HIGH	8370	1.25	HIGH
C17	6580	1.10	MODERATE	6680	1.06	MODERATE	7290	1.09	MODERATE
C18	5840	0.97	MODERATE	6240	0.99	MODERATE	7050	1.05	MODERATE
C19	5960	0.99	MODERATE	6300	1.00	MODERATE	6810	1.02	MODERATE
F1	5640	0.94	LOW	5990	0.95	MODERATE	6800	1.01	MODERATE
F1	5920	0.98	MODERATE	7090	1.13	HIGH	8020	1.20	HIGH
F2	6310	1.05	MODERATE	7250	1.15	HIGH	8010	1.20	HIGH
F3	6300	1.05	MODERATE	7280	1.16	HIGH	8130	1.21	HIGH
F3	6240	1.04	MODERATE	7610	1.21	HIGH	8140	1.21	HIGH
F4	6710	1.12	HIGH	7380	1.17	HIGH	8420	1.26	HIGH
F4	6180	1.03	MODERATE	7210	1.15	HIGH	7920	1.18	HIGH

Days of hydration	28 DAY			56 DAY			90 DAY		
F4	5740	0.96	MODERATE	6240	0.99	MODERATE	6500	0.97	MODERATE
F5	5560	0.93	LOW	6500	1.03	MODERATE	7550	1.13	HIGH
F5	5810	0.97	MODERATE	7290	1.16	HIGH	7770	1.16	HIGH
F6	6270	1.04	MODERATE	7370	1.17	HIGH	8220	1.23	HIGH
F6	5220	0.87	LOW	6170	0.98	MODERATE	6680	1.00	MODERATE
F9	6110	1.02	MODERATE	6760	1.07	MODERATE	7280	1.09	MODERATE
F10	5550	0.92	LOW	5900	0.94	LOW	7130	1.06	MODERATE
F11	5350	0.89	LOW	6080	0.97	MODERATE	6520	0.97	MODERATE
F11	5130	0.85	LOW	5820	0.92	LOW	6340	0.95	LOW
F12	4730	0.79	LOW	5180	0.82	LOW	5870	0.88	LOW
F15-1	5800	0.97	MODERATE	6460	1.03	MODERATE	6800	1.01	MODERATE
F15-2	---	---	---	6700	1.07	MODERATE	7410	1.11	HIGH
F16	5520	0.92	LOW	6600	1.05	MODERATE	7090	1.06	MODERATE
F17	4580	0.76	LOW	6000	0.95	MODERATE	6620	0.99	MODERATE
F27	6010	1.00	MODERATE	6830	1.09	MODERATE	7110	1.06	MODERATE
F28	5000	0.83	LOW	5720	0.91	LOW	---	---	---
RF2	5800	0.97	MODERATE	6600	1.05	MODERATE	7250	1.08	MODERATE
RF3	5920	0.99	MODERATE	6430	1.02	MODERATE	6720	1.00	MODERATE
RF4	6170	1.03	MODERATE	6990	1.11	HIGH	7810	1.17	HIGH
RF5	5470	0.91	LOW	6260	0.99	MODERATE	6780	1.01	MODERATE
RF6-1	5420	0.90	LOW	---	---	---	6350	0.95	LOW
RF6-2	5280	0.88	LOW	6160	0.98	MODERATE	6720	1.00	MODERATE
RF7-1	5620	0.94	LOW	6260	0.99	MODERATE	6600	0.99	MODERATE
RF11	5200	0.87	LOW	5760	0.92	LOW	6620	0.99	MODERATE
UF1	5090	0.85	LOW	5980	0.95	MODERATE	6720	1.00	MODERATE
UF2	5100	0.85	LOW	5780	0.92	LOW	6480	0.97	MODERATE
UF3	4660	0.78	LOW	5490	0.87	LOW	6330	0.94	LOW
UF4	4810	0.80	LOW	5540	0.88	LOW	6340	0.95	LOW
BC3	6080	1.01	MODERATE	6550	1.04	MODERATE	7270	1.08	MODERATE
BF9	5670	0.94	LOW	6170	0.98	MODERATE	6820	1.02	MODERATE
BTF1	5600	0.93	LOW	6730	1.07	MODERATE	7160	1.07	MODERATE

TABLE A1-8: Compressive Strength Data Classification of Coal Ash at 20% Replacement for 180-day Ages

Days of hydration	180 DAY		
Sample#	AVG	SCORE	RATING
C1	7690	1.11	HIGH
C1	9200	1.33	HIGH
C2	9050	1.31	HIGH
C3	7480	1.08	MODERATE
C3	8630	1.25	HIGH
C4	7850	1.13	HIGH
C4	8450	1.22	HIGH
C5	7550	1.09	MODERATE
C5	9750	1.41	HIGH
C6	7100	1.03	MODERATE
C6	8190	1.18	HIGH
C7	7820	1.13	HIGH
C7	8790	1.27	HIGH
C8	7100	1.03	MODERATE
C11	9360	1.35	HIGH
C12	7840	1.13	HIGH
C12	7540	1.09	MODERATE
C13	8070	1.17	HIGH
C13	7220	1.04	MODERATE
C14	7410	1.07	MODERATE
C14	8300	1.20	HIGH
C15	7430	1.07	MODERATE
C15	7030	1.02	MODERATE
C16	8040	1.16	HIGH
C17	7030	1.02	MODERATE
C18	7210	1.04	MODERATE
C19	6760	0.98	MODERATE
F1	7250	1.05	MODERATE
F1	8660	1.25	HIGH
F2	8660	1.25	HIGH
F3	8550	1.24	HIGH
F3	8610	1.24	HIGH
F4	8580	1.24	HIGH
F4	8630	1.25	HIGH

Days of hydration	180 DAY		
F4	7270	1.05	MODERATE
F5	8460	1.22	HIGH
F5	8480	1.23	HIGH
F6	8940	1.29	HIGH
F6	7380	1.07	MODERATE
F9	7220	1.04	MODERATE
F10	7530	1.09	MODERATE
F11	7070	1.02	MODERATE
F11	6830	0.99	MODERATE
F12	6360	0.92	LOW
F15-1	7080	1.02	MODERATE
F15-2	7990	1.15	HIGH
F16	7010	1.01	MODERATE
F17	7490	1.08	MODERATE
F27	7990	1.15	HIGH
F28	---	---	---
RF2	8350	1.21	HIGH
RF3	7260	1.05	MODERATE
RF4	8010	1.16	HIGH
RF5	7220	1.04	MODERATE
RF6-1	6560	0.95	LOW
RF6-2	7010	1.01	MODERATE
RF7-1	6760	0.98	MODERATE
RF11	7030	1.02	MODERATE
UF1	7730	1.12	HIGH
UF2	7610	1.10	MODERATE
UF3	7050	1.02	MODERATE
UF4	7530	1.09	MODERATE
BC3	7730	1.12	HIGH
BF9	7900	1.14	HIGH
BTF1	7740	1.12	HIGH

TABLE A1-9: Compressive Strength Data and T-Test Analysis of Coal Ash at 40% Replacement for 3-, 7-, and 14-day Ages

Days of hydration	3 DAY			7 DAY			14 DAY		
Sample#	AVERAGE	STD	TTEST	AVERAGE	STD	TTEST	AVERAGE	STD	TTEST
C1	3460	158	---	4970	57	---	6620	348	---
C2	2880	90	---	4040	230	---	5000	12	---
C3	3060	130	---	4700	153	---	6040	216	---
C4	3510	43	---	5000	150	---	6380	228	---
C5	3120	86	---	4400	136	---	5060	67	---
C6	3070	205	---	4950	341	---	5650	580	---
C6	2360	47	---	2970	98	---	3720	233	---
C7	2580	181	---	4590	89	---	5300	280	---
C7	2820	130	---	4310	56	---	5350	69	---
C8	2230	123	---	2610	186	---	3570	234	---
C11	3600	134	---	4610	47	---	5550	187	---
C12	3050	7	---	4010	331	---	4770	99	---
C12	2690	214	---	4060	383	---	5570	274	---
C13	3900	279	---	5190	251	---	6000	506	---
C13	3320	213	---	4700	32	---	5920	255	---
C14	2580	164	---	3690	90	---	4900	68	---
C15	4280	342	---	5320	281	---	6710	160	---
C15	3310	146	---	4540	215	---	5190	14	---
C16	3320	439	---	5040	215	---	5810	452	---
F1	2840	40	---	3600	482	---	4680	407	---
F2	3200	83	---	3770	131	---	4450	134	---
F3	2380	54	---	3040	31	---	3790	123	---
F4	3680	183	---	4250	229	---	5250	278	---
F4	2730	123	---	3580	47	---	4310	198	---
F5	2300	66	---	3310	91	---	3640	166	---
F6	2360	309	---	2620	228	---	3560	130	---
F11	2220	160	---	2790	186	---	4000	263	---
F11	2050	66	---	2880	15	---	3330	59	---
F12	2520	32	---	2850	207	---	3600	95	---
F15-1	2190	177	---	3000	197	---	3950	108	---
F15-2	2590	128	---	2920	124	---	3500	284	---
F17	2020	143	---	2410	99	---	3330	180	---
F27	2190	140	---	2830	211	---	3610	230	---
RF4	2130	214	0.001	2890	303	0.173	3510	205	0.000

Days of hydration	3 DAY			7 DAY			14 DAY		
RF3	2340	143	0.046	3170	78	0.138	3880	182	0.640
RF5	2210	116	0.000	2790	285	0.035	3560	72	0.000
RF6-1	1930	108	0.000	2450	97	0.000	2840	132	0.000
RF6-2	2280	85	0.001	2620	116	0.000	3100	251	0.000
RF11	2290	88	0.002	2980	151	0.315	---	---	---
UF3	1420	137	0.000	1750	220	0.000	3370	84	0.000
BC3	2940	126	0.000	4010	175	0.000	4560	204	0.000
BF9	2540	84	0.595	3470	88	0.000	4020	230	0.407

TABLE A1-10: Compressive Strength Data and T-Test Analysis of Coal Ash at 40% Replacement for 28-, 56-, and 90-day Ages

Days of hydration	28 DAY			56 DAY			90 DAY		
Sample#	AVERAGE	STD	TTEST	AVERAGE	STD	TTEST	AVERAGE	STD	TTEST
C1	7240	249	---	8160	331	---	8180	89	---
C2	5500	108	---	6340	14	---	6720	191	---
C3	7320	25	---	7950	62	---	8440	198	---
C4	7150	147	---	8170	323	---	8520	423	---
C5	6260	271	---	7030	52	---	7040	121	---
C6	6480	134	---	6070	338	---	4630	169	---
C6	4780	266	---	5630	74	---	6010	73	---
C7	6460	544	---	4870	1377	---	8090	504	---
C7	6480	57	---	7330	364	---	7720	317	---
C8	4950	271	---	5660	414	---	6140	507	---
C11	6240	176	---	7160	34	---	7400	173	---
C12	5310	117	---	6220	134	---	7440	690	---
C12	6300	281	---	7450	589	---	8550	631	---
C13	5730	535	---	7590	456	---	7760	328	---
C13	6650	163	---	7120	373	---	7490	190	---
C14	6380	156	---	6850	51	---	7020	39	---
C15	---	---	---	7160	628	---	6600	1207	---
C15	6030	307	---	6520	70	---	7860	689	---
C16	6710	751	---	7520	889	---	8370	568	---
F1	5640	287	---	6800	77	---	7640	445	---
F2	5520	273	---	6090	109	---	7120	187	---

Days of hydration	28 DAY			56 DAY			90 DAY		
F3	5060	288	---	5630	178	---	6030	181	---
F4	5730	529	---	6280	313	---	6370	2075	---
F4	5620	4	---	6330	26	---	7750	514	---
F5	4650	113	---	5400	137	---	6260	163	---
F6	4360	313	---	5390	157	---	6790	277	---
F11	4810	286	---	5460	353	---	6290	314	---
F11	4540	49	---	5680	420	---	5880	403	---
F12	4550	193	---	5630	297	---	5770	488	---
F15-1	5220	97	---	6350	450	---	6990	277	---
F15-2	5030	142	---	5780	124	---	6750	557	---
F17	3630	177	---	4800	125	---	---	---	---
F27	4830	106	---	5690	132	---	5950	236	---
RF4	4740	265	0.294	5760	284	0.999	5840	488	0.005
RF3	4820	428	0.762	5510	330	0.088	6340	358	0.381
RF5	4400	153	0.000	5070	501	0.004	5930	278	0.001
RF6-1	3380	190	0.000	4660	322	0.000	5020	199	0.000
RF6-2	4290	916	0.114	5250	264	0.000	5520	383	0.000
RF11	5090	327	0.129	5740	440	0.916	6730	601	0.396
UF3	4170	70	0.000	5430	195	0.002	---	---	---
BC3	5400	479	0.015	6030	439	0.134	6360	490	0.487
BF9	4700	485	0.372	5930	223	0.124	6370	321	0.383

TABLE A1-11: Compressive Strength Data and T-Test Analysis of Coal Ash at 40% Replacement for 180-day Ages

Days of hydration	180 DAY		
Sample#	AVERAGE	STD	TTEST
C1	8880	353	---
C2	7470	152	---
C3	9650	142	---
C4	8880	515	---
C5	7540	132	---
C6	7520	212	---
C6	6750	213	---
C7	8600	429	---

Days of hydration	180 DAY		
C7	8330	363	---
C8	6800	430	---
C11	7990	74	---
C12	7500	195	---
C12	8770	757	---
C13	8180	415	---
C13	7890	260	---
C14	7450	270	---
C15	9220	361	---
C15	8250	153	---
C16	8900	818	---
F1	7720	328	---
F2	7640	283	---
F3	6260	64	---
F4	7850	857	---
F4	8100	219	---
F5	6400	455	---
F6	6940	454	---
F11	---	---	---
F11	6350	122	---
F12	---	---	---
F15-1	7460	640	---
F15-2	7190	537	---
F17	5870	563	---
F27	6480	973	---
RF4	5860	276	0.000
RF3	5990	333	0.000
RF5	6790	203	0.032
RF6-1	5120	373	0.000
RF6-2	5990	424	0.000
RF11	---	---	---
UF3	7310	577	0.776
BC3	7000	437	0.614
BF9	6530	253	0.000

TABLE A1-12: Compressive Strength Data Classification of Coal Ash at 40% Replacement at 3-, 7-, 14-day Ages

Days of hydration	3 DAY			7 DAY			14 DAY		
Sample#	AVG	SCORE	RATING	AVG	SCORE	RATING	AVG	SCORE	RATING
C1	3460	0.86	LOW	4970	0.99	MODERATE	6620	1.21	HIGH
C2	2880	0.71	LOW	4040	0.81	LOW	5000	0.91	LOW
C3	3060	0.76	LOW	4700	0.94	LOW	6040	1.10	HIGH
C4	3510	0.87	LOW	5000	1.00	MODERATE	6380	1.16	HIGH
C5	3120	0.77	LOW	4400	0.88	LOW	5060	0.92	LOW
C6	3070	0.76	LOW	4950	0.99	MODERATE	5650	1.03	MODERATE
C6	2360	0.59	LOW	2970	0.59	LOW	3720	0.68	LOW
C7	2580	0.64	LOW	4590	0.92	LOW	5300	0.97	MODERATE
C7	2820	0.70	LOW	4310	0.86	LOW	5350	0.97	MODERATE
C8	2230	0.55	LOW	2610	0.52	LOW	3570	0.65	LOW
C11	3600	0.89	LOW	4610	0.92	LOW	5550	1.01	MODERATE
C12	3050	0.76	LOW	4010	0.80	LOW	4770	0.87	LOW
C12	2690	0.67	LOW	4060	0.81	LOW	5570	1.01	MODERATE
C13	3900	0.97	MODERATE	5190	1.04	MODERATE	6000	1.09	MODERATE
C13	3320	0.82	LOW	4700	0.94	LOW	5920	1.08	MODERATE
C14	2580	0.64	LOW	3690	0.74	LOW	4900	0.89	LOW
C15	4280	1.06	MODERATE	5320	1.06	MODERATE	6710	1.22	HIGH
C15	3310	0.82	LOW	4540	0.91	LOW	5190	0.95	LOW
C16	3320	0.82	LOW	5040	1.01	MODERATE	5810	1.06	MODERATE
F1	2840	0.70	LOW	3600	0.72	LOW	4680	0.85	LOW
F2	3200	0.79	LOW	3770	0.75	LOW	4450	0.81	LOW
F3	2380	0.59	LOW	3040	0.61	LOW	3790	0.69	LOW
F4	3680	0.91	LOW	4250	0.85	LOW	5250	0.96	MODERATE
F4	2730	0.68	LOW	3580	0.71	LOW	4310	0.79	LOW
F5	2300	0.57	LOW	3310	0.66	LOW	3640	0.66	LOW
F6	2360	0.58	LOW	2620	0.52	LOW	3560	0.65	LOW
F11	2220	0.55	LOW	2790	0.56	LOW	4000	0.73	LOW
F11	2050	0.51	LOW	2880	0.58	LOW	3330	0.61	LOW
F12	2520	0.62	LOW	2850	0.57	LOW	3600	0.66	LOW
F15-1	2190	0.54	LOW	3000	0.60	LOW	3950	0.72	LOW
F15-2	2590	0.64	LOW	2920	0.58	LOW	3500	0.64	LOW
F17	2020	0.50	LOW	2410	0.48	LOW	3330	0.61	LOW
F27	2190	0.54	LOW	2830	0.56	LOW	3610	0.66	LOW

Days of hydration	3 DAY			7 DAY			14 DAY		
RF4	2130	0.53	LOW	2890	0.58	LOW	3510	0.64	LOW
RF3	2340	0.58	LOW	3170	0.63	LOW	3880	0.71	LOW
RF5	2210	0.55	LOW	2790	0.56	LOW	3560	0.65	LOW
RF6-1	1930	0.48	LOW	2450	0.49	LOW	2840	0.52	LOW
RF6-2	2280	0.56	LOW	2620	0.52	LOW	3100	0.56	LOW
RF11	2290	0.57	LOW	2980	0.60	LOW	---	---	---
UF3	1420	0.35	LOW	1750	0.35	LOW	3370	0.61	LOW
BC3	2940	0.73	LOW	4010	0.80	LOW	4560	0.83	LOW
BF9	2540	0.63	LOW	3470	0.69	LOW	4020	0.73	LOW

TABLE A1-13: Compressive Strength Data Classification of Coal Ash at 40% Replacement at 28-, 56-, 90-day Ages

Days of hydration	28 DAY			56 DAY			90 DAY		
Sample#	AVG	SCORE	RATING	AVG	SCORE	RATING	AVG	SCORE	RATING
C1	7240	1.21	HIGH	8160	1.30	HIGH	8180	1.22	HIGH
C2	5500	0.92	LOW	6340	1.01	MODERATE	6720	1.00	MODERATE
C3	7320	1.22	HIGH	7950	1.26	HIGH	8440	1.26	HIGH
C4	7150	1.19	HIGH	8170	1.30	HIGH	8520	1.27	HIGH
C5	6260	1.04	MODERATE	7030	1.12	HIGH	7040	1.05	MODERATE
C6	6480	1.08	MODERATE	6070	0.96	MODERATE	4630	0.69	LOW
C6	4780	0.80	LOW	5630	0.90	LOW	6010	0.90	LOW
C7	6460	1.08	MODERATE	4870	0.77	LOW	8090	1.21	HIGH
C7	6480	1.08	MODERATE	7330	1.17	HIGH	7720	1.15	HIGH
C8	4950	0.82	LOW	5660	0.90	LOW	6140	0.92	LOW
C11	6240	1.04	MODERATE	7160	1.14	HIGH	7400	1.10	HIGH
C12	5310	0.88	LOW	6220	0.99	MODERATE	7440	1.11	HIGH
C12	6300	1.05	MODERATE	7450	1.18	HIGH	8550	1.28	HIGH
C13	5730	0.95	MODERATE	7590	1.21	HIGH	7760	1.16	HIGH
C13	6650	1.11	HIGH	7120	1.13	HIGH	7490	1.12	HIGH
C14	6380	1.06	MODERATE	6850	1.09	MODERATE	7020	1.05	MODERATE
C15	---	---	---	7160	1.14	HIGH	6600	0.98	MODERATE
C15	6030	1.00	MODERATE	6520	1.04	MODERATE	7860	1.17	HIGH
C16	6710	1.12	HIGH	7520	1.20	HIGH	8370	1.25	HIGH
F1	5640	0.94	LOW	6800	1.08	MODERATE	7640	1.14	HIGH

Days of hydration	28 DAY			56 DAY			90 DAY		
F2	5520	0.92	LOW	6090	0.97	MODERATE	7120	1.06	MODERATE
F3	5060	0.84	LOW	5630	0.89	LOW	6030	0.90	LOW
F4	5730	0.95	MODERATE	6280	1.00	MODERATE	6370	0.95	MODERATE
F4	5620	0.94	LOW	6330	1.01	MODERATE	7750	1.16	HIGH
F5	4650	0.77	LOW	5400	0.86	LOW	6260	0.94	LOW
F6	4360	0.73	LOW	5390	0.86	LOW	6790	1.01	MODERATE
F11	4810	0.80	LOW	5460	0.87	LOW	6290	0.94	LOW
F11	4540	0.76	LOW	5680	0.90	LOW	5880	0.88	LOW
F12	4550	0.76	LOW	5630	0.90	LOW	5770	0.86	LOW
F15-1	5220	0.87	LOW	6350	1.01	MODERATE	6990	1.04	MODERATE
F15-2	5030	0.84	LOW	5780	0.92	LOW	6750	1.01	MODERATE
F17	3630	0.60	LOW	4800	0.76	LOW	---	---	---
F27	4830	0.80	LOW	5690	0.90	LOW	5950	0.89	LOW
RF4	4740	0.79	LOW	5760	0.92	LOW	5840	0.87	LOW
RF3	4820	0.80	LOW	5510	0.88	LOW	6340	0.95	LOW
RF5	4400	0.73	LOW	5070	0.81	LOW	5930	0.89	LOW
RF6-1	3380	0.56	LOW	4660	0.74	LOW	5020	0.75	LOW
RF6-2	4290	0.71	LOW	5250	0.83	LOW	5520	0.82	LOW
RF11	5090	0.85	LOW	5740	0.91	LOW	6730	1.00	MODERATE
UF3	4170	0.69	LOW	5430	0.86	LOW	---	---	---
BC3	5400	0.90	LOW	6030	0.96	MODERATE	6360	0.95	MODERATE
BF9	4700	0.78	LOW	5930	0.94	LOW	6370	0.95	MODERATE

TABLE A1-14: Compressive Strength Data Classification of Coal Ash at 40% Replacement at 180-day Age

Days of hydration	180 DAY		
Sample#	AVG	SCORE	RATING
C1	8880	1.28	HIGH
C2	7470	1.08	MODERATE
C3	9650	1.40	HIGH
C4	8880	1.28	HIGH
C5	7540	1.09	MODERATE
C6	7520	1.09	MODERATE
C6	6750	0.98	MODERATE

Days of hydration	180 DAY		
C7	8600	1.24	HIGH
C7	8330	1.20	HIGH
C8	6800	0.98	MODERATE
C11	7990	1.16	HIGH
C12	7500	1.08	MODERATE
C12	8770	1.27	HIGH
C13	8180	1.18	HIGH
C13	7890	1.14	HIGH
C14	7450	1.08	MODERATE
C15	9220	1.33	HIGH
C15	8250	1.19	HIGH
C16	8900	1.29	HIGH
F1	7720	1.12	HIGH
F2	7640	1.10	HIGH
F3	6260	0.90	LOW
F4	7850	1.13	HIGH
F4	8100	1.17	HIGH
F5	6400	0.93	LOW
F6	6940	1.00	MODERATE
F11	---	---	---
F11	6350	0.92	LOW
F12	---	---	---
F15-1	7460	1.08	MODERATE
F15-2	7190	1.04	MODERATE
F17	5870	0.85	LOW
F27	6480	0.94	LOW
RF4	5860	0.85	LOW
RF3	5990	0.87	LOW
RF5	6790	0.98	MODERATE
RF6-1	5120	0.74	LOW
RF6-2	5990	0.87	LOW
RF11	---	---	---
UF3	7310	1.06	MODERATE
BC3	7000	1.01	MODERATE
BF9	6530	0.94	LOW

TABLE A1-15: Electrical Resistivity Data and T-Test Analysis of Coal Ash at 20% Replacement at 3-, 7-, and 14-day Ages

Days of hydration	3 DAY			7 DAY			14 DAY		
Sample#	AVG (kΩ·cm)	STDEV	T-TEST	AVG (kΩ·cm)	STDEV	T-TEST	AVG (kΩ·cm)	STDEV	T-TEST
100% OPC	5.02	0.48	---	6.39	0.51	---	7.80	0.71	---
100% OPC	5.33	0.37	---	6.58	0.41	---	7.83	0.47	---
100% OPC	8.40	0.38	---	10.18	0.51	---	11.78	0.78	---
C1	6.75	0.43	---	8.50	0.32	---	10.47	0.68	---
C1	4.98	0.34	---	6.52	0.32	---	8.96	0.39	---
C2	5.35	0.24	---	6.57	0.36	---	7.98	0.47	---
C3	6.78	0.30	---	8.40	0.69	---	10.60	0.59	---
C3	5.26	0.34	---	6.43	0.40	---	7.41	0.33	---
C4	5.88	0.28	---	7.04	0.51	---	9.59	0.51	---
C4	5.53	0.40	---	7.02	0.59	---	9.90	0.52	---
C5	5.70	0.33	---	7.23	0.37	---	8.42	0.39	---
C5	4.97	0.29	---	6.28	0.32	---	7.23	0.25	---
C6	7.13	0.57	---	10.29	0.63	---	13.68	1.57	---
C6	5.66	0.37	---	9.21	0.61	---	12.81	0.81	---
C7	5.17	0.30	---	6.36	0.64	---	8.25	0.74	---
C7	5.07	0.17	---	6.33	0.37	---	8.16	0.49	---
C8	5.46	0.55	---	6.65	0.90	---	9.36	0.77	---
C11	5.18	0.29	---	6.78	0.39	---	7.98	0.68	---
C12	6.42	0.40	---	7.90	0.42	---	10.22	1.02	---
C12	6.41	0.56	---	7.67	0.61	---	10.84	0.48	---
C13	6.65	0.25	---	8.40	0.47	---	9.55	1.56	---
C13	5.68	0.28	---	7.22	0.38	---	9.11	0.59	---
C14	6.37	0.67	---	8.48	0.55	---	9.87	0.99	---
C14	5.58	0.37	---	5.06	3.58	---	10.41	0.73	---
C15	6.24	0.62	---	7.83	1.11	---	9.23	0.96	---
C15	6.46	0.31	---	7.88	0.54	---	8.62	0.54	---
C16	5.59	0.27	---	7.66	0.82	---	9.32	0.71	---
C17	5.99	0.26	---	7.65	0.42	---	9.69	0.64	---
C18	6.03	0.26	---	7.73	0.37	---	9.15	0.37	---
C19	5.22	0.39	---	6.71	0.36	---	7.68	0.48	---
F1	5.46	0.55	---	6.73	0.47	---	8.87	0.82	---

Days of hydration	3 DAY			7 DAY			14 DAY		
F1	5.22	0.35	---	6.83	0.40	---	8.91	0.92	---
F2	5.25	0.15	---	6.53	0.37	---	8.47	0.42	---
F3	5.46	0.30	---	6.54	0.39	---	9.23	0.58	---
F3	5.15	0.31	---	6.33	0.52	---	8.31	0.40	---
F4	5.53	0.52	---	6.55	0.54	---	8.44	0.68	---
F4	5.21	0.25	---	6.40	0.28	---	7.97	0.57	---
F4	6.96	0.49	---	---	---	---	9.64	0.58	---
F5	5.35	0.40	---	5.78	0.33	---	6.83	0.54	---
F5	4.85	0.22	---	5.96	0.21	---	8.03	0.44	---
F6	5.02	0.21	---	6.58	0.46	---	7.07	0.46	---
F6	6.20	0.58	---	7.75	0.71	---	10.27	0.36	---
F9	6.18	0.41	---	7.82	0.51	---	10.01	0.41	---
F10	5.89	0.25	---	7.26	0.30	---	8.92	0.42	---
F11	6.06	0.32	---	8.41	0.55	---	8.97	0.66	---
F11	6.31	0.40	---	7.30	0.25	---	8.71	0.47	---
F12	5.44	0.42	---	---	---	---	7.32	0.59	---
F15-1	5.36	0.50	---	6.51	0.48	---	7.55	0.70	---
F15-2	5.11	0.50	---	6.25	0.54	---	7.69	0.42	---
F16	5.39	0.31	---	6.54	0.44	---	8.10	0.64	---
F17	4.93	0.51	---	5.65	0.52	---	7.23	0.54	---
F18	5.14	0.29	---	6.88	0.35	---	7.57	0.58	---
F28	5.08	0.28	---	6.75	0.54	---	8.22	0.46	---
RF2	4.92	0.32	0.000	6.14	0.55	0.000	7.37	0.36	0.000
RF3	5.62	0.49	0.072	6.76	0.42	0.495	8.82	0.58	0.000
RF4	5.03	0.31	0.000	5.77	0.30	0.000	7.61	0.69	0.000
RF5	5.32	0.32	0.018	7.57	0.76	0.000	8.34	0.67	0.283
RF6-1	5.71	0.36	0.000	7.40	0.93	0.000	8.43	0.60	0.053
RF6-2	5.12	0.36	0.000	6.15	0.43	0.000	7.34	0.61	0.000
RF7-1	6.59	0.40	0.000	7.81	0.50	0.000	8.81	0.59	0.000
RF11	6.75	0.41	0.000	7.66	0.31	0.000	9.97	0.69	0.000
UF1	5.28	0.39	0.011	4.86	0.52	0.000	5.52	0.59	0.000
UF2	4.82	0.76	0.000	6.08	0.44	0.000	6.16	0.63	0.000
UF3	4.67	0.33	0.000	4.67	0.41	0.000	4.99	0.46	0.000
UF4	4.41	0.39	0.000	4.38	0.44	0.000	4.78	0.51	0.000
BC3	4.96	0.28	0.000	7.33	0.61	0.058	9.43	0.92	0.496
BF9	4.04	0.25	0.000	5.93	0.58	0.000	7.53	0.67	0.000
BTF1	4.95	0.30	0.000	6.35	0.55	0.001	7.02	0.59	0.000

TABLE A1-16: Electrical Resistivity Data and T-Test Analysis of Coal Ash at 20% Replacement at 28-, 56-, and 90-day Ages

Days of hydration	28 DAY			56 DAY			90 DAY		
Sample#	AVG (kΩ·cm)	STDEV	T-TEST	AVG (kΩ·cm)	STDEV	T-TEST	AVG (kΩ·cm)	STDEV	T-TEST
100% OPC	8.78	0.72	---	10.13	1.30	---	10.57	1.17	---
100% OPC	8.76	0.83	---	9.59	0.61	---	10.45	0.82	---
100% OPC	11.68	1.05	---	13.74	0.75	---	15.01	0.71	---
C1	14.34	0.62	---	25.36	1.44	---	29.68	1.80	---
C1	13.08	1.04	---	19.80	0.68	---	24.20	1.21	---
C2	10.76	0.75	---	15.33	0.68	---	19.81	0.66	---
C3	14.49	0.78	---	22.48	1.21	---	37.88	2.01	---
C3	9.48	0.45	---	11.58	0.54	---	14.36	0.71	---
C4	12.47	0.82	---	18.38	0.52	---	20.82	7.19	---
C4	14.38	0.70	---	21.58	0.93	---	27.03	1.64	---
C5	11.26	0.50	---	14.89	0.59	---	18.70	0.92	---
C5	11.03	0.50	---	18.83	0.56	---	25.49	1.53	---
C6	19.75	2.25	---	22.45	2.80	---	27.03	4.60	---
C6	18.73	0.90	---	25.11	1.32	---	29.06	2.11	---
C7	10.91	1.05	---	19.15	1.28	---	25.06	1.92	---
C7	11.01	0.32	---	14.67	0.74	---	20.67	1.18	---
C8	13.71	1.02	---	23.62	2.36	---	33.67	2.19	---
C11	11.83	0.77	---	17.31	0.85	---	23.68	0.91	---
C12	14.55	0.78	---	23.67	1.37	---	30.18	2.21	---
C12	14.33	1.42	---	25.33	1.29	---	29.77	1.77	---
C13	13.32	1.67	---	19.48	1.16	---	23.15	1.82	---
C13	13.40	0.41	---	17.07	0.87	---	21.97	1.51	---
C14	15.03	0.67	---	21.74	1.45	---	28.40	1.91	---
C14	16.28	0.97	---	24.81	1.18	---	31.94	1.87	---
C15	10.91	0.62	---	12.89	1.21	---	16.58	1.15	---
C15	10.63	0.61	---	12.74	0.71	---	16.35	0.91	---
C16	13.65	0.95	---	17.80	1.38	---	21.52	1.68	---
C17	12.54	1.27	---	19.33	1.18	---	23.35	1.27	---
C18	11.14	0.50	---	14.25	0.60	---	17.21	0.72	---
C19	10.61	0.59	---	14.66	0.52	---	19.98	0.85	---
F1	13.87	1.34	---	28.76	1.73	---	39.49	2.21	---

Days of hydration	28 DAY			56 DAY			90 DAY		
F1	13.20	0.67	---	23.58	1.62	---	34.23	2.34	---
F2	12.93	0.54	---	22.83	1.75	---	31.94	2.23	---
F3	14.32	1.05	---	29.18	1.40	---	41.35	3.67	---
F3	14.24	0.68	---	27.61	1.46	---	38.35	1.69	---
F4	10.16	0.98	---	14.31	1.09	---	17.45	0.94	---
F4	11.39	0.55	---	19.19	0.74	---	26.82	0.95	---
F4	12.83	1.02	---	16.85	1.64	---	19.86	1.16	---
F5	9.95	0.86	---	19.16	1.63	---	27.61	1.95	---
F5	10.68	0.70	---	20.31	1.18	---	28.89	1.16	---
F6	10.84	0.67	---	24.24	1.72	---	31.82	1.07	---
F6	13.33	0.87	---	25.32	1.35	---	35.47	1.90	---
F9	14.52	0.78	---	29.44	1.89	---	40.09	2.12	---
F10	14.45	0.55	---	26.76	1.37	---	35.87	1.74	---
F11	12.48	1.49	---	23.96	1.70	---	39.04	4.48	---
F11	13.60	0.88	---	17.98	12.86	---	37.19	2.09	---
F12	11.29	1.23	---	21.96	2.48	---	29.62	1.68	---
F15-1	12.46	0.59	---	24.33	0.80	---	35.38	2.07	---
F15-2	---	---	---	17.68	1.37	---	---	---	---
F16	14.47	0.81	---	26.42	0.91	---	40.05	3.25	---
F17	---	---	---	25.61	2.05	---	35.61	2.92	---
F18	11.96	0.98	---	21.35	1.20	---	33.88	1.47	---
F28	11.65	0.85	---	17.32	1.22	---	---	---	---
RF2	11.13	1.20	0.000	22.20	1.87	0.027	35.07	2.93	0.050
RF3	12.68	1.10	0.816	23.86	1.55	0.018	35.00	1.34	0.004
RF4	10.58	0.80	0.000	21.42	1.31	0.000	30.27	2.17	0.000
RF5	10.63	0.83	0.000	15.96	1.08	0.000	22.86	1.84	0.000
RF6-1	10.00	0.42	0.000	15.16	0.69	0.000	21.69	0.89	0.000
RF6-2	10.30	0.62	0.000	21.57	1.44	0.000	28.01	1.40	0.000
RF7-1	12.09	0.94	0.004	22.11	1.25	0.002	30.85	1.92	0.000
RF11	12.44	1.16	0.370	20.69	0.93	0.000	42.54	2.82	0.000
UF1	6.23	0.66	0.000	12.29	0.84	0.000	18.92	1.22	0.000
UF2	8.85	0.86	0.000	20.98	1.36	0.000	26.47	1.31	0.000
UF3	6.68	0.64	0.000	11.70	1.58	0.000	18.46	1.87	0.000
UF4	8.36	2.76	0.000	11.22	1.28	0.000	18.18	1.83	0.000
BC3	11.89	0.74	0.000	13.63	2.90	0.000	22.71	1.03	0.000
BF9	10.08	0.77	0.000	20.01	1.21	0.000	28.94	1.75	0.000
BTF1	9.32	0.97	0.000	19.20	1.22	0.000	22.83	2.98	0.000

TABLE A1-17: Electrical Resistivity Data Classification of Coal Ash at 20% Replacement for 3-, 7-, and 14-day Ages

Days of hydration	3 DAY			7 DAY			14 DAY		
Sample#	AVG (kΩ·cm)	STDEV	T-TEST	AVG (kΩ·cm)	STDEV	T-TEST	AVG (kΩ·cm)	STDEV	T-TEST
C1	6.75	1.08	MODERATE	8.50	1.10	MODERATE	10.47	1.15	MODERATE
C1	4.98	0.80	LOW	6.52	0.84	LOW	8.96	0.98	LOW
C2	5.35	0.86	LOW	6.57	0.85	LOW	7.98	0.87	LOW
C3	6.78	1.08	MODERATE	8.40	1.09	MODERATE	10.60	1.16	MODERATE
C3	5.26	0.84	LOW	6.43	0.83	LOW	7.41	0.81	LOW
C4	5.88	0.94	LOW	7.04	0.91	LOW	9.59	1.05	MODERATE
C4	5.53	0.88	LOW	7.02	0.91	LOW	9.90	1.08	MODERATE
C5	5.70	0.91	LOW	7.23	0.94	LOW	8.42	0.92	LOW
C5	4.97	0.79	LOW	6.28	0.81	LOW	7.23	0.79	LOW
C6	7.13	1.14	MODERATE	10.29	1.33	MODERATE	13.68	1.50	MODERATE
C6	5.66	0.91	LOW	9.21	1.19	MODERATE	12.81	1.40	MODERATE
C7	5.17	0.83	LOW	6.36	0.82	LOW	8.25	0.90	LOW
C7	5.07	0.81	LOW	6.33	0.82	LOW	8.16	0.89	LOW
C8	5.46	0.87	LOW	6.65	0.86	LOW	9.36	1.02	MODERATE
C11	5.18	0.83	LOW	6.78	0.88	LOW	7.98	0.87	LOW
C12	6.42	1.03	MODERATE	7.90	1.02	MODERATE	10.22	1.12	MODERATE
C12	6.41	1.03	MODERATE	7.67	0.99	LOW	10.84	1.19	MODERATE
C13	6.65	1.06	MODERATE	8.40	1.09	MODERATE	9.55	1.04	MODERATE
C13	5.68	0.91	LOW	7.22	0.94	LOW	9.11	1.00	LOW
C14	6.37	1.02	MODERATE	8.48	1.10	MODERATE	9.87	1.08	MODERATE
C14	5.58	0.89	LOW	5.06	0.66	LOW	10.41	1.14	MODERATE
C15	6.24	1.00	LOW	7.83	1.01	MODERATE	9.23	1.01	MODERATE
C15	6.46	1.03	MODERATE	7.88	1.02	MODERATE	8.62	0.94	LOW
C16	5.59	0.89	LOW	7.66	0.99	LOW	9.32	1.02	MODERATE
C17	5.99	0.96	LOW	7.65	0.99	LOW	9.69	1.06	MODERATE
C18	6.03	0.96	LOW	7.73	1.00	MODERATE	9.15	1.00	MODERATE
C19	5.22	0.83	LOW	6.71	0.87	LOW	7.68	0.84	LOW
F1	5.46	0.87	LOW	6.73	0.87	LOW	8.87	0.97	LOW
F1	5.22	0.83	LOW	6.83	0.88	LOW	8.91	0.97	LOW
F2	5.25	0.84	LOW	6.53	0.85	LOW	8.47	0.93	LOW
F3	5.46	0.87	LOW	6.54	0.85	LOW	9.23	1.01	MODERATE
F3	5.15	0.82	LOW	6.33	0.82	LOW	8.31	0.91	LOW
F4	5.53	0.88	LOW	6.55	0.85	LOW	8.44	0.92	LOW
F4	5.21	0.83	LOW	6.40	0.83	LOW	7.97	0.87	LOW
F4	6.96	1.11	MODERATE	---	---	---	9.64	1.05	MODERATE
F5	5.35	0.86	LOW	5.78	0.75	LOW	6.83	0.75	LOW
F5	4.85	0.78	LOW	5.96	0.77	LOW	8.03	0.88	LOW
F6	5.02	0.80	LOW	6.58	0.85	LOW	7.07	0.77	LOW
F6	6.20	0.99	LOW	7.75	1.00	MODERATE	10.27	1.12	MODERATE
F9	6.18	0.99	LOW	7.82	1.01	MODERATE	10.01	1.10	MODERATE

Days of hydration	3 DAY			7 DAY			14 DAY		
F10	5.89	0.94	LOW	7.26	0.94	LOW	8.92	0.98	LOW
F11	6.06	0.97	LOW	8.41	1.09	MODERATE	8.97	0.98	LOW
F11	6.31	1.01	MODERATE	7.30	0.95	LOW	8.71	0.95	LOW
F12	5.44	0.87	LOW	---	---	---	7.32	0.80	LOW
F15-1	5.36	0.86	LOW	6.51	0.84	LOW	7.55	0.83	LOW
F15-2	5.11	0.82	LOW	6.25	0.81	LOW	7.69	0.84	LOW
F16	5.39	0.86	LOW	6.54	0.85	LOW	8.10	0.89	LOW
F17	4.93	0.79	LOW	5.65	0.73	LOW	7.23	0.79	LOW
F18	5.14	0.82	LOW	6.88	0.89	LOW	7.57	0.83	LOW
F28	5.08	0.81	LOW	6.75	0.88	LOW	8.22	0.90	LOW
RF2	4.92	0.79	LOW	6.14	0.80	LOW	7.37	0.81	LOW
RF3	5.62	0.90	LOW	6.76	0.88	LOW	8.82	0.96	LOW
RF4	5.03	0.80	LOW	5.77	0.75	LOW	7.61	0.83	LOW
RF5	5.32	0.85	LOW	7.57	0.98	LOW	8.34	0.91	LOW
RF6-1	5.71	0.91	LOW	7.40	0.96	LOW	8.43	0.92	LOW
RF6-2	5.12	0.82	LOW	6.15	0.80	LOW	7.34	0.80	LOW
RF7-1	6.59	1.05	MODERATE	7.81	1.01	MODERATE	8.81	0.96	LOW
RF11	6.75	1.08	MODERATE	7.66	0.99	LOW	9.97	1.09	MODERATE
UF1	5.28	0.84	LOW	4.86	0.63	LOW	5.52	0.60	LOW
UF2	4.82	0.77	LOW	6.08	0.79	LOW	6.16	0.67	LOW
UF3	4.67	0.75	LOW	4.67	0.61	LOW	4.99	0.55	LOW
UF4	4.41	0.71	LOW	4.38	0.57	LOW	4.78	0.52	LOW
BC3	4.96	0.79	LOW	7.33	0.95	LOW	9.43	1.03	MODERATE
BF9	4.04	0.65	LOW	5.93	0.77	LOW	7.53	0.82	LOW
BTF1	4.95	0.79	LOW	6.35	0.82	LOW	7.02	0.77	LOW

TABLE A1-18: Electrical Resistivity Data Classification of Coal Ash at 20% Replacement for 28-, 56-, and 90-day Ages

Days of hydration	28 DAY			56 DAY			90 DAY		
Sample#	AVG (kΩ·cm)	STDEV	T-TEST	AVG (kΩ·cm)	STDEV	T-TEST	AVG (kΩ·cm)	STDEV	T-TEST
C1	14.34	1.47	HIGH	25.36	2.27	HIGH	29.68	2.47	HIGH
C1	13.08	1.34	HIGH	19.80	1.78	HIGH	24.20	2.02	HIGH
C2	10.76	1.10	HIGH	15.33	1.37	HIGH	19.81	1.65	HIGH
C3	14.49	1.49	HIGH	22.48	2.02	HIGH	37.88	3.15	HIGH
C3	9.48	0.97	HIGH	11.58	1.04	HIGH	14.36	1.20	HIGH
C4	12.47	1.28	HIGH	18.38	1.65	HIGH	20.82	1.73	HIGH
C4	14.38	1.48	HIGH	21.58	1.93	HIGH	27.03	2.25	HIGH

Days of hydration	28 DAY			56 DAY			90 DAY		
C5	11.26	1.16	HIGH	14.89	1.33	HIGH	18.70	1.56	HIGH
C5	11.03	1.13	HIGH	18.83	1.69	HIGH	25.49	2.12	HIGH
C6	19.75	2.03	HIGH	22.45	2.01	HIGH	27.03	2.25	HIGH
C6	18.73	1.92	HIGH	25.11	2.25	HIGH	29.06	2.42	HIGH
C7	10.91	1.12	HIGH	19.15	1.72	HIGH	25.06	2.09	HIGH
C7	11.01	1.13	HIGH	14.67	1.31	HIGH	20.67	1.72	HIGH
C8	13.71	1.41	HIGH	23.62	2.12	HIGH	33.67	2.80	HIGH
C11	11.83	1.22	HIGH	17.31	1.55	HIGH	23.68	1.97	HIGH
C12	14.55	1.49	HIGH	23.67	2.12	HIGH	30.18	2.51	HIGH
C12	14.33	1.47	HIGH	25.33	2.27	HIGH	29.77	2.48	HIGH
C13	13.32	1.37	HIGH	19.48	1.75	HIGH	23.15	1.93	HIGH
C13	13.40	1.38	HIGH	17.07	1.53	HIGH	21.97	1.83	HIGH
C14	15.03	1.54	HIGH	21.74	1.95	HIGH	28.40	2.37	HIGH
C14	16.28	1.67	HIGH	24.81	2.22	HIGH	31.94	2.66	HIGH
C15	10.91	1.12	HIGH	12.89	1.16	HIGH	16.58	1.38	HIGH
C15	10.63	1.09	HIGH	12.74	1.14	HIGH	16.35	1.36	HIGH
C16	13.65	1.40	HIGH	17.80	1.60	HIGH	21.52	1.79	HIGH
C17	12.54	1.29	HIGH	19.33	1.73	HIGH	23.35	1.94	HIGH
C18	11.14	1.14	HIGH	14.25	1.28	HIGH	17.21	1.43	HIGH
C19	10.61	1.09	HIGH	14.66	1.31	HIGH	19.98	1.66	HIGH
F1	13.87	1.42	HIGH	28.76	2.58	HIGH	39.49	3.29	HIGH
F1	13.20	1.36	HIGH	23.58	2.11	HIGH	34.23	2.85	HIGH
F2	12.93	1.33	HIGH	22.83	2.05	HIGH	31.94	2.66	HIGH
F3	14.32	1.47	HIGH	29.18	2.62	HIGH	41.35	3.44	HIGH
F3	14.24	1.46	HIGH	27.61	2.48	HIGH	38.35	3.19	HIGH
F4	10.16	1.04	HIGH	14.31	1.28	HIGH	17.45	1.45	HIGH
F4	11.39	1.17	HIGH	19.19	1.72	HIGH	26.82	2.23	HIGH
F4	12.83	1.32	HIGH	16.85	1.51	HIGH	19.86	1.65	HIGH
F5	9.95	1.02	HIGH	19.16	1.72	HIGH	27.61	2.30	HIGH
F5	10.68	1.10	HIGH	20.31	1.82	HIGH	28.89	2.41	HIGH
F6	10.84	1.11	HIGH	24.24	2.17	HIGH	31.82	2.65	HIGH
F6	13.33	1.37	HIGH	25.32	2.27	HIGH	35.47	2.95	HIGH
F9	14.52	1.49	HIGH	29.44	2.64	HIGH	40.09	3.34	HIGH
F10	14.45	1.48	HIGH	26.76	2.40	HIGH	35.87	2.99	HIGH
F11	12.48	1.28	HIGH	23.96	2.15	HIGH	39.04	3.25	HIGH
F11	13.60	1.40	HIGH	17.98	1.61	HIGH	37.19	3.10	HIGH
F12	11.29	1.16	HIGH	21.96	1.97	HIGH	29.62	2.47	HIGH

Days of hydration	28 DAY			56 DAY			90 DAY		
F15-1	12.46	1.28	HIGH	24.33	2.18	HIGH	35.38	2.95	HIGH
F15-2	---	---	---	17.68	1.58	HIGH	---	---	---
F16	14.47	1.49	HIGH	26.42	2.37	HIGH	40.05	3.34	HIGH
F17	---	---	---	25.61	2.30	HIGH	35.61	2.96	HIGH
F18	11.96	1.23	HIGH	21.35	1.91	HIGH	33.88	2.82	HIGH
F28	11.65	1.20	HIGH	17.32	1.55	HIGH	---	---	---
RF2	11.13	1.14	HIGH	22.20	1.99	HIGH	35.07	2.92	HIGH
RF3	12.68	1.30	HIGH	23.86	2.14	HIGH	35.00	2.91	HIGH
RF4	10.58	1.09	HIGH	21.42	1.92	HIGH	30.27	2.52	HIGH
RF5	10.63	1.09	HIGH	15.96	1.43	HIGH	22.86	1.90	HIGH
RF6-1	10.00	1.03	HIGH	15.16	1.36	HIGH	21.69	1.81	HIGH
RF6-2	10.30	1.06	HIGH	21.57	1.93	HIGH	28.01	2.33	HIGH
RF7-1	12.09	1.24	HIGH	22.11	1.98	HIGH	30.85	2.57	HIGH
RF11	12.44	1.28	HIGH	20.69	1.85	HIGH	42.54	3.54	HIGH
UF1	6.23	0.64	HIGH	12.29	1.10	HIGH	18.92	1.58	HIGH
UF2	8.85	0.91	HIGH	20.98	1.88	HIGH	26.47	2.20	HIGH
UF3	6.68	0.69	HIGH	11.70	1.05	HIGH	18.46	1.54	HIGH
UF4	8.36	0.86	HIGH	11.22	1.01	HIGH	18.18	1.51	HIGH
BC3	11.89	1.22	HIGH	13.63	1.22	HIGH	22.71	1.89	HIGH
BF9	10.08	1.04	HIGH	20.01	1.79	HIGH	28.94	2.41	HIGH
BTF1	9.32	0.96	HIGH	19.20	1.72	HIGH	22.83	1.90	HIGH

TABLE A1-19: Electrical Resistivity Data Classification of Coal Ash at 20% Replacement for 180-day Age

Days of hydration	180 DAY		
Sample#	AVG (kΩ·cm)	STDEV	T-TEST
C1	41.65	3.24	HIGH
C1	31.53	2.45	HIGH
C2	26.85	2.09	HIGH
C3	42.22	3.28	HIGH
C3	18.18	1.41	HIGH
C4	31.22	2.43	HIGH
C4	36.77	2.86	HIGH

Days of hydration	180 DAY		
C5	24.99	1.94	HIGH
C5	34.70	2.70	HIGH
C6	30.46	2.37	HIGH
C6	31.85	2.48	HIGH
C7	---	---	---
C7	27.18	2.11	HIGH
C8	58.20	4.52	HIGH
C11	34.00	2.64	HIGH
C12	48.39	3.76	HIGH
C12	49.62	3.86	HIGH
C13	27.53	2.14	HIGH
C13	19.26	1.50	HIGH
C14	39.13	3.04	HIGH
C14	45.45	3.53	HIGH
C15	19.78	1.54	HIGH
C15	18.93	1.47	HIGH
C16	36.69	2.85	HIGH
C17	36.18	2.81	HIGH
C18	24.09	1.87	HIGH
C19	31.65	2.46	HIGH
F1	73.49	5.71	HIGH
F1	47.77	3.71	HIGH
F2	44.14	3.43	HIGH
F3	62.36	4.85	HIGH
F3	54.85	4.26	HIGH
F4	27.46	2.13	HIGH
F4	42.01	3.27	HIGH
F4	26.85	2.09	HIGH
F5	51.21	3.98	HIGH
F5	46.54	3.62	HIGH
F6	54.29	4.22	HIGH
F6	57.52	4.47	HIGH
F9	57.63	4.48	HIGH
F10	54.79	4.26	HIGH
F11	55.58	4.32	HIGH
F11	63.73	4.95	HIGH
F12	---	---	---
F15-1	72.30	5.62	HIGH

Days of hydration	180 DAY		
F15-2	50.36	3.92	HIGH
F16	67.70	5.26	HIGH
F17	73.03	5.68	HIGH
F18	52.15	4.05	HIGH
F28	---	---	---
RF2	54.13	4.21	HIGH
RF3	61.03	4.74	HIGH
RF4	47.99	3.73	HIGH
RF5	39.80	3.09	HIGH
RF6-1	36.75	2.86	HIGH
RF6-2	46.22	3.59	HIGH
RF7-1	52.58	4.09	HIGH
RF11	49.71	3.86	HIGH
UF1	32.31	2.51	HIGH
UF2	40.19	3.12	HIGH
UF3	35.65	2.77	HIGH
UF4	34.69	2.70	HIGH
BC3	25.74	2.00	HIGH
BF9	42.70	3.32	HIGH
BTF1	50.78	3.95	HIGH

TABLE A1-20: Electrical Resistivity Data and T-Test Analysis of Coal Ash at 40% Replacement for 3-, 7-, and 14-day Ages

Days of hydration	3 DAY			7 DAY			14 DAY		
Sample#	AVG (kΩ·cm)	STDEV	T-TEST	AVG (kΩ·cm)	STDEV	T-TEST	AVG (kΩ·cm)	STDEV	T-TEST
0	8.40	0.38	---	10.18	0.51	---	11.78	0.78	---
C1	4.53	0.25	---	6.93	0.56	---	14.53	0.60	---
C2	4.10	0.14	---	6.08	0.39	---	10.40	0.33	---
C3	4.04	0.45	---	6.13	0.37	---	10.08	0.65	---
C4	4.42	0.08	---	6.95	0.33	---	11.86	0.63	---
C5	4.82	0.35	---	6.40	0.31	---	10.83	0.58	---
C6	4.38	0.24	---	6.29	0.77	---	9.28	0.69	---
C6	4.06	0.18	---	5.18	0.26	---	8.32	0.48	---

Days of hydration	3 DAY			7 DAY			14 DAY		
C7	4.06	0.48	---	5.34	0.49	---	8.95	0.83	---
C7	4.61	0.25	---	6.17	0.20	---	10.87	0.52	---
C8	3.44	0.64	---	4.94	0.22	---	9.02	0.74	---
C11	4.85	0.44	---	7.99	0.41	---	12.78	0.92	---
C12	4.27	0.37	---	5.68	0.42	---	9.72	0.83	---
C12	5.44	0.34	---	7.23	0.32	---	11.72	0.62	---
C13	6.71	0.65	---	13.59	1.16	---	23.34	1.55	---
C13	4.52	0.30	---	7.69	0.46	---	12.53	0.67	---
C14	3.85	0.25	---	6.20	0.31	---	11.03	0.79	---
C15	4.81	0.49	---	6.07	0.85	---	7.73	0.97	---
C15	4.39	0.38	---	5.75	0.20	---	8.05	0.59	---
C16	3.86	0.35	---	5.44	0.36	---	9.36	0.60	---
F1	5.60	0.57	---	7.05	0.80	---	11.08	0.61	---
F2	5.43	0.32	---	7.03	0.28	---	9.78	0.37	---
F3	4.47	0.22	---	6.20	0.39	---	10.68	0.58	---
F4	5.38	0.56	---	6.76	0.76	---	10.98	0.70	---
F4	4.23	0.26	---	5.91	0.47	---	9.59	0.91	---
F5	4.53	0.30	---	7.38	0.33	---	9.68	0.39	---
F6	4.15	0.61	---	4.95	0.23	---	7.32	0.36	---
F11	4.07	0.21	---	5.21	0.40	---	9.98	0.63	---
F11	4.56	0.27	---	5.97	0.44	---	8.78	0.77	---
F12	3.69	0.25	---	4.42	0.20	---	7.18	0.51	---
F15-1	3.62	0.21	---	4.86	0.39	---	7.80	0.42	---
F15-2	3.56	0.20	---	5.00	0.33	---	7.41	0.61	---
F17	3.93	0.38	---	5.00	0.46	---	9.40	0.68	---
F27	4.11	0.20	---	4.93	0.28	---	8.07	0.41	---
RF3	4.13	0.27	0.049	4.60	0.28	0.000	8.43	0.63	0.000
RF4	4.38	0.19	0.015	5.23	0.27	0.000	7.87	0.79	0.000
RF5	4.38	0.18	0.009	5.12	0.28	0.000	6.54	0.37	0.000
RF6-1	4.22	0.22	0.562	5.11	0.39	0.000	6.69	0.49	0.000
RF6-2	3.12	0.25	0.000	4.42	0.40	0.000	8.16	0.71	0.000
RF11	4.21	0.53	0.660	4.90	0.42	0.000	---	---	---
UF3	5.94	0.66	0.000	6.48	0.49	0.000	8.66	0.76	0.035
BC3	5.12	0.43	0.000	11.52	0.88	0.000	17.21	1.02	0.000
BF9	2.75	0.17	0.000	5.61	0.73	0.425	10.99	0.70	0.000

TABLE A1-21: Electrical Resistivity Data Classification of Coal Ash at 40% Replacement for 28-, 56-, and 90-day Ages

Days of hydration	28 DAY			56 DAY			90 DAY		
Sample#	AVG (kΩ·cm)	STDEV	T-TEST	AVG (kΩ·cm)	STDEV	T-TEST	AVG (kΩ·cm)	STDEV	T-TEST
0	11.68	1.05	---	13.74	0.75	---	15.01	0.71	---
C1	22.28	1.40	---	42.76	1.88	---	55.34	4.58	---
C2	14.23	0.67	---	27.06	1.07	---	39.89	2.24	---
C3	17.08	1.18	---	25.08	3.10	---	34.54	2.23	---
C4	18.42	1.13	---	29.11	2.49	---	41.07	4.06	---
C5	19.62	0.83	---	32.01	2.20	---	43.67	2.20	---
C6	15.85	0.92	---	24.26	2.10	---	29.89	2.27	---
C6	17.39	1.23	---	39.34	3.61	---	58.87	5.50	---
C7	17.21	1.63	---	25.94	2.66	---	35.20	3.80	---
C7	19.73	1.01	---	32.15	2.09	---	48.79	3.12	---
C8	27.69	2.27	---	45.06	3.60	---	70.03	4.62	---
C11	21.78	1.51	---	34.06	2.42	---	45.58	1.93	---
C12	16.90	1.27	---	33.95	3.02	---	39.67	5.42	---
C12	20.33	0.83	---	35.93	1.60	---	48.67	4.48	---
C13	33.38	3.11	---	58.77	3.87	---	53.12	4.23	---
C13	21.10	1.15	---	30.62	1.81	---	39.77	1.35	---
C14	19.05	1.07	---	33.30	1.53	---	42.17	2.83	---
C15	10.31	1.57	---	15.38	1.48	---	21.20	1.53	---
C15	11.61	0.93	---	16.83	1.50	---	21.38	2.34	---
C16	15.67	1.37	---	25.59	1.93	---	34.57	2.82	---
F1	22.65	1.13	---	43.89	2.86	---	73.38	9.86	---
F2	19.13	0.59	---	35.61	1.50	---	50.14	3.40	---
F3	25.77	1.90	---	52.56	2.02	---	85.13	5.46	---
F4	14.44	1.27	---	25.43	1.48	---	29.54	4.10	---
F4	16.93	0.73	---	33.54	2.72	---	55.48	3.44	---
F5	18.28	1.25	---	40.35	2.62	---	64.31	7.90	---
F6	12.63	0.50	---	27.20	2.05	---	43.43	3.89	---
F11	18.95	1.18	---	26.74	1.64	---	40.96	2.60	---
F11	19.36	1.33	---	39.03	2.00	---	63.66	4.40	---
F12	16.47	1.27	---	32.98	2.23	---	55.08	3.65	---
F15-1	16.41	0.81	---	36.70	2.83	---	56.98	3.40	---

Days of hydration	28 DAY			56 DAY			90 DAY		
F15-2	21.96	1.23	---	37.24	2.82	---	59.85	8.59	---
F17	16.12	1.32	---	42.02	1.84	---	58.74	5.43	---
F27	18.23	0.99	---	37.23	2.80	---	61.27	3.35	---
RF3	17.31	0.91	0.002	35.78	2.73	0.46	52.84	3.45	0.283
RF4	16.14	1.09	0.000	32.13	1.78	0.00	50.58	4.18	0.002
RF5	12.13	0.62	0.000	25.14	1.47	0.00	38.82	2.62	0.000
RF6-1	13.85	0.58	0.000	27.41	1.54	0.00	39.10	2.41	0.000
RF6-2	21.76	1.63	0.000	42.41	2.26	0.00	61.78	5.27	0.000
RF11	15.96	1.36	0.000	40.49	4.32	0.00	66.79	8.65	0.000
UF3	8.79	0.67	0.000	17.95	1.87	0.00	---	---	---
BC3	27.47	3.56	0.000	37.06	2.85	0.01	47.51	5.88	0.000
BF9	22.14	1.56	0.000	38.16	5.65	0.01	54.09	7.23	0.918

TABLE A1-22: Electrical Resistivity Data Classification of Coal Ash at 40% Replacement for 180-day Age

Days of hydration	180 DAY		
Sample#	AVG (kΩ·cm)	STDEV	T-TEST
0	16.54	1.25	---
C1	101.45	8.98	---
C2	74.39	3.79	---
C3	53.87	3.49	---
C4	63.94	5.96	---
C5	71.68	6.04	---
C6	45.34	2.06	---
C6	93.80	4.80	---
C7	57.93	3.20	---
C7	86.05	11.54	---
C8	92.45	12.47	---
C11	74.20	6.55	---
C12	62.83	7.30	---
C12	79.49	3.59	---
C13	84.31	10.41	---
C13	57.66	3.62	---

Days of hydration	180 DAY		
C14	80.16	6.35	---
C15	27.36	2.85	---
C15	37.38	1.49	---
C16	59.74	4.96	---
F1	122.86	8.18	---
F2	98.35	3.50	---
F3	105.73	6.52	---
F4	41.30	5.27	---
F4	88.53	6.32	---
F5	121.91	15.72	---
F6	102.78	11.90	---
F11	90.17	5.15	---
F11	100.99	7.45	---
F12	109.23	8.39	---
F15-1	95.69	8.30	---
F15-2	123.53	13.97	---
F17	109.31	19.95	---
F27	127.87	7.22	---
RF3	104.67	6.74	0.025
RF4	102.13	5.15	0.311
RF5	69.87	5.20	0.000
RF6-1	70.12	5.20	0.000
RF6-2	94.79	10.07	0.018
RF11	118.18	8.10	0.000
UF3	123.20	4.26	0.000
BC3	47.87	4.92	0.000
BF9	64.30	7.44	0.000

TABLE A1-23: Electrical Resistivity Data Classification of Coal Ash at 40% Replacement for 3-, 7-, and 14-day Ages

Days of hydration	3 DAY			7 DAY			14 DAY		
Sample#	AVG (kΩ·cm)	STDEV	T-TEST	AVG (kΩ·cm)	STDEV	T-TEST	AVG (kΩ·cm)	STDEV	T-TEST
0	8.40	1.34	MODERATE	10.18	1.32	MODERATE	11.78	1.29	MODERATE
C1	4.53	0.73	LOW	6.93	0.90	LOW	14.53	1.59	MODERATE
C2	4.10	0.66	LOW	6.08	0.79	LOW	10.40	1.14	MODERATE
C3	4.04	0.65	LOW	6.13	0.80	LOW	10.08	1.10	MODERATE
C4	4.42	0.71	LOW	6.95	0.90	LOW	11.86	1.30	MODERATE
C5	4.82	0.77	LOW	6.40	0.83	LOW	10.83	1.19	MODERATE
C6	4.38	0.70	LOW	6.29	0.82	LOW	9.28	1.01	MODERATE
C6	4.06	0.65	LOW	5.18	0.67	LOW	8.32	0.91	LOW
C7	4.06	0.65	LOW	5.34	0.69	LOW	8.95	0.98	LOW
C7	4.61	0.74	LOW	6.17	0.80	LOW	10.87	1.19	MODERATE
C8	3.44	0.55	LOW	4.94	0.64	LOW	9.02	0.99	LOW
C11	4.85	0.78	LOW	7.99	1.04	MODERATE	12.78	1.40	MODERATE
C12	4.27	0.68	LOW	5.68	0.74	LOW	9.72	1.06	MODERATE
C12	5.44	0.87	LOW	7.23	0.94	LOW	11.72	1.28	MODERATE
C13	6.71	1.07	MODERATE	13.59	1.76	MODERATE	23.34	2.55	MODERATE
C13	4.52	0.72	LOW	7.69	1.00	LOW	12.53	1.37	MODERATE
C14	3.85	0.62	LOW	6.20	0.80	LOW	11.03	1.21	MODERATE
C15	4.81	0.77	LOW	6.07	0.79	LOW	7.73	0.85	LOW
C15	4.39	0.70	LOW	5.75	0.75	LOW	8.05	0.88	LOW
C16	3.86	0.62	LOW	5.44	0.70	LOW	9.36	1.02	MODERATE
F1	5.60	0.90	LOW	7.05	0.91	LOW	11.08	1.21	MODERATE

F2	5.43	0.87	LOW	7.03	0.91	LOW	9.78	1.07	MODERATE
F3	4.47	0.71	LOW	6.20	0.80	LOW	10.68	1.17	MODERATE
F4	5.38	0.86	LOW	6.76	0.88	LOW	10.98	1.20	MODERATE
F4	4.23	0.68	LOW	5.91	0.77	LOW	9.59	1.05	MODERATE
F5	4.53	0.73	LOW	7.38	0.96	LOW	9.68	1.06	MODERATE
F6	4.15	0.66	LOW	4.95	0.64	LOW	7.32	0.80	LOW
F11	4.07	0.65	LOW	5.21	0.67	LOW	9.98	1.09	MODERATE
F11	4.56	0.73	LOW	5.97	0.77	LOW	8.78	0.96	LOW
F12	3.69	0.59	LOW	4.42	0.57	LOW	7.18	0.79	LOW
F15-1	3.62	0.58	LOW	4.86	0.63	LOW	7.80	0.85	LOW
F15-2	3.56	0.57	LOW	5.00	0.65	LOW	7.41	0.81	LOW
F17	3.93	0.63	LOW	5.00	0.65	LOW	9.40	1.03	MODERATE
F27	4.11	0.66	LOW	4.93	0.64	LOW	8.07	0.88	LOW
RF3	4.13	0.66	LOW	4.60	0.60	LOW	8.43	0.92	LOW
RF4	4.38	0.70	LOW	5.23	0.68	LOW	7.87	0.86	LOW
RF5	4.38	0.70	LOW	5.12	0.66	LOW	6.54	0.72	LOW
RF6-1	4.22	0.67	LOW	5.11	0.66	LOW	6.69	0.73	LOW
RF6-2	3.12	0.50	LOW	4.42	0.57	LOW	8.16	0.89	LOW
RF11	4.21	0.67	LOW	4.90	0.63	LOW	---	---	---
UF3	5.94	0.95	LOW	6.48	0.84	LOW	8.66	0.95	LOW
BC3	5.12	0.82	LOW	11.52	1.49	MODERATE	17.21	1.88	MODERATE
BF9	2.75	0.44	LOW	5.61	0.73	LOW	10.99	1.20	MODERATE

TABLE A1-24: Electrical Resistivity Data Classification of Coal Ash at 40% Replacement for 28-, 56-, and 90-day Ages

Days of hydration	28 DAY			56 DAY			90 DAY		
Sample#	AVG (kΩ·cm)	STDEV	T-TEST	AVG (kΩ·cm)	STDEV	T-TEST	AVG (kΩ·cm)	STDEV	T-TEST
0	11.68	1.20	MODERATE	13.74	1.23	MODERATE	15.01	1.25	MODERATE
C1	22.28	2.29	MODERATE	42.76	3.83	HIGH	55.34	4.61	HIGH
C2	14.23	1.46	MODERATE	27.06	2.43	MODERATE	39.89	3.32	HIGH
C3	17.08	1.75	MODERATE	25.08	2.25	MODERATE	34.54	2.88	MODERATE
C4	18.42	1.89	MODERATE	29.11	2.61	MODERATE	41.07	3.42	HIGH
C5	19.62	2.01	MODERATE	32.01	2.87	MODERATE	43.67	3.64	HIGH
C6	15.85	1.63	MODERATE	24.26	2.17	MODERATE	29.89	2.49	MODERATE
C6	17.39	1.79	MODERATE	39.34	3.53	HIGH	58.87	4.90	HIGH
C7	17.21	1.77	MODERATE	25.94	2.33	MODERATE	35.20	2.93	MODERATE
C7	19.73	2.03	MODERATE	32.15	2.88	MODERATE	48.79	4.06	HIGH
C8	27.69	2.84	MODERATE	45.06	4.04	HIGH	70.03	5.83	HIGH
C11	21.78	2.24	MODERATE	34.06	3.05	HIGH	45.58	3.80	HIGH
C12	16.90	1.74	MODERATE	33.95	3.04	HIGH	39.67	3.30	HIGH
C12	20.33	2.09	MODERATE	35.93	3.22	HIGH	48.67	4.05	HIGH
C13	33.38	3.43	HIGH	58.77	5.27	HIGH	53.12	4.42	HIGH
C13	21.10	2.17	MODERATE	30.62	2.74	MODERATE	39.77	3.31	HIGH
C14	19.05	1.96	MODERATE	33.30	2.99	MODERATE	42.17	3.51	HIGH
C15	10.31	1.06	MODERATE	15.38	1.38	MODERATE	21.20	1.77	MODERATE
C15	11.61	1.19	MODERATE	16.83	1.51	MODERATE	21.38	1.78	MODERATE
C16	15.67	1.61	MODERATE	25.59	2.29	MODERATE	34.57	2.88	MODERATE
F1	22.65	2.33	MODERATE	43.89	3.93	HIGH	73.38	6.11	HIGH
F2	19.13	1.96	MODERATE	35.61	3.19	HIGH	50.14	4.18	HIGH
F3	25.77	2.65	MODERATE	52.56	4.71	HIGH	85.13	7.09	HIGH
F4	14.44	1.48	MODERATE	25.43	2.28	MODERATE	29.54	2.46	MODERATE
F4	16.93	1.74	MODERATE	33.54	3.01	HIGH	55.48	4.62	HIGH
F5	18.28	1.88	MODERATE	40.35	3.62	HIGH	64.31	5.35	HIGH
F6	12.63	1.30	MODERATE	27.20	2.44	MODERATE	43.43	3.62	HIGH
F11	18.95	1.95	MODERATE	26.74	2.40	MODERATE	40.96	3.41	HIGH
F11	19.36	1.99	MODERATE	39.03	3.50	HIGH	63.66	5.30	HIGH
F12	16.47	1.69	MODERATE	32.98	2.96	MODERATE	55.08	4.59	HIGH
F15-1	16.41	1.69	MODERATE	36.70	3.29	HIGH	56.98	4.74	HIGH
F15-2	21.96	2.26	MODERATE	37.24	3.34	HIGH	59.85	4.98	HIGH
F17	16.12	1.66	MODERATE	42.02	3.77	HIGH	58.74	4.89	HIGH
F27	18.23	1.87	MODERATE	37.23	3.34	HIGH	61.27	5.10	HIGH
RF3	17.31	1.78	MODERATE	35.78	3.21	HIGH	52.84	4.40	HIGH
RF4	16.14	1.66	MODERATE	32.13	2.88	MODERATE	50.58	4.21	HIGH
RF5	12.13	1.25	MODERATE	25.14	2.25	MODERATE	38.82	3.23	HIGH
RF6-1	13.85	1.42	MODERATE	27.41	2.46	MODERATE	39.10	3.26	HIGH
RF6-2	21.76	2.23	MODERATE	42.41	3.80	HIGH	61.78	5.14	HIGH
RF11	15.96	1.64	MODERATE	40.49	3.63	HIGH	66.79	5.56	HIGH
UF3	8.79	0.90	LOW	17.95	1.61	MODERATE	---	---	---

Days of hydration	28 DAY			56 DAY			90 DAY		
BC3	27.47	2.82	MODERATE	37.06	3.32	HIGH	47.51	3.96	HIGH
BF9	22.14	2.27	MODERATE	38.16	3.42	HIGH	54.09	4.50	HIGH

TABLE A1-25: Electrical Resistivity Data Classification of Coal Ash at 40% Replacement for 180-day Age

Days of hydration	180 DAY		
Sample#	AVG (kΩ·cm)	STDEV	T-TEST
0	16.54	1.29	MODERATE
C1	101.45	7.89	HIGH
C2	74.39	5.78	HIGH
C3	53.87	4.19	HIGH
C4	63.94	4.97	HIGH
C5	71.68	5.57	HIGH
C6	45.34	3.52	HIGH
C6	93.80	7.29	HIGH
C7	57.93	4.50	HIGH
C7	86.05	6.69	HIGH
C8	92.45	7.19	HIGH
C11	74.20	5.77	HIGH
C12	62.83	4.88	HIGH
C12	79.49	6.18	HIGH
C13	84.31	6.55	HIGH
C13	57.66	4.48	HIGH
C14	80.16	6.23	HIGH
C15	27.36	2.13	MODERATE
C15	37.38	2.91	MODERATE
C16	59.74	4.64	HIGH
F1	122.86	9.55	HIGH
F2	98.35	7.65	HIGH
F3	105.73	8.22	HIGH
F4	41.30	3.21	HIGH
F4	88.53	6.88	HIGH

Days of hydration	180 DAY		
F5	121.91	9.48	HIGH
F6	102.78	7.99	HIGH
F11	90.17	7.01	HIGH
F11	100.99	7.85	HIGH
F12	109.23	8.49	HIGH
F15-1	95.69	7.44	HIGH
F15-2	123.53	9.60	HIGH
F17	109.31	8.50	HIGH
F27	127.87	9.94	HIGH
RF3	104.67	8.14	HIGH
RF4	102.13	7.94	HIGH
RF5	69.87	5.43	HIGH
RF6-1	70.12	5.45	HIGH
RF6-2	94.79	7.37	HIGH
RF11	118.18	9.19	HIGH
UF3	123.20	9.58	HIGH
BC3	47.87	3.72	HIGH
BF9	64.30	5.00	HIGH

Table A1-26: T-Test Analysis of Conventional and Non-Traditional Coal Ash Average Performance

		Reclaimed to Conventional Class F		Unprocessed to Conventional Class F		Blended to Conventional Class F		Bottom to Conventional	Blended to Conventional Class C	
		20%	40%	20%	40%	20%	40%	20%	20%	40%
48HR HEAT OF HYDRATION		0.268	0.177	0.005	0.296	0.051	0.026	0.000	0.124	0.000
Slump		0.355	0.742	0.001	0.000	0.003	0.039	0.049	0.354	0.138
Compressive Strength	3d	0.065	0.000	0.000	0.000	0.016	0.595		0.006	0.019
	7d	0.507	0.001	0.000	0.000	0.541	0.000	0.056	0.015	0.000
	14d	0.536	0.000	0.000	0.000	0.074	0.407	0.238	0.004	0.000
	28d	0.629	0.001	0.000	0.000	0.896	0.372	0.565	0.312	0.002
	56d	0.174	0.000	0.000	0.002	0.086	0.124	0.168	0.006	0.004
	90d	0.001	0.000	0.000	---	0.023	0.383	0.695	0.757	0.001
	180d	0.001	0.000	0.062	0.763	0.293	0.001	0.865	0.861	0.000
Resistivity	3d	0.085	0.096	0.000	0.000	0.000	0.000	0.000	0.000	0.002
	7d	0.107	0.000	0.000	0.000	0.003	0.664	0.073	0.307	0.000
	14d	0.405	0.000	0.000	0.279	0.013	0.000	0.000	0.735	0.000
	28d	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	56d	0.000	0.244	0.000	0.000	0.000	0.166	0.000	0.134	0.000
	90d	0.002	0.310	0.000	0.954	0.000	---	0.000	0.005	0.025
	180d	0.000	0.000	0.000	0.060	0.000	0.000	0.038	0.000	0.000

This table shows the p-value related to the t-test performed on each data set. Each non-traditional coal ash was tested against the results of conventional coal ash of the same class. For example, Reclaimed Class F in column 1 was compared to Conventional Class F. Data that had a t-test resulting in a p-value at or greater than 0.05 was considered statistically similar and colored green. T-tests that did not meet this, were considered not statistically similar and colored red in the table.

Table A1-27: Performance Classification of Class F Coal Ash

Coal Ash Type	Content	Workability	Heat of Hydration	Early Strength	Long Term Strength	Electrical Resistivity
Conventional	20%	↔	↔	↓	↔	↑
	40%	↑	↓	↓	↔	↑
Reclaimed	20%	↔	↔	↓	↔	↑

	40%	↑	↔	↓	↔	↑
Unprocessed	20%	↓	↔	↓	↔	↑
	40%	↓	↓	↓	↔	↑
Blended	20%	↑	↔	↓	↔	↑
	40%	↑	↑	↓	↔	↑
Bottom	20%	↔	↑	↓	↔	↑

Table A1-28: Performance Classification of Class C Coal Ash

Coal Ash Type	Content	Workability	Heat of Hydration	Early Strength	Long Term Strength	Electrical Resistivity
Conventional	20%	↔	↑	↔	↑	↑
	40%	↑	↔	↓	↑	↑
Blended	20%	↑	↔	↓	↔	↑
	40%	↑	↑	↓	↔	↑

APPENDIX B

ANALYSIS OF THE VARIABILITY IN SLUMP PERFORMANCE BETWEEN DIFFERENT COAL ASH SOURCES

A3.1.0 INTRODUCTION

The performance of concrete using varying sources of coal ash has shown to vary in terms of the slump test. Past studies have been conducted by Shinhyu Kang, Zane Lloyd and Loren Emerson to better understand this fluctuation in results [21, 23, and 25]. Dr. Kang and Mr. Lloyd investigated how the particle size distribution of each coal ash may relate to its slump performance. Mr. Lloyd found that there was no significant correlation between the distribution profile of each coal ash and their slump performance.

Another reason for the change in slump performance was thought to be the fineness of each coal ash. Clear evidence of this reasoning can be seen in the low slump performance of unprocessed coal ash. The unprocessed coal ash used in this study were sieved using a # 4 sieve (4.77mm) to remove contaminants, but the process did not ensure uniform particle size similar to that of conventional coal ash.

To evaluate the correlation between fineness of each coal ash and their slump performance, Kang compared the dry-sieved sieve analysis of each coal ash to the slump performance achieved by their use at both 20% and 40% replacement. This comparison is provided below in Figure A2-1 through Figure A2-4. The analysis shown no direct correlation between the fineness of each coal ash and the slump performance achieved through their use in concrete.

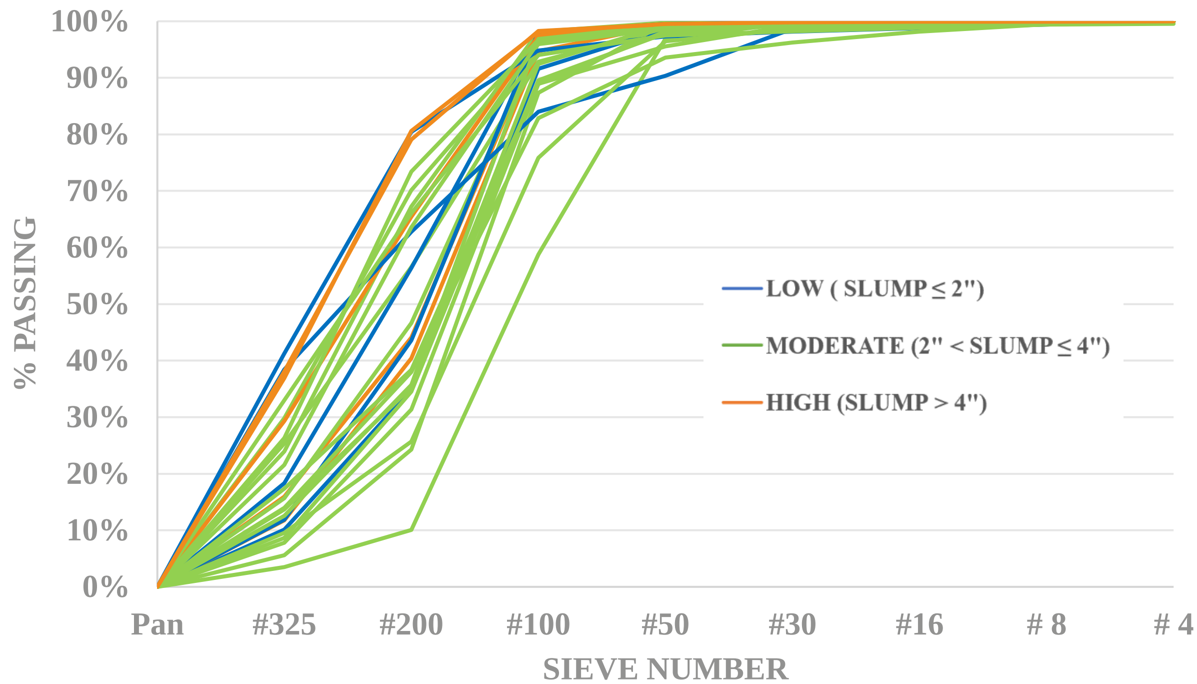

Figure A2-1: Correlation of coal ash fineness to slump performance at 20% replacement.

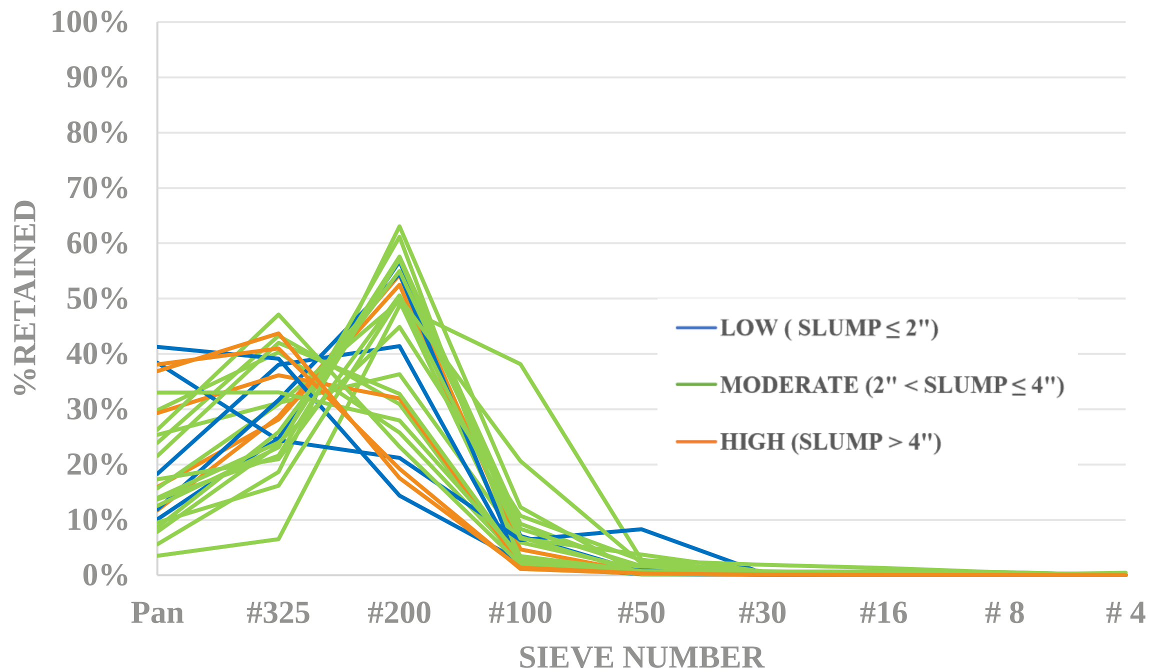

Figure A2-2: Correlation of coal ash fineness to slump performance at 20% replacement.

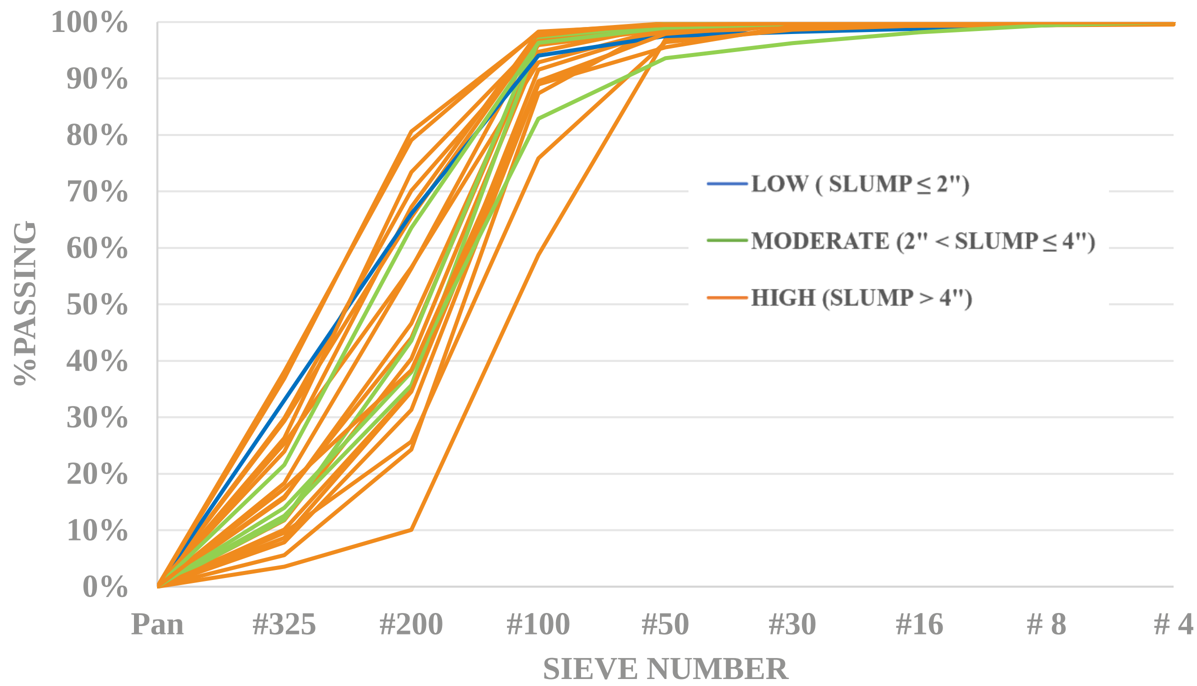

Figure A2-3: Correlation of coal ash fineness to slump performance at 40% replacement.

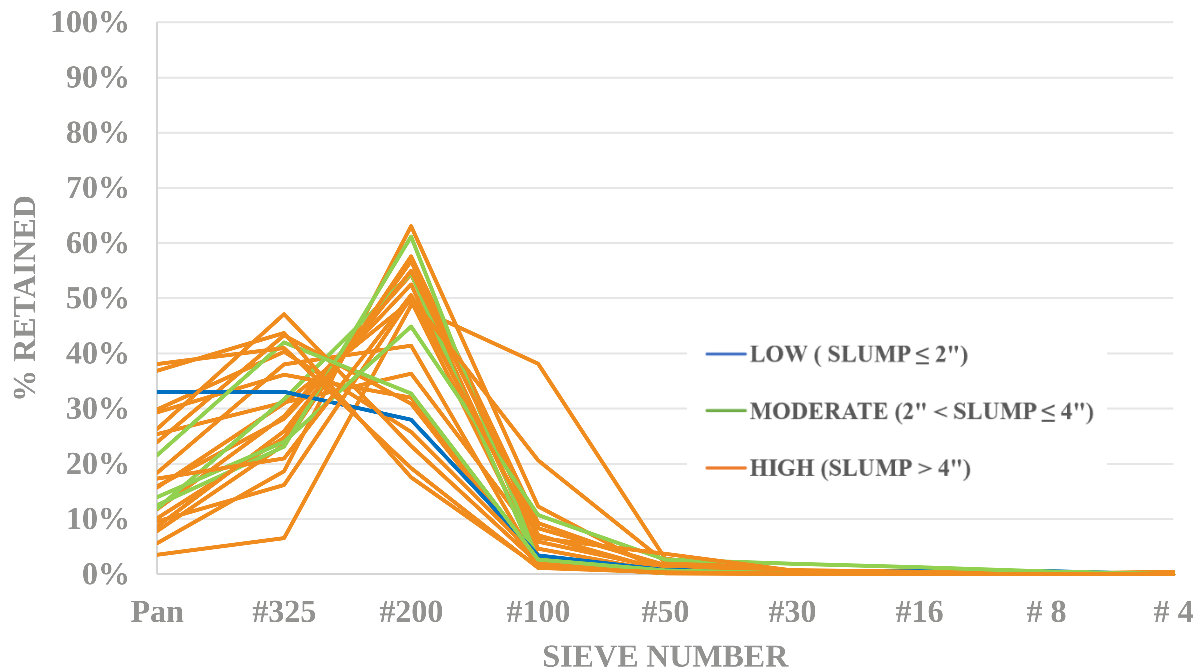

Figure A2-4: Correlation of coal ash fineness to slump performance at 40% replacement.

A3.2

A3.2.1 Laboratory Materials

Multiple types and sources of coal ash were used in this study and are listed in Table A2-1. Each coal ash was given an identification label. The letters are used as identifiers for the type of coal ash and are as follows: Class F coal ash is denoted with an "F", Class C coal ash is denoted with an "C", reclaimed coal ash is denoted with an "R", unprocessed coal ash is denoted with a "U", blended Class F coal ash is denoted by a "BF", blended Class C coal ash is denoted with a "BC", and bottom Class F coal ash is denoted by "BTF". Each label is then followed by a number to serve as a unique label for the coal ash. If two shipments from the samples from the same source were obtained at separate times, then the sources were labeled "-1" and "-2" respectively. Limited numbers of reclaimed, unprocessed, blended, and bottom ashes are reported because they were all that could be obtained in enough quantity to complete the testing.

Table A2-1: Coal Ash Types and Number of Sources

Coal Ash Type	ID	Number of Sources
Class F	F #	16
Class C	C #	17
Reclaimed Class F	R #	8
Unprocessed Class F	U #	4
Blended Class F	BF #	1
Blended Class C	BC #	1
Bottom Class F	BTF #	1

Each coal ash source's physical and chemical characteristics were measured using an automated scanning electron microscopy (ASEM). The technique used allowed for the rapid measurement of thousands of individual particles within each sample of the coal ash. [1, 16-20] These measurements are provided in Table2-2 and Table 2-3. Table 2-2 shows the proportion of 11 chemical oxides (SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, SO_3, Na_2O, K_2O, TiO_2, P_2O_5, SrO) found in each coal ash sample as a percentage of the total.

Table A2-2: Bulk Oxide Analysis Using ASEM

Coal Ash Source	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TiO_2	P_2O_5	SrO
F1	48.76	23.79	7.39	12.53	2.97	0.48	0.86	2.05	0.78	0.09	0.29

Coal Ash Source	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TiO_2	P_2O_5	SrO
F2	50.40	20.91	3.89	17.09	3.69	0.54	1.04	1.37	0.70	0.05	0.32
F3	48.81	26.62	6.65	9.30	1.95	0.28	1.75	1.93	1.46	0.14	1.10
F4	45.34	27.39	4.00	14.61	3.59	0.70	1.48	0.65	1.09	0.37	0.76
F5	53.18	25.36	11.21	2.06	0.19	0.89	0.97	4.43	0.71	0.03	0.96
F6	51.87	25.71	12.32	2.50	0.32	0.67	1.61	4.13	0.66	0.05	0.16
F9	48.27	25.01	5.86	12.59	3.32	0.49	1.33	1.77	1.12	0.18	0.06
F10	53.59	27.76	2.79	10.53	2.50	0.47	0.33	1.27	0.45	0.28	0.02
F11	58.33	21.87	6.87	3.67	1.42	0.59	2.17	4.25	0.22	0.36	0.24
F12	59.18	25.01	9.54	1.59	0.24	0.12	0.05	3.62	0.51	0.02	0.11
F15-1	57.14	23.42	10.16	1.94	0.41	0.58	1.24	3.74	0.84	0.10	0.43
F15-2	57.02	18.62	13.77	3.86	0.44	0.78	0.60	3.57	0.80	0.16	0.12
F16	59.95	21.16	6.46	7.37	1.91	0.21	0.31	1.72	0.67	0.08	0.13
F17	60.46	18.65	3.97	5.64	0.41	0.28	5.62	2.62	0.55	0.00	1.80
F27	52.88	23.86	12.25	5.26	0.39	0.61	0.40	3.36	0.47	0.12	0.39
C1	36.20	21.72	5.35	23.15	5.38	0.67	3.58	1.01	0.80	1.90	0.23
C2	35.82	19.18	5.60	26.88	5.49	0.98	3.00	0.88	0.73	1.25	0.18
C3	25.32	19.26	5.22	32.50	7.76	2.60	3.42	0.63	1.08	1.89	0.32
C4	36.70	22.82	4.53	22.45	4.33	1.19	3.44	0.95	1.28	1.09	1.22
C5	31.25	22.46	5.38	26.06	5.95	0.56	4.30	0.84	0.84	2.11	0.23
C6	27.66	22.88	4.23	21.54	4.52	2.55	12.61	0.76	1.27	0.67	1.32
C7	35.28	20.61	4.74	24.72	4.93	0.74	4.26	1.23	1.64	0.82	1.00
C8	40.11	22.61	4.54	19.45	5.72	0.76	3.74	0.91	0.64	1.42	0.10
C9	31.49	24.02	5.96	25.71	5.35	0.99	3.72	0.61	0.94	1.12	0.10
C10	36.04	19.30	5.06	22.70	7.77	1.97	4.78	0.57	1.03	0.32	0.47
C11	30.96	20.77	6.38	27.15	7.14	1.59	3.45	0.73	0.78	0.83	0.23
C12	31.82	22.87	5.68	28.24	5.52	1.08	2.28	1.02	0.78	0.46	0.25
C13	25.15	21.20	6.22	30.47	7.78	1.04	4.02	0.56	1.22	2.18	0.15
C14	29.66	21.03	5.92	30.29	5.35	1.87	2.22	0.55	1.04	1.61	0.46
C15	29.85	17.66	4.73	31.75	9.32	1.19	2.57	0.76	0.83	1.08	0.24
C16	37.07	22.64	5.20	25.60	4.38	1.02	1.95	0.87	0.55	0.54	0.16
C17	36.93	22.94	6.17	24.02	3.78	0.72	2.71	0.63	1.50	0.44	0.13
C18	28.80	18.37	5.69	32.08	7.29	2.72	2.59	0.38	0.78	0.88	0.32
C19	35.30	24.08	4.52	23.82	5.27	1.01	3.67	0.60	0.93	0.59	0.16
RF2	57.55	30.47	5.15	1.45	0.26	0.07	0.03	3.43	1.05	0.06	0.49
RF3	54.53	30.54	7.33	2.94	0.15	0.13	0.02	3.61	0.63	0.02	0.10
RF4	53.50	26.22	9.91	4.62	0.70	0.35	0.08	3.53	0.51	0.14	0.42
RF5	57.88	27.51	6.62	2.37	0.24	0.17	0.13	4.08	0.59	0.03	0.38
RF6-1	56.30	26.90	9.32	1.45	0.64	0.11	0.01	4.20	0.75	0.21	0.08
RF6-2	53.01	27.42	10.24	4.07	0.41	0.49	0.37	3.12	0.74	0.10	0.03
RF7-1	59.12	20.68	5.95	9.07	1.90	0.56	0.25	1.67	0.42	0.00	0.38

Coal Ash Source	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TiO_2	P_2O_5	SrO
RF11	57.56	17.93	5.20	12.79	2.35	0.36	0.17	2.29	1.00	0.19	0.13
UF1	53.04	25.31	11.45	3.36	0.52	0.93	0.35	4.39	0.41	0.18	0.03
UF2	57.57	23.51	10.12	2.82	0.49	0.48	0.21	3.85	0.67	0.19	0.05
UF3	52.39	22.24	11.18	4.98	0.45	3.94	0.18	3.80	0.78	0.01	0.06
UF4	61.59	19.64	11.25	1.98	0.38	0.64	0.22	3.32	0.77	0.03	0.19
BF9	44.85	15.74	11.02	17.48	3.50	1.94	2.14	1.48	0.87	0.80	0.12
BC3	31.40	19.63	5.25	29.27	6.56	1.39	3.69	0.79	0.91	0.93	0.12
BTF2	60.37	14.88	5.99	13.20	1.70	0.82	0.06	1.26	1.43	0.01	0.26

Table A2-3: Particle Size Distribution Using ASEM

Coal Ash Source	ASEM				#325 Sieve
	D50	D90	Average	STDEV	% Retained
F1	1.68	4.14	2.19	1.74	20.45%
F2	2.15	5.10	2.73	2.11	13.00%
F3	2.24	4.45	2.67	1.65	23.10%
F4	1.68	4.57	2.33	2.06	21.80%
F5	2.07	5.21	2.71	2.20	18.71%
F6	2.03	4.96	2.62	2.00	30.24%
F9	2.09	4.48	2.18	1.70	32.00%
F10	2.05	4.29	2.39	1.61	15.00%
F11	1.71	3.96	3.26	2.77	25.00%
F12	2.06	3.93	3.32	2.93	25.18%
F15-1	2.45	6.48	3.56	2.89	19.07%
F15-2	2.37	6.80	3.10	2.27	---
F16	2.48	6.38	2.64	2.31	44.80%
F17	2.45	6.71	3.59	2.92	22.14%
C1	1.49	3.68	1.97	1.64	15.22%
C2	1.6	3.91	2.09	1.67	20.42%
C3	1.3	3.09	1.69	1.32	51.91%
C4	1.71	4.31	2.30	1.85	17.82%
C5	1.63	4.08	2.17	1.80	14.90%
C6	1.48	4.55	2.17	2.09	12.03%
C7	1.67	3.53	2.05	1.42	18.58%
C8	1.73	3.61	2.10	1.46	24.21%
C9	1.44	3.54	1.91	1.59	---
C10	3.08	9.72	4.34	4.00	---

Coal Ash Source	ASEM				#325 Sieve
	D50	D90	Average	STDEV	% Retained
C11	1.62	4.09	2.14	1.72	14.29%
C12	1.35	4.75	2.14	2.15	15.49%
C13	1.76	4.26	2.23	1.78	12.57%
C14	1.64	3.73	2.40	2.29	27.82%
C15	1.59	4.15	2.11	1.75	24.52%
C16	1.37	3.68	1.90	1.68	30.75%
C17	1.36	3.82	1.96	1.95	16.96%
C18	1.39	3.79	1.93	1.71	16.56%
C19	1.43	3.72	1.93	1.68	23.72%
RF2	2.37	6.15	3.11	2.45	29.50%
RF3	1.83	5.09	2.56	2.29	36.75%
RF4	2.23	6.95	3.19	2.83	30.50%
RF5	2.32	6.11	3.09	2.65	54.37%
RF6-1	1.90	4.89	2.58	2.34	50.60%
RF6-2	2.36	6.76	3.29	2.82	26.79%
RF7-1	2.78	7.00	3.57	2.95	---
RF11	2.09	4.46	2.54	1.68	---
UF1	2.20	5.52	2.90	2.41	---
UF2	2.61	6.89	3.51	2.97	21.47%
UF3	2.02	5.88	2.90	2.81	27.69%
UF4	1.87	4.60	2.54	2.32	28.61%
BF9	1.68	4.05	2.18	1.74	19.77%
BC3	1.76	4.50	2.32	1.78	17.99%
BTF1	3.07	7.37	3.99	3.05	11.89%

All of the laboratory concrete mixtures in this research used a Type I cement that met the requirements of ASTM C150. Both the oxide analysis and Bogue calculations for this cement is shown in Table A2-4. The aggregates used were locally available #57 crushed limestone and natural sand used in commercial concrete. The crushed limestone had a maximum nominal aggregate size of 3/4 in. Both the crushed limestone and the sand met ASTM C33 specifications. No chemical admixtures were used in this study. The mixture design of the concrete yielded enough workability that there was no need for water reducing admixtures. Air entrainer was not used to minimize the number of variables used in the testing.

Table A2-4: OPC Type I Cement Oxide Analysis and Bogue Calculations

Oxide %								Bogue Calculation			
CaO	SiO_2	Al_2O_3	Fe_2O_3	Na_2O	MgO	SO_3	K_2O	C3S	C2S	C3A	C4AF
62.1	21.1	4.7	2.6	0.2	2.4	3.2	0.3	56.7	17.8	8.2	7.8

A3.2.2 Concrete Mixture Design

Coal ash samples were tested at 20% and 40% substitution rates and compared to a conventional concrete mixture using 100% OPC. The mixture design used maintained a 29% paste content and a water-cement ratio of 0.45. These mixture designs are provided in Table A2-5. The paste volume and water-cement ratio of the concrete mixture design allowed for adequate workability of the concrete.

Table A2-5: Concrete Mixture Design per cubic yard

Mixture	w/cm	OPC (lbs)	Coal Ash (lbs)	Water (lbs)	Paste (%)	Coarse (lbs)	Fine (lbs)
0% Coal ash	0.45	625	0	281	28.8	1903	1243
20% Coal Ash	0.45	500	125	281	28.9	1900	1240
40% Coal Ash	0.45	375	250	281	29.0	1892	1228

A3.2.3 Concrete Mixing Procedure

Aggregates were collected from outside storage piles and brought into a temperature-controlled room at 23°C for at least 24 hours before mixing. Aggregates were placed in the mixer and spun, and a representative sample was taken for moisture correction. At the time of mixing all aggregate was loaded into the mixer along with approximately one half of the mixing water. This combination was mixed for three minutes to allow the aggregates to approach the saturated surface dry (SSD) condition and ensure that the aggregates were evenly distributed.

Next, the cement, coal ash, and the remaining water was added and mixed for three minutes. The resulting mixture rested for two minutes while the sides of the mixing drum were scraped. After the rest period, the mixer was started, and the concrete was mixed for three minutes.

A3.2.4 Testing Procedure

Slump measurements were taken from each wheelbarrow following ASTM C143 and averaged. The air content was measured using an ASTM C231[9] Type B air pressure meter. Unit weight was collected according to ASTM C138, and a Phoenix Test was conducted following the test methods to measure the actual water-cement ratio in the fresh concrete [**Error! Reference source not found.**].

The concrete was then used to make 66 samples of 4”x8” cylinders, prepared according to ASTM C192[12]. These cylinders were then placed in a controlled environment chamber at 70 ˚F and 100% RH until the day of testing. Compressive strength ASTM C39[14] and electrical resistivity AASHTO T 358 testing was completed at 3, 7, 14, 28, 56, 90, and 180 days. The samples were left in their cylinder molds until they were tested. This was done to prevent leaching from the surface of the cylinder by the spray in the moisture curing room for the resistivity samples.

A3.2.5 Wet Sieving

To determine the fineness of each coal ash, each material was wet sieved using a #325 sieve following ASTM C430-17. Each coal ash sample was tested 3 times. The #325 sieve was tared to the nearest 0.0005g and 1 gram of the given sample was weighed out and placed on the sieve. The material was then dampened using deionized water and then held under nozzle meeting ASTM C430-17 specifications emitting 10psi of water. The sieve was held under the nozzle for 1 minute and moved in a circular motion in the horizontal plane. Following this, each sample was rinsed with deionized water. A damp cloth was then used to blot the lower surface of the sieve. The sieve was then placed in a furnace at 110 degrees Celsius for 2 minutes to allow the sieve and sample to dry. After this time, the sieve was removed and weighed to the nearest 0.0005g.

A3.3 RESULTS AND DISCUSSION

The slump performance of concrete tested in this study shown to have high variability. The slump results achieved by concrete in this study are depicted in Figure A2-5 and Figure A2-6 below.

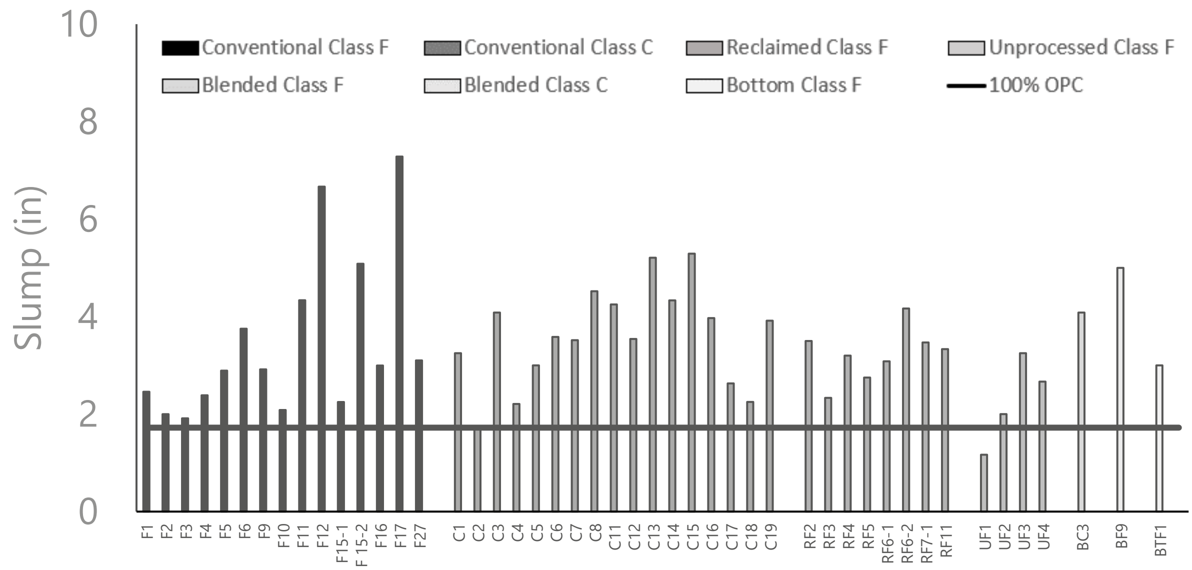

Figure A2-5: Average Slump Performance of Each Coal Ash at 20% Replacement

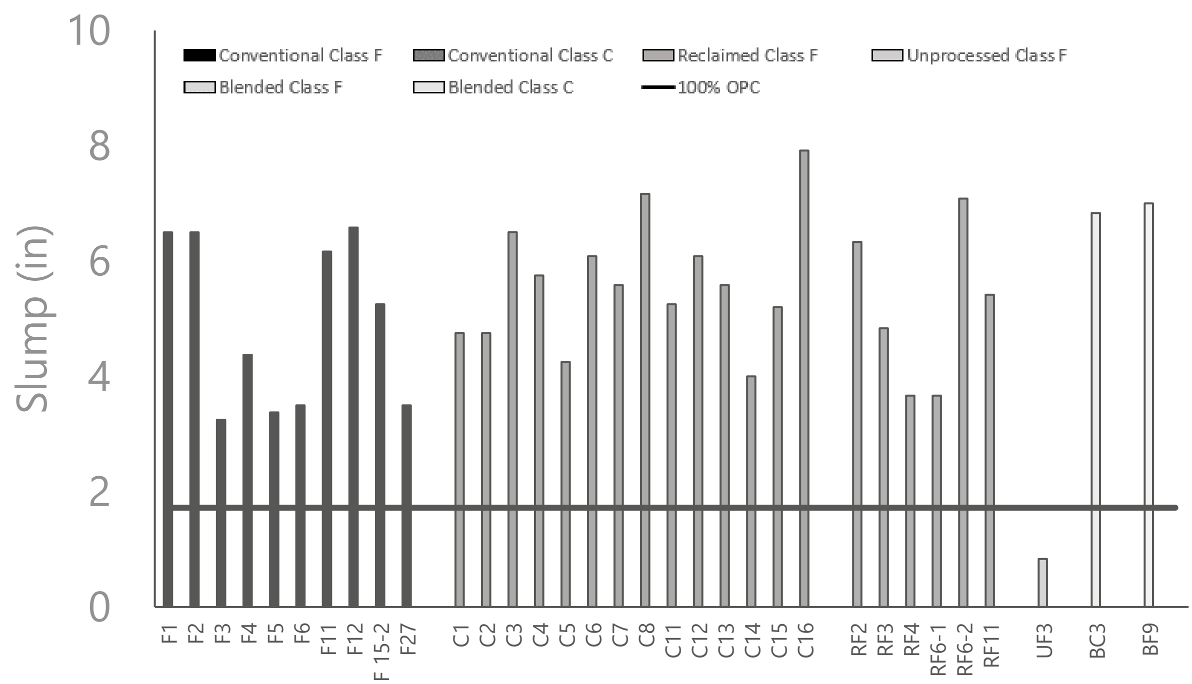

Figure A2-6: Average Slump Performance of Each Coal Ash at 40% Replacement

Figure A2-5 and Figure A2-6 shows that each coal ash type shown to have variable slump performance between the coal ash sources used. Each concrete mixture design used is uniform for each graph. The only variable changed is the source of the coal ash used. Increasing the content of coal ash in concrete also effected the slump performance of each coal ash on average as discussed in chapter II of this report.

One possible reason for the variation in slump performance achieved by different coal ash sources is the fineness of each coal ash. The fineness of each coal ash was found following ASTM C430-17. Figure A2-7 depicts this fineness in terms of percent retained on a #325 sieve and in relation to the slump performance achieved by each coal ash.

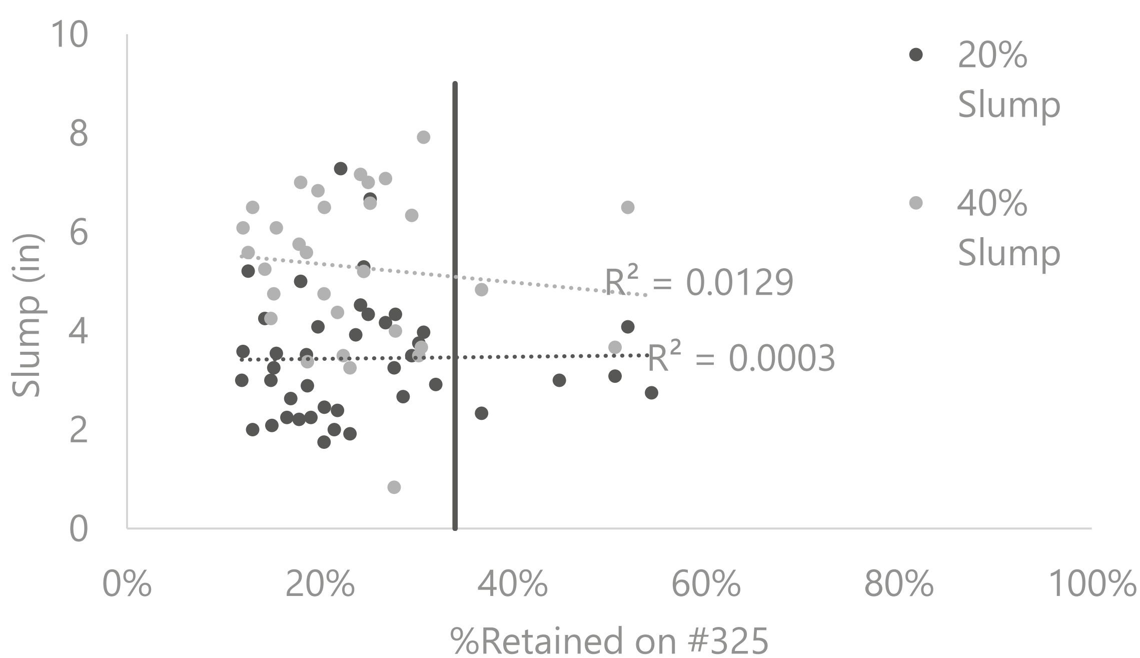

Figure A2-7: Slump Performance in Relation to Coal Ash Fineness

No correlation was shown between the fineness of coal ash and the resulting slump performance when used at 20% and 40% replacement. The R-Squared value was found for both the 20% and 40% coal ash slump data. The R-Squared value provides a calculable means to measure how well a regression model fits the observed data. A high R-Squared value indicates a high correlation between the model and data. The R-Squared value for 20% and 40% coal ash substitution shown to be low, indicating the model does not fit the observed data.

The study also found that some coal ash shown to be greater than the 34% retained limit set by ASTM C618. These coal ash samples included 3 reclaimed coal ash, 1 conventional Class f coal ash, and 1 conventional Class c coal ash. From Figure A2-8, one can see that this larger fineness did not change the slump performance of the concrete. The slump achieved by each of these coal ashes shown to fall within the range of slump achieved by other coal ash in the study. Figure A2-9 and Figure A2-10 show how each of these coal ash samples performed in terms of compressive strength when used at 20% replacement.

From the figure, one can see that each coal maintained a similar performance to their respective average. Coal ash C3 used at 40% shown to have a greater long term compressive strength than that of the average found for conventional Class C coal ash. Figure A2-11 and Figure A2-12 show how each of these coal ash samples performed in terms of resistivity. The average performance of each coal ash sample shown to fall within the standard deviation of the average of performances of other sources of its type.

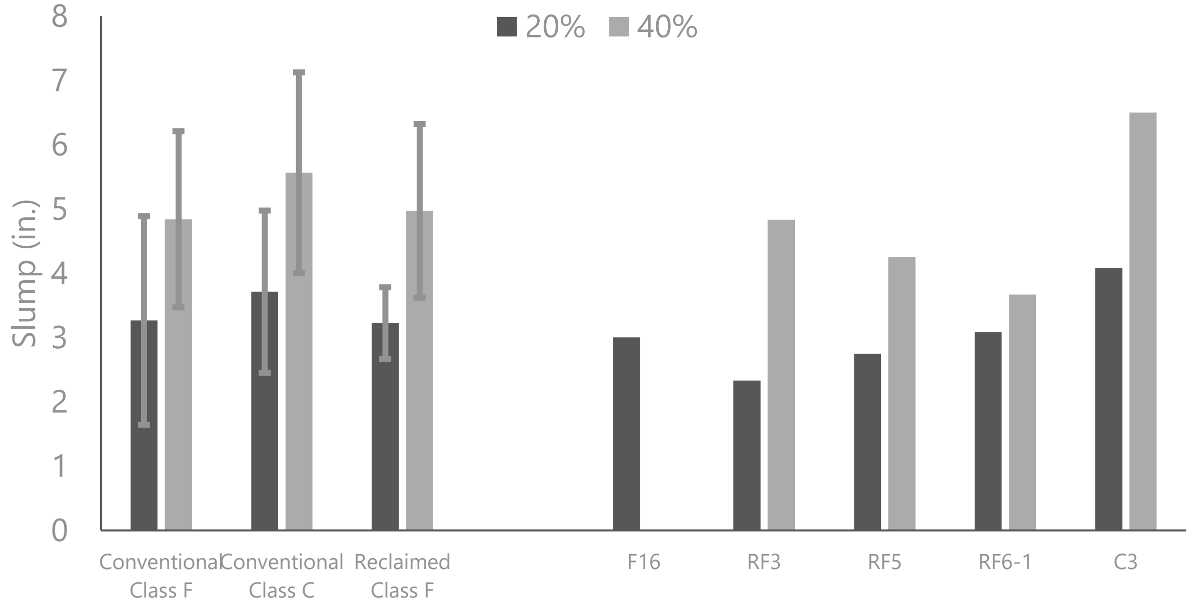

Figure A2-8: Slump Performance Comparison of Low Fineness Coal Ash

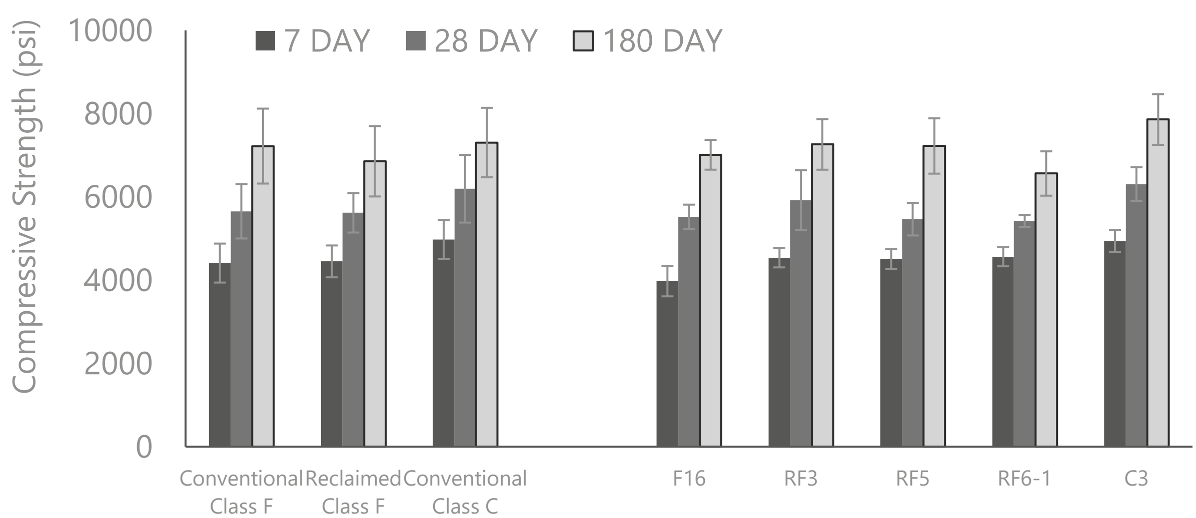

Figure A2-9: Compressive Strength Comparison of Low Fineness Coal Ash at 20%

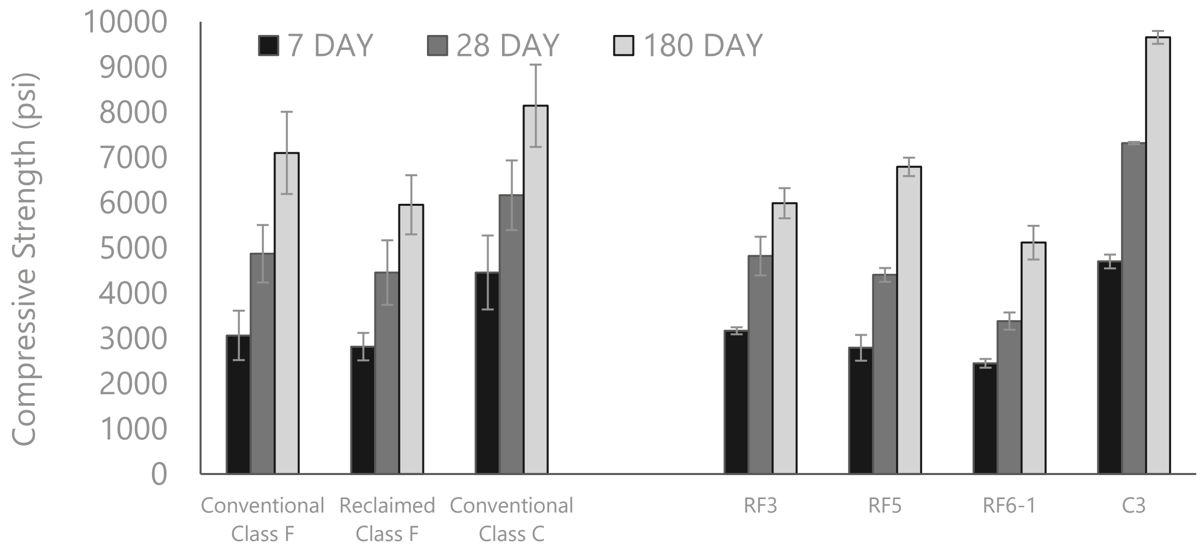

Figure A2-10: Compressive Strength Comparison of Low Fineness Coal Ash at 40%

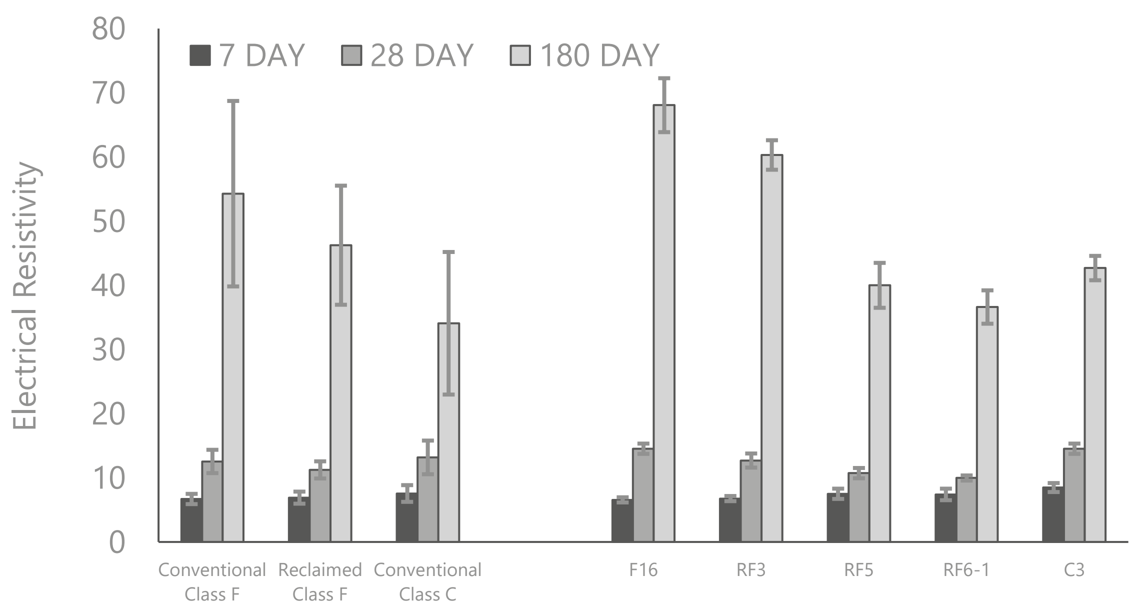

Figure A2-11: Resistivity Comparison of Low Fineness Coal Ash at 20%

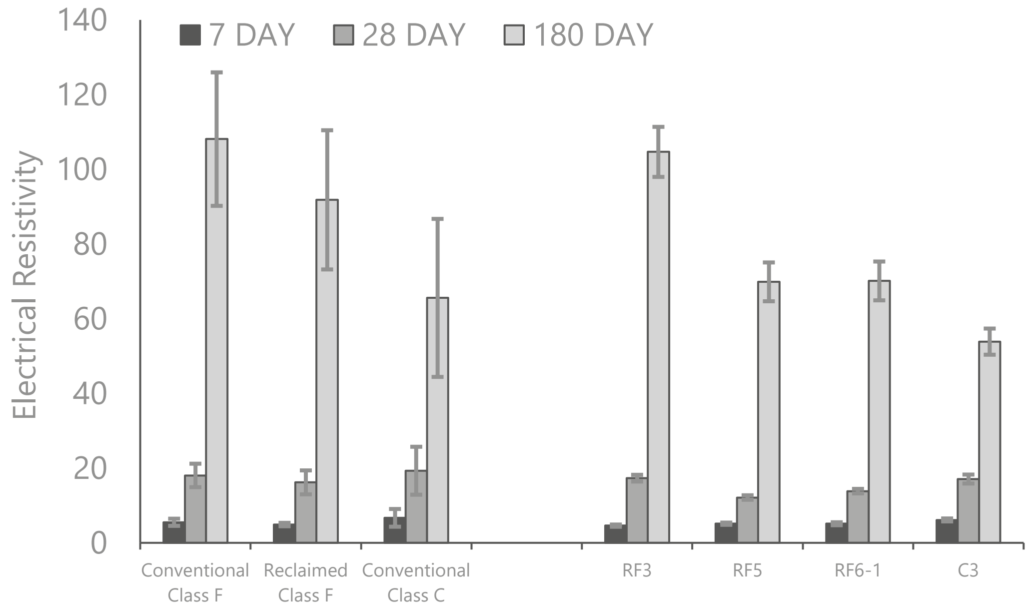

Figure A2-12: Resistivity Comparison of Low Fineness Coal Ash at 40%

To conclude, no significant correlation was found between the fineness of each coal ash and its slump performance in concrete. Additionally, coal ash samples that shown to have a lower fineness (more than 34%) than what is allowed by ASTM C618, showed to still maintain similar concrete performance to other coal ashes of higher fineness.

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