Civil and Environmental Engineering Department

Assessment of Mississippi Concrete with Gravel Aggregates, 25 to 35% Fly Ash, and Ordinary Portland Cement or Portland-Limestone Cement

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16. Abstract

This report summarizes findings of 114 laboratory produced concrete mixtures that were intended to improve understanding of concrete produced in Mississippi with gravel aggregates, fly ash, and either ordinary portland cement (OPC) or portland-limestone cement (PLC). Data was collected in two phases. Phase 1 incorporated variations of a concrete mix design readily used by a Mississippi concrete producer to assess options within the market. Phase 2 incorporated concrete mixtures produced without admixtures and with washed aggregates to identify fundamental mechanisms that could be useful for producers as they select materials and proportion mixtures for actual projects. The major finding from the marketplace assessment was that producers should consider implementing ASTM C595 Type IL PLC in place of ASTM C150 Type I OPC if they have not already done so as considerable evidence was provided that PLC is very likely a better Mississippi marketplace cement for most applications. The phase 2 mechanisms evaluations revealed that higher elastic modulus values were statistically correlated to higher coarse aggregate bulk specific gravity values. Phase 2 also showed that aggregate shape (rounded or crushed) and mineralogy (chert gravel versus calcium carbonate limestone) affect bonding and by way of cement paste testing these effects were somewhat quantified. When the aggregates were washed, limestone achieved a near to full bond, followed by a lesser bond to crushed gravel, and the lowest bond to rounded gravel.

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A portion of the raw materials utilized in this project were remaining from previous research on portland-limestone cement (PLC) that culminated with Dr. Jay Shannon's doctoral dissertation. Kyle Beckman of MMC Materials provided the baseline mix design utilized in this effort and assisted the research team in obtaining some raw materials. Les Howell (Delta Industries) and Aaron Wade (formerly of Delta Industries) facilitated acquisition of the remaining raw materials. Cement and fly ash sources have been anomalously identified in this report, and as such suppliers of these materials are not named in the acknowledgements but their support is appreciated.

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Tim Cost, LafargeHolcim – retired, was very active in conceptualizing the need for this research and working within MCA to secure funding.

LIST OF SYMBOLS AND ACRONYMS

ε	Strain
μ	Sample mean
σ	Sample standard deviation
AL	Alabama
AM	Admixture
CA	Coarse aggregate
CG	Crushed gravel
COV	Coefficient of variation
CP	Cement paste
CS	Sand
D	Days
d	Diameter of specimen
dr	Dial reading
E	Modulus of elasticity
f_c	Concrete compressive strength
f_{cp}	Cement paste compressive strength
FA	Fly ash
GR	Gravel
l	Length of specimen
LOI	Loss on ignition
LS	Limestone
MCA	Mississippi Concrete Association
MDOT	Mississippi Department of Transportation
MS	Mississippi
OD	Oven dry
OPC	Ordinary portland cement
P	Maximum applied load
PG	Pea gravel
PLC	Portland limestone cement
SCM	Supplementary cementitious material
SG	Specific Gravity
SR	Surface resistivity
SSD	Saturated surface dry
t_{C403}	Concrete setting time according to ASTM C403
T	Splitting tensile strength
UW	Unit weight
w/cm	Water to cementitious materials ratio

CHAPTER 1 – INTRODUCTION

1.1 Introduction and Background

Generally speaking, this report investigates three raw material categories: gravel aggregates native to Mississippi (MS), fly ash supplied into Mississippi, and two cement types available in Mississippi (ASTM C150 Type I and ASTM C595 Type IL). These raw material categories have been investigated with the purpose of providing Mississippi concrete producers more information on how to more effectively use concrete produced with combinations of these materials. Background that provides rationale for selecting these three raw material categories for a systematic investigation is provided in the remainder of this section.

Mississippi concrete heavily relies upon native sources of smooth faced gravel aggregates. For context, Varner (2016) provides a fairly comprehensive assessment of all sources of washed gravel in the state. Mississippi concrete mixtures usually contain rounded gravels and two cementitious materials (plants with two cementitious silos are the most prevalent in the market). The Mississippi Department of Transportation (MDOT) provided concrete practices on their projects from mid-fall of 2007 to mid-summer of 2014 and approximately 96% of their structural concrete mixes contained fly ash and 93% of their mixes contained rounded gravel aggregates.

Gravels are naturally harder to bond together than are crushed aggregates such as limestone. Thus paste-aggregate-bond (PAB) can be a major influence in MS concrete properties and variability. In the majority of cases, rounded and smooth gravels are more workable (i.e. have a lower water demand) than crushed limestone, but they also lead to lower and more variable concrete compressive strengths (PAB is often part of the reason), especially when ordinary portland cement (OPC) such as ASTM C150 Type I and elevated fly ash levels are used. To adjust for the lower and more variable compressive strengths, mixtures containing gravel are often overdesigned. These overdesigns can increase shrinkage cracking from increased cementitious content. Crushed limestone tends to produce higher strengths with less variability but with higher water demand. A key drawback from using limestone is it is usually more expensive in MS. As such, finding ways to improve gravel aggregate concretes is of value, and is the focus of this report.

Issues with PAB can be sporadic and can appear or disappear from normal variability or changes in cement source or type. Other factors affecting PAB include supplementary cementitious materials (SCMs), SCM levels, admixture types and dosages (admixtures can lead to air void clustering around aggregates), and gravel source (and cleanliness). Silica fume, slag cement, and portland-limestone cement (PLC) have the potential to mitigate PAB concerns. PLC in particular has gained traction in the MS market for reasons discussed in Section 1.3.

Largely in response to the content in Section 1.3, the Mississippi Department of Transportation (MDOT) approved AASHTO M240 Type IL PLC statewide in October of 2014 through Special Provision No. 907-701.5 that has amended their Standard Specifications (MDOT 2017). A key change was an increase in the allowable amount of fly ash (35% as opposed to 25%) when Type IL cement is used instead of ASTM C150 or AASHTO M85 Type I or Type II ordinary portland cement (OPC). Effectively, MDOT's specification allows producers to use an extra 10% fly ash with PLC, which makes inclusion of fly ash interactions with OPC and PLC timely to include in this study.

Historically, the extent PAB affects concrete with smooth gravels has varied widely. For reference, 28 day compressive strengths have varied by a factor of two for common non airentrained (AE) concrete with a Type A/D water reducer (WR) containing under 564 lb/yd^3 (pcy) of cement. AE concrete can have compressive strength differences exceeding factors of two, especially if air clustering occurs near aggregates. PAB deficiencies, however, can be completely mitigated as evidenced by strengths of concrete containing gravel equaled or exceeded those of parallel limestone mixes. This occurrence is not common within Mississippi concrete. Shannon et al. (2017b), however, documented some cases where concrete with gravel aggregates was stronger than corresponding limestone mixes (as already noted, this occurrence isn't expected to be prevalent within a market). All cases were at SCM levels at or below 50% and utilized PLC.

Tim Cost, PE, F.ACI (LafargeHolcim, Retired and currently President of V.T. Cost Consulting, LLC), was instrumental in initiation of this study and provided internal data on the state-of-the-art for smooth faced gravel aggregates that is summarized throughout the following paragraphs, which in some occasions is supplemented with other data. Data from around the year 2000 was provided for comparing crushed limestone and smooth gravels in concrete with 517 lb/yd^3 total cementitious materials, a 0.57 water to cement (*w/cm*) ratio, Type I cement, and either 0 or 25% Class C fly ash. With limestone aggregates, 28 day compressive strengths were similar for 0 and 25% Class C fly ash, but with gravel aggregates 28 day compressive strengths were about 13% lower for 25% Class C fly ash compared to 0% Class C fly ash. Absent Class C fly ash, concrete produced with limestone was about 6% stronger than concrete produced with gravel at 28 days.

A second data set was provided where 517 lb/yd^3 total cementitious content mixtures absent AE were produced with limestone and smooth gravel aggregates from Mississippi with Class C fly ash levels of 0, 15, 20, 25, and 30%. Relative to the 0% fly ash mixes, 7 and 28 day compressive strengths from concrete with limestone aggregates were always within 5%. At 7 days, concrete made with gravel aggregates had compressive strength reductions of 5, 17, 15, and 26% at 15, 20, 25, and 30% Class C fly ash. At 28 days, gravel aggregate compressive strength reductions were 0, 10, 12, and 16% for increasing fly ash amounts. These compressive strength reductions are indicative of PAB issues, and petrography of these gravel aggregate specimens showed higher *w/cm* ratios and some microcracks.

Inclusion of fly ash in the investigation documented in this report is supported from several perspectives. First, higher fly ash levels with OPC and gravel aggregates is known to have the potential for PAB problems. Second, PLC has shown considerable improvements with gravel aggregates and fly ash (see Section 1.3), and third there are nationwide concerns about fly ash supply and properties over the foreseeable future. AASHTO (2016) is a committee report from a task force convened in 2016 to document issues facing the coal industry and their impact to fly ash supply to Departments of Transportation (DOTs). Findings were that fly ash supply concerns were not minimal, nor were they regional. The report also stated that a number of DOTs had already started funding research into fly ash alternatives (Ferraro et al. 2016 is an example for the Florida DOT). AASHTO (2016) contained results of a comprehensive survey where over 80% of the respondents indicated fly ash issues and there were multiple concerns expressed for the future. The report stated that long term fly ash supply was predicted to remain constant or slightly increase, and that beneficial reuse at the present time is less than 50% of available supply.

According to ACCA (2019), 64% of coal ash produced in 2017 was recycled. This was an 8% increase from 2016, but this was only 4% increase by volume, due to closing coal-fueled power plants. The American Coal Ash Association (ACAA) is working to find utility in the 36% (according to their data) of ash that is being disposed of for beneficial use. Strides are being made to reclaim ash from its disposal sites to be used in a beneficial way in industry. Note this project does not consider re-conditioned fly ash; this study is only noted for context of the market.

1.2 Objectives and Scope

The primary objective of this report is to provide improved understanding of properties that can be achieved in concrete containing smooth faced rounded gravels native to Mississippi, fly ash, and either OPC or PLC. Rationale for evaluating these three material categories was provided in the previous section. These material categories were evaluated in the context of MDOT's new specification where up to 35% fly ash can be used with PLC and up to 25% fly ash can be used with OPC. It is noted that the majority of the concrete produced in Mississippi is for customers other than MDOT, but MDOT specifications remain a market driver, in particular for concrete plants with two cementitious silos that desire to supply MDOT concrete. Laboratory produced concrete with controlled proportions were used throughout this report, and the proportions selected were mindful of the needs of concrete producers to supply a diverse customer base. The proportions evaluated are producible with a concrete plant with two cementitious silos and no other special equipment. Some of the concrete data collected and reported herein is for general use by the industry, while other concrete produced was analyzed for specific purposes.

From a fundamental perspective, concrete strength is related to: cement paste properties, aggregate properties, and properties of the bond between cement paste and aggregates. This report made use of concrete and cement paste (cementitious materials, admixtures, and water) mechanical properties to provide insight into what was limiting properties of a given concrete system, which is often PAB when gravels are used. Work occurring within the timeframe of this report that is mentioned in Section 1.3 improved cement paste testing protocols, and those improved protocols were used in this work. Improved cement paste mechanical property protocols allow for more direct assessment of the strength properties gap between concrete with crushed limestone and rounded gravel aggregates.

This report investigates up to 35% replacement of fly ash with multiple MS market aggregates in combination with several different MS market cements and fly ash sources. All data collected is available in Chapter 3 and was collected as described in Chapter 2. The data collected can be divided into two phases. The first phase of data incorporated a concrete mix design readily used by one Mississippi concrete producer as a baseline and made systematic substitutions of raw ingredients and fly ash replacement rates to evaluate the effects on resulting mechanical properties. Findings from this investigation that assessed the MS marketplace are provided in Chapter 4.

The second phase of concrete mixtures produced are not intended for actual use in the Mississippi marketplace, but rather aimed to identify fundamental trends and mechanisms that could be applicable to concrete proportioning. Some early discussions that ultimately led to this project related to PAB discussed items such as: do certain gravel aggregate characteristics (e.g. water absorption, specific gravity, mineralogy) lead to mechanical property differences? Another item discussed was whether crushed gravel would be less prone to PAB than rounded gravel with otherwise identical properties such as water absorption and mineralogy. Findings from phase 2 mixtures are provided in Chapter 5, and this chapter was limited to a summary of findings that might be of value to a producer selecting ingredients and proportions.

1.3 Companion Research

A considerable amount of research relevant to the current report has already been completed at Mississippi State University (MSU) on PLC as currently specified in ASTM C595 or AASHTO M240. This work is housed in several publications (Cost et al. 2013; Cost et al. 2014; Cost et al. 2015; Howard et al. 2015; Shannon 2015; Shannon et al. 2015; Shannon et al. 2017a;

Shannon et al. 2017b). Findings from this body of work showed performance and environmental benefits are possible through PLC's synergies with SCMs, especially those of PLC, Class C fly ash, and gravel aggregates. Most of this work was performed on concrete with 40 to 70% cement replacement with SCM's where the replacement rates were based on work at Davis-Wade Stadium. The PLC's evaluated were, for practical purposes, ground to Blaine fineness levels of over 500 m^2/kg for reasons outlined in Cost et al. (2013) and Hansen et al. (2019b) to provide the early strength and setting characteristics that often influence cement purchasing in North American markets.

Type IL PLC was introduced to the Jackson market in early 2015. Results from twelve truck mixed concretes are available, but were not shown in this report for brevity. These twelve mixes were used for a diverse array of purposes and have served as case studies of sorts for the approach taken by MDOT to allow 10% more fly ash when PLC is used. Assessment of these projects where there was usually more Class C fly ash when PLC was used were more economical mixes that also had improved strength properties with a lower environmental footprint. To date, PLC has led to several successful projects in Mississippi including, but not limited to, slip-form paving, runway repair, multi-floor structures, wastewater sewage treatment facilities, energy distribution facilities, parking garages, auger piles, shotcrete, and slabs on grade. The overall market trends appear to be modestly higher fly ash replacement rates or slightly reduced cementitious content that are accompanied by excellent placing and finishing with reduced bleed rates and related surface discolorations and reduced finishing defects.

In addition to the PLC findings summarized in the previous paragraphs, a large amount of cement paste (CP) compressive strength testing was also performed. CP is cementitious materials, water, and admixtures (no coarse or fine aggregate). As shown in the next few paragraphs, CP testing has been showing promise to help explain certain concrete behaviors, and additional cement paste testing was performed specifically for this report.

Shannon et al. (2015) found that PLC performed better in concretes with fly ash (especially with gravel aggregates) in almost every case. At the 40% replacement level, PLC showed noticeably higher strengths with PLC in concrete and cement paste results. Additionally, PLC showed faster setting times with otherwise similar fresh mix properties. Petrography showed potential interfacial zone improvement with PLC. Shannon et al. (2015) also notes that CP may have the capabilities of diagnosing some paste aggregate bond effects when used in tandem with concrete, however the cement paste data investigated was not extensive. Shannon et al. (2017b) also used cement paste to help explain behavior seen at 70% replacement. The cement paste and gravel concrete data was able to show that paste aggregate bond problems developed at the highest replacement level. More specifically, the cement paste PLC to OPC comparisons showed PLC strengths to be considerably higher than OPC while the opposite was shown for concrete. Shannon et al. (2017b) concluded that PLC with replacements up to 50% show benefit to compressive strength after which paste aggregate bond becomes a problem. Shannon et al. (2017a) found that PLC used with high cement replacement rates showed benefits to concrete properties, especially at early ages. Synergies with PLC and Class C fly ash were also evident.

These aforementioned studies showed potential usefulness of CP compressive strengths, which was comprehensively assessed in Hansen et al. (2019a). Cement paste measurements were shown to generally track with concrete compressive strengths, or to identify potential PAB concerns, indicating that behaviors seen in concrete would likely be better understood with accompanying cement paste testing. This is an important point to make because cement paste data can be collected much faster and with less effort. Additionally, Hansen et al. (2019) showed how cement paste measurements can be compared with concrete for diagnosing concrete behaviors and general paste aggregate bond conditions. One of the concerns for cement paste measurements from this study was the higher variability in cement paste measurements. Hansen and Howard (2019) was able to reduce the variability of cement paste measurements from a different handling process from previously collected cement paste data. Four methods were vetted which led to a new recommended production method that was employed in this report. Additional time tolerances to compressive strength testing were also recommended.

This report uses the information from the work at MSU to date and builds upon that information. Since the majority of the previous works were conducted on higher than normal replacement mixtures with fly ash and slag cement (40-70%), this report focused on 0%, 25%, and 35% mixtures with only fly ash (the case studies mentioned earlier were mostly in the 20 to 35% replacement rate with fly ash). Behaviors at 35% fly ash or less are of primary concern since they can be produced and are being produced currently under MDOT specifications.

CHAPTER 2 – EXPERIMENTAL PROGRAM

2.1 Overview

This chapter discusses materials, production methods, testing methods, and mixture designs. Experiments were conducted in two phases. Phase 1 and Phase 2 protocols are described in each section as they differ in some cases. Phase 1 constitutes 74 mixtures made with conventional concrete materials and proportions. Phase 2 contains 40 mixtures with aggregates 0.5 in and smaller without admixtures which are not meant to be produced in practice, but were intended to examine specific mechanisms. Overall, 2052 concrete specimens and 770 corresponding cement paste specimens were produced for this report.

2.2 Materials Tested

The following sections present aggregate, cement, supplementary cementitious material (SCM), and admixture properties used in this report. In addition, material processing is described for Phase 1 and Phase 2 materials. The four coarse aggregates for Phase 1 represent Mississippi (MS) market aggregates. The three gravels came from different geographic areas within the state while the limestone came from neighboring Alabama. Phase 2 coarse aggregates were selected based on geography and particle shape. The cements for Phase 1 and 2 represent a range of cements used in the state. Three representative MS market fly ashes were used for Phase 1 while only two were used for Phase 2.

2.2.1 Fine Aggregates

A sand fine aggregate was supplied by a local concrete producer and used for Phases 1 and 2. For Phase 1 the sand was air dried in ambient conditions until the moisture content equalized. Once the moisture content was constant, a splitter was used to homogenize the material before being stored in 5-gallon buckets. The splitting operation homogenized 6 buckets of material simultaneously. From these 6 buckets one representative moisture content was collected for use in mixture design. Buckets were given identification numbers so this moisture content could be used during batching. Sand that was handled and processed in this manner is labeled CS1.

For Phase 2, CS1 sourced material was further processed by washing in a 3ft^3 concrete mixer. One 5-gallon bucket of material was washed at a time for approximately 5 minutes. The process was similar to the mechanized version of ASTM C117. The material was then drained and spread over plastic sheeting to dry. The sand was mixed regularly, and moisture contents were taken to determine when the moisture content equalized. The washed material was split and stored the same as CS1 except buckets were labeled as CS1(w) with w indicating it has been washed. The splitting and washing processes are shown in Figure 2.1. Properties of the fine aggregate before and after washing are given in Table 2.1.

a.) Splitter Hopper

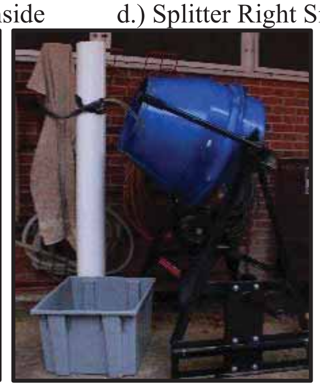
b.) Splitter Left Side

c.) Splitter Inside

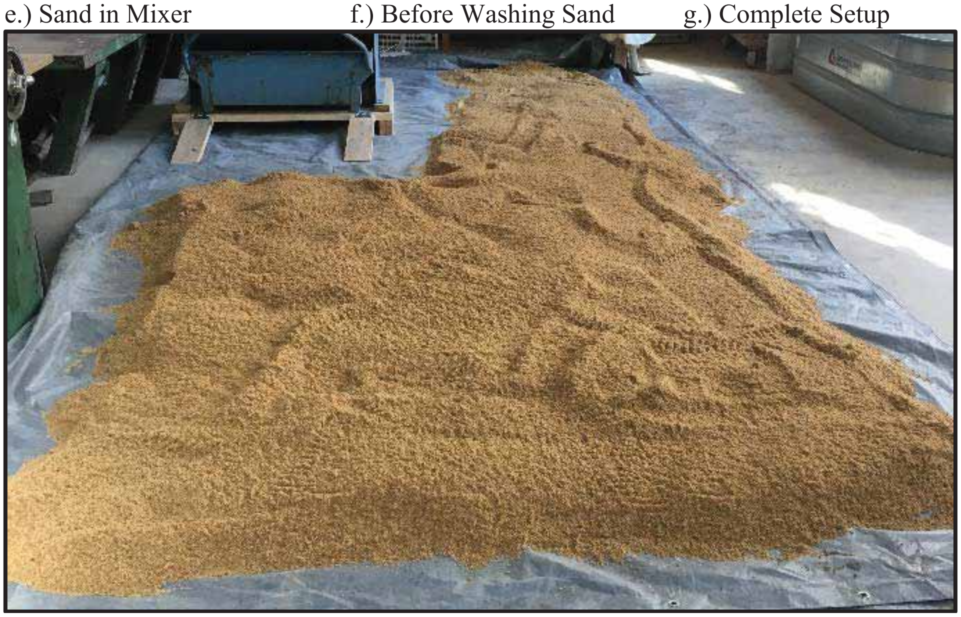
d.) Splitter Right Side

e.) Sand in Mixer

f.) Before Washing Sand



g.) Complete Setup



h.) Sand Drying

Figure 2.1. Sand Splitting, Washing, and Drying Operations

Table 2.1. Fine Aggregate Properties

Aggregate	CS1	CS1(w)
Source	Bacco	Bacco
Phase	1	2
Water Absorption (%)	0.8	1.2
Bulk Specific Gravity (OD)	2.58	2.56
Bulk Specific Gravity (SSD)	2.60	2.59
Fineness Modulus	2.46	2.75
Sand Equivalency	---	99
% Passing No. 4	99	99
% Passing No. 8	86	82
% Passing No. 16	78	71
% Passing No. 30	66	57
% Passing No. 50	22	16
% Passing No. 100	2	1
% Passing No. 200	---	0.1

Notes: OD = Oven dry, SSD = saturated surface dry

2.2.2 Coarse Aggregates

Phase 1 incorporated four coarse aggregates (CA): size 57 gravel from north MS (GR1), size 67 gravel from south MS (GR2), size 57 gravel from central MS (GR3), and size 57 limestone from AL (LS1). The sizes are denoted according to ASTM C33. GR1 was sampled from Columbus, MS. GR2 and GR3 were acquired from concrete producers in Gulfport, MS and Crystal Springs, MS, respectively. Representative sampling is shown in Figure 2.2a-b. LS1 was acquired from Tuscaloosa, AL. Coarse aggregates were chosen in coordination with Mississippi Concrete Association (MCA) member companies.

a.) GR2 Material Acquisition b.) GR3 Material Acquisition

c.) Splitter Hopper d.) Splitter Left Side e.) Splitter Inside f.) Splitter Right Side

g.) Water Filling Up Mixer h.) Before Washing Gravel i.) Complete Setup

j.) Gravel Drying k.) Before and After Gravel Washing

Figure 2.2. Gravel Acquisition, Splitting, Washing, and Drying

Phase 2 incorporated four aggregates: crushed gravel from North MS (CG), pea gravel from North MS (PG), GR2 from Phase 1 that was further processed before use, and a limestone from AL (LS). Phase 2 aggregates were sieved and washed and denoted as CG(w), PG(w), GR2(w), and LS(w) for the rest of this report. The Phase 2 coarse aggregates were sieved and material larger than 0.5 in. and smaller than a No. 4 sieve was discarded. The purpose was to keep the coarse aggregates in a similar size range for Phase 2. Coarse aggregates between 0.5 in. and No. 4 sieve were washed in a 3ft^3 concrete mixer for approximately 3 minutes to remove fine particles similarly to fine aggregates (Figure 2.2g-i). The only difference between washing the fine and coarse aggregate was the time of washing. The material was then drained and spread over plastic sheeting to dry (Figure 2.2j). The material was mixed regularly by hand, and moisture contents were taken until moisture content equalized. With exception of LS(w), all aggregates were split similarly to the fine aggregate after reaching a consistent moisture content (Figure 2.2c-f). LS(w) was sieved into two size ranges initially, -0.5 in.|+0.38 in. and -0.38 in.|+No. 4, and combined by hand to achieve a 50% mixture of the two sizes. The coarse aggregate gradations and specific gravities for Phase 1 and Phase 2 are given in Table 2.2.

Table 2.2. Coarse Aggregate Properties – Phases 1 and 2

	Phase 1 Aggregates				**Phase 2 Aggregates**			
Aggregate ID	GR1	GR2	GR3	LS1	CG(w)	PG(w)	GR2(w)	LS(w)
Source	Bacco	Lafarge	Krystal	Vulcan	Scribner	Bacco	Lafarge	Vulcan
ASTM C33 Size	57	67	57	57	---	---	---	---
Water Absorption (%)	3.2	3.8	3.1	0.4	4.1	3.9	3.3	0.3
Bulk Specific Gravity (OD)	2.39	2.40	2.45	2.72	2.35	2.36	2.42	2.76
Bulk Specific Gravity (SSD)	2.47	2.49	2.53	2.73	2.45	2.45	2.50	2.77
% Passing 1.50 in.	---	---	---	---	---	---	---	---
% Passing 1.00 in.	96	100	95	98	---	---	---	---
% Passing 0.75 in.	84	96	84	84	---	---	---	---
% Passing 0.50 in.	62	64	47	38	100	100	96	96
% Passing 0.38 in.	32	22	26	16	85	100	34	56
% Passing 0.31 in.	---	---	---	---	63	98	10	30
% Passing 0.265 in.	---	---	---	---	45	81	4	15
% Passing No. 3.5	---	---	---	---	21	37	1	6
% Passing No. 4	6	1	2	5	4	4	0	1
% Passing No. 8	0	0	1	4	---	---	---	---
% Passing No. 200	---	---	---	---	0.2	0.1	0.2	0.5

Note: LS1 is from Tuscaloosa, AL, and LS(w) is from Calera, AL

2.2.3 Admixtures

The admixtures used in Phase 1 are given in Table 2.3 along with the respective dosage rates for gravel concrete, limestone concrete, and cement paste. Initial trial testing of concrete had the same dosage rates as the cement paste. The admixture dosage rates of concrete were adjusted to achieve desired fresh mix properties. Concrete with limestone had to use a slightly higher dosage of the high range water reducer (Glenium 7500) than gravel concrete. Some cement paste testing was conducted at the same dosage rates as the gravel concrete to investigate admixture effects on cement paste results (discussed later). No admixtures were used in Phase 2 mixtures.

Table 2.3. Phase 1 Admixtures

Admixture	Admixture ID	Type	GR Concrete Dosage Rate (oz./cwt)	LS Concrete Dosage Rate (oz./cwt)	Cement Paste Dosage Rate[1] (oz./cwt)
Pozzolith 322	AM1	C494 A,B,D	1.5	1.5	3.0
Glenium 7500	AM2	C494 A,F	2.0	2.8	3.5
Z-60	AM3	C494 S	3.0	3.0	3.7
MB-AE 90	AM4	C260 Air Entraining	0.3	0.3	0.3

Note: AM= Admixture, GR= Gravel, LS= Limestone
1: Some cement paste was made at GR concrete dosage rates for verification purposes and these specimens were denoted with (*).

2.2.4 Cement

Five cements were used in Phase 1 from 3 different cement producers. Three cements were ASTM C150 Type I portland cement (OPC) and two were ASTM C595 Type IL portland-limestone cement (PLC). Each cement has an ID which specifies type and source. For example, OPC2 and PLC2 indicate an OPC and PLC from source 2. Phase 2 only used two cements. OPC1b and PLC1b were obtained from the same source as OPC1 and PLC1 but at a different time. Table 2.4 displays the cement properties. All the cements varied in limestone content and Blaine fineness.

Table 2.4. Cement Properties

	Phase 1 Cements					Phase 2 Cements	
Cement ID	OPC1	PLC1	OPC2	PLC2	OPC3	OPC1b	PLC1b
Type	C150-I	C595-IL	C150-I	C595-IL	C150-I	C150-I	C595-IL
SiO2	20.2	---	19.0	17.8	19.0	20.4	---
Al2O3	4.7	---	5.7	5.3	4.6	4.8	---
Fe2O3	3.3	---	3.4	3.4	3.2	3.4	---
CaO	64.7	---	64.1	63.4	63.1	66.3	---
MgO	0.9	0.9	0.8	0.8	3.1	1	1
SO3	3.2	3.2	3.2	3.9	3.3	3.1	3.2
Na2O	---	---	0.13	0.12	0.07	---	---
K2O	---	---	0.64	0.61	0.52	---	---
LOI	2.5	4.4	2.31	4.71	2.7	2.4	4.8
% Limestone	4.3	10.0	2.2	9.0	4.1	4.4	10.0
Blaine Fineness (m^2/kg)	418	530	432	522	407	405	550
1-Day Strengths (psi)	---	---	2557	2882	2176	---	---
3-Day Strengths (psi)	4045	4460	4169	4616	3742	3887	4496
7-Day Strenghts (psi)	5185	5285	5135	5506	4612	5033	5685
28-Day Strengths (psi)	---	6685	6302	6203	6106	---	7049
Vicat Initial (min)	102	110	90	95	105	111	113
Vicat Final (min)	---	---	170	160	205	---	---

Note: LOI = loss on ignition, psi = pounds per square inch, Strengths are ASTM C109 mortar cube strengths

2.2.5 Supplementary Cementitious Materials

For Phase 1, three ASTM C618 fly ash (FA) materials were used. FA1 was a lower calcium Class F fly ash. FA2 was a higher calcium Class F fly ash. FA3 was a Class C fly ash. Fly ash properties are given in Table 2.5 which were typical source properties provided by suppliers. For Phase 2, FA2 and FA3a were used. FA3a came from the same source as FA3 but at a different time.

Table 2.5. Fly Ash Properties – Phases 1 and 2

SCM ID	FA1	FA2	FA3	FA3a
Phase	1	1 and 2	1	2
Class	F	F	C	C
SiO2	54.1	47.3	38.3	37.9
Al2O3	27.5	21.3	20.5	20.1
Fe2O3	7.4	16.2	6.3	6.7
CaO	1.6	6.5	22.1	23.2
SO3	0.4	2.4	1.6	1.6
Na2O	0.7	0.6	1.5	1.5
K2O	0.9	2.3	---	0.6
LOI	3.5	0.9	0.5	0.4
Fineness (%)	18.5	12.7	15.7	23.8
SG	2.16	2.43	2.63	2.60

Note: SG = specific gravity

2.3 Concrete Specimen Production

Batching and mixing of materials were the same for Phase 1 and Phase 2 with the exception of admixture addition in Phase 1. Materials were pre-batched and conditioned in one of two places: 1) if the temperature was less than 60°F, materials were stored inside a temperature controlled building; or 2) when the temperature was 60°F or higher, materials were stored in an exterior non temperature controlled building. In some cases, warm batch water was added to the mixtures. Mixing was conducted in accordance with ASTM C192 using a 6ft^3 mixer to produce 2ft^3 batches. The water to cementitious (*w/cm*) ratio of concrete was 0.44 for Phase 1 and 0.52 for Phase 2. For Phase 1, admixtures were added with the first half of the batch water except for the high range water reducer (AM2). AM2 was added in halves when introducing head water and tail water. There was no admixture in Phase 2. Concrete mixture designs for Phase 1 and Phase 2 are given in Tables 2.6 and 2.7. Overall, there were 114 mixtures, each with 18 specimens. There were 2,052 total specimens produced, but due to two testing errors, only 2,050 specimen data points were included in this report.

In accordance with ASTM C192, specimens were produced by filling 4 in. by 8 in. cylinder molds in two equal lifts and rodding 25 times per lift. The sides of the molds were tapped 12 times to consolidate the concrete between lifts. Once the second lift was complete, the specimens were placed on a lab bench, floated, and covered with a plastic bag and a rubber band to prevent moisture evaporation (Figure 2.3a). After approximately 24 hours, the specimens were extruded with compressed air and placed into a 100% humidity, 73.5±3.5°F moist room (Figure 2.3b).

a.) Specimens on Counter

b.) Specimens in Curing Room

Figure 2.3 Specimen Curing

The mixture identification (Mix ID) terminology used throughout this report is explained in this paragraph. Equation 2.1 shows how Mix IDs are interpreted. For example, Mix 23 (65OPC1/35FA2-GR2) is interpreted as 65% OPC1 cement with 35% FA2 made with GR2 aggregate. Fly ash replacement rates used 2017 Edition Mississippi Department of Transportation (MDOT) specifications (i.e. Red Book) as a guide. The MDOT Red Book specifies a maximum of 25% fly ash replacement with OPC, but a maximum of 35% fly ash replacement can be used with PLC.

$$1A/2B\text{-}C \tag{2.1}$$

Where,

1 = % Cement (100, 75, or 65)
A = Cement ID (OPC1, PLC1, OPC2, PLC2, OPC3, OPC1b, or PLC1b)
2 = % Fly Ash (0, 25, or 35)
B = Fly ash ID (FA1, FA2, FA3, or FA3a)
C = Aggregate ID (GR1, GR2, GR3, LS1, CG(w), PG(w), GR2(w), or LS(w))

Table 2.6. Phase 1 Mix Designs on a 1 yd^3 Basis

Mix No.	Mix ID	CA (lb)	Sand (lb)	Cement (lb)	Fly Ash (lb)	Air (%)	Water (lb)	Mix No.	Mix ID	CA (lb)	Sand (lb)	Cement (lb)	Fly Ash (lb)	Air (%)	Water (lb)
1	75OPC2/25FA2-GR1	1735	1204	426	142	4.5	250	38	65PLC2/35FA3-GR1	1735	1201	369	199	4.5	250
2	75OPC2/25FA2-LS1	1918	1204	426	142	4.5	250	39	100OPC3/0FA-GR2	1749	1238	568	0	4.5	250
3	75OPC1/25FA2-GR1	1735	1204	426	142	4.5	250	40	65PLC2/35FA3-GR2	1749	1201	369	199	4.5	250
4	75PLC1/25FA2-GR1	1735	1198	426	142	4.5	250	41	65OPC3/35FA3-GR2	1749	1206	369	199	4.5	250
5	75PLC2/25FA2-GR1	1735	1198	426	142	4.5	250	42	75OPC3/25FA2-GR2	1749	1204	426	142	4.5	250
6	75OPC1/25FA2-LS1	1918	1204	426	142	4.5	250	43	65PLC2/35FA2-GR2	1749	1185	369	199	4.5	250
7	75PLC1/25FA2-LS1	1917	1198	426	142	4.5	250	44	75OPC1/25FA3-GR3	1777	1215	426	142	4.5	250
8	75PLC2/25FA2-LS1	1918	1198	426	142	4.5	250	45	75PLC1/25FA3-LS1	1918	1210	426	142	4.5	250
9	65OPC1/35FA2-GR1	1735	1190	369	199	4.5	250	46	75PLC1/25FA3-GR1	1735	1210	426	142	4.5	250
10	65OPC1/35FA2-LS1	1918	1190	369	199	4.5	250	47	75PLC1/25FA3-GR3	1777	1210	426	142	4.5	250
11	65OPC3/35FA2-GR1	1735	1190	369	199	4.5	250	48	75PLC2/25FA3-LS1	1918	1210	426	142	4.5	250
12	65OPC3/35FA2-LS1	1918	1190	369	199	4.5	250	49	75PLC2/25FA3-GR1	1735	1210	426	142	4.5	250
13	100PLC1/0FA-GR1	1735	1231	568	0	4.5	250	50	75PLC2/25FA3-GR3	1777	1210	426	142	4.5	250
14	100PLC1/0FA-GR2	1749	1231	568	0	4.5	250	51	65OPC2/35FA3-LS1	1918	1206	369	199	4.5	250
15	100PLC1/0FA-GR3	1777	1231	568	0	4.5	250	52	65OPC2/35FA3-GR1	1735	1206	369	199	4.5	250
16	100PLC1/0FA-LS1	1918	1231	568	0	4.5	250	53	65OPC2/35FA3-GR3	1777	1206	369	199	4.5	250
17	75OPC3/25FA3-LS1	1918	1215	426	142	4.5	250	54	65OPC2/35FA2-LS1	1918	1190	369	199	4.5	250
18	75OPC3/25FA3-GR1	1735	1215	426	142	4.5	250	55	65OPC2/35FA2-GR1	1735	1190	369	199	4.5	250
19	75OPC3/25FA3-GR2	1749	1215	426	142	4.5	250	56	65OPC2/35FA2-GR3	1777	1190	369	199	4.5	250
20	75OPC3/25FA3-GR3	1777	1215	426	142	4.5	250	57	65OPC1/35FA3-LS1	1918	1206	369	199	4.5	250
21	65OPC3/35FA2-GR2	1749	1190	369	199	4.5	250	58	65OPC1/35FA3-GR1	1735	1206	369	199	4.5	250
22	65OPC3/35FA2-GR3	1777	1190	369	199	4.5	250	59	65OPC1/35FA3-GR3	1777	1206	369	199	4.5	250
23	65OPC1/35FA2-GR2	1749	1190	369	199	4.5	250	60	100OPC1/0FA-LS1	1918	1238	568	0	4.5	250
24	65OPC1/35FA2-GR3	1777	1190	369	199	4.5	250	61	100OPC1/0FA-GR1	1735	1238	568	0	4.5	250
25	65PLC2/35FA2-LS1	1918	1185	369	199	4.5	250	62	75OPC2/25FA3-GR3	1777	1215	426	142	4.5	250
26	65PLC2/35FA2-GR1	1735	1185	369	199	4.5	250	63	65PLC1/35FA1-LS1	1918	1158	369	199	4.5	250
27	65PLC1/35FA2-LS1	1918	1185	369	199	4.5	250	64	65PLC1/35FA1-GR1	1735	1158	369	199	4.5	250
28	65PLC1/35FA2-GR1	1735	1185	369	199	4.5	250	65	75OPC1/25FA1-LS1	1918	1185	426	142	4.5	250
29	75PLC1/25FA2-GR2	1749	1198	426	142	4.5	250	66	75OPC1/25FA1-GR1	1735	1185	426	142	4.5	250
30	75PLC1/25FA2-GR3	1777	1198	426	142	4.5	250	67	65OPC1/35FA1-LS1	1918	1163	369	199	4.5	250
31	75OPC2/25FA3-LS1	1918	1215	426	142	4.5	250	68	65OPC1/35FA1-GR1	1735	1163	369	199	4.5	250
32	75OPC2/25FA3-GR1	1735	1215	426	142	4.5	250	69	65PLC2/35FA3-GR3	1777	1201	369	199	4.5	250
33	75OPC1/25FA3-LS1	1918	1215	426	142	4.5	250	70	65PLC1/35FA3-GR3	1777	1201	369	199	4.5	250
34	75OPC1/25FA3-GR1	1735	1215	426	142	4.5	250	71	75OPC2/25FA2-GR3	1777	1204	426	142	4.5	250
35	65PLC1/35FA3-LS1	1918	1201	369	199	4.5	250	72	75OPC1/25FA2-GR3	1777	1204	426	142	4.5	250
36	65PLC1/35FA3-GR1	1735	1201	369	199	4.5	250	73	65PLC1/35FA2-GR3	1777	1185	369	199	4.5	250
37	65PLC2/35FA3-LS1	1918	1201	369	199	4.5	250	74	65PLC2/35FA2-GR3	1777	1185	369	199	4.5	250

Note: Aggregate masses reported are at saturated surface dry (SSD)
Water added (250 lb) was in excess of aggregate absorption

Table 2.7. Phase 2 Mix Designs on a 1 yd^3 Basis

Mix No.	Mix ID	CA (lb)	Sand (lb)	Cement (lb)	Fly Ash (lb)	Air (%)	Water (lb)
75	100OPC1b/0FA-LS(w)	1936	1233	568	0	2.0	295
76	100PLC1b/0FA-LS(w)	1936	1225	568	0	2.0	295
77	75OPC1b/25FA2-LS(w)	1936	1198	426	142	2.0	295
78	75PLC1b/25FA2-LS(w)	1936	1192	426	142	2.0	295
79	75OPC1b/25FA3a-LS(w)	1936	1208	426	142	2.0	295
80	75PLC1b/25FA3a-LS(w)	1936	1202	426	142	2.0	295
81	65OPC1b/35FA2-LS(w)	1936	1184	369	199	2.0	295
82	65PLC1b/35FA2-LS(w)	1936	1179	369	199	2.0	295
83	65OPC1b/35FA3a-LS(w)	1936	1198	369	199	2.0	295
84	65PLC1b/35FA3a-LS(w)	1936	1193	369	199	2.0	295
85	100OPC1b/0FA-GR2(w)	1746	1233	568	0	2.0	295
86	100PLC1b/0FA-GR2(w)	1746	1225	568	0	2.0	295
87	75OPC1b/25FA2-GR2(w)	1746	1198	426	142	2.0	295
88	75PLC1b/25FA2-GR2(w)	1746	1192	426	142	2.0	295
89	75OPC1b/25FA3a-GR2(w)	1746	1208	426	142	2.0	295
90	75PLC1b/25FA3a-GR2(w)	1746	1202	426	142	2.0	295
91	65OPC1b/35FA2-GR2(w)	1746	1184	369	199	2.0	295
92	65PLC1b/35FA2-GR2(w)	1746	1179	369	199	2.0	295
93	65OPC1b/35FA3a-GR2(w)	1746	1198	369	199	2.0	295
94	65PLC1b/35FA3a-GR2(w)	1746	1193	369	199	2.0	295
95	100OPC1b/0FA-CG1(w)	1713	1233	568	0	2.0	295
96	100PLC1b/0FA-CG1(w)	1713	1225	568	0	2.0	295
97	75OPC1b/25FA2-CG1(w)	1713	1198	426	142	2.0	295
98	75PLC1b/25FA2-CG1(w)	1713	1192	426	142	2.0	295
99	75OPC1b/25FA3a-CG1(w)	1713	1208	426	142	2.0	295
100	75PLC1b/25FA3a-CG1(w)	1713	1202	426	142	2.0	295
101	65OPC1b/35FA2-CG1(w)	1713	1184	369	199	2.0	295
102	65PLC1b/35FA2-CG1(w)	1713	1179	369	199	2.0	295
103	65OPC1b/35FA3a-CG1(w)	1713	1198	369	199	2.0	295
104	65PLC1b/35FA3a-CG1(w)	1713	1193	369	199	2.0	295
105	100OPC1b/0FA-PG1(w)	1716	1233	568	0	2.0	295
106	100PLC1b/0FA-PG1(w)	1716	1225	568	0	2.0	295
107	75OPC1b/25FA2-PG1(w)	1716	1198	426	142	2.0	295
108	75PLC1b/25FA2-PG1(w)	1716	1192	426	142	2.0	295
109	75OPC1b/25FA3a-PG1(w)	1716	1208	426	142	2.0	295
110	75PLC1b/25FA3a-PG1(w)	1716	1202	426	142	2.0	295
111	65OPC1b/35FA2-PG1(w)	1716	1184	369	199	2.0	295
112	65PLC1b/35FA2-PG1(w)	1716	1179	369	199	2.0	295
113	65OPC1b/35FA3a-PG1(w)	1716	1198	369	199	2.0	295
114	65PLC1b/35FA3a-PG1(w)	1716	1193	369	199	2.0	295

Note: Aggregate masses reported are at SSD
Water added (295 lb) was in excess of aggregate absorption

2.3.1 Concrete Testing

The fresh mixed concrete was tested for slump (ASTM C143), unit weight (ASTM C138), air content using the pressure method (ASTM C231), set time (ASTM C403), and mixture temperature. Once specimens hardened, four tests were conducted. Surface resistivity (SR) (AASHTO TP 95) was conducted at 3, 7, 28, 56 days (D) for Phase 1 and Phase 2. After surface resistivity the same specimens were tested for compressive strength (f_c) and elastic modulus (E) in accordance with ASTM C39 and ASTM C469, respectively. Specimens were tested at 3, 7, 28, and 56D for f_c, while E was only determined at 7 and 28D. The fourth test conducted was splitting tensile (*T*) in accordance with ASTM C496. Tensile strength was determined at 7 and 28D. After tensile testing, photographs were taken of the fractured face of one specimen from every mixture to visually assess fractured faces. These photos are contained in Appendix A. Compressive strength, modulus of elasticity, and tensile testing were conducted the same in Phase 1 and Phase 2, while resistivity testing was slightly different between phases.

2.3.1.1 Slump Test (ASTM C143)

The slump cone was filled in three lifts and each lift was rodded 25 times. After the three lifts were complete, the cone was lifted vertically in 5 ± 2 seconds. The slump cone was placed upside down on the plate next to the slumped concrete. Using the tamping rod and a ruler, the slump was measured and recorded to the nearest 0.25 in. from the bottom of the rod to the concrete's displaced center.

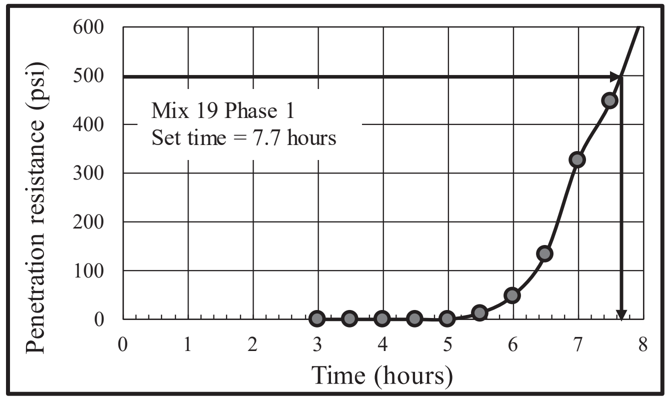
2.3.1.2 Unit Weight (ASTM C138) and Air Content (ASTM C231)

Unit weight (UW) and air content used the same measure and were performed simultaneously. The measure was filled in three even lifts, rodding each lift 25 times, and then each lift was consolidated by tapping the measure with a rubber mallet 12 times. After final consolidation, a fiberglass strike-off plate was used to remove excess concrete. If needed the edge of the plate was used to smooth out the surface of the concrete. Excess concrete was removed from the outside of the measure and the weight was recorded for UW determination. After the weight was measured, the vertical type B air meter was attached to the top of the measure. Once attached, the valves were opened and water was added to fill any remaining voids. Water was added until air bubbles stopped coming out of the opposite valve, and then the valves were closed. Air pressure was built up within the air meter until reaching the calibration point. The pressure was released with a simultaneous blow from the rubber mallet against the side of the measure and the air content was recorded to the nearest tenth of a percent.

2.3.1.3 Set Time (ASTM C403)

A No. 4 sieve was used to separate mixed concrete where any particle larger than a No. 4 sieve was discarded, leaving all remaining material for set time measurements. The container was filled with sieved concrete to a height of approximately 5.5 in. and the temperature was recorded before placing the specimen on a lab bench. Beginning at 3 hours, the specimen was tested every half hour with a handheld penetrometer until it reached a resistance of at least 500 psi. The concrete set time (t_{C403}) was determined by graphing the resistance over time and finding the time corresponding to 500 psi. Figure 2.4 shows an example specimen and typical penetration versus time curve.

a.) Penetrometer Setting



b.) Example Set Time Curve

Figure 2.4. Concrete Setting Time

2.3.1.4 Surface Resistivity (AASHTO TP 95)

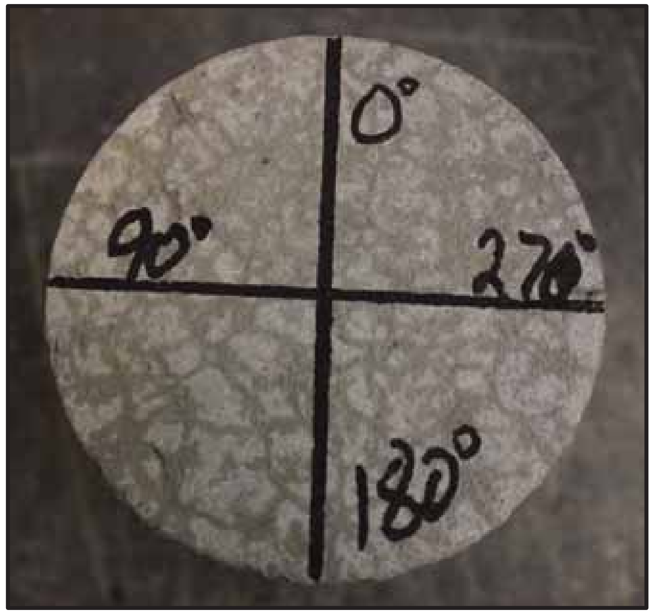
For Phase 1, surface resistivity (SR) testing was performed at 3, 7, 28, and 56D using AASHTO TP 95 as a guide, but with some deviations. Readings were taken on saturated surface wet specimens, but only four readings per specimen were recorded (instead of 8 readings) and the coefficient of variation (COV) was not calculated at 28 and 56D. Resistivity for Phase 2 was conducted in accordance with TP 95. In Phase 2, eight readings on each specimen were recorded and the COV for 28 and 56D specimens was calculated (equation 2.2). Specimens were tested at saturated surface wet conditions immediately after removal from the moist room. The top of the specimen was marked to indicate four points 90° apart. The specimen was then placed in a holder to prevent rolling. The tips of the resistivity meter were dipped in water to ensure saturation and then pressed against the surface of the cylinder for readings. The sensors on the resistivity meter were spaced equidistant from the top and bottom edges of the cylinder while avoiding any voids which may appear on the surface. Once the first reading was taken, the cylinder was rotated 90° so that the next point was facing upward and the process was repeated until each point had two readings. The surface resistivity process is shown in Figure 2.5. For 28 and 56D specimens, the readings were averaged, sample standard deviation determined, and COV calculated. If a specimen had a COV of greater than 7.5%, the specimen was submerged in a 68-77°F water bath for 2 hours and the resistivity readings were repeated immediately upon removal from the bath. For this data set, this procedure was only required for four specimens. The readings with the lower COV, whether initial or after submersion, were reported.

$$COV = \frac{\sigma}{\mu} * 100 \qquad (2.2)$$

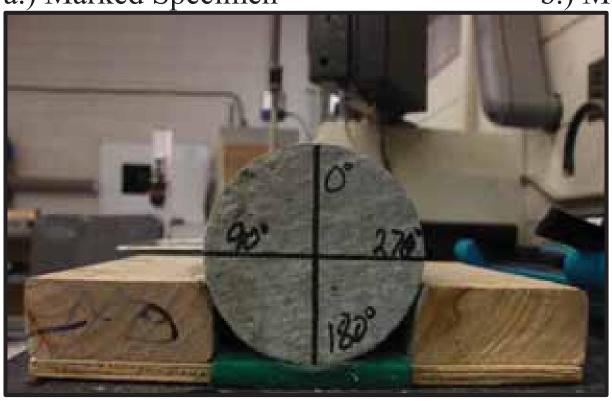
Where,

COV = Coefficient of Variation
σ = Sample Standard Deviation
μ = Sample Mean

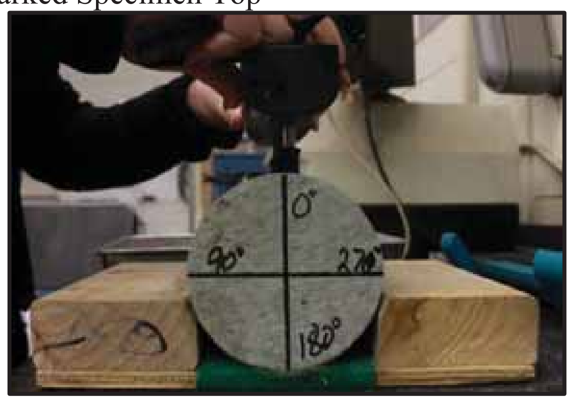
a.) Marked Specimen



b.) Marked Specimen Top



c.) Specimen in Holder



d.) Specimen Being Tested

Figure 2.5. Surface Resistivitiy Testing

2.3.1.5 Compressive Strength (ASTM C39)

Tests for compressive strength (f_c) were conducted at 3, 7, 28, and 56D according to ASTM C39. Three specimens were tested for each test day and averaged. In Phase 1, specimens were individually taken from the moist room, tested for resistivity, then tested for f_c using a 600 kip capacity load frame, and readings were recorded in psi. For Phase 2, specimens were individually taken from the moist room, tested for resistivity, and placed back in the moist room while other specimens were tested for resistivity. Resistivity testing did not prevent C39 time tolerances from being met. The purpose of placing Phase 2 specimens back in the moist room was to keep specimens moist while checking required COV for resistivity (at 28 and 56D). Phase 2 specimens were not tested for f_c until specimens were found to be within the required COV or until those that were outside the COV requirement had been soaked for 2 hours. When testing for f_c, the tops and bottoms of specimens were covered with metal caps containing ASTM C1231 70 durometer unbonded neoprene pads rated for loads up to 12,000 psi. All tests used the standard load rate of 35±15 psi/s. Specimens were loaded until failure and the maximum stress was recorded. An example testing setup is shown in Figure 2.6.

Figure 2.6. Example f_c Testing Setup

2.3.1.6 Modulus of Elasticity (ASTM C469)

Of the three specimens selected for f_c testing, two underwent ASTM C469 (with one deviation) to find the modulus of elasticity (E). Specimens tested for E had a collar with a dial to measure the change in length of the specimen during loading. To determine the maximum load, one specimen was broken and 40% of the maximum load from that specimen was used for modulus testing. This is a deviation from the standard. ASTM C469 requires the average of two concrete compressive strengths to determine 40% of the max load for one modulus determination. The authors elected to collect two modulus replicates based on one f_c value instead of one modulus value based on two f_c replicates.

Once the collar was attached, the specimen was placed in the load frame using the same caps as in f_c testing. During loading dial displacements were recorded at 8, 16, 24, 32, and 40% of the maximum load previously recorded. The modulus testing underwent three loading cycles. Readings for cycle 1 were discarded and cycle 2 and 3 were averaged. The dial readings were converted to strain using equation 2.3 (gage length was 5.25 in). The modulus of the two replicates was determined by the slope of the stress-strain line and the two modulus values were averaged for one representative value. The modulus testing setup is shown in Figure 2.7.

$$\varepsilon = \frac{dr * .0001}{2 * 5.25} \tag{2.3}$$

Where,

ε = Strain

dr = Dial Reading

a.) Specimen with Modulus Collar b.) Modulus Test Setup
Figure 2.7. Example Modulus Testing

2.3.1.7 Splitting Tensile Testing (ASTM C496)

Splitting Tensile strength (*T*) was determined in accordance with ASTM C496. Three specimens were tested at 7 and 28D and averaged. Specimens were placed in the load frame with bearing strips between them. Bearing strips were made from 1/8 in. thick birchwood that were 1 in. wide by 8.25 in. long. Specimens were loaded at a ramp rate of 2.5±0.83 psi/s. Specimens were loaded until failure. The maximum load was recorded and T was calculated using equation 2.4. The tensile setup and an example tested specimen are shown in Figure 2.8.

$$T = 2P/\pi l d \tag{2.4}$$

Where,
T = Splitting Tensile Strength
P = Maximum Applied Load Indicated by the Testing Machine
l = Length of Specimen
d = Diameter of Specimen

a.) Tensile Test Setup b) Example Fractured Face

Figure 2.8. Splitting Tensile Testing

2.4 Cement Paste Specimen Production and Testing

2.4.1 Cement Paste Specimen Production

Cement paste (CP) specimens were produced for Phase 1 and Phase 2. CP specimens can be more easily produced than concrete mixtures. Over 20 different CP mixtures can be produced in one day by one lab operator. The next paragraph summarizes the cement paste mixing and cylinder production methods, which were conducted as recommended by Hansen and Howard (2019).

CP cylinders (2 in. by 4 in.) were made by adding powdered cementitious materials with the same proportions as concrete (no aggregates) into a mixing bowl. All materials were conditioned for approximately 24 hours prior to mixing. Water and admixture (if used) were combined and then added to the dry cementitious materials. The *w/cm* ratio of cement paste specimens matched their corresponding concrete at 0.44 and 0.52 for Phase 1 and 2, respectively. The cement paste mix designs for Phase 1 and 2 can be found in Tables 2.8 and 2.9. The horizontal line in Table 2.8 differentiates the main paste study from an admixture dosage study discussed later in this report. Admixture effects specimens were denoted with an (*). A hand-held kitchen mixer was used to mix the ingredients on low for 30 Seconds (s) and then on medium for another 30s. The cement paste was then poured into 2 in. by 4 in. cylinders using a funnel. CP cylinders were filled all the way to the top, and the corner of a plastic bag was secured on the top of specimens with a rubber band to prevent moisture evaporation. The mixing process is shown in Figure 2.9. CP cylinders were cured the same as concrete. Cement paste can sometimes show high variability, especially at later ages, so specimens were made in batches of five. The maximum and minimum loads were removed and the middle three values were averaged and used for compressive strength determination.

Table 2.8. Phase 1 Cement Paste Mix Designs (quantities for one batch of 5 cylinders)

Mix ID	Cement (lb)	Fly Ash (lb)	Water (lb)	AM1 (mL)	AM2 (mL)	AM3 (mL)	AM4 (mL)
100OPC1/0FA	2.98	0	1.31	2.6	3.1	3.3	0.3
100PLC1/0FA	2.98	0	1.31	2.6	3.1	3.3	0.3
100OPC2/0FA	2.98	0	1.31	2.6	3.1	3.3	0.3
100PLC2/0FA	2.98	0	1.31	2.6	3.1	3.3	0.3
100OPC3/0FA	2.98	0	1.31	2.6	3.1	3.3	0.3
85OPC1/15FA1	2.53	0.45	1.31	2.6	3.1	3.3	0.3
85PLC1/15FA1	2.53	0.45	1.31	2.6	3.1	3.3	0.3
85OPC2/15FA1	2.53	0.45	1.31	2.6	3.1	3.3	0.3
85PLC2/15FA1	2.53	0.45	1.31	2.6	3.1	3.3	0.3
85OPC3/15FA1	2.53	0.45	1.31	2.6	3.1	3.3	0.3
85OPC1/15FA2	2.53	0.45	1.31	2.6	3.1	3.3	0.3
85PLC1/15FA2	2.53	0.45	1.31	2.6	3.1	3.3	0.3
85OPC2/15FA2	2.53	0.45	1.31	2.6	3.1	3.3	0.3
85PLC2/15FA2	2.53	0.45	1.31	2.6	3.1	3.3	0.3
85OPC3/15FA2	2.53	0.45	1.31	2.6	3.1	3.3	0.3
85OPC1/15FA3	2.53	0.45	1.31	2.6	3.1	3.3	0.3
85PLC1/15FA3	2.53	0.45	1.31	2.6	3.1	3.3	0.3
85OPC2/15FA3	2.53	0.45	1.31	2.6	3.1	3.3	0.3
85PLC2/15FA3	2.53	0.45	1.31	2.6	3.1	3.3	0.3
85OPC3/15FA3	2.53	0.45	1.31	2.6	3.1	3.3	0.3
75OPC1/25FA1	2.23	0.74	1.31	2.6	3.1	3.3	0.3
75PLC1/25FA1	2.23	0.74	1.31	2.6	3.1	3.3	0.3
75OPC2/25FA1	2.23	0.74	1.31	2.6	3.1	3.3	0.3
75PLC2/25FA1	2.23	0.74	1.31	2.6	3.1	3.3	0.3
75OPC3/25FA1	2.23	0.74	1.31	2.6	3.1	3.3	0.3
75OPC1/25FA2	2.23	0.74	1.31	2.6	3.1	3.3	0.3
75PLC1/25FA2	2.23	0.74	1.31	2.6	3.1	3.3	0.3
75OPC2/25FA2	2.23	0.74	1.31	2.6	3.1	3.3	0.3
75PLC2/25FA2	2.23	0.74	1.31	2.6	3.1	3.3	0.3
75OPC3/25FA2	2.23	0.74	1.31	2.6	3.1	3.3	0.3
75OPC1/25FA3	2.23	0.74	1.31	2.6	3.1	3.3	0.3
75PLC1/25FA3	2.23	0.74	1.31	2.6	3.1	3.3	0.3
75OPC2/25FA3	2.23	0.74	1.31	2.6	3.1	3.3	0.3
75PLC2/25FA3	2.23	0.74	1.31	2.6	3.1	3.3	0.3
75OPC3/25FA3	2.23	0.74	1.31	2.6	3.1	3.3	0.3
65OPC1/35FA1	1.93	1.04	1.31	2.6	3.1	3.3	0.3
65PLC1/35FA1	1.93	1.04	1.31	2.6	3.1	3.3	0.3
65OPC2/35FA1	1.93	1.04	1.31	2.6	3.1	3.3	0.3
65PLC2/35FA1	1.93	1.04	1.31	2.6	3.1	3.3	0.3
65OPC3/35FA1	1.93	1.04	1.31	2.6	3.1	3.3	0.3
65OPC1/35FA2	1.93	1.04	1.31	2.6	3.1	3.3	0.3
65PLC1/35FA2	1.93	1.04	1.31	2.6	3.1	3.3	0.3
65OPC2/35FA2	1.93	1.04	1.31	2.6	3.1	3.3	0.3
65PLC2/35FA2	1.93	1.04	1.31	2.6	3.1	3.3	0.3
65OPC3/35FA2	1.93	1.04	1.31	2.6	3.1	3.3	0.3
65OPC1/35FA3	1.93	1.04	1.31	2.6	3.1	3.3	0.3
65PLC1/35FA3	1.93	1.04	1.31	2.6	3.1	3.3	0.3
65OPC2/35FA3	1.93	1.04	1.31	2.6	3.1	3.3	0.3
65PLC2/35FA3	1.93	1.04	1.31	2.6	3.1	3.3	0.3
65OPC3/35FA3	1.93	1.04	1.31	2.6	3.1	3.3	0.3
100OPC3/0FA*	2.98	0	1.31	1.3	1.8	2.6	0.3
75OPC3/25FA1*	2.23	0.74	1.31	1.3	1.8	2.6	0.3
75OPC3/25FA2*	2.23	0.74	1.31	1.3	1.8	2.6	0.3
75OPC3/25FA3*	2.23	0.74	1.31	1.3	1.8	2.6	0.3
65OPC3/35FA1*	1.93	1.04	1.31	1.3	1.8	2.6	0.3
65OPC3/35FA2*	1.93	1.04	1.31	1.3	1.8	2.6	0.3
65OPC3/35FA3*	1.93	1.04	1.31	1.3	1.8	2.6	0.3

Table 2.9 Phase 2 Cement Paste Mix Designs

Mix ID	Cement (lb)	Fly Ash (lb)	Water (lb)
100OPC1b/0FA	2.98	0	1.55
100PLC1b/0FA	2.98	0	1.55
75OPC1b/25FA2	2.23	0.74	1.55
75PLC1b/25FA2	2.23	0.74	1.55
75OPC1b/25FA3a	2.23	0.74	1.55
75PLC1b/25FA3a	2.23	0.74	1.55
65OPC1b/35FA2	1.93	1.04	1.55
65PLC1b/35FA2	1.93	1.04	1.55
65OPC1b/35FA3a	1.93	1.04	1.55
65PLC1b/35FA3a	1.93	1.04	1.55

Note: No admixtures were used in Phase 2

a.) Cement Paste Mixing Equipment b.) Cement Paste Mixing

c.) Filled Specimen d.) Topped Specimen e.) Ex. Specimen f.) f_{cp} Testing Setup

Figure 2.9. Equipment for Paste Specimen Production

2.4.2 Cement Paste Testing

Phase 1 tested 2 in. by 4 in. cylindrical specimens in compression at 7 and 28D. Phase 2 tested 2 in. by 4 in. specimens in compression at 3, 7, 28, and 56D. Cement paste compressive strength is denoted f_{cp}. All cement paste specimens were cured and tested in accordance with ASTM C192 and C39, respectively. Compressive testing used 70 durometer neoprene pads, similarly to concrete. For strength analysis, the minimum and maximum value were removed. After this removal process, the three remaining strengths were averaged. The compressive strength test setup is shown in Figure 2.9f.

CHAPTER 3 – TEST RESULTS

3.1 Phase 1 Results

There were 74 concrete mixtures and 57 cement paste mixtures made for Phase 1 of this report which totals 1332 and 570 specimens, respectively. In addition to hardened concrete cylinders, concrete's fresh mix properties (slump, temperature, air content, unit weight [UW], and set time [t_{C403}]) were measured and are reported in Table 3.1. Hardened concrete specimens were tested for compressive strength (f_c), modulus of elasticity (E), splitting tensile strength (*T*), and surface resistivity (SR). These values are reported in Tables 3.2 and 3.3. Cement paste was only tested for compressive strength (f_{cp}) (Table 3.4). A testing matrix is given in Table 3.5 which details where results were utilized in this report, since not all mixtures for Phase 1 produced were analyzed in any meaningful detail. Some Phase 1 mixtures were produced for general knowledge for use by MCA member companies.

3.2 Phase 2 Results

There were 40 concrete mixtures and 10 cement paste mixtures made for Phase 2 of this report which totals 720 and 200 specimens, respectively. In addition to hardened concrete cylinders, concrete's fresh mix properties (slump, temperature, air content, UW, and t_{C403}) were measured and are reported in Table 3.6. Hardened concrete specimens were tested for f_c, E, *T*, and SR. These values are reported in Tables 3.7 and 3.8. Table 3.9 helps explain the AASHTO TP95 categories for resistivity. Cement paste was only tested for f_{cp} (Table 3.10).

3.3 Mix Terminology

The mixture identification (Mix ID) terminology used throughout this report is explained in this paragraph. Equation 3.1 (repeated from equation 2.1) shows how Mix IDs are interpreted. For example, Mix 23 (65OPC1/35FA2-GR2) is interpreted as 65% OPC1 cement with 35% FA2 made with GR2 aggregate. Fly ash replacement rates used MDOT' specification book (2017) (Red Book) as a guide. The MDOT Red Book specifies a maximum of 25% fly ash replacement with OPC, but a maximum of 35% fly ash replacement can be used with PLC. Cement paste IDs would be interpreted the same except there is not an aggregate identifier (i.e. 65OPC1/35FA2).

1A/2B-C (3.1)

Where,

1 = % Cement (100, 75, 65)
A = Cement ID (OPC1, PLC1, OPC2, PLC2, OPC3, OPC1b, or PLC1b)
2 = % Fly Ash (0, 25, 35)
B = Fly ash ID (FA1, FA2, FA3, or FA3a)
C = Aggregate ID (GR1, GR2, GR3, LS1, CG(w), PG(w), GR2(w), LS(w))

Table 3.1. Phase 1 Fresh Mixed Concrete Results

Mix No.	Mix ID	UW (lb/ft^3)	Slump (in)	Air (%)	t_{C403} (hr)	Mix No.	Mix ID	UW (lb/ft^3)	Slump (in)	Air (%)	t_{C403} (hr)
1	75OPC2/25FA2-GR1	138.6	7.25	4.7	6.5	38	65PLC2/35FA3-GR1	138.0	8.00	5.0	6.5
2	75OPC2/25FA2-LS1	148.6	7.00	4.1	5.5	39	100OPC3/0FA-GR2	135.6	7.50	6.5	4.5
3	75OPC1/25FA2-GR1	136.2	7.75	5.5	6.0	40	65PLC2/35FA3-GR2	140.4	8.50	4.2	7.0
4	75PLC1/25FA2-GR1	138.0	6.75	5.7	5.5	41	65OPC3/35FA3-GR2	137.8	8.75	5.2	7.0
5	75PLC2/25FA2-GR1	138.4	7.00	5.2	5.5	42	75OPC3/25FA2-GR2	138.2	8.00	5.0	6.0
6	75OPC1/25FA2-LS1	146.3	5.75	4.8	6.0	43	65PLC2/35FA2-GR2	140.6	7.75	4.0	6.5
7	75PLC1/25FA2-LS1	149.2	4.00	3.0	6.0	44	75OPC1/25FA3-GR3	140.3	8.50	4.7	6.0
8	75PLC2/25FA2-LS1	149.4	4.00	3.8	5.5	45	75PLC1/25FA3-LS1	149.6	6.25	3.5	4.5
9	65OPC1/35FA2-GR1	136.6	8.00	5.2	7.5	46	75PLC1/25FA3-GR1	140.1	8.00	5.0	5.0
10	65OPC1/35FA2-LS1	148.2	5.00	3.7	6.5	47	75PLC1/25FA3-GR3	140.8	7.25	5.1	5.5
11	65OPC3/35FA2-GR1	136.5	7.75	5.3	7.5	48	75PLC2/25FA3-LS1	150.1	5.25	3.2	4.5
12	65OPC3/35FA2-LS1	144.2	6.50	5.5	7.0	49	75PLC2/25FA3-GR1	141.0	7.75	4.2	5.0
13	100PLC1/0FA-GR1	138.9	5.25	5.1	4.0	50	75PLC2/25FA3-GR3	141.5	6.75	4.4	5.5
14	100PLC1/0FA-GR2	141.4	5.00	5.0	4.5	51	65OPC2/35FA3-LS1	148.3	7.50	3.6	6.0
15	100PLC1/0FA-GR3	140.4	5.75	5.6	3.5	52	65OPC2/35FA3-GR1	139.2	8.25	4.9	6.0
16	100PLC1/0FA-LS1	150.2	2.50	3.1	3.5	53	65OPC2/35FA3-GR3	140.6	8.50	4.8	6.5
17	75OPC3/25FA3-LS1	143.5	7.75	5.9	6.5	54	65OPC2/35FA2-LS1	149.9	6.25	3.1	6.5
18	75OPC3/25FA3-GR1	135.9	7.75	5.8	7.0	55	65OPC2/35FA2-GR1	139.1	8.00	4.5	6.5
19	75OPC3/25FA3-GR2	136.2	8.75	5.5	7.5	56	65OPC2/35FA2-GR3	141.9	8.50	3.8	7.5
20	75OPC3/25FA3-GR3	138.6	7.75	5.5	7.0	57	65OPC1/35FA3-LS1	147.8	7.75	3.9	6.5
21	65OPC3/35FA2-GR2	137.4	8.00	5.1	7.0	58	65OPC1/35FA3-GR1	139.3	8.00	4.7	6.5
22	65OPC3/35FA2-GR3	138.4	7.50	5.3	7.0	59	65OPC1/35FA3-GR3	140.4	8.25	5.0	6.5
23	65OPC1/35FA2-GR2	138.6	7.75	4.6	7.5	60	100OPC1/0FA-LS1	150.0	3.25	3.5	3.5
24	65OPC1/35FA2-GR3	139.6	7.50	4.6	7.0	61	100OPC1/0FA-GR1	139.3	7.50	5.5	3.5
25	65PLC2/35FA2-LS1	147.0	4.75	4.3	6.0	62	75OPC2/25FA3-GR3	141.1	8.25	4.9	5.5
26	65PLC2/35FA2-GR1	138.2	7.75	5.0	7.0	63	65PLC1/35FA1-LS1	150.5	2.25	2.0	3.5
27	65PLC1/35FA2-LS1	151.2	4.00	3.0	6.0	64	65PLC1/35FA1-GR1	142.6	4.50	2.2	3.5
28	65PLC1/35FA2-GR1	139.6	6.25	4.4	6.0	65	75OPC1/25FA1-LS1	151.4	3.75	1.7	4.0
29	75PLC1/25FA2-GR2	138.9	6.50	4.7	5.5	66	75OPC1/25FA1-GR1	142.8	7.00	2.1	3.5
30	75PLC1/25FA2-GR3	139.0	5.00	5.1	5.0	67	65OPC1/35FA1-LS1	149.7	3.75	1.0	4.0
31	75OPC2/25FA3-LS1	144.7	6.75	5.1	6.0	68	65OPC1/35FA1-GR1	140.9	7.00	2.4	4.0
32	75OPC2/25FA3-GR1	137.0	8.00	3.5	6.0	69	65PLC2/35FA3-GR3	141.9	8.25	4.2	6.0
33	75OPC1/25FA3-LS1	145.2	6.50	4.9	6.0	70	65PLC1/35FA3-GR3	141.1	8.00	4.7	5.5
34	75OPC1/25FA3-GR1	137.5	8.00	5.0	6.0	71	75OPC2/25FA2-GR3	141.3	6.75	4.1	5.0
35	65PLC1/35FA3-LS1	147.0	6.50	4.1	6.0	72	75OPC1/25FA2-GR3	141.2	7.50	4.7	5.5
36	65PLC1/35FA3-GR1	137.5	7.50	4.8	6.0	73	65PLC1/35FA2-GR3	142.6	7.00	3.5	6.0
37	65PLC2/35FA3-LS1	147.0	6.25	4.2	6.5	74	65PLC2/35FA2-GR3	142.8	7.75	3.7	6.5

Note: Mix temperature ranged from 63.3 to 86.1°F

Table 3.2. Phase 1 Hardened Concrete Properties – Compressive Strength and Modulus of Elasticity

Mix No.	Mix ID	Compressive Strength (psi)				E (10^6 psi)		Mix No.	Mix ID	Compressive Strength (psi)				E (10^6 psi)	
		3D	7D	28D	56D	7D	28D			3D	7D	28D	56D	7D	28D
1	75OPC2/25FA2-GR1	2719	3333	4471	5054	4.80	4.90	38	65PLC2/35FA3-GR1	2189	3103	4618	5274	4.95	5.25
2	75OPC2/25FA2-LS1	3675	4635	5638	6491	5.40	6.05	39	100OPC3/0FA-GR2	1957	2410	3367	3511	4.53	4.60
3	75OPC1/25FA2-GR1	2203	3185	4328	5427	4.70	5.25	40	65PLC2/35FA3-GR2	1752	2353	3545	3841	4.40	5.20
4	75PLC1/25FA2-GR1	2554	3508	4934	5064	4.85	5.70	41	65OPC3/35FA3-GR2	1486	2026	3532	3761	4.20	4.65
5	75PLC2/25FA2-GR1	2605	3223	4461	5097	4.80	5.45	42	75OPC3/25FA2-GR2	1741	2235	3389	3926	4.30	4.60
6	75OPC1/25FA2-LS1	3541	4557	6254	7568	5.60	6.25	43	65PLC2/35FA2-GR2	1482	2020	3008	3856	4.50	5.15
7	75PLC1/25FA2-LS1	4167	5180	6582	7589	6.70	6.35	44	75OPC1/25FA3-GR3	1696	2612	3878	4538	4.35	4.70
8	75PLC2/25FA2-LS1	3456	4352	5899	6790	5.55	5.95	45	75PLC1/25FA3-LS1	3890	5001	6899	7706	5.85	6.35
9	65OPC1/35FA2-GR1	1983	2650	4504	5110	4.75	5.35	46	75PLC1/25FA3-GR1	2569	3385	4421	5266	4.75	5.15
10	65OPC1/35FA2-LS1	2926	4014	6182	7564	5.30	6.20	47	75PLC1/25FA3-GR3	2361	3190	4247	4554	4.85	5.00
11	65OPC3/35FA2-GR1	1996	2773	3976	4584	4.45	5.10	48	75PLC2/25FA3-LS1	3686	4972	6755	7477	5.70	6.15
12	65OPC3/35FA2-LS1	2682	3718	5307	6474	5.20	5.80	49	75PLC2/25FA3-GR1	2332	3185	4077	5201	4.70	5.35
13	100PLC1/0FA-GR1	3431	4114	5060	6057	5.40	5.85	50	75PLC2/25FA3-GR3	2263	2723	3825	4216	4.75	5.45
14	100PLC1/0FA-GR2	2972	3468	4335	5042	5.15	5.65	51	65OPC2/35FA3-LS1	3323	4512	6253	7181	5.60	6.00
15	100PLC1/0FA-GR3	3253	3902	5074	5196	5.30	5.65	52	65OPC2/35FA3-GR1	2065	2770	3687	4083	4.65	4.90
16	100PLC1/0FA-LS1	5323	6122	7414	7873	6.20	6.60	53	65OPC2/35FA3-GR3	1944	2615	3423	3801	4.70	4.70
17	75OPC3/25FA3-LS1	2993	3984	5835	6565	5.10	5.45	54	65OPC2/35FA2-LS1	2917	3754	5077	6028	5.05	5.25
18	75OPC3/25FA3-GR1	1956	2770	4486	5051	4.40	5.20	55	65OPC2/35FA2-GR1	2008	2342	3622	4330	4.20	4.65
19	75OPC3/25FA3-GR2	1712	2483	3439	3872	4.35	5.05	56	65OPC2/35FA2-GR3	1880	2528	3357	3883	4.25	4.65
20	75OPC3/25FA3-GR3	1759	2813	3875	4310	4.55	5.25	57	65OPC1/35FA3-LS1	2464	4033	6179	7149	5.00	5.65
21	65OPC3/35FA2-GR2	1388	2105	3046	3463	4.40	4.85	58	65OPC1/35FA3-GR1	1743	2457	3646	4441	4.65	4.80
22	65OPC3/35FA2-GR3	1644	2266	3459	4202	4.40	5.35	59	65OPC1/35FA3-GR3	1521	2207	3565	4406	4.10	4.65
23	65OPC1/35FA2-GR2	1454	2101	3142	3821	4.45	4.95	60	100OPC1/0FA-LS1	4000	4970	6644	7028	5.45	6.05
24	65OPC1/35FA2-GR3	1787	2409	3966	4291	4.90	5.20	61	100OPC1/0FA-GR1	2762	3336	4574	4946	4.90	5.00
25	65PLC2/35FA2-LS1	2671	3573	5260	6360	5.90	5.70	62	75OPC2/25FA3-GR3	2362	2916	3946	4289	4.50	4.60
26	65PLC2/35FA2-GR1	1878	2533	3865	4871	4.80	5.20	63	65PLC1/35FA1-LS1	2937	3931	5537	6548	5.10	5.55
27	65PLC1/35FA2-LS1	3335	4183	5967	6407	5.80	6.05	64	65PLC1/35FA1-GR1	1997	2629	3964	4240	4.45	5.10
28	65PLC1/35FA2-GR1	2254	2920	4295	4736	5.00	5.35	65	75OPC1/25FA1-LS1	3081	4059	6004	7065	4.95	5.75
29	75PLC1/25FA2-GR2	2033	2678	3798	4220	4.80	5.05	66	75OPC1/25FA1-GR1	2022	2832	4285	4975	4.50	5.20
30	75PLC1/25FA2-GR3	2313	2971	3902	4372	4.75	4.85	67	65OPC1/35FA1-LS1	2644	3466	5827	6615	5.20	5.75
31	75OPC2/25FA3-LS1	3466	4744	5819	6476	5.40	6.20	68	65OPC1/35FA1-GR1	1529	2542	4531	4731	4.15	5.05
32	75OPC2/25FA3-GR1	2597	3335	4346	4443	4.95	4.95	69	65PLC2/35FA3-GR3	1939	2554	4040	4566	4.60	4.90
33	75OPC1/25FA3-LS1	3238	4485	6100	6850	5.50	5.85	70	65PLC1/35FA3-GR3	2020	2578	4015	4541	4.55	4.85
34	75OPC1/25FA3-GR1	2170	3064	4233	5351	4.60	5.15	71	75OPC2/25FA2-GR3	2204	2994	3766	4072	4.75	4.90
35	65PLC1/35FA3-LS1	3281	4140	6350	7496	5.60	6.50	72	75OPC1/25FA2-GR3	2050	2730	4117	4820	4.30	5.05
36	65PLC1/35FA3-GR1	2164	2917	4281	4649	4.75	5.35	73	65PLC1/35FA2-GR3	1870	2518	3718	4272	4.10	5.10
37	65PLC2/35FA3-LS1	3260	4349	6254	6651	5.30	6.30	74	65PLC2/35FA2-GR3	1650	2181	3044	4193	4.15	4.90

Table 3.3. Phase 1 Hardened Concrete Properties – Resistivity and Splitting Tensile Strength

Mix No.	Mix ID	Resistivity (kΩ-cm)				*T* (psi)		Mix No.	Mix ID	Resistivity (kΩ-cm)				*T* (psi)	
		3D	7D	28D	56D	7D	28D			3D	7D	28D	56D	7D	28D
1	75OPC2/25FA2-GR1	5.5	7.4	11.4	17.4	424	523	38	65PLC2/35FA3-GR1	5.1	6.8	18.5	27.8	434	514
2	75OPC2/25FA2-LS1	7.1	8.8	15.5	25.0	416	637	39	100OPC3/0FA-GR2	8.0	9.8	14.4	17.7	411	472
3	75OPC1/25FA2-GR1	7.0	9.1	16.1	26.5	265	511	40	65PLC2/35FA3-GR2	4.6	6.8	16.7	27.4	399	509
4	75PLC1/25FA2-GR1	7.3	9.5	16.4	25.6	425	529	41	65OPC3/35FA3-GR2	5.4	6.5	11.7	16.9	327	440
5	75PLC2/25FA2-GR1	5.8	7.2	13.5	23.8	453	421	42	75OPC3/25FA2-GR2	6.8	9.0	15.2	25.6	373	439
6	75OPC1/25FA2-LS1	7.2	9.1	16.7	31.2	475	554	43	65PLC2/35FA2-GR2	4.5	6.2	14.4	26.8	287	416
7	75PLC1/25FA2-LS1	7.9	10.7	17.0	30.8	537	566	44	75OPC1/25FA3-GR3	6.0	7.0	11.5	16.8	414	562
8	75PLC2/25FA2-LS1	5.5	7.8	14.5	27.6	487	554	45	75PLC1/25FA3-LS1	6.9	9.5	20.4	31.4	577	652
9	65OPC1/35FA2-GR1	6.3	8.5	15.6	30.5	367	525	46	75PLC1/25FA3-GR1	6.7	8.4	15.9	26.4	472	559
10	65OPC1/35FA2-LS1	6.5	8.0	17.7	34.8	449	618	47	75PLC1/25FA3-GR3	6.2	8.6	17.1	26.1	477	568
11	65OPC3/35FA2-GR1	6.3	8.0	13.9	26.4	292	519	48	75PLC2/25FA3-LS1	6.1	8.7	19.7	30.7	558	690
12	65OPC3/35FA2-LS1	6.1	8.4	16.8	31.4	445	472	49	75PLC2/25FA3-GR1	5.3	6.9	14.6	23.1	434	584
13	100PLC1/0FA-GR1	8.4	10.4	14.3	17.6	569	401	50	75PLC2/25FA3-GR3	5.8	7.3	15.7	24.4	436	531
14	100PLC1/0FA-GR2	7.8	9.8	13.5	16.5	455	608	51	65OPC2/35FA3-LS1	5.7	7.9	20.3	33.3	526	694
15	100PLC1/0FA-GR3	8.4	9.9	13.6	17.5	610	639	52	65OPC2/35FA3-GR1	5.1	6.3	10.2	15.0	419	501
16	100PLC1/0FA-LS1	9.9	11.5	15.0	18.0	660	737	53	65OPC2/35FA3-GR3	4.5	6.2	10.0	13.9	420	505
17	75OPC3/25FA3-LS1	7.0	9.0	16.6	29.4	436	624	54	65OPC2/35FA2-LS1	6.2	7.8	15.8	31.0	460	582
18	75OPC3/25FA3-GR1	6.6	7.3	12.7	21.1	457	550	55	65OPC2/35FA2-GR1	6.1	7.0	13.8	21.8	395	474
19	75OPC3/25FA3-GR2	6.3	7.7	12.8	21.9	382	479	56	65OPC2/35FA2-GR3	5.4	6.5	12.9	21.2	416	504
20	75OPC3/25FA3-GR3	6.1	7.2	12.3	21.9	421	580	57	65OPC1/35FA3-LS1	6.0	7.8	19.2	33.4	433	608
21	65OPC3/35FA2-GR2	5.4	7.9	15.6	26.4	318	425	58	65OPC1/35FA3-GR1	5.9	7.1	10.9	16.7	373	513
22	65OPC3/35FA2-GR3	5.9	8.2	15.6	27.8	317	478	59	65OPC1/35FA3-GR3	5.2	6.4	9.5	15.5	351	483
23	65OPC1/35FA2-GR2	5.5	7.5	16.1	29.6	353	477	60	100OPC1/0FA-LS1	9.3	12.8	17.0	19.0	589	743
24	65OPC1/35FA2-GR3	5.5	7.1	17.0	32.2	377	518	61	100OPC1/0FA-GR1	8.5	10.3	14.4	19.4	490	593
25	65PLC2/35FA2-LS1	4.8	6.5	16.5	32.1	419	563	62	75OPC2/25FA3-GR3	5.4	6.4	10.4	15.2	450	530
26	65PLC2/35FA2-GR1	4.9	6.3	15.1	28.0	368	492	63	65PLC1/35FA1-LS1	6.7	7.7	20.0	37.9	489	640
27	65PLC1/35FA2-LS1	7.0	8.6	18.5	33.1	413	600	64	65PLC1/35FA1-GR1	6.2	7.3	16.7	29.9	368	499
28	65PLC1/35FA2-GR1	6.1	8.1	18.1	29.7	364	572	65	75OPC1/25FA1-LS1	6.8	8.4	16.3	30.0	517	668
29	75PLC1/25FA2-GR2	6.4	8.4	15.9	26.1	367	534	66	75OPC1/25FA1-GR1	6.7	8.0	14.3	26.9	391	560
30	75PLC1/25FA2-GR3	6.9	8.5	16.9	28.7	368	564	67	65OPC1/35FA1-LS1	6.3	7.6	20.1	37.0	443	621
31	75OPC2/25FA3-LS1	6.2	8.6	17.4	29.7	520	668	68	65OPC1/35FA1-GR1	6.2	6.9	15.8	28.4	416	536
32	75OPC2/25FA3-GR1	5.4	6.8	10.1	16.5	481	554	69	65PLC2/35FA3-GR3	5.3	7.2	16.4	25.4	367	514
33	75OPC1/25FA3-LS1	6.7	8.2	18.1	33.5	566	669	70	65PLC1/35FA3-GR3	5.6	8.2	18.0	31.3	414	571
34	75OPC1/25FA3-GR1	6.0	6.6	12.5	20.4	403	584	71	75OPC2/25FA2-GR3	6.4	7.4	12.4	20.3	443	505
35	65PLC1/35FA3-LS1	5.9	8.0	23.1	37.7	504	698	72	75OPC1/25FA2-GR3	6.6	9.0	15.6	28.3	444	535
36	65PLC1/35FA3-GR1	5.9	8.1	18.7	34.5	495	543	73	65PLC1/35FA2-GR3	6.2	8.5	17.7	32.1	413	501
37	65PLC2/35FA3-LS1	5.2	7.5	25.1	39.2	460	686	74	65PLC2/35FA2-GR3	4.9	6.6	14.9	27.6	376	496

Table 3.4 Phase 1 Cement Paste f_{cp} Results (psi)

Mix ID	7D	28D	Mix ID	7D	28D
100OPC1/0FA	6326	8798	75OPC3/25FA2	3797	6083
100PLC1/0FA	7727	9651	75OPC1/25FA3	4012	7754
100OPC2/0FA	6208	8192	75PLC1/25FA3	5474	8506
100PLC2/0FA	6061	7195	75OPC2/25FA3	5050	7440
100OPC3/0FA	5927	7960	75PLC2/25FA3	5099	8027
85OPC1/15FA1	4052	7666	75OPC3/25FA3	4510	8291
85PLC1/15FA1	5668	8286	65OPC1/35FA1	3026	6299
85OPC2/15FA1	5548	7172	65PLC1/35FA1	3939	6450
85PLC2/15FA1	5469	6400	65OPC2/35FA1	4047	6074
85OPC3/15FA1	5285	7141	65PLC2/35FA1	3686	6026
85OPC1/15FA2	4757	6947	65OPC3/35FA1	3124	6083
85PLC1/15FA2	6287	7990	65OPC1/35FA2	3079	5437
85OPC2/15FA2	5606	7106	65PLC1/35FA2	3763	5901
85PLC2/15FA2	5856	6618	65OPC2/35FA2	3749	5401
85OPC3/15FA2	4873	6374	65PLC2/35FA2	3485	5545
85OPC1/15FA3	4972	8097	65OPC3/35FA2	3126	5245
85PLC1/15FA3	6263	8879	65OPC1/35FA3	3708	7165
85OPC2/15FA3	5795	7788	65PLC1/35FA3	4615	7831
85PLC2/15FA3	5723	7470	65OPC2/35FA3	4300	6434
85OPC3/15FA3	4957	7852	65PLC2/35FA3	4817	8268
75OPC1/25FA1	3758	7277	65OPC3/35FA3	4176	7749
75PLC1/25FA1	4997	7479	100OPC3/0FA*	5404	7311
75OPC2/25FA1	4858	6573	75OPC3/25FA1*	3942	6140
75PLC2/25FA1	4479	6406	75OPC3/25FA2*	3728	5570
75OPC3/25FA1	3906	6735	75OPC3/25FA3*	4101	6614
75OPC1/25FA2	3899	6280	65OPC3/35FA1*	3398	5660
75PLC1/25FA2	4698	7084	65OPC3/35FA2*	3161	4893
75OPC2/25FA2	4280	6227	65OPC3/35FA3*	3459	5979
75PLC2/25FA2	4222	6241			

Table 3.5 – Testing Matrix for Chapter 4

Cement	Aggregate	Cement Combination						
		0% FA	25% FA1	25% FA2	25% FA3	35% FA1	35% FA2	35% FA3
OPC1	LS1	4.2, 4.4	4.4	4.3, 4.4	4.3, 4.4	4.4	4.3, 4.4	4.3, 4.4
	GR1	4.2, 4.4	4.4	4.3, 4.4	4.3, 4.4	4.4	4.3, 4.4	4.3, 4.4
	GR2	---	---	---	---	---	N/A	---
	GR3	---	---	4.3	4.3	---	4.3	4.3
PLC1	LS1	4.2, 4.4	---	4.3, 4.4	4.3, 4.4	4.4	4.3, 4.4	4.3, 4.4
	GR1	4.2, 4.4	---	4.3, 4.4	4.3, 4.4	4.4	4.3, 4.4	4.3, 4.4
	GR2	4.2	---	N/A	---	---	---	---
	GR3	4.2, 4.4	---	4.3, 4.4	4.3	---	4.3, 4.4	4.3, 4.4
OPC2	LS1	---	---	4.3	4.3	---	4.3	4.3
	GR1	---	---	4.3	4.3	---	4.3	4.3
	GR2	---	---	---	---	---	---	---
	GR3	---	---	4.3	4.3	---	4.3	4.3
PLC2	LS1	---	---	4.3	4.3	---	4.3	4.3
	GR1	---	---	4.3	4.3	---	4.3	4.3
	GR2	---	---	---	---	---	N/A	N/A
	GR3	---	---	---	4.3	---	4.3	4.3
OPC3	LS1	---	---	---	N/A	---	N/A	---
	GR1	---	---	---	N/A	---	N/A	---
	GR2	4.4	---	4.4	4.4	---	4.4	4.4
	GR3	---	---	---	N/A	---	N/A	---

Note: “---“ means the mixture was not produced. “N/A” means the mixture was not analyzed in any detail.
A number in the table indicates which section(s) where data was analyzed.

Table 3.6. Phase 2 Fresh Mixed Concrete Results

Mix No.	Mix ID	UW (lb/ft^3)	Slump (in)	Air (%)	t_{C403} (hr)
75	100OPC1b/0FA-LS(w)	150.3	7.00	1.3	3.5
76	100PLC1b/0FA-LS(w)	150.2	3.75	1.5	3.5
77	75OPC1b/25FA2-LS(w)	151.4	8.50	0.8	5.5
78	75PLC1b/25FA2-LS(w)	150.6	7.50	0.8	5.0
79	75OPC1b/25FA3a-LS(w)	151.2	6.25	1.3	4.5
80	75PLC1b/25FA3a-LS(w)	150.6	6.00	1.4	4.0
81	65OPC1b/35FA2-LS(w)	151.1	8.75	0.6	6.5
82	65PLC1b/35FA2-LS(w)	150.3	7.75	0.8	6.0
83	65OPC1b/35FA3a-LS(w)	151.1	7.50	1.2	4.0
84	65PLC1b/35FA3a-LS(w)	150.1	6.75	1.4	4.0
85	100OPC1b/0FA-GR2(w)	144.6	8.00	1.2	3.5
86	100PLC1b/0FA-GR2(w)	143.7	7.50	1.3	3.5
87	75OPC1b/25FA2-GR2(w)	144.1	8.50	0.6	5.5
88	75PLC1b/25FA2-GR2(w)	143.1	8.25	0.9	5.0
89	75OPC1b/25FA3a-GR2(w)	144.6	8.50	1.0	4.5
90	75PLC1b/25FA3a-GR2(w)	143.8	7.50	1.1	4.5
91	65OPC1b/35FA2-GR2(w)	143.9	9.25	0.5	6.5
92	65PLC1b/35FA2-GR2(w)	143.8	8.50	0.6	6.5
93	65OPC1b/35FA3a-GR2(w)	143.4	7.75	0.7	4.5
94	65PLC1b/35FA3a-GR2(w)	143.4	7.25	1.2	4.5
95	100OPC1b/0FA-CG1(w)	142.2	3.25	1.6	4.0
96	100PLC1b/0FA-CG1(w)	142.6	2.75	2.0	3.5
97	75OPC1b/25FA2-CG1(w)	141.9	7.25	1.0	5.5
98	75PLC1b/25FA2-CG1(w)	141.9	7.50	1.3	5.5
99	75OPC1b/25FA3a-CG1(w)	142.0	7.75	1.5	4.5
100	75PLC1b/25FA3a-CG1(w)	142.0	4.00	1.7	4.0
101	65OPC1b/35FA2-CG1(w)	142.6	8.00	1.0	6.5
102	65PLC1b/35FA2-CG1(w)	141.6	7.50	1.1	6.5
103	65OPC1b/35FA3a-CG1(w)	142.2	7.50	1.3	4.5
104	65PLC1b/35FA3a-CG1(w)	141.4	7.75	1.5	4.5
105	100OPC1b/0FA-PG1(w)	142.4	6.50	2.0	4.0
106	100PLC1b/0FA-PG1(w)	141.1	6.00	2.1	3.5
107	75OPC1b/25FA2-PG1(w)	141.5	7.75	1.2	6.0
108	75PLC1b/25FA2-PG1(w)	141.0	7.00	1.4	5.5
109	75OPC1b/25FA3a-PG1(w)	142.4	7.00	1.8	4.5
110	75PLC1b/25FA3a-PG1(w)	142.0	6.75	1.8	4.5
111	65OPC1b/35FA2-PG1(w)	141.9	8.25	0.8	6.5
112	65PLC1b/35FA2-PG1(w)	141.6	6.25	1.8	6.0
113	65OPC1b/35FA3a-PG1(w)	142.6	7.00	1.6	4.5
114	65PLC1b/35FA3a-PG1(w)	141.4	6.75	1.9	4.5

Note: Mix temp for phase 2 ranged from 78.3 to 86.1 °F

Table 3.7. Phase 2 Hardened Concrete Properties – f_c, E, and *T*

Mix No.	Mix ID	Compressive Strength (psi)				E (10^6 psi)		*T* (psi)	
		3D	7D	28D	56D	7D	28D	7D	28D
75	100OPC1b/0FA-LS(w)	3426	4644	6104	7046	5.49	5.71	562	553
76	100PLC1b/0FA-LS(w)	3825	4755	6523	6900	5.51	6.39	555	676
77	75OPC1b/25FA2-LS(w)	2723	3720	5075	5876	4.86	5.80	468	603
78	75PLC1b/25FA2-LS(w)	2937	3945	5497	6435	5.12	5.48	420	452
79	75OPC1b/25FA3a-LS(w)	3527	4696	6676	7076	5.43	6.15	564	574
80	75PLC1b/25FA3a-LS(w)	3818	4938	6418	7052	4.96	5.76	596	696
81	65OPC1b/35FA2-LS(w)	2198	3122	4455	5456	5.77	5.62	411	468
82	65PLC1b/35FA2-LS(w)	2449	3160	4795	5850	4.57	5.49	434	522
83	65OPC1b/35FA3a-LS(w)	3366	4665	6393	7082	5.51	6.06	562	624
84	65PLC1b/35FA3a-LS(w)	3397	4756	6326	6885	5.55	5.78	543	669
85	100OPC1b/0FA-GR2(w)	2529	3407	4825	5090	4.76	4.69	458	569
86	100PLC1b/0FA-GR2(w)	2826	3708	4915	5349	4.35	4.88	522	586
87	75OPC1b/25FA2-GR2(w)	2103	2847	4062	4813	4.37	4.91	378	474
88	75PLC1b/25FA2-GR2(w)	2068	2577	3696	4379	3.85	4.55	377	489
89	75OPC1b/25FA3a-GR2(w)	2461	3474	4686	4981	4.67	4.81	466	583
90	75PLC1b/25FA3a-GR2(w)	2682	3442	4801	4971	4.53	4.89	477	576
91	65OPC1b/35FA2-GR2(w)	1752	2341	3829	4525	3.91	4.93	347	409
92	65PLC1b/35FA2-GR2(w)	1633	2409	3652	4132	4.27	4.71	320	447
93	65OPC1b/35FA3a-GR2(w)	2355	3389	4779	4950	4.50	5.14	467	497
94	65PLC1b/35FA3a-GR2(w)	2461	3278	4403	4752	4.43	4.51	463	537
95	100OPC1b/0FA-CG1(w)	2505	3782	5253	5948	4.49	4.74	457	590
96	100PLC1b/0FA-CG1(w)	2733	3932	4924	5250	4.40	4.72	509	604
97	75OPC1b/25FA2-CG1(w)	1996	2854	4377	5328	3.57	4.78	403	557
98	75PLC1b/25FA2-CG1(w)	1851	2582	3583	4319	3.94	4.17	357	528
99	75OPC1b/25FA3a-CG1(w)	2386	3636	4818	5574	4.26	4.41	488	596
100	75PLC1b/25FA3a-CG1(w)	2644	3533	4720	5134	3.83	4.47	479	569
101	65OPC1b/35FA2-CG1(w)	1685	2360	3888	4492	4.03	4.86	332	498
102	65PLC1b/35FA2-CG1(w)	1736	2362	3460	4384	3.75	4.40	317	481
103	65OPC1b/35FA3a-CG1(w)	2403	3576	5442	5648	4.28	4.72	431	574
104	65PLC1b/35FA3a-CG1(w)	2570	3590	4988	5661	4.00	4.57	454	629
105	100OPC1b/0FA-PG1(w)	2336	3538	4869	5327	4.42	4.88	471	578
106	100PLC1b/0FA-PG1(w)	2722	3613	4586	4822	4.48	4.81	460	588
107	75OPC1b/25FA2-PG1(w)	1861	2653	4101	4681	4.31	4.75	380	558
108	75PLC1b/25FA2-PG1(w)	1864	2584	3528	4194	3.82	4.62	312	466
109	75OPC1b/25FA3a-PG1(w)	2322	3184	4414	4624	4.34	4.71	429	583
110	75PLC1b/25FA3a-PG1(w)	2371	3352	4388	4384	4.19	4.67	454	559
111	65OPC1b/35FA2-PG1(w)	1029	2188	3721	4405	3.55	4.42	312	453
112	65PLC1b/35FA2-PG1(w)	1805	2424	3606	4317	4.06	4.60	371	505
113	65OPC1b/35FA3a-PG1(w)	2313	3379	4471	5221	4.13	4.77	431	537
114	65PLC1b/35FA3a-PG1(w)	2286	2984	4181	4779	4.15	4.39	381	555

Table 3.8. Phase 2 Hardened Concrete Properties – Resistivity Readings and Category

Mix No.	Mix ID	SR (kΩ-cm)							
		3D	TP-95 Category	7D	TP-95 Category	28D	TP-95 Category	56D	TP-95 Category
75	100OPC1b/0FA-LS(w)	7.7	High	9.7	High	10.6	High	12.2	Moderate
76	100PLC1b/0FA-LS(w)	6.8	High	8.3	High	9.6	High	11.2	High
77	75OPC1b/25FA2-LS(w)	5.9	High	7.9	High	12.0	Moderate	19.5	Moderate
78	75PLC1b/25FA2-LS(w)	4.9	High	6.5	High	11.2	High	19.7	Moderate
79	75OPC1b/25FA3a-LS(w)	6.2	High	8.0	High	9.7	High	11.1	High
80	75PLC1b/25FA3a-LS(w)	5.6	High	6.6	High	8.6	High	10.7	High
81	65OPC1b/35FA2-LS(w)	5.3	High	7.5	High	13.9	Moderate	26.1	Low
82	65PLC1b/35FA2-LS(w)	4.3	High	6.0	High	13.2	Moderate	26.4	Low
83	65OPC1b/35FA3a-LS(w)	5.9	High	7.1	High	9.4	High	11.0	High
84	65PLC1b/35FA3a-LS(w)	5.9	High	7.0	High	8.9	High	11.1	High
85	100OPC1b/0FA-GR2(w)	6.5	High	7.7	High	9.5	High	12.0	High
86	100PLC1b/0FA-GR2(w)	5.7	High	6.9	High	9.2	High	10.6	High
87	75OPC1b/25FA2-GR2(w)	6.1	High	7.9	High	12.4	Moderate	21.0	Low
88	75PLC1b/25FA2-GR2(w)	5.2	High	6.9	High	11.5	High	20.4	Moderate
89	75OPC1b/25FA3a-GR2(w)	5.7	High	7.4	High	8.7	High	10.7	High
90	75PLC1b/25FA3a-GR2(w)	5.2	High	6.2	High	8.5	High	10.9	High
91	65OPC1b/35FA2-GR2(w)	5.4	High	7.4	High	14.8	Moderate	25.8	Low
92	65PLC1b/35FA2-GR2(w)	4.8	High	6.3	High	15.0	Moderate	27.2	Low
93	65OPC1b/35FA3a-GR2(w)	5.7	High	6.8	High	8.9	High	10.6	High
94	65PLC1b/35FA3a-GR2(w)	5.2	High	6.1	High	8.8	High	10.9	High
95	100OPC1b/0FA-CG1(w)	5.5	High	6.5	High	8.5	High	10.8	High
96	100PLC1b/0FA-CG1(w)	5.4	High	6.3	High	8.0	High	9.4	High
97	75OPC1b/25FA2-CG1(w)	5.2	High	6.2	High	10.2	High	17.3	Moderate
98	75PLC1b/25FA2-CG1(w)	4.8	High	5.7	High	9.9	High	19.0	Moderate
99	75OPC1b/25FA3a-CG1(w)	5.0	High	5.9	High	7.7	High	9.8	High
100	75PLC1b/25FA3a-CG1(w)	4.9	High	5.5	High	7.5	High	10.1	High
101	65OPC1b/35FA2-CG1(w)	5.1	High	6.2	High	12.2	Moderate	22.2	Low
102	65PLC1b/35FA2-CG1(w)	4.3	High	5.7	High	12.7	Moderate	24.1	Low
103	65OPC1b/35FA3a-CG1(w)	5.0	High	5.6	High	7.2	High	10.0	High
104	65PLC1b/35FA3a-CG1(w)	4.9	High	5.4	High	7.6	High	10.5	High
105	100OPC1b/0FA-PG1(w)	5.0	High	6.0	High	8.4	High	9.8	High
106	100PLC1b/0FA-PG1(w)	5.1	High	5.6	High	8.3	High	9.5	High
107	75OPC1b/25FA2-PG1(w)	4.9	High	6.2	High	11.0	High	18.2	Moderate
108	75PLC1b/25FA2-PG1(w)	4.5	High	5.6	High	11.0	High	18.9	Moderate
109	75OPC1b/25FA3a-PG1(w)	4.9	High	5.6	High	8.1	High	9.8	High
110	75PLC1b/25FA3a-PG1(w)	4.6	High	5.2	High	7.9	High	9.8	High
111	65OPC1b/35FA2-PG1(w)	4.7	High	6.1	High	13.0	Moderate	23.5	Low
112	65PLC1b/35FA2-PG1(w)	4.5	High	5.9	High	14.5	Moderate	28.0	Low
113	65OPC1b/35FA3a-PG1(w)	4.6	High	5.4	High	7.8	High	10.1	High
114	65PLC1b/35FA3a-PG1(w)	4.6	High	5.2	High	7.9	High	10.1	High

Note: Higher resistivity values are desired. Categories are explained in Table 3.9.

Table 3.9 AASHTO TP 95 Categories

Chloride Ion Penetration	SR (kΩ-cm)
High	<12
Moderate	12-21
Low	21-37
Very Low	37-254
Negligible	>254

Table 3.10 Phase 2 Cement Paste Results

Mix ID	f_{cp} (psi)			
	3D	7D	28D	56D
100OPC1b/0FA	3625	4654	6916	7678
100PLC1b/0FA	4274	6056	7362	7924
75OPC1b/25FA2	2452	3208	4809	6471
75PLC1b/25FA2	2884	3771	5144	6432
75OPC1b/25FA3a	3130	4471	6751	6745
75PLC1b/25FA3a	4209	5215	6616	6611
65OPC1b/35FA2	2103	2641	4031	5509
65PLC1b/35FA2	2324	3005	3866	5773
65OPC1b/35FA3a	3345	4157	6241	7206
65PLC1b/35FA3a	4095	5694	6736	7143

CHAPTER 4 – ANALYSIS OF PHASE 1 MIXTURES TO EVALUATE MISSISSIPPI'S MARKETPLACE

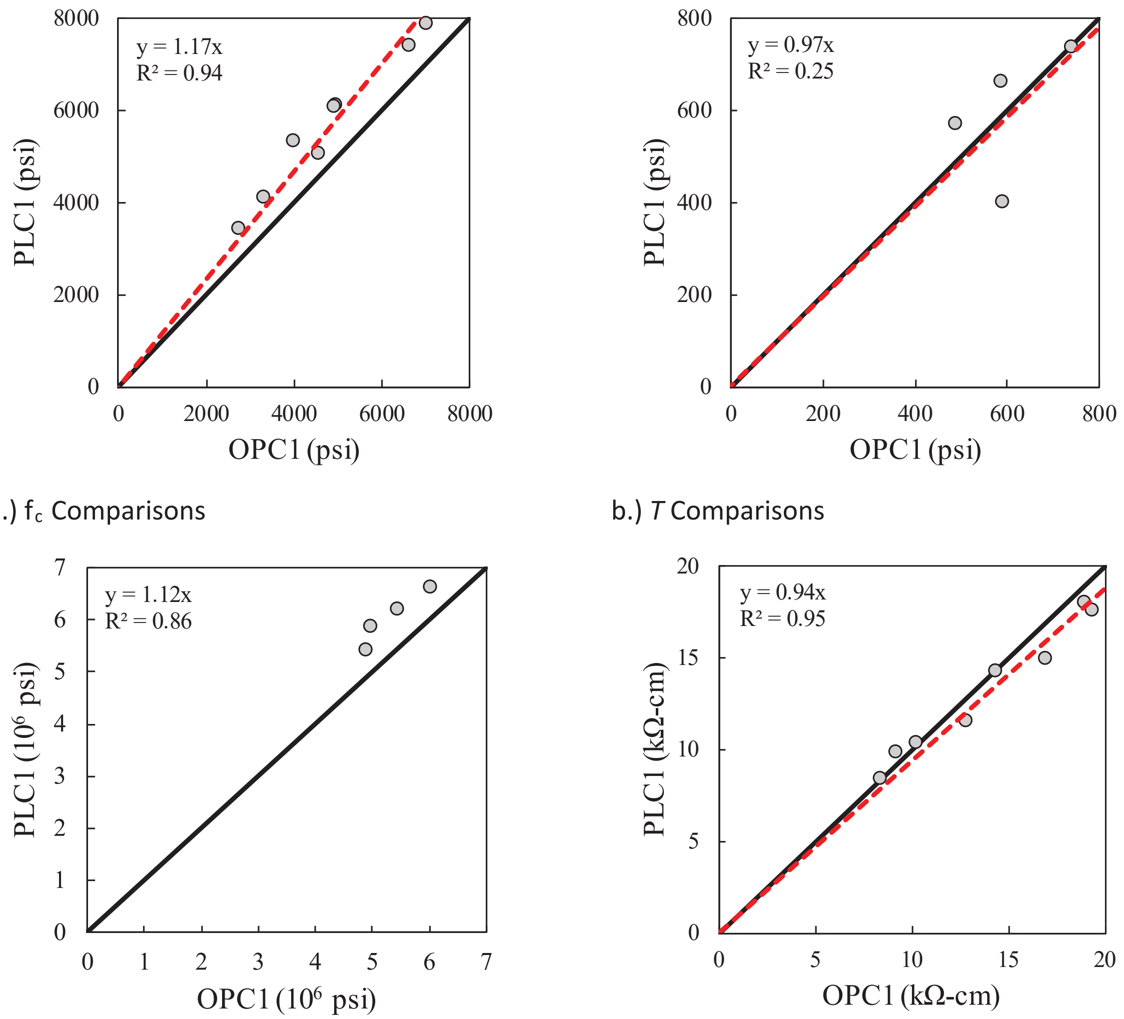
4.1 Overview

This chapter investigates the majority of mixes 1-74 with a few exceptions noted in Table 3.5. These mixes represent options already being used or being considered (that are allowable under existing specifications) as marketplace mixtures. This chapter explores these mixtures in a lab controlled experiment to assess relative performance behaviors. Companion works show PLC's implementation into segments of Mississippi's concrete market that were briefly summarized in Chapter 1. This implementation data is only mentioned herein, and this data does not generally have directly comparable cases as would occur in a designed experiment. The data in this chapter has several directly comparable cases where a focus is concrete properties at MDOT 2017 Red Book allowable fly ash levels 25% (with OPC) or 35% (with PLC). Gravel aggregates are the focus to examine PAB or other aggregate interaction effects at 25 to 35% fly ash in conjunction with OPC or PLC.

Much of the analysis in this chapter uses an analysis technique referred to as regression through the origin (RTO) to make an equality plot. A quick explanation of equality plots is given here. Equality plots have the same x and y-axis with a line of equality (slope of 1) bisecting the graph. The data for equality plots is an ordered pair of similar data. When assessed with linear RTO, equality plots can show variable favorability. For example, in Figure 4.1a an RTO slope of 1.17 indicates PLC strengths are higher than OPC by approximately 17%.

4.2 Properties of Reference Mixtures Absent Fly Ash

Figure 4.1 compares four OPC1 and PLC1 mixtures that do not contain any fly ash. PLC1 clearly performs better in f_c and E while OPC1 slightly outperforms in SR (*T* was similar between cements). The correlation of the data is very high except for *T* and E, though this may be due to the lack of data points available. The fresh mix properties showed similar results with regards to setting, unit weight, and air content. Slump showed OPC to be more workable than PLC. Other literature suggests mixtures without SCMs show similar performance between PLC and OPC (Shannon et al., 2015; Shannon et al., 2017b).



a.) f_c Comparisons

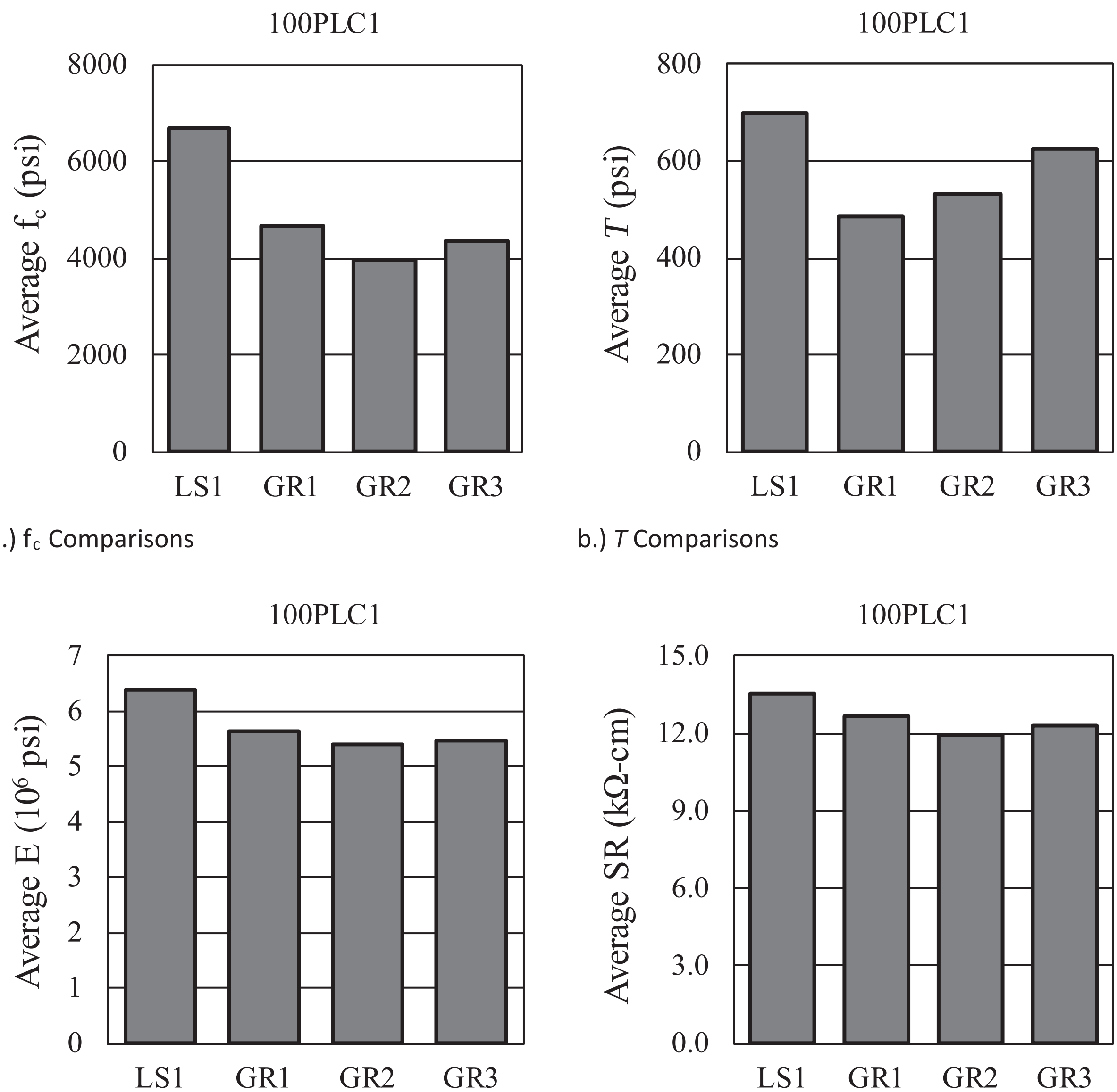
b.) *T* Comparisons

c.) E Comparisons

d.) SR Comparisons

Figure 4.1. OPC versus PLC Comparisons Absent Fly Ash

Four 100% PLC mixes were evaluated with respect to fresh mixed properties, f_c, *T*, E, and SR to investigate aggregate differences with PLC. The fresh mix properties showed LS1 to be less workable (2.5 in lower slump) and have lower air content (3.1%) than the gravel aggregates which were all similar (approximately 5.25 in slump and 5.2% air). For hardened property tests, LS1 outperformed the gravels (Figure 4.2). When comparing the gravels, in all cases except *T*, GR1 performance was best followed by GR3 then GR2. GR3 had higher tensile strengths followed by GR2 then GR1 although only 4 data points were available for this comparison. Since LS1 is a crushed material and all three gravels were uncrushed, it is no surprise that with destructive tests gravels performed worse. This is likely due to difficulty in bonding with the smooth faced gravels. The non-destructive tests, SR and E, show less of an effect from the aggregate type when compared to f_c and *T*. Later in this chapter aggregate type is shown to be meaningful in certain situations with OPC.



a.) f_c Comparisons
b.) *T* Comparisons
c.) E Comparisons
d.) SR Comparisons

Figure 4.2. Aggregate Effects Comparisons Absent Fly Ash

4.3 Comparison of OPC and PLC at 25 to 35% Fly Ash

This section investigates 47 mixtures detailed in Table 3.5. Two OPC and PLC pairs (OPC1/PLC1 and OPC2/PLC2) are used with 25% and 35% FA2 and FA3. Additionally, three different aggregates (LS1, GR1, and GR3) are used with the previous cement combinations to form as close to a blocked experimental matrix as possible with the raw material quantities that were available (a fully blocked experiment would have had 48 mixes instead of 47). These mixtures are investigated with respect to fresh mixed and hardened properties. Seven other CP mixtures are included in the CP compressive strength section for a small admixture dosage rate analysis.

4.3.1 Fresh Mixed Properties

Figure 4.3a shows that OPC mixtures were more workable in almost all cases. The air content shows high variability (Figure 4.3b) with no statistically significant differences (Table 4.1). The unit weight (Figure 4.3c) shows good correlation but was statistically different with a mean difference of 1.0 pcf. This difference is not practically meaningful. The setting time shows PLC to be significantly faster on average with a mean difference of 0.6 hr. This magnitude of setting difference is similar to values found in literature (Howard et al., 2015; Shannon et al., 2017a; Shannon et al., 2017b; Shannon et al., 2015). The paired t-tests' p-value and mean difference are shown in Table 4.1. Overall, the fresh mix properties indicate PLC mixtures set faster but at the loss of some workability.

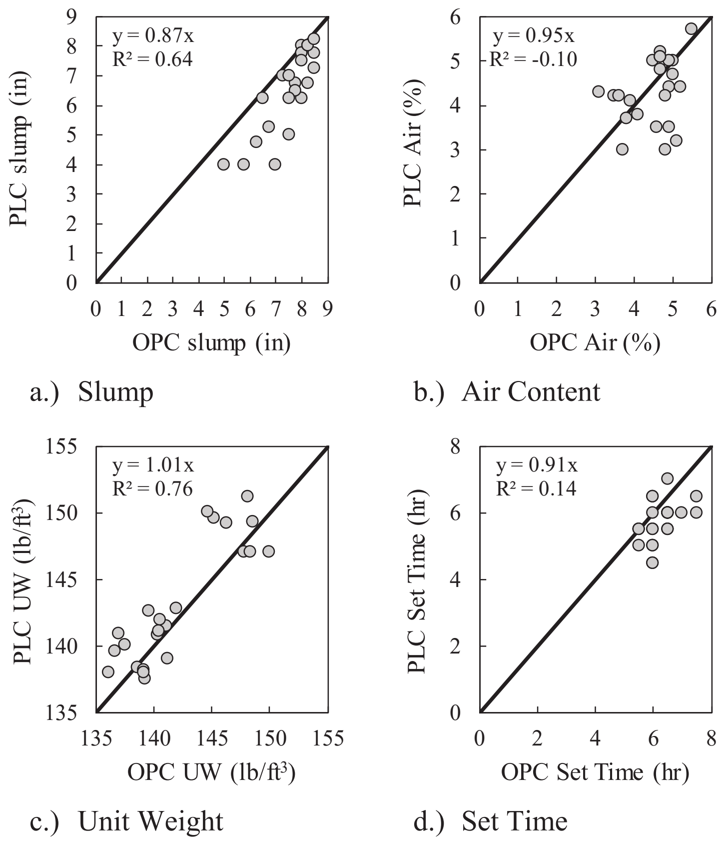


Figure 4.3. Fresh Mix Properties

Table 4.1. Fresh Mix Paired t-Tests

Property	Paired t-Tests	
	p-value	Mean Difference (OPC-PLC)
Slump	<0.01	1.0 in
Air Content	0.246	0.2 %
Unit Weight	0.039	-1.0 lb/ft^3
Set Time	<0.01	0.6 hr

Note: All tests were conducted at a significance level of 0.05

4.3.2 Compressive Strength – Concrete

Globally PLC strength is slightly higher than OPC (Figure 4.4a). At 25% replacement, this trend holds the same (Figure 4.4b). At 35% cement replacement, OPC and PLC are practically the same (Figure 4.4c), although strengths up to 28D show 4-7% higher strengths for PLC. At 56D, PLC is only 2% higher on average. The differences become evident when separating the data by fly ash class. Class C fly ash shows noticeable increased compressive strength with PLC (Figure 4.4d) while Class F fly ash shows equal performance when either OPC or PLC is used (Figure 4.4e). All aggregates show slight PLC favorability (Figure 4.4f-h). PLC and Class C fly ash benefits are reinforced by Figure 4.5. The PLC and Class C fly ash combination was able to perform 9%, 7%, and 7% better than OPC with LS1, GR1, and GR3 concrete, respectively.

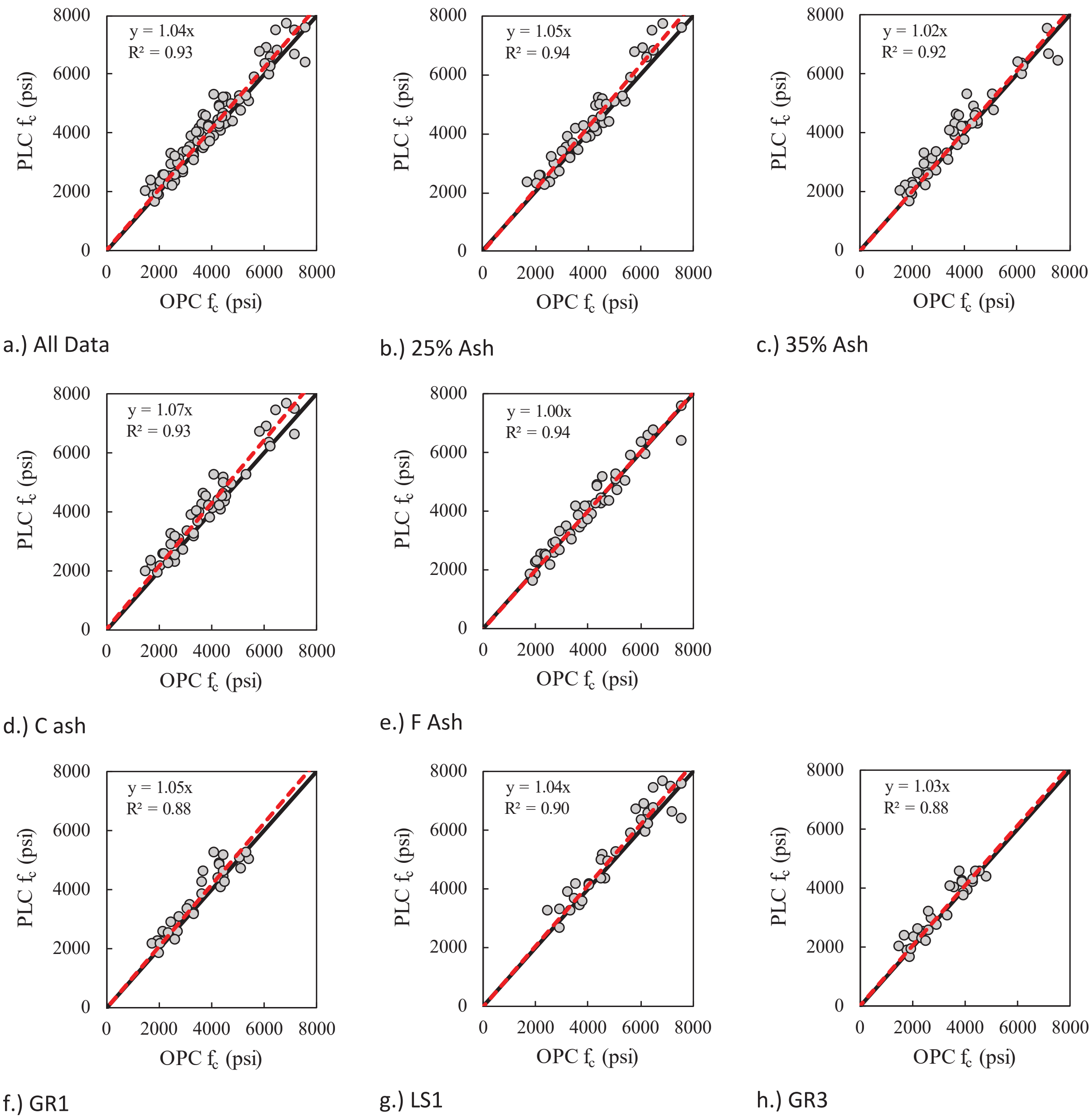
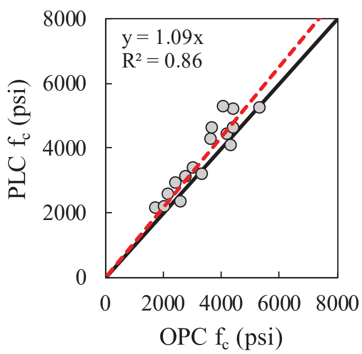
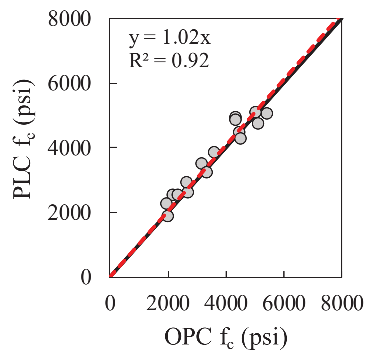


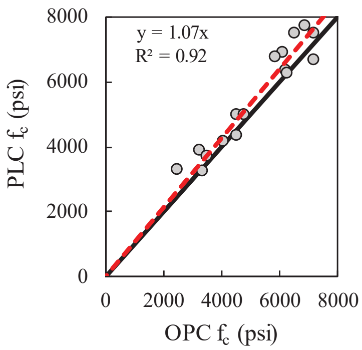
Figure 4.4. Concrete Compressive Strength Global Trends



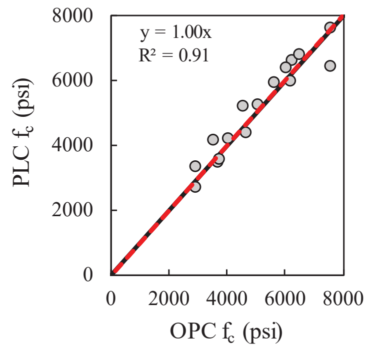
a.) GR1 with C Ash



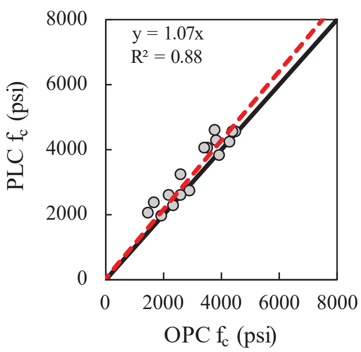
b.) GR1 with F Ash



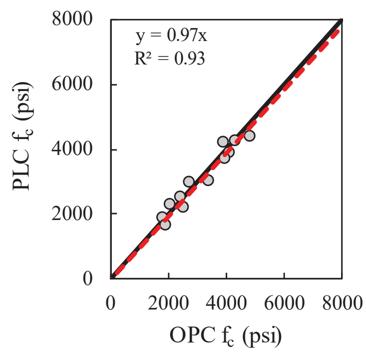
c.) LS1 with C Ash



d.) LS1 with F Ash



e.) GR3 with C Ash



f.) GR3 with F Ash

Figure 4.5. Fly Ash Effects on Concrete Compressive Strength by Aggregate Type

A summary of statistical differences for compressive strength are shown in Table 4.2. Analysis was conducted according to least significant difference statistical testing which compared OPC and PLC pairs for each aggregate and break day. Each cell of Table 4.2 contains an identifier which describes if the PLC strength was stronger (S), weaker (W), or not different (ND) statistically. Underneath this identifier in parentheses is the average mean difference (AMD) for each mixture to show the magnitude of difference. PLC with Class C fly ash was statistically equal to OPC 48% of the time and stronger than OPC 48% of the time (equal or better 96% of the time). PLC1 shows slightly better performance with Class F fly ash than PLC2. PLC1 with Class F fly ash was equal to OPC1 67% of the time and stronger than OPC1 29% of the time (statistically equal or better 96% of the time). PLC2 with Class F fly ash was equal to OPC2 75% of the time and stronger than OPC2 only 5% of the time (statistically equal or better 80% of the time). Globally PLC was equal to OPC 58% of the time and better than OPC 34% of the time (statistically equal or better 92% of the time). These results indicate that PLC is rarely going to perform worse than OPC with respect to compressive strength when SCMs are used. PLC1 was only statistically weaker in one case (35% Class F fly ash with limestone aggregates – a rare combination for MS concrete). PLC 2 had the remaining six cases where OPC was statistically stronger. Of these six cases, five had average differences of 350 psi or less and the 6th case was 530 psi. Statistically stronger cases were as much as 1191 psi.

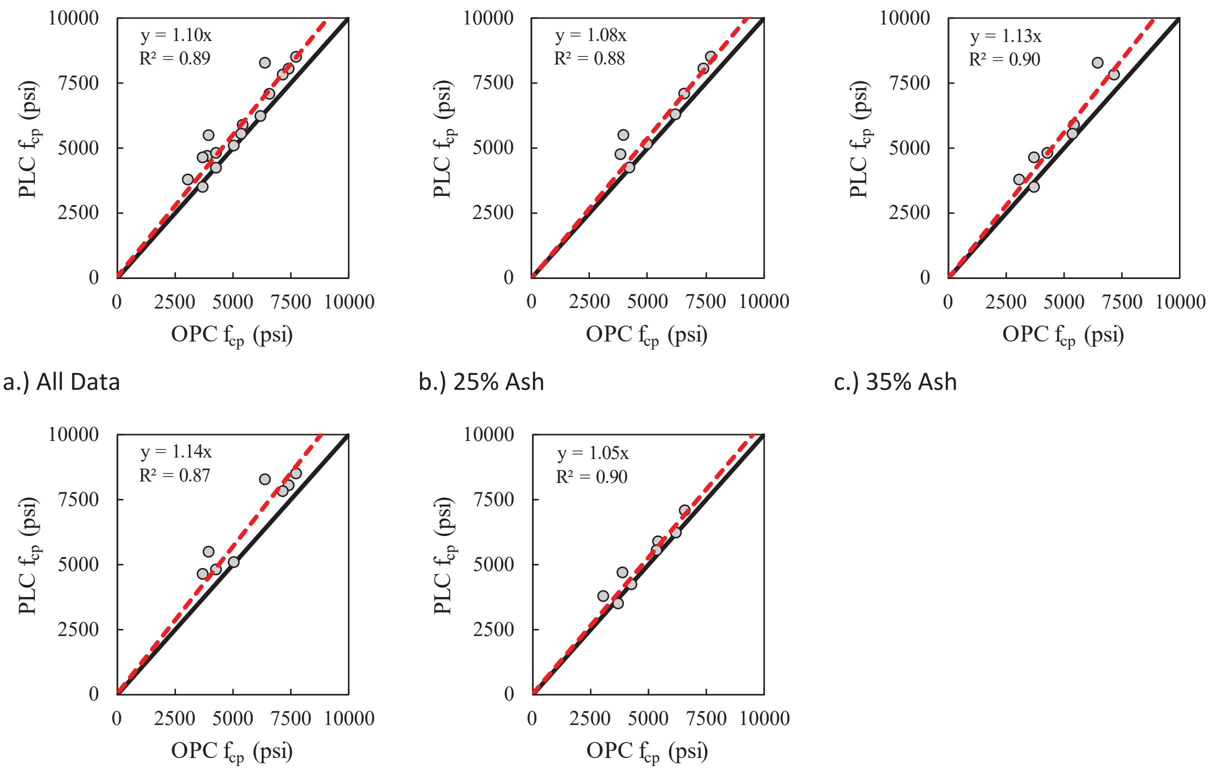
Table 4.2. Concrete Compressive Strength Statistics Summary

Aggregate	Day	PLC1				PLC2			
		25% C Ash	25% F Ash	35% C Ash	35% F Ash	25% C Ash	25% F Ash	35% C Ash	35% F Ash
GR1	3	S (+399)	S (+351)	S (+421)	S (+270)	W (-265)	ND (-114)	ND (+124)	ND (-130)
	7	ND (+321)	ND (+323)	S (+460)	ND (+270)	ND (-150)	ND (-109)	ND (+333)	ND (+191)
	28	ND (+188)	S (+606)	S (+635)	ND (-208)	ND (-10)	ND (-270)	S (+931)	ND (+243)
	56	ND (-84)	ND (-363)	ND (+207)	ND (-374)	S (+758)	ND (+43)	S (+1191)	S (+541)
LS1	3	S (+652)	S (+626)	S (+817)	S (+409)	ND (+221)	ND (-219)	ND (-63)	W (-246)
	7	S (+516)	S (+623)	ND (+106)	ND (+169)	S (+228)	W (-283)	ND (-164)	ND (-181)
	28	S (+799)	ND (+329)	ND (+171)	ND (-214)	S (+936)	ND (+261)	ND (+1)	ND (+183)
	56	S (+855)	ND (+22)	S (+347)	W (-1157)	S (+1001)	ND (+299)	W (-530)	ND (+332)
GR3	3	S (+665)	S (+263)	S (+499)	ND (+83)	ND (-99)	---	ND (-5)	W (-229)
	7	S (+578)	ND (+241)	S (+371)	ND (+109)	ND (-194)	---	ND (-61)	W (-347)
	28	ND (+369)	ND (-215)	S (+449)	ND (-248)	ND (-121)	---	S (+617)	ND (-313)
	56	ND (+17)	ND (-447)	ND (+135)	ND (-19)	ND (-73)	---	S (+765)	ND (+310)

Note: S indicates PLC compressive strength was statistically stronger than OPC
W indicates PLC compressive strength was statistically weaker than OPC
ND indicates PLC compressive strength was not different statistically than OPC
--- indicates no data is available
Value in parentheses is PLC compressive strength – OPC compressive strength in psi
Statistical differences were based on least squares mean

4.3.3 Compressive Strength – Cement Paste

Cement paste (CP) compressive strength trends are similar to concrete (Figure 4.6). Concrete and cement paste both showed PLC performed better with Class C fly ash than Class F fly ash. The cement paste trends for all data and for 25% fly ash are also similar to concrete. One interesting trend can be seen in Figure 4.6c. Cement paste data shows PLC is considerably better with 35% fly ash (13% better), but this is not seen in the concrete (2% better). This is likely due to paste aggregate bond effects. The statistical comparisons in Table 4.3 indicate that PLC1 is significantly higher than OPC1 in all cases. PLC2 is only statistically higher than OPC2 38% of the time although PLC2 is never statistically lower.



a.) All Data
b.) 25% Ash
c.) 35% Ash
d.) C ash
e.) F Ash

Figure 4.6. Cement Paste Compressive Strength Global Trends

Table 4.3. Cement Paste Compressive Strength Statistics Summary

Type	Day	PLC1				PLC2			
		25%C	25%F	35%C	35%F	25%C	25%F	35%C	35%F
CP	7	S (+1462)	S (+799)	S (+907)	S (+684)	ND (+49)	ND (-58)	S (+517)	ND (-264)
	28	S (+752)	S (+470)	S (+666)	S (+464)	S (+587)	ND (+14)	S (+1834)	ND (+144)

Note: S indicates PLC compressive strength was statistically stronger than OPC
ND indicates PLC compressive strength was not different statistically than OPC
Value in parentheses is PLC compressive strength – OPC compressive strength in psi
Statistical differences were based on least squares mean

4.3.4 Concrete to Cement Paste Compressive Strength Comparisons

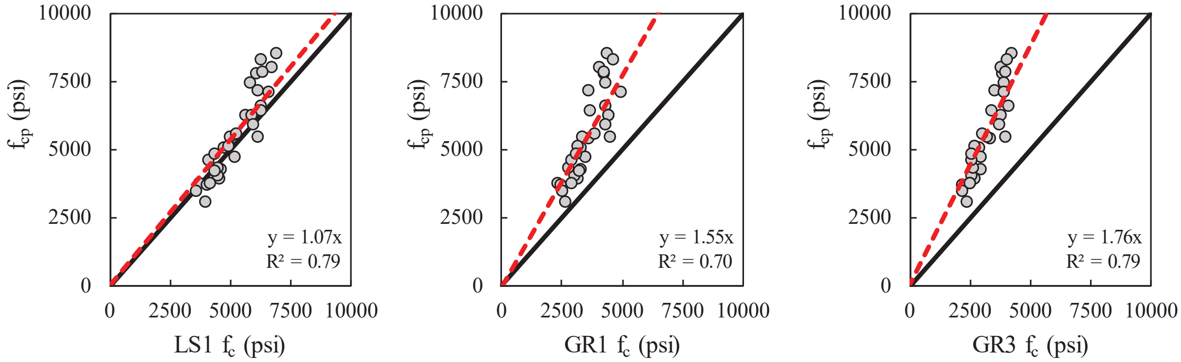
Before analyzing CP versus concrete, an assessment of admixture effects was performed since the CP and concrete of this chapter did not have the same admixture dosages. The bulk of CP measurements were collected before the concrete was produced and before the final admixture dosage rate for the concrete was determined. As such, the CP measurements collected have a different admixture dosage rate than the concrete. Seven CP mixtures were produced at the concrete admixture dosage rates for cases with 0, 25, and 35% fly ash replacement with FA1, FA2, and FA3 combined with OPC3. This comparison showed CP strengths at the same admixture dosage rates as the concrete was 11% weaker on average with an R^2 of 0.89 than the CP produced originally, also with an R^2 of 0.89. This indicates admixture dosage rates can affect cement paste strength, but the differences were consistent in this investigation. Ultimately the authors believe this to be of little concern because the general trends of CP and concrete would very likely only change in magnitude but not in conclusions drawn from CP and concrete comparisons. For example, a slope of 1.2 between CP and concrete with different admixtures would just be reduced to roughly 1.1 for CP and concrete with the same admixtures.

Concrete and CP individual trends were found to be similar in the previous sections. This section details the 1 to 1 comparisons of concrete and cement paste. Hansen et al. (2019a) found that cement paste generally tracks with concrete performance and that cement paste can be used to better understand concrete compressive strength behaviors. Figure 4.7a-c helps show that concrete and cement paste strengths correlated well when the concrete data was sorted by aggregate type. If these mixtures are separated by fly ash class, the correlations get even better (Figure 4.7d-i).

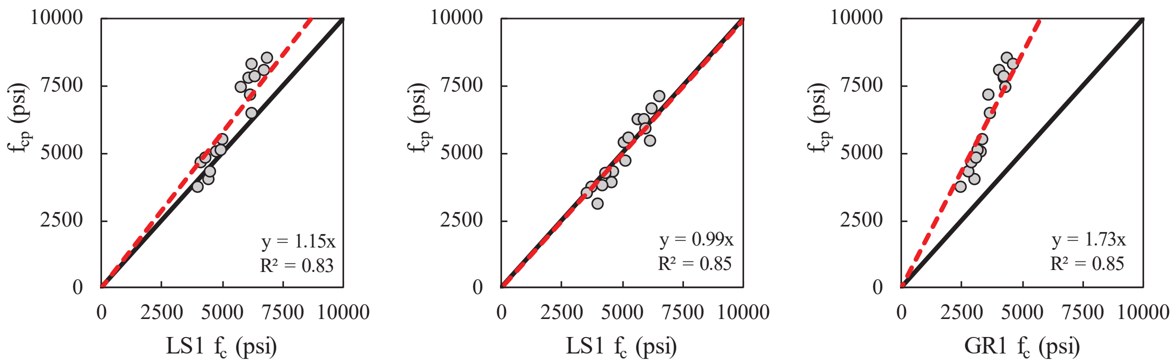
The slopes from Figure 4.7 indicate that the differences between cement paste and concrete strength with Class C fly ash is considerably higher than the difference between similar mixtures with Class F fly ash. By looking at CP and concrete strengths together (Figure 4.8), a more comprehensive comparison can be observed. The four mixtures in Figure 4.8 are 35% fly ash (C and F) with two different PLCs and three different aggregates. This figure clearly shows that Class C fly ash makes a better cementitious system (e.g. higher CP strength), but this large benefit does not correlate to a 1 to 1 benefit in concrete. However, the concrete does see some benefit. With Class F fly ash, the LS1 concrete is limited by the cement paste strength, but when Class C fly ash is added the LS1 concrete is able to reach higher strengths mainly due to the increased CP strength. This benefit is also seen in GR3 concrete. GR1 concrete does not see much benefit with PLC1, but with PLC2 GR1 also receives an increase in compressive strength with Class C fly ash. With CP strength measurements this behavior was able to be identified and then verified with concrete strengths.

In the opinion of the authors, the data presented in this report ended up being a favorable case for OPC. In other words, in the author's opinion, OPC fared at least as good or likely better relative to PLC than it would if studies like this were repeated with random combinations of fly ash, admixtures, and gravel aggregates. This is stated as an opinion since no definitive data is available to support this opinion, but there is anecdotal supporting information presented in the remainder of this paragraph. As discussed in Chapter 1, paste-aggregate bond (PAB) issues are well documented in Mississippi concrete with gravel aggregates, OPC, and higher fly ash replacement rates. However, it was also noted in Chapter 1 that PAB issues do not occur with all combinations of materials. Previous research at MSU with PLC at 40% fly ash replacement referenced in Chapter 1 has documented severe strength losses with OPC and gravel aggregates that did not occur with PLC under the same conditions. The mixtures evaluated in this report with

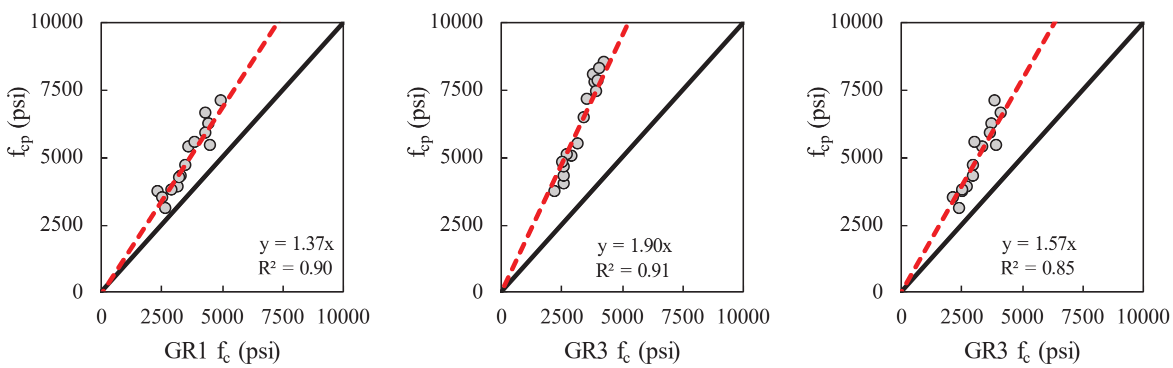
OPC, gravel aggregates and up to 35% fly ash did not show any obvious signs of PAB problems, which should not be expected over the entire Mississippi market based on past histories. On the contrary, PLC has not observed PAB problems at replacement rates of 40% fly ash or less.



a.) LS1 concrete vs. CP b.) GR1 concrete vs. CP c.) GR3 concrete vs. CP

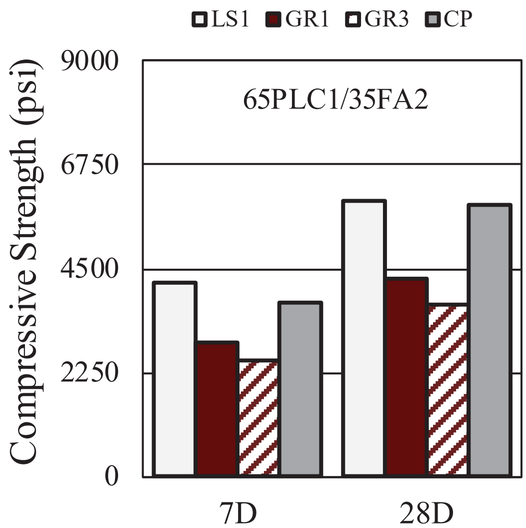


a.) LS1 concrete with C ash vs. CP b.) LS1 concrete with F ash vs. CP c.) GR1 concrete with C Ash vs. CP

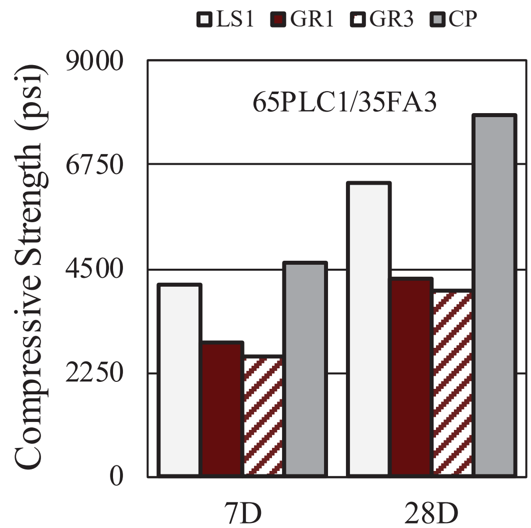


d.) GR1 concrete with F ash vs. CP e.) GR3 concrete with C ash vs. CP f.) GR3 concrete with F ash vs. CP

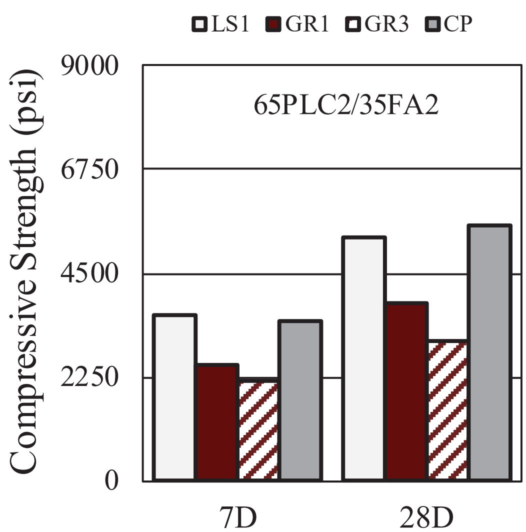
Figure 4.7. Cement Paste to Concrete Comparisons



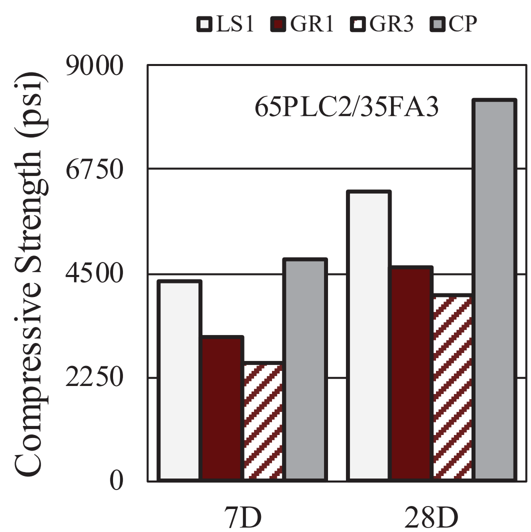
a.) PLC1 35% Class F fly Ash



b.) PLC1 35% Class C fly ash



c.) PLC2 35% Class F fly ash

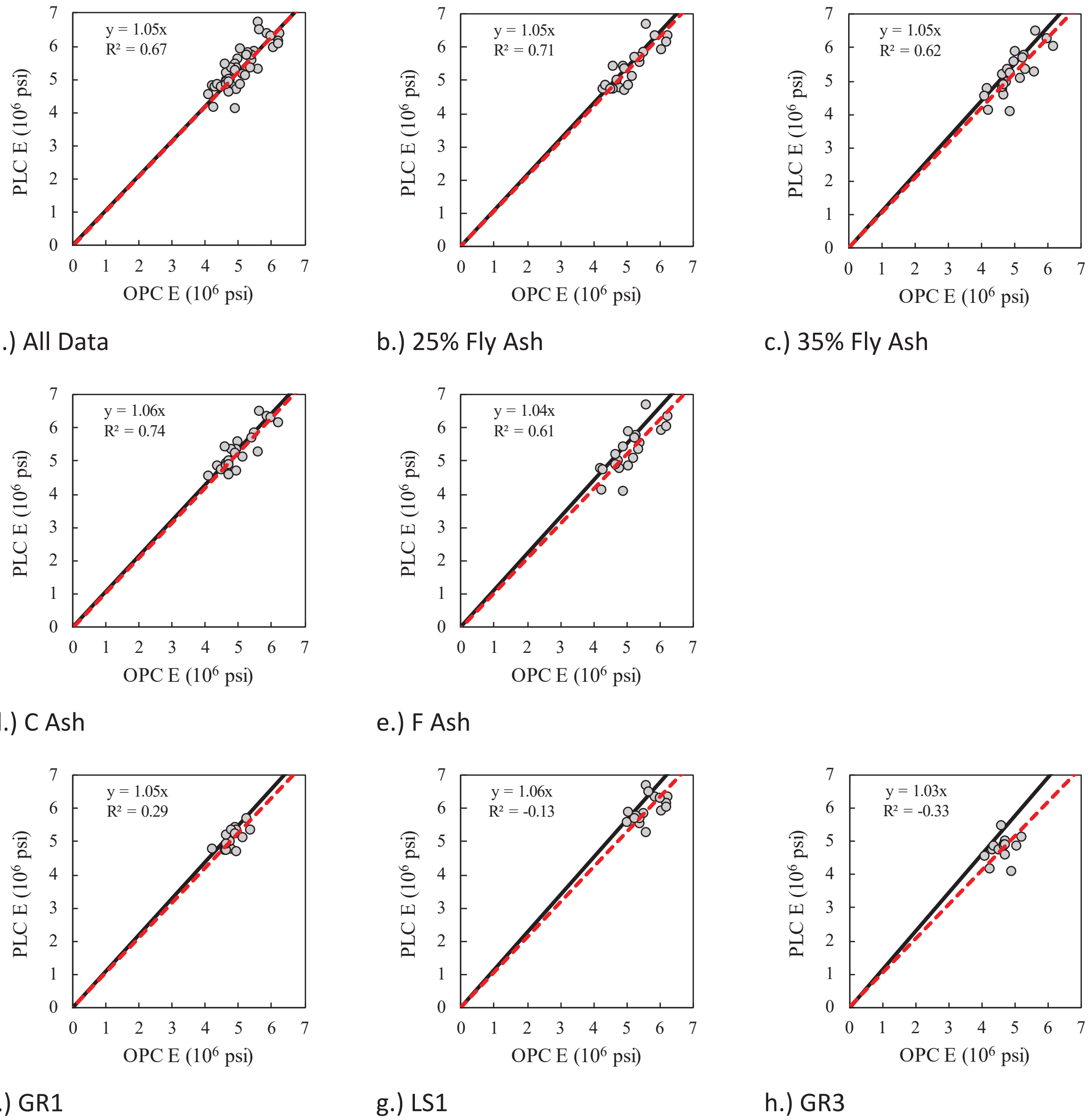


d.) PLC2 35% Class C fly ash

Figure 4.8. Example Paste Aggregate Bond Verification

4.3.5 Modulus of Elasticity

The majority of this report's trends show a 5% higher modulus of elasticity (E) on average for mixtures with PLC (Figure 4.9 and 4.10) regardless of fly ash class, aggregate type, or cementitious proportions. For mixtures with GR3 and Class F fly ash the trend shows OPC modulus is slightly higher (Figure 4.10f). Table 4.4 summarizes the statistical differences for elastic modulus which shows in all but 1 case that the modulus of PLC is equal or higher than comparable cases with OPC.

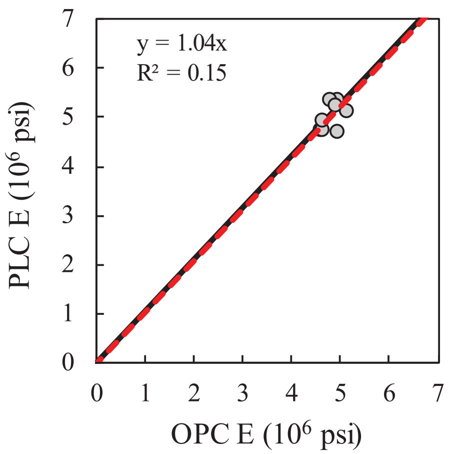


a.) All Data b.) 25% Fly Ash c.) 35% Fly Ash

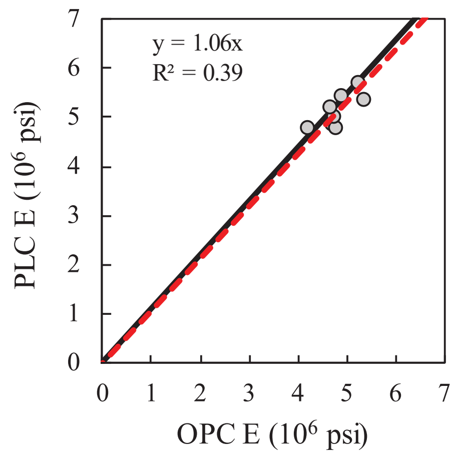
d.) C Ash e.) F Ash

f.) GR1 g.) LS1 h.) GR3

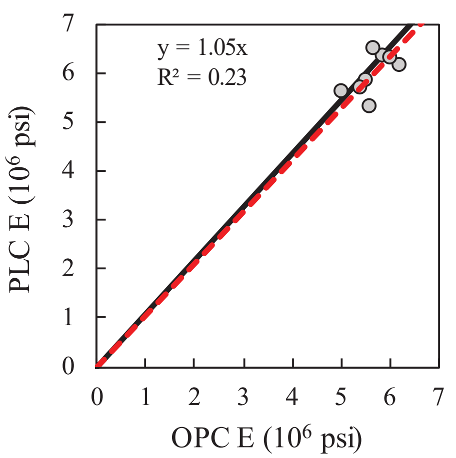
Figure 4.9. Global Modulus Trends



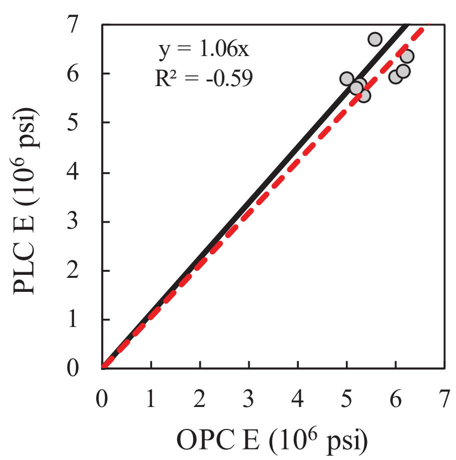
a.) GR1 with C Ash



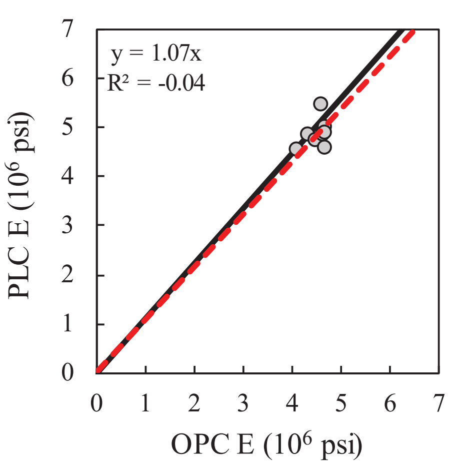
b.) GR1 with F Ash



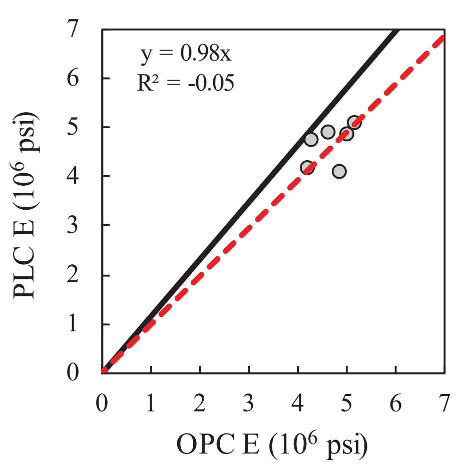
c.) LS1 with C Ash



d.) LS1 with F Ash



e.) GR3 with C Ash



f.) GR3 with F Ash

Figure 4.10. Elastic Modulus Fly Ash Effects for Each Aggregate

Table 4.4. Elastic Modulus Statistics Summary

Aggregate	Day	PLC1				PLC2			
		25% C Ash	25% F Ash	35% C Ash	35% F Ash	25% C Ash	25% F Ash	35% C Ash	35% F Ash
GR1	7	ND (+0.14)	ND (+0.14)	ND (+0.10)	ND (+0.28)	ND (-0.24)	ND (+0.00)	ND (+0.32)	H (+0.54)
	28	ND (-0.03)	H (+0.43)	H (+0.55)	ND (+0.00)	ND (+0.36)	H (+0.54)	ND (+0.39)	H (+0.57)
LS1	7	ND (+0.35)	H (+1.10)	ND (+0.61)	ND (+0.50)	ND (+0.32)	ND (+0.13)	ND (-0.30)	H (+0.82)
	28	ND (+0.50)	ND (+0.06)	H (+0.83)	ND (-0.13)	ND (-0.04)	ND (-0.12)	ND (+0.33)	ND (+0.43)
GR3	7	ND (+0.51)	ND (+0.45)	ND (+0.42)	L (-0.79)	ND (+0.24)	---	ND (-0.07)	ND (-0.06)
	28	ND (+0.30)	ND (-0.16)	ND (+0.20)	ND (-0.10)	H (+0.84)	---	ND (+0.21)	ND (+0.29)

Note: H indicates PLC modulus was statistically higher than OPC
L indicates PLC modulus was statistically lower than OPC
ND indicates PLC modulus was not different statistically than OPC
--- indicates no data is available
Value in parentheses is PLC modulus – OPC modulus in millions of psi
Statistical differences were based on least squares mean

4.3.6 Splitting Tensile Strength

Overall, there does not seem to be a considerable preference for PLC or OPC (Figure 4.11 and 4.12) based on splitting tensile strength (*T*) results. The only cases which show a larger margin is when the data are reduced to one aggregate and fly ash class (Figure 4.12). In these cases, there is a slight favoring of PLC with Class C fly ash. Table 4.5 summarizes the statistical differences which shows no clear trends. The only noteworthy conclusion from Table 4.5 is that PLC1 with 35% Class C fly ash showed better tensile strength in every case (except one) with all aggregates. This may indicate some modest potential bonding issues with the OPC at this fly ash level, and that fly ash level increases beyond 35% might have led to PAB problems with OPC that are known to occur in MS concrete.

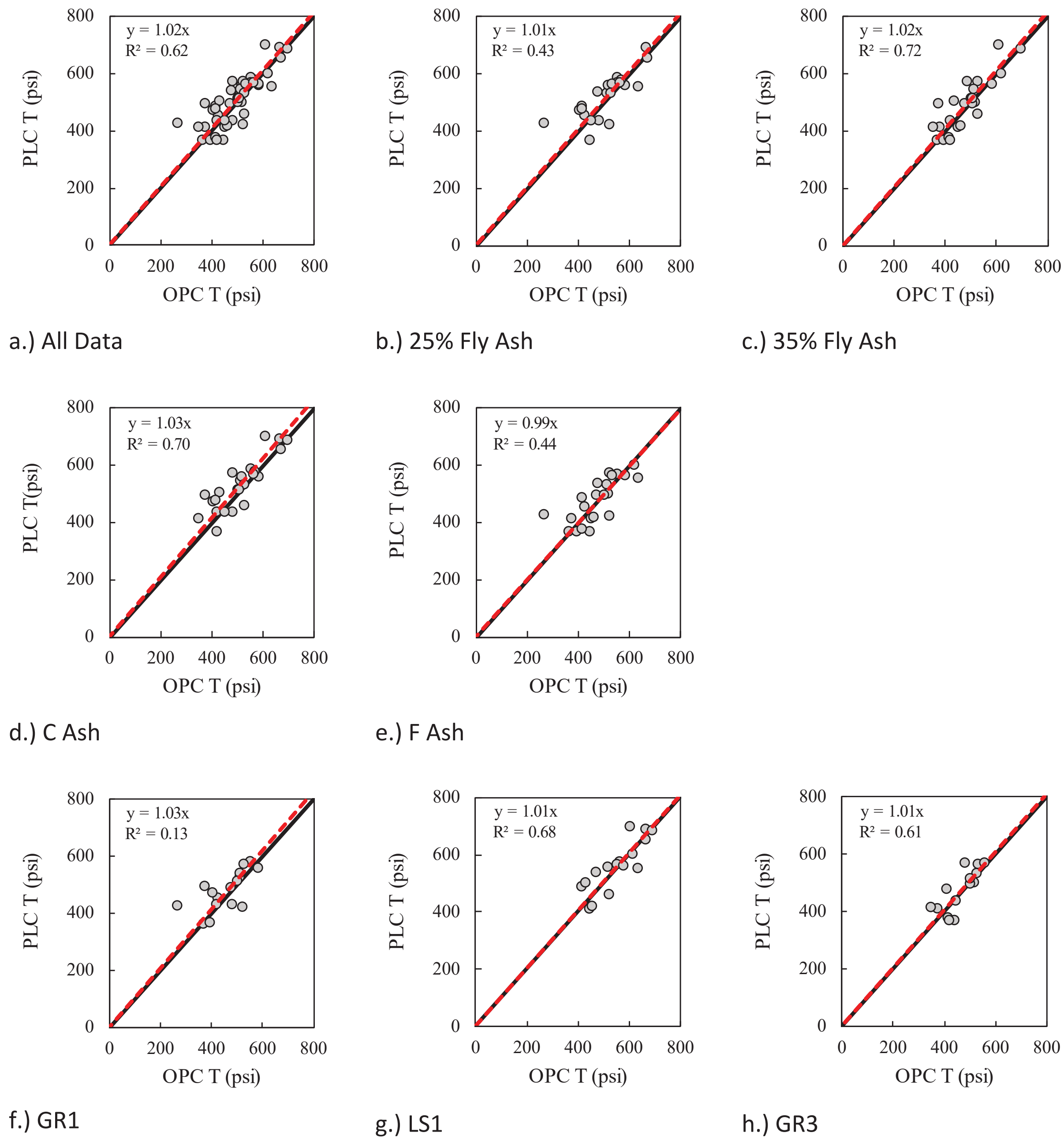
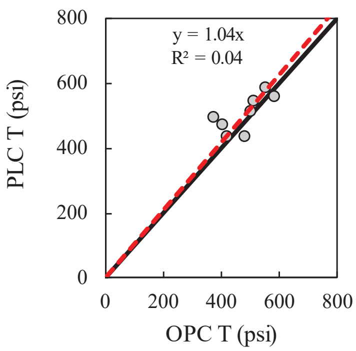
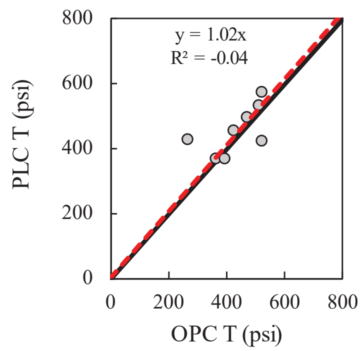


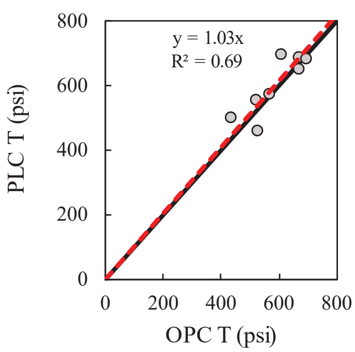
Figure 4.11. Splitting Tensile Strength Global Trends



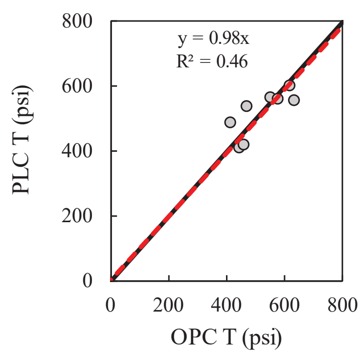
a.) GR1 with C Ash



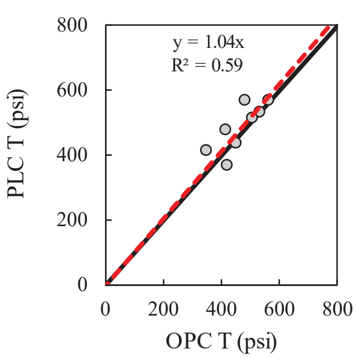
b.) GR1 with F Ash



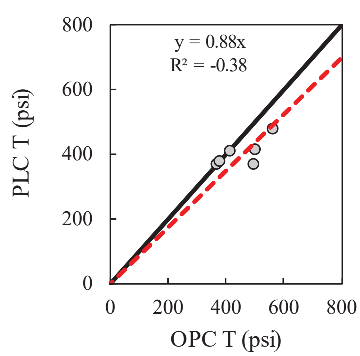
c.) LS1 with C Ash



d.) LS1 with F Ash



e.) GR3 with C Ash



f.) GR3 with F Ash

Figure 4.12. Splitting Tensile Strength Fly Ash Effects for Each Aggregate

Table 4.5. Tensile Strength Statistics Summary

Aggregate	Day	PLC1				PLC2			
		25% C Ash	25% F Ash	35% C Ash	35% F Ash	25% C Ash	25% F Ash	35% C Ash	35% F Ash
GR1	7	ND (+69)	S (+160)	S (+122)	ND (-2)	ND (-47)	ND (+3)	ND (+14)	ND (-27)
	28	ND (-25)	ND (+18)	ND (+30)	ND (+47)	ND (+30)	W (-102)	ND (+13)	ND (+18)
LS1	7	ND (-10)	S (+63)	S (+71)	ND (-37)	ND (+38)	S (+71)	W (-66)	ND (+41)
	28	ND (-17)	ND (+12)	S (+91)	ND (-18)	ND (+22)	W (-82)	ND (-9)	ND (-19)
GR3	7	S (+63)	W (-77)	S (+63)	ND (+36)	ND (-14)	---	ND (-53)	ND (-40)
	28	ND (+6)	ND (+29)	S (+87)	ND (-18)	ND (+1)	---	ND (+9)	ND (-8)

Note: S indicates PLC tensile strength was statistically stronger than OPC
W indicates PLC tensile strength was statistically weaker than OPC
ND indicates PLC strength was not different statistically than OPC
--- indicates no data is available
Value in parentheses is PLC tensile strength – OPC tensile strength in psi
Statistical differences were based on least squares mean

4.3.7 Surface Resistivity

Resistivity trends were very clear showing that SR benefitted from PLC in almost every case (Figure 4.13). Class C fly ash with PLC was an especially interesting situation with gravel aggregates. When separating the data by aggregate type and fly ash class the two gravels showed 51% and 61% higher resistivity values with PLC (Figure 4.14). Excess permeability at the interfacial transition zone when gravel aggregates, OPC, and Class C fly ash are combined may be causing this effect. Almost all the data interpreted indicates PLC has equivalent or better performance with a potential increase of 60% in resistivity possible in certain cases with gravel aggregates.

Table 4.6 summarizes SR statistics. Globally PLC was equal to OPC 35% of the time and better than OPC 53% of the time (better or equal 88% of the time). PLC with Class C fly ash was not different than OPC 27% of the time and better than OPC 69% of the time (better or equal 96% of the time). PLC with Class F fly ash was equal to OPC 43% of the time and better than OPC 36% of the time (better or equal 79% of the time). PLC with gravel aggregates was equal to OPC 33% of the time and better than OPC 60% of the time (better or equal 93% of the time). PLC with gravel aggregates and Class C Fly Ash was equal to OPC 19% of the time and better than OPC 81% of the time (better or equal 100% of the time). This data indicates that SR for a specific concrete mixture performed at a higher level with PLC rather than OPC, especially when gravel aggregates and Class C fly ash were used together.

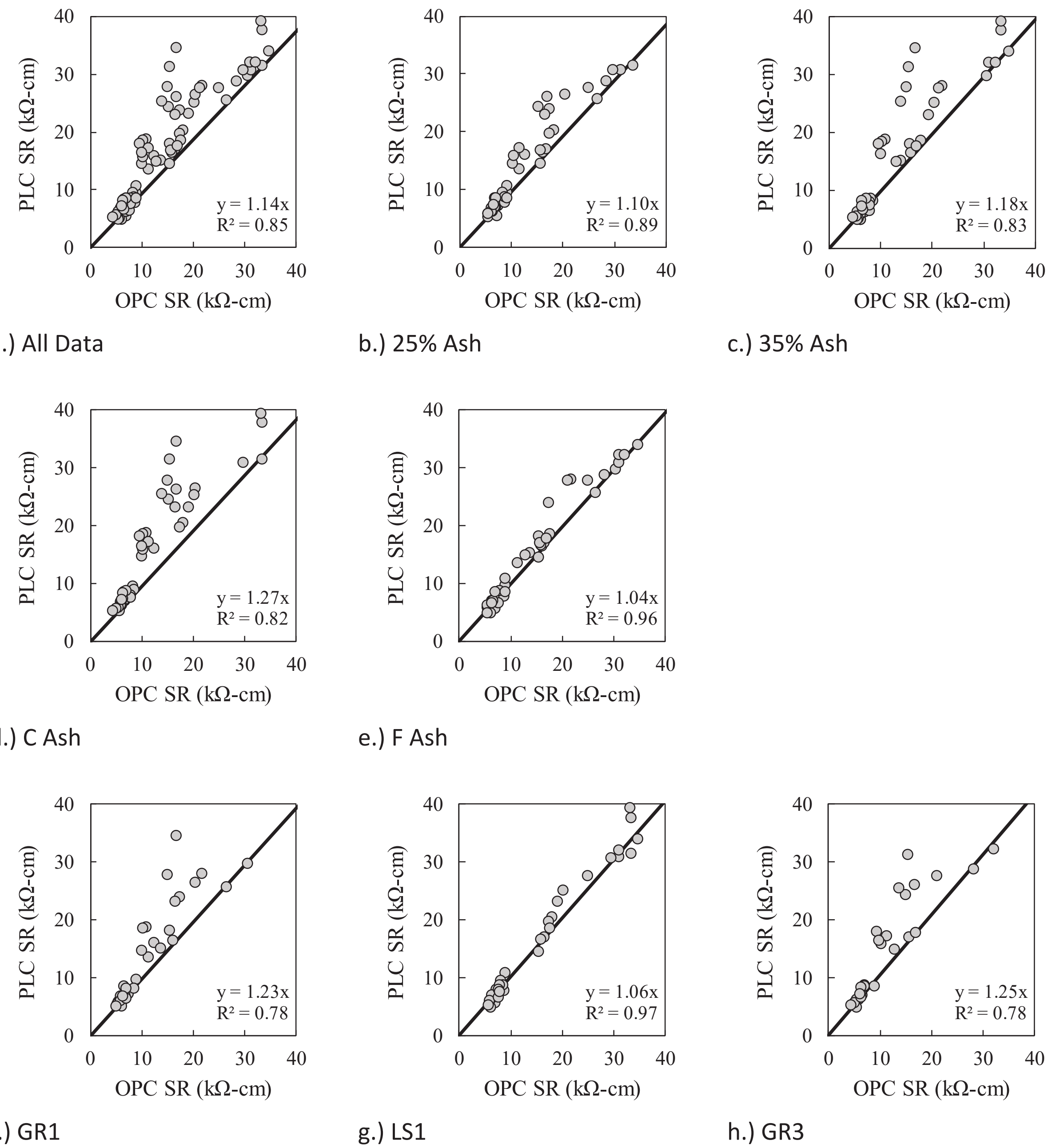


Figure 4.13. Global Surface Resistivity Trends

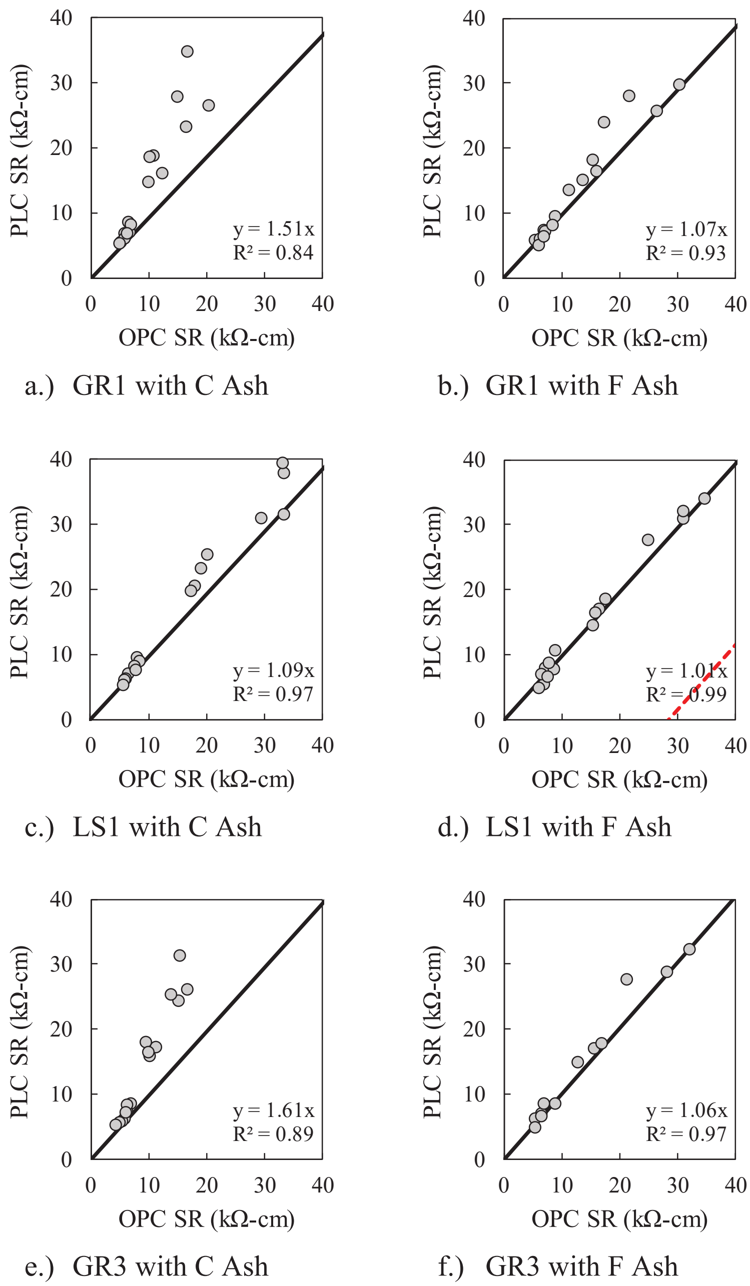


Figure 4.14. Surface Resistivity Fly Ash Effects for Each Aggregate

Table 4.6. Surface Resistivity Statistics Summary

Aggregate	Day	PLC1				PLC2			
		25% C Ash	25% F Ash	35% C Ash	35% F Ash	25% C Ash	25% F Ash	35% C Ash	35% F Ash
GR1	3	H (+0.8)	ND (+0.3)	ND (0.0)	ND (-0.3)	ND (0.0)	ND (+0.3)	ND (0.0)	L (-1.2)
	7	H (+1.8)	ND (+0.5)	H (+1.1)	ND (-0.4)	ND (0.0)	ND (-0.2)	ND (+0.5)	L (-0.7)
	28	H (+3.5)	ND (+0.3)	H (+7.9)	H (+2.5)	H (+4.4)	H (+2.1)	H (+8.3)	H (+1.3)
	56	H (+6.0)	ND (-0.9)	H (+17.8)	ND (-0.8)	H (+6.6)	H (+6.5)	H (+12.8)	H (+6.2)
LS1	3	ND (+0.2)	H (+0.6)	ND (-0.1)	H (+0.5)	ND (0.0)	L (-1.6)	L (-0.5)	L (-1.3)
	7	H (+1.2)	H (+1.6)	ND (+0.2)	H (+0.6)	ND (+0.2)	L (-1.0)	ND (-0.4)	L (-1.3)
	28	H (+2.3)	ND (+0.4)	H (+3.9)	H (+0.8)	H (+2.3)	L (-1.0)	H (+4.8)	ND (+0.7)
	56	L (-2.2)	ND (-0.4)	H (+4.3)	ND (-0.8)	ND (+1.1)	H (+2.7)	H (+6.0)	ND (+1.1)
GR3	3	ND (+0.2)	ND (+0.3)	H (+0.4)	H (+0.7)	H (+0.4)	---	H (+0.8)	L (-0.6)
	7	H (+1.6)	L (-0.5)	H (+1.9)	H (+1.4)	H (+0.9)	---	H (+1.0)	ND (+0.1)
	28	H (+5.7)	H (+1.2)	H (+8.5)	ND (+0.7)	H (+5.4)	---	H (+6.4)	H (+2.0)
	56	H (+9.3)	ND (+0.4)	H (+15.9)	ND (0.0)	H (+9.2)	---	H (+11.5)	H (+6.4)

Note: H indicates PLC resistivity was statistically higher than OPC
L indicates PLC resistivity was statistically lower than OPC
ND indicates PLC resistivity was not different statistically than OPC
--- indicates no data is available
Value in parentheses is PLC resistivity – OPC resistivity in kΩ-cm
Statistical differences were based on least squares mean

4.4 Effects of Fly Ash Class and Replacement Rate on Fresh and Hardened Concrete

The previous section compared OPC and PLC relationships for each property tested by way of concrete or cement paste. Overall the results showed PLC to be equivalent or better in most cases. Additionally, Class C fly ash combined with PLC showed enhanced performance in some cases highlighting previously documented synergies between these materials. This section investigates and expands on the effects of fly ash class and replacement rate.

4.4.1 Hardened Properties

The fly ash class or source can be ranked for each property to show general trends. The fly ash ranking for f_c is FA3>FA2>FA1 while *T* ranks the fly ashes FA3>FA1>FA2. For E the fly ashes rank FA2>FA3>FA1, and SR ranks the fly ashes FA1>FA2>FA3. When looking separately at OPC versus PLC, *T* and E follow the global trends. The f_c rankings for OPC mixtures differed from global trends with FA2>FA3>FA1, although the differences were small, and PLC followed the global trends. The trends for SR were different if observed globally or separated by cement type (OPC or PLC). OPC SR showed FA2>FA1>FA3 with FA1 and FA2 being approximately equivalent while PLC ranked the fly ashes FA3>FA1>FA2. These trends follow what was observed in previous sections mainly that PLC and Class C fly ash (FA3) perform well together (highest f_c, *T*, and SR). The fly ash proportion trends were consistent. In f_c, *T*, and E, 0%>25%>35%, while SR showed that 35%>25%>0%. This follows expected trends with slightly reduced mechanical performance as cement replacement increased. Additionally, it is expected that SR would increase with cement replacement increases due to the pozzolanic activity which would making the concrete more resistant to chloride ion penetration.

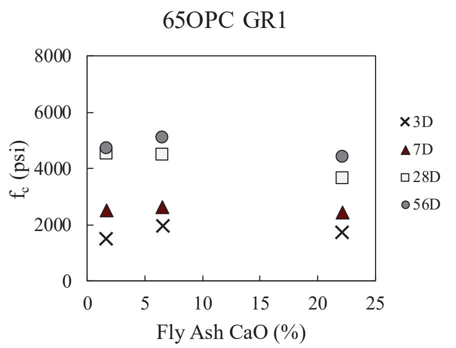
4.4.2 Fresh Mixed Properties

Slump, air content, and set time were similar regardless of the percent replacement with fly ash or the type of cement used (OPC or PLC). Fresh mix properties for FA2 and FA3 follow expected trends of fly ash addition while FA1 differed in slump and set time and had very low air contents. For FA1, FA2, and FA3, the unit weight was practically unchanged with 25 and 35% fly ash replacement. FA2 and FA3 had considerably longer set times that increased with greater replacement while FA1 showed little change in set time. There was practically no change in slump with FA1 addition even at higher percentages. FA2 and FA3, however, showed an initial increase in slump which increased further with fly ash addition. FA2 and FA3 addition did not appear to affect the air content of the mixtures, whereas FA1 mixes had very low air content compared to the other mixtures.

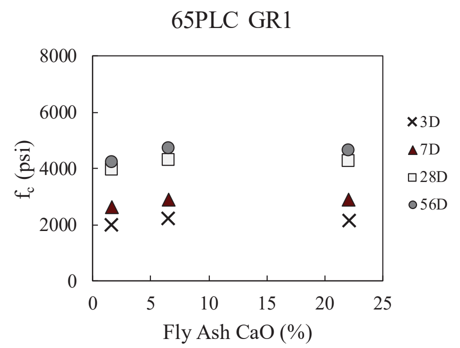
4.4.3 CaO Content Effects

Recall that FA1, FA2, and FA3 CaO contents are 1.6, 6.5, and 22.1%, respectively. These CaO contents show different responses with OPC and PLC. With respect to f_c, OPC mixtures tend to increase then decrease as CaO content increases, while PLC mixes increase then increase slightly or remain the same (Figure 4.15a-b) With respect to *T*, 35% replacement OPC mixes show no increase or decrease when CaO content increases and at 25% there is a decrease in strength followed by an increase, while PLC mixes increase in strength with CaO content (examples given in Figures 4.15c-d). OPC sees a slight increase in E between 1.6% and 6.5% CaO content, but at 22.1%, E drops to approximately equal to slightly less than 1.6% CaO. Whereas, except for one instance, E with PLC increased as the CaO content increased (Figure 4.15e-f).

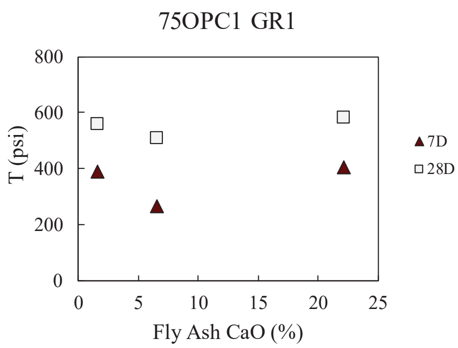
As stated in section 4.3, the results for SR vary if it is being assessed globally or by cement type (OPC or PLC). Globally, SR shows as CaO increases the SR decreases. For OPC mixtures, SR increases then decreases as CaO increases while PLC SR increases with increased CaO. As mentioned previously, it is evident that the aggregates impacted these interactions. When OPC1 is combined with LS1 the variation as CaO content increases was small, but when OPC1 was combined with GR1 there was a noticeable decrease in SR at 56 days from 6.5% to 22.1% CaO (Figure 4.15g). However, when the same mixture replaces OPC with PLC the SR actually increases as CaO increases (Figure 4.15h). It appears that substituting PLC with OPC, in cases using fly ash with high CaO contents and gravel aggregates, can lead to equivalent or perhaps better performance when compared to lower CaO fly ashes.



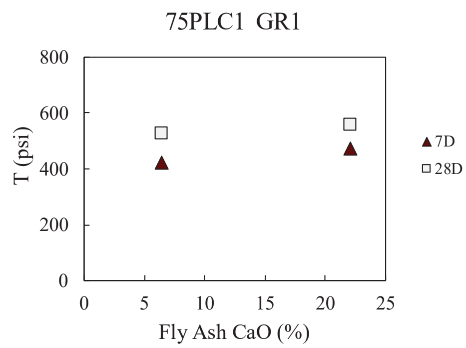
a.) f_c with OPC



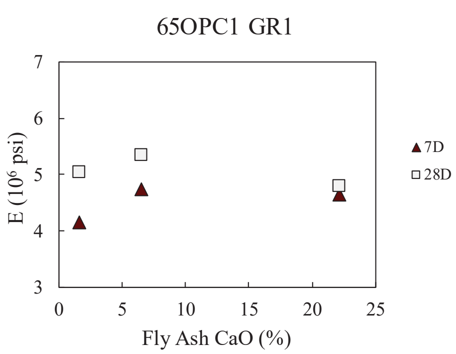
b.) f_c with PLC



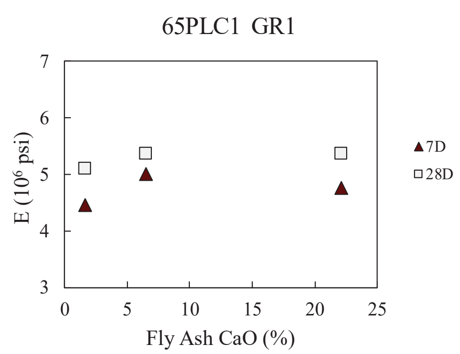
c.) *T* with OPC



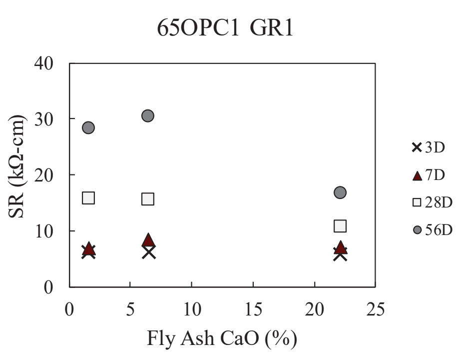
d.) *T* with PLC



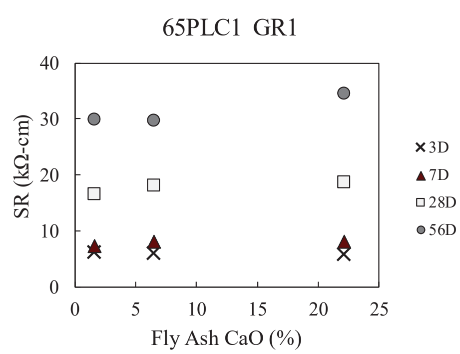
e.) E with OPC



f.) E with PLC



g.) SR with OPC



h.) SR with PLC

Figure 4.15. Fly Ash CaO Effects on Hardened Concrete Properties

CHAPTER 5 – ANALYSIS OF MIXTURES TO UNDERSTAND FUNDAMENTAL MECHANISMS

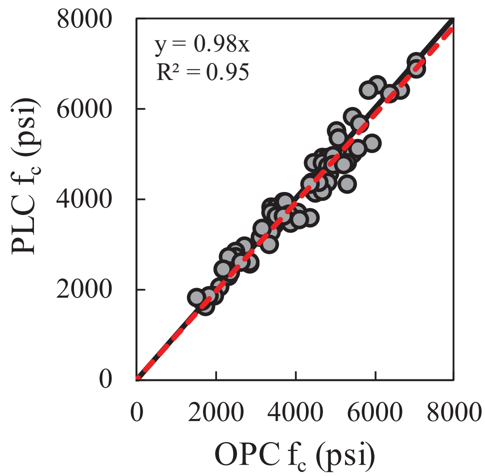
5.1 Overview

This chapter conducts a cursory mechanisms analysis of the phase 2 test results for the purpose of presenting general trends. These mixtures are not meant to be produced; they contain no admixtures, have a tight size range of coarse aggregates, and all the materials were washed. Their purpose is to isolate fundamental mechanisms since as noted in Chapter 1 there were some discussions along these lines leading up to this project. A more detailed analysis is forthcoming, but much of the planned analysis would not be of first order interest to producers. This chapter gives a point by point analysis of factors which may be of specific interest for producers. A total of 40 mixtures (75-114) make up a completely blocked experiment with four aggregates (LS(w), GR2(w), PG(w), and CG(w)), two cements (OPC1b and PLC1b), two fly ashes (FA2 and FA3a), and three fly ash loadings (0%, 25%, and 35%). Since these concrete mixtures have limited variables, the fundamental effects on concrete properties can be assessed. The remainder of this chapter presents five points of potential interest for concrete producers that might be of general assistance when selecting materials or proportions.

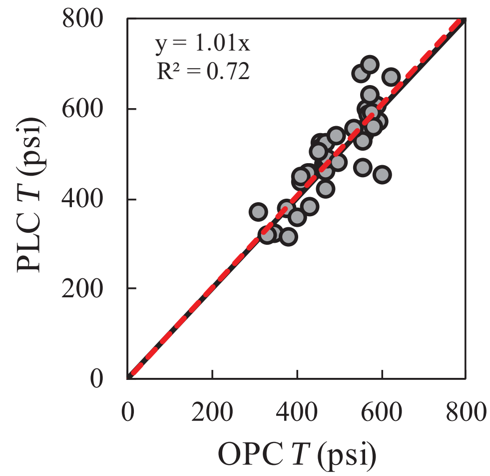
5.2 Point 1 – OPC to PLC Comparisons

Figure 5.1 shows the OPC and PLC comparisons for each of the four hardened concrete properties. The results indicate that for these mixtures OPC and PLC were approximately equal for each property. The only modest difference was f_c at 3D, which showed measurable increase (6%) with use of PLC. The implications of Figure 5.1 are minimal from the author's perspective in terms of marketplace acceptance of PLC. Figure 5.1 does, however, show that the synergies that lead to PLC outperforming PLC are not present in all cases. Even when these synergies are not present, PLC remains a more environmentally friendly cement producing the same mechanical properties as OPC in these cases.

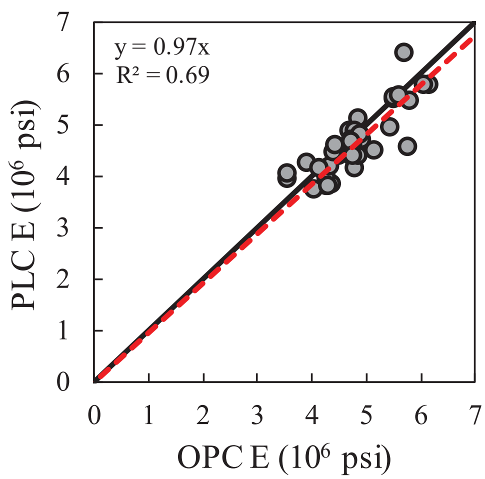
Recall the mixtures evaluated in this chapter have a high *w/cm* ratio of 0.52. It is possible that this additional water has diluted the cement paste to a level that cementitious differences are minimized. Also recall aggregates have been washed and there are no admixtures and note that some of the same raw ingredients from Chapter 4 were also used in Chapter 5. In Chapter 4, synergies were noticed with PLC for some combinations with these replicate materials.



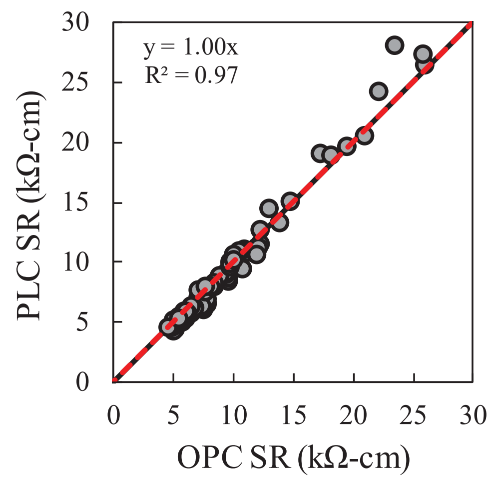
a.) Compressive Strength



b.) Splitting Tensile Strength



c.) Elastic Modulus

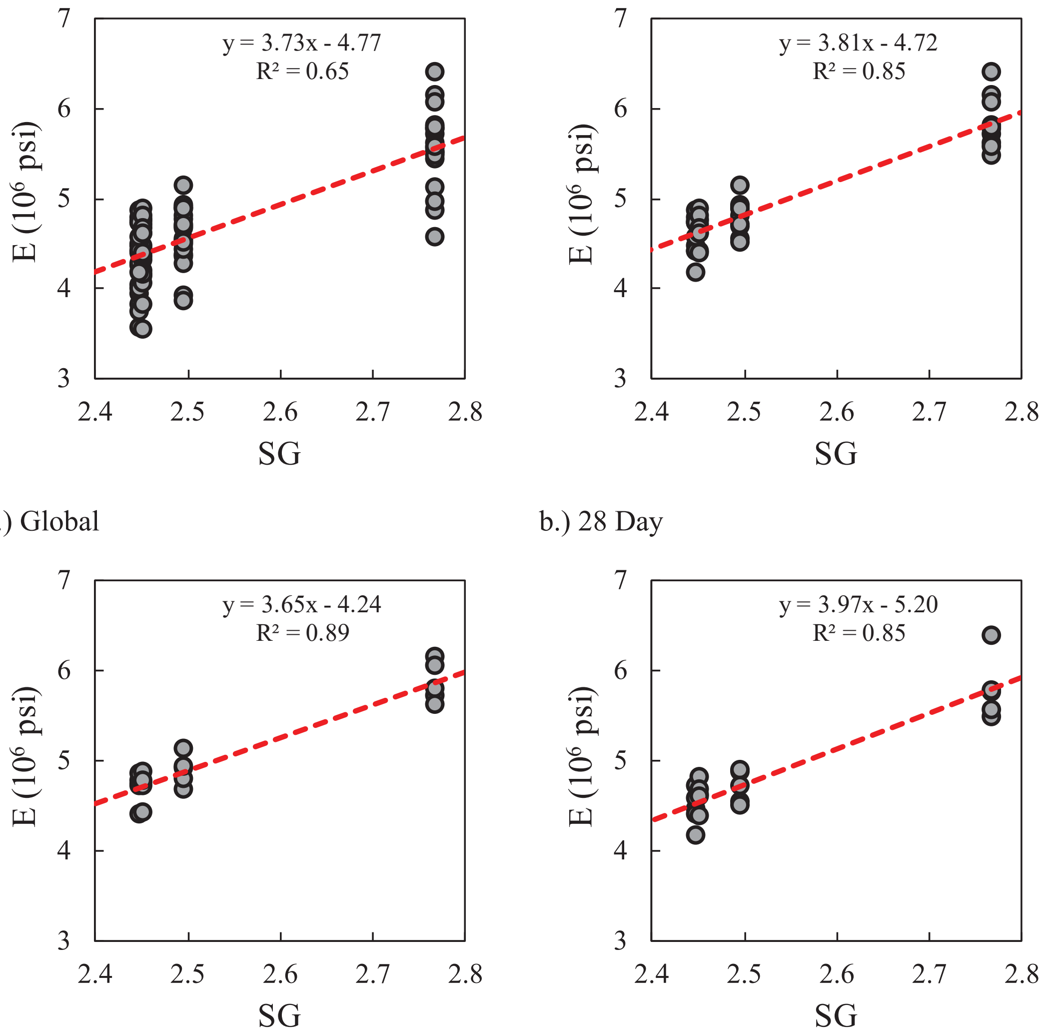


d.) Surface Resistivity

Figure 5.1 – Global OPC to PLC Comparisons

5.3 Point 2 – Elastic Modulus and Bulk Specific Gravity Relationships

The elastic modulus and bulk specific gravity (SG) had a strong relationship in this data set (Figure 5.2). When the all the data is considered SG and E have an R^2 of 0.65. When the data is confined to testing age (Figure 5.2b) and/or cement type (Figure 5.2c-d) the relationship becomes much stronger. Other relationships such as proportions and fly ash class show consistent R^2 above 0.80. Linear regression indicates that SG is a statistically significant variable which can be used to explain the variation in E. This may help producers understand elastic modulus for cases where it is a design consideration. Note there were no considerable differences when the aggregates were crushed or rounded. A higher specific gravity value led to higher E values in this investigation.



a.) Global

b.) 28 Day

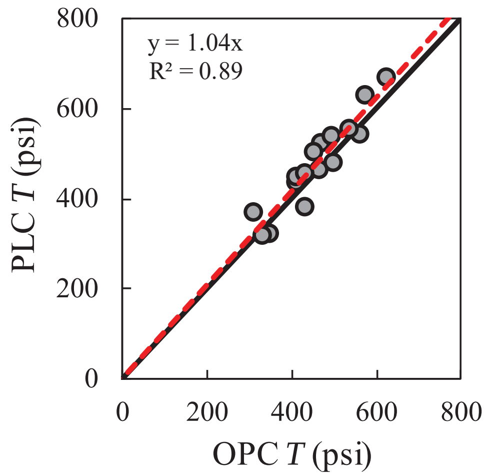
c.) OPC 28 Day Modulus

d.) PLC 28 Day Modulus

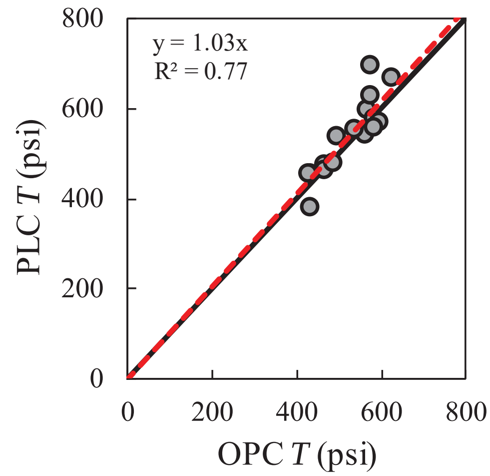
Figure 5.2 – Elastic Modulus and Specific Gravity Relationships

5.4 Point 3 – Splitting Tensile Strength

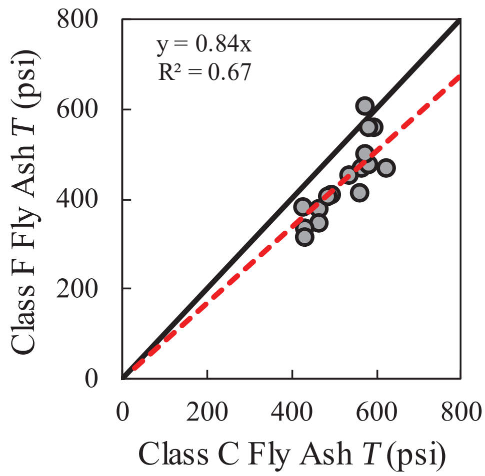
Globally splitting tensile strength was not considerably different between OPC and PLC. Figure 5.3a-b show the two cases where *T* was best when using PLC. As replacement rates increase PLC begins performing slightly better than OPC indicating the OPC bond may have been weakening. Additionally, Class C fly ash is noticeably better than Class F fly ash mixtures. Class C fly ash with OPC and PLC had 16% and 22% higher split tensile strengths, respectively, relative to similar Class F fly ash mixtures.



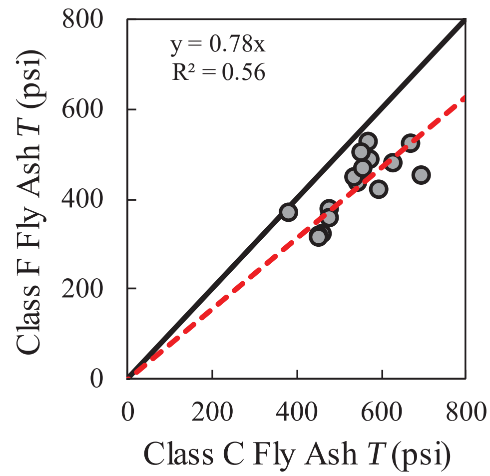
a.) 35% Fly Ash



b.) Class C Fly Ash



c.) OPC Class C versus Class F fly ash

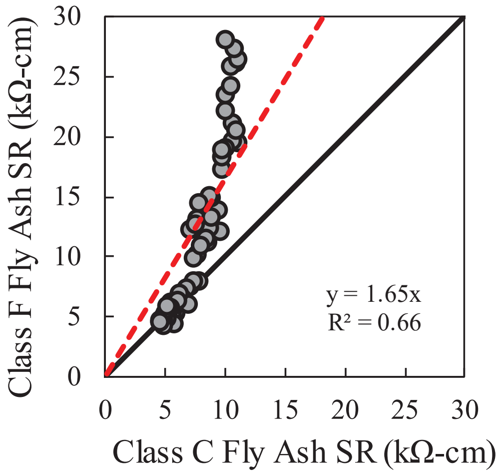


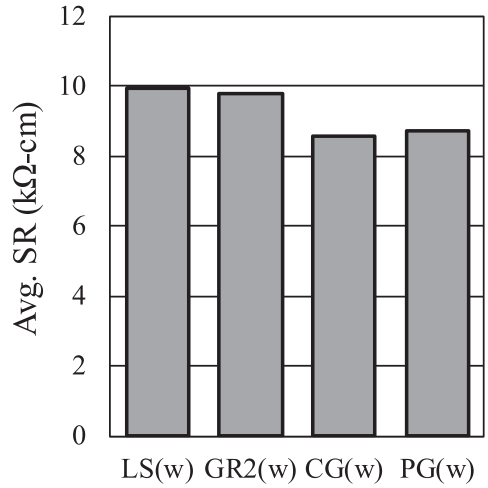
d.) PLC Class C versus Class F fly ash

Figure 5.3 – Splitting Tensile Results

5.5 Point 4 – Surface Resistivity

SR showed equal performance relative to cement type (OPC or PLC). However, SR showed a noticeable effect relative to fly ash class as can be seen in Figure 5.4a. Class F fly ash was 65% higher on average than similar mixtures with Class C fly ash. The reasons for this are unknown. Of key importance is the complete contradiction to the results in Chapter 4 which found better performance with Class C fly ash especially when combined with PLC. Further investigation into this behavior could be worthwhile. In addition to fly ash class, it seems aggregate type is important. Figure 5.4b shows the average SR values for each aggregate. The similar gravels (CG(w) and PG(w)) performed approximately equal while the third gravel (GR2(w)) was comparable to LS(w). A producer should be aware that the resistivity appears to be affected by the aggregate type.





a.) Fly Ash Class Effects

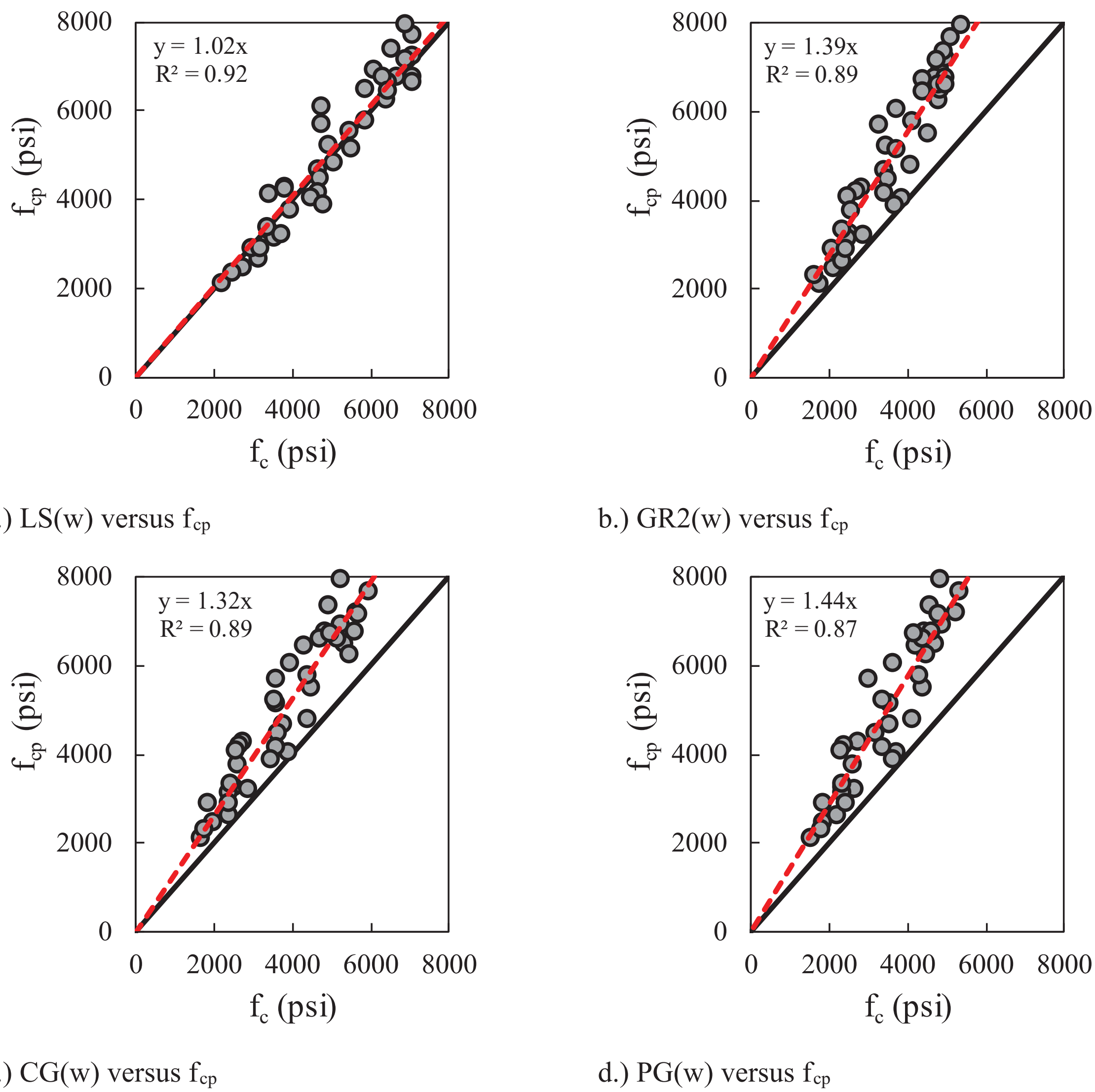
b.) Aggregate Effects

Figure 5.4 – Phase 2 Surface Resistivity Results

5.6 Point 5 – Bonding Efficiency

The bonding efficiency of aggregates and cement paste can be assessed by comparing concrete and cement paste compressive strengths as seen in Figure 5.5. A question that often arises is the extent to which aggregates have bonded to cement paste. As shown in Figure 5.5a, when fine particles were washed from the limestone aggregates, a near full bond appears to have formed as concrete was able to achieve comparable strengths to the cement paste. As documented in Hansen et al. 2019a, cement paste is stronger than ready mixed concrete produced from the same cementitious system in almost all cases. It is noteworthy that when no admixtures were present and no fine particles coated the crushed limestone, what appears to be a full to nearly full bond was achieved. For reference, concrete containing admixtures and limestone aggregates that had not been washed was evaluated by Hansen et al. (2019a) and Hansen et al. (2019b). In those studies, cement paste (CP) was 21 to 39% stronger than concrete produced with limestone aggregates.

Figures 5.5b to 5.5d compare CP to concrete in terms of compressive strength for the three gravel aggregates evaluated. The crushed gravel (Figure 5.5c) performed best as cement paste was only 32% stronger than concrete produced with this same paste and crushed gravel. The two rounded gravels (Figures 5.5b and 5.5d) performed the worst with paste being 39 to 44% stronger than the concrete produced with this paste and rounded gravels. This data indicates that crushing gravel improved bonding for these materials, but not nearly to the level of crushed limestone. This data shows that aggregate mineralogy (i.e. chert gravel versus calcium carbonate in limestone) and shape (rounded versus crushed) affect bond. This data also shows the usefulness of cement paste mechanical property measurements when assessing concrete systems.



a.) LS(w) versus f_{cp}

b.) GR2(w) versus f_{cp}

c.) CG(w) versus f_{cp}

d.) PG(w) versus f_{cp}

Figure 5.5 – Concrete f_c with Different Aggregates versus Cement f_{cp}

CHAPTER 6 – SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1 Summary

This report contains findings of 114 laboratory produced concrete mixtures that were intended to improve understanding of concrete produced with gravel aggregates, fly ash, and either ordinary portland cement (OPC) or portland-limestone cement (PLC). Fly ash levels evaluated were 25 to 35% to align with current MDOT specifications. Motivation for this project was largely based on Mississippi's heavy use of rounded gravel aggregates to produce concrete and the historical problems that can occur with bonding when higher fly ash levels are used with gravel and OPC. This report was intended to improve understanding of properties that can be achieved within concrete mixtures containing gravel aggregates, fly ash, and either OPC or PLC. A large experimental program was conducted where concrete and cement paste were tested, largely for mechanical properties but also for fresh mixed and resistivity properties.

Data was collected in two phases. Phase 1 incorporated a concrete mix design that is readily used by one Mississippi concrete producer as a baseline and made systematic substitutions of raw ingredients and fly ash replacement rates to evaluate the effects on resulting mechanical properties for the Mississippi concrete market. Phase 2 incorporated concrete mixtures produced without admixtures and with washed aggregates to identify fundamental mechanisms that could be useful for producers as they select materials and proportion mixtures for actual projects.

6.2 Conclusions

Analysis of Mississippi marketplace proportions (phase 1) generally showed that mixtures containing ASTM C595 Type IL PLC were equal to or better than those containing ASTM C150 Type I OPC when several properties were considered. This analysis was also, in the opinion of the authors, a favorable scenario for OPC. Fresh mixed properties consistently showed that setting time and workability decreased with PLC. Workability loss was the main negative observed with PLC, but was at a level that can be efficiently corrected by admixture adjustments. Compressive strengths of concrete and cement paste indicated that PLC rarely performs worse than OPC. Additionally, PLC with Class C fly ash continuously behaved synergistically, especially when used with gravel aggregates. Cement paste strengths were informative relative to concrete strengths indicating cement paste testing can be a useful tool to categorize expected concrete behavior. Modulus of elasticity showed a consistent 5% benefit with PLC. Splitting tensile strength showed equivalent results between OPC and PLC except with 35% Class C fly ash which performed statistically better with PLC. With regard to surface resistivity, PLC showed equivalent or better performance 88% of the time, and Class C fly ash outperformed Class F fly ash. Results showed that as fly ash loading increased from 0 to 35% that the compressive strength, tensile strength, and elastic modulus decreased while surface resistivity showed the reverse trend (i.e. resistivity increased as fly ash level increased) which would typically be expected. Fly ash class was an important variable. The main conclusion is that PLC performs very well in the Mississippi marketplace and has not shown signs of paste-aggregate bond problems at higher fly ash loadings.

Analysis of phase 2 mixtures led to five points of potential interest to Mississippi concrete producers. The first point was that OPC and PLC led to the same overall properties when aggregates were washed, no admixtures were present, and the *w/cm* ratio was at a relatively high value of 0.52. The second point was that coarse aggregate specific gravity and concrete elastic modulus were highly correlated and the correlations were statistically significant. Higher elastic modulus values were recorded for higher specific gravity coarse aggregates. The third point was that Class C fly ash had roughly 20% higher split tensile strength than Class F fly ash. The fourth point was that Class F fly ash had, on average, a 65% higher surface resistivity than Class C fly ash. These findings are in complete contradiction to those presented in the previous paragraph from the Mississippi marketplace mixtures where fly ash performance was reversed for surface resistivity. The fifth and final point relates to bonding to aggregates of different shape and mineralogy. With washed aggregates and no admixtures, limestone was able to form a near to full bond with cement paste. Crushed gravel did not form a full bond to cement paste based on the data collected, and was only modestly better than rounded gravel, which had the lowest bond to cement paste. Mineralogy and shape where shown to affect bonding properties with aggregates used in Mississippi.

6.3 Recommendations

This report led to the four recommendations listed below.

1. Mississippi concrete producers are encouraged to use the data stored in this report for benchmarking or other purposes over time. Some of the data contained in this report was collected at the request of Mississippi concrete producers, and with all data organized in tables alongside several combinations, it is anticipated that there will be future uses for this data beyond the analysis contained herein.
2. Additional evaluation of resistivity testing for the purpose of evaluating concrete's long term durability is recommended. Phase 1 and 2 resistivity data contradicted each other, and with neighboring states performing detailed assessments of resistivity testing, Mississippi might be wise to do a more comprehensive analysis with their materials and mixtures.
3. Measuring compressive strength of cement paste at the same *w/cm* ratio and with the same admixture dosages as corresponding concrete has shown to be a promising approach, and it is recommended that producers consider making use of this technique to gain more understanding of their concrete mixtures.
4. The main recommendation from this report is for producers who aren't or haven't already to consider implementing ASTM C595 Type IL PLC into their operations, especially in mixtures that use gravel aggregates and Class C fly ash. This report provides considerable evidence that PLC is very likely to be a better Mississippi marketplace cement than ASTM C150 Type I for most applications.

CHAPTER 7 - REFERENCES

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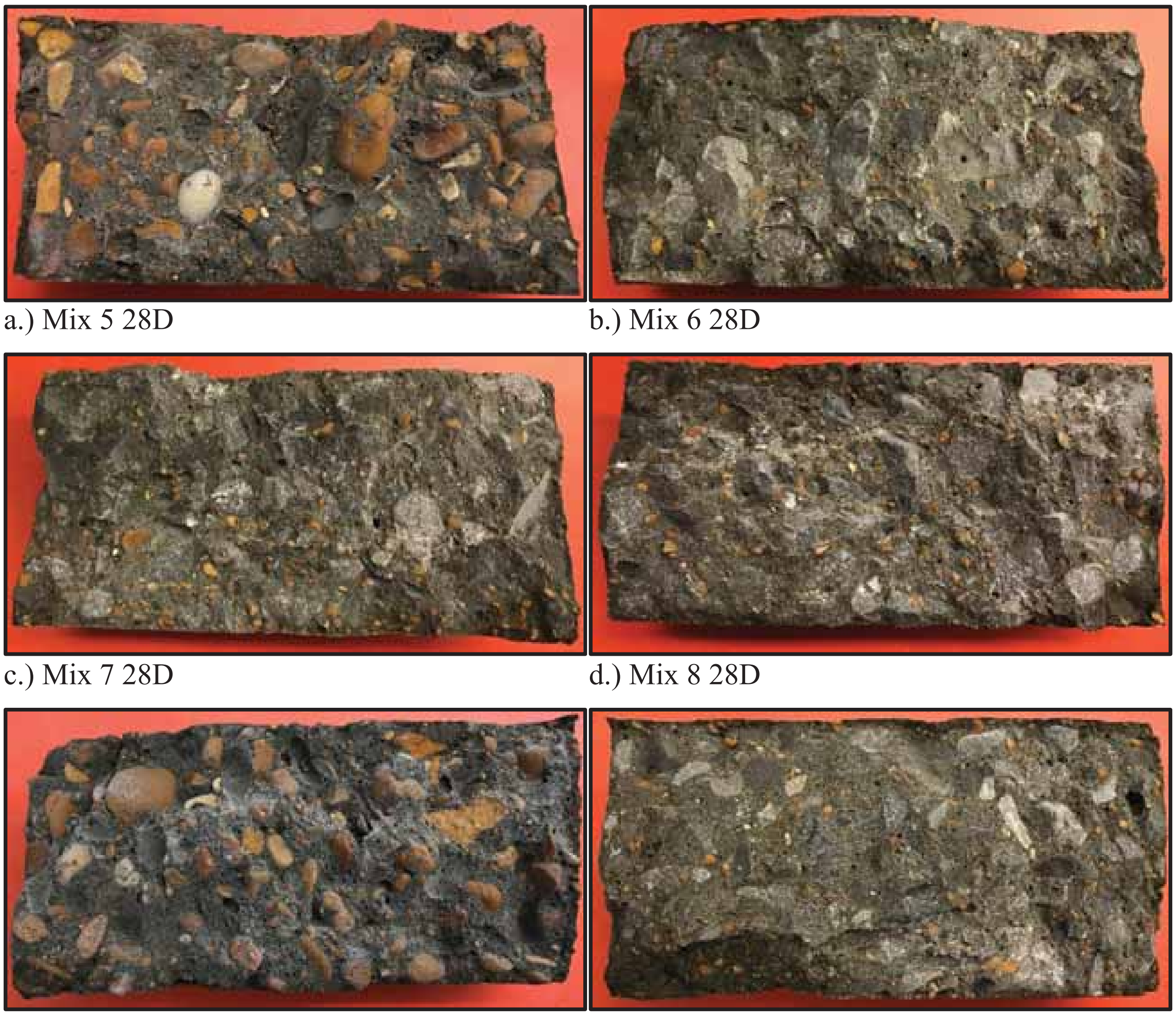
Appendix A

A simple indicator that paste-aggregate bond (PAB) may be affecting strength can be obtained through visual examination of tested specimens. Minimal numbers of broken aggregates coupled with many sockets where cement paste is visible in the failure plane implies poor PAB. Concrete mixtures with strong bond between paste and aggregates can see most aggregates broken along failure planes after curing for even a modest amount of time (e.g. 7 days).



a.) Mix 5 28D b.) Mix 6 28D

c.) Mix 7 28D d.) Mix 8 28D

e.) Mix 9 28D f.) Mix 10 28D

Figure A.1. Mixes 5-10 (28D only)


a.) Mix 11 28D


b.) Mix 12 28D


c.) Mix 14 28D


d.) Mix 15 28D


e.) Mix 16 28D


f.) Mix 17 28D

Figure A.2. Mixes 11, 12, 14, 15, 16, and 17 (28D only)


a.) Mix 18 7D


b.) Mix 18 28D


c.) Mix 19 7D


d.) Mix 19 28D


e.) Mix 20 7D


f.) Mix 20 28D

Figure A.3. Mixes 18-20


a.) Mix 21 28D


b.) Mix 22 28D


c.) Mix 23 28D


d.) Mix 24 28D


e.) Mix 25 28D


f.) Mix 26 28D

Figure A.4. Mixes 21-26 (28D only)

a.) Mix 27 28D

b.) Mix 28 28D

c.) Mix 29 28D

d.) Mix 30 28D

e.) Mix 31 7D

f.) Mix 32 28D

Figure A.5. Mixes 27-32 (28D only)

a.) Mix 33 28D

b.) Mix 34 28D

c.) Mix 35 28D

d.) Mix 36 28D

e.) Mix 37 28D

f.) Mix 38 28D

Figure A.6. Mixes 33-38 (28D only)


a.) Mix 39 7D


b.) Mix 39 28D


c.) Mix 40 7D


d.) Mix 40 28D


e.) Mix 41 7D


f.) Mix 41 28D

Figure A.7. Mixes 39-41

a.) Mix 42 7D

b.) Mix 42 28D

c.) Mix 43 7D

d.) Mix 43 28D

e.) Mix 44 7D

f.) Mix 44 28D

Figure A.8. Mixes 42-44

a.) Mix 45 7D

b.) Mix 45 28D

c.) Mix 46 7D

d.) Mix 46 28D

e.) Mix 47 7D

f.) Mix 47 28D

Figure A.9. Mixes 45-47

a.) Mix 48 7D

b.) Mix 48 28D

c.) Mix 49 7D

d.) Mix 49 28D

e.) Mix 50 7D

f.) Mix 50 28D

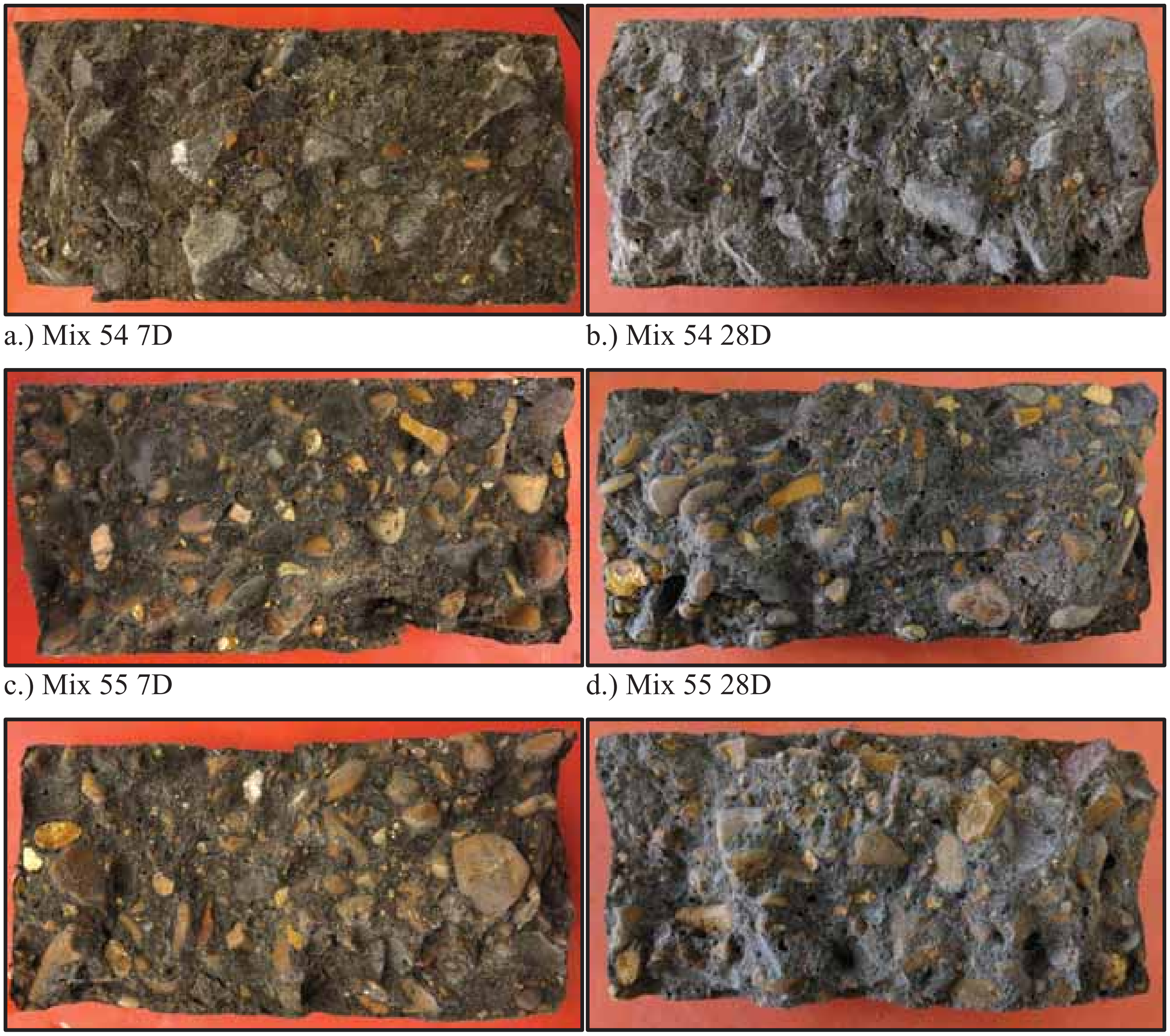
Figure A.10. Mixes 48-50


a.) Mix 51 7D
b.) Mix 51 28D


c.) Mix 52 7D
d.) Mix 52 28D


e.) Mix 53 7D
f.) Mix 53 28D

Figure A.11. Mixes 51-53



a.) Mix 54 7D
b.) Mix 54 28D
c.) Mix 55 7D
d.) Mix 55 28D
e.) Mix 56 7D
f.) Mix 56 28D

Figure A.12. Mixes 54-56


a.) Mix 57 7D


b.) Mix 57 28D


c.) Mix 58 7D


d.) Mix 58 28D


e.) Mix 59 7D


f.) Mix 59 28D

Figure A.13. Mixes 57-59


a.) Mix 60 7D


b.) Mix 60 28D


c.) Mix 61 7D


d.) Mix 61 28D


e.) Mix 62 7D


f.) Mix 62 28D

Figure A.14. Mixes 60-62


a.) Mix 63 7D


b.) Mix 63 28D


c.) Mix 64 7D


d.) Mix 64 28D


e.) Mix 65 7D


f.) Mix 65 28D

Figure A.15. Mixes 63-65

a.) Mix 66 7D

b.) Mix 66 28D

c.) Mix 67 7D

d.) Mix 67 28D

e.) Mix 68 7D

f.) Mix 68 28D

Figure A.16. Mixes 66-68

a.) Mix 69 7D

b.) Mix 69 28D

c.) Mix 70 7D

d.) Mix 70 28D

e.) Mix 71 7D

f.) Mix 71 28D

Figure A.17. Mixes 69-71


a.) Mix 72 7D


b.) Mix 72 28D


c.) Mix 73 7D


d.) Mix 73 28D


e.) Mix 74 7D


f.) Mix 74 28D

Figure A.18. Mixes 72-74

a.) Mix 75 7D

b.) Mix 75 28D

c.) Mix 76 7D

d.) Mix 76 28D

e.) Mix 77 7D

f.) Mix 77 28D

Figure A.19. Mixes 75-77


a.) Mix 78 7D


b.) Mix 78 28D


c.) Mix 79 7D


d.) Mix 79 28D


e.) Mix 80 7D


f.) Mix 80 28D

Figure A.20. Mixes 78-80

a.) Mix 81 7D

b.) Mix 81 28D

c.) Mix 82 7D

d.) Mix 82 28D

e.) Mix 83 7D

f.) Mix 83 28D

Figure A.21. Mixes 81-83


a.) Mix 84 7D


b.) Mix 84 28D


c.) Mix 85 7D


d.) Mix 85 28D


e.) Mix 86 7D


f.) Mix 86 28D

Figure A.22. Mixes 84-86


a.) Mix 87 7D


b.) Mix 87 28D


c.) Mix 88 7D


d.) Mix 88 28D


e.) Mix 89 7D


f.) Mix 89 28D

Figure A.23. Mixes 87-89


a.) Mix 90 7D


b.) Mix 90 28D


c.) Mix 91 7D


d.) Mix 91 28D


e.) Mix 92 7D


f.) Mix 92 28D

Figure A.24. Mixes 90-92


a.) Mix 93 7D


b.) Mix 93 28D


c.) Mix 94 7D


d.) Mix 94 28D


e.) Mix 95 7D


f.) Mix 95 28D

Figure A.25. Mixes 93-95


a.) Mix 96 7D


b.) Mix 96 28D


c.) Mix 97 7D


d.) Mix 97 28D


e.) Mix 98 7D


f.) Mix 98 28D

Figure A.26. Mixes 96-98

a.) Mix 99 7D

b.) Mix 99 28D

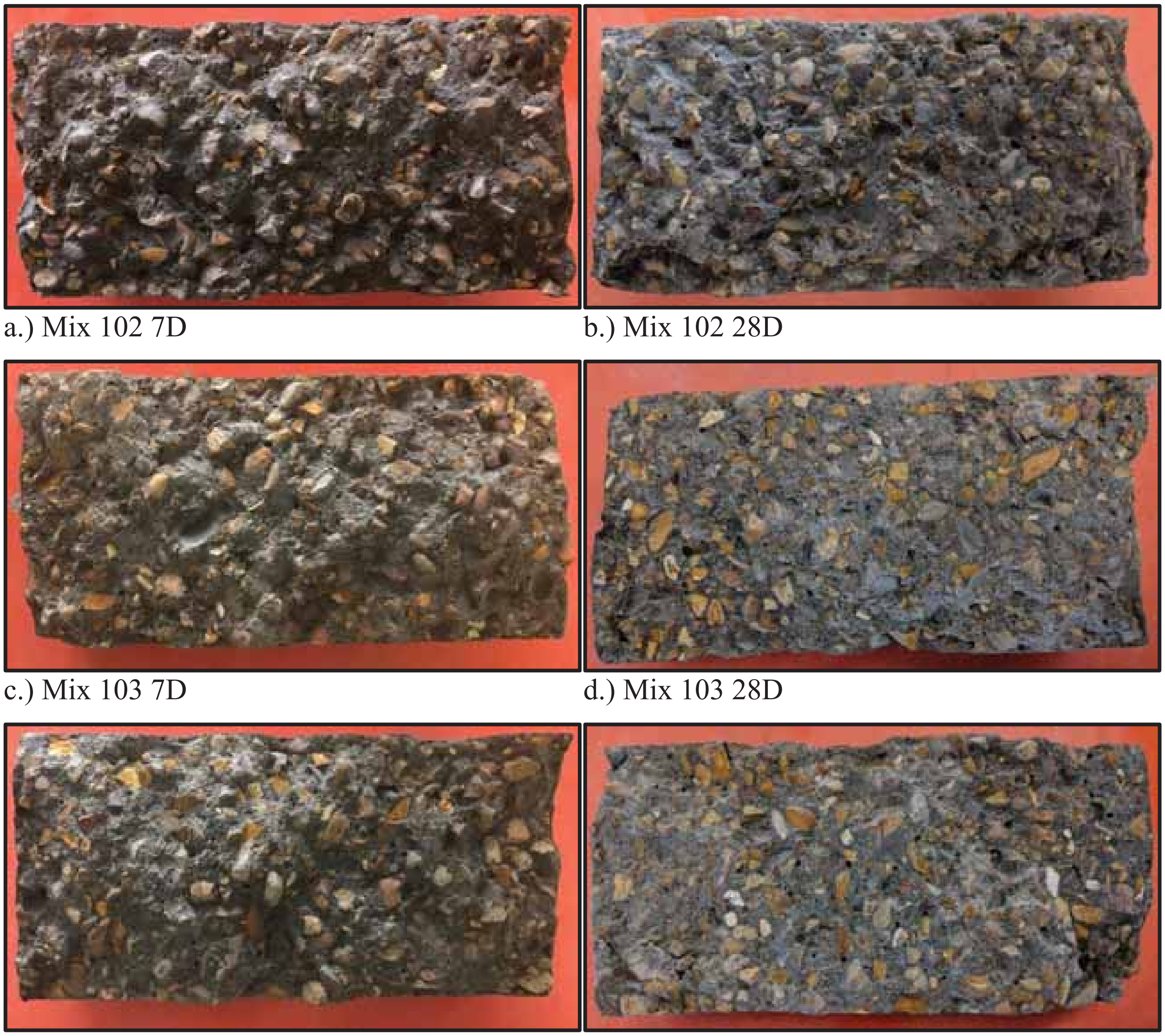
c.) Mix 100 7D

d.) Mix 100 28D

e.) Mix 101 7D

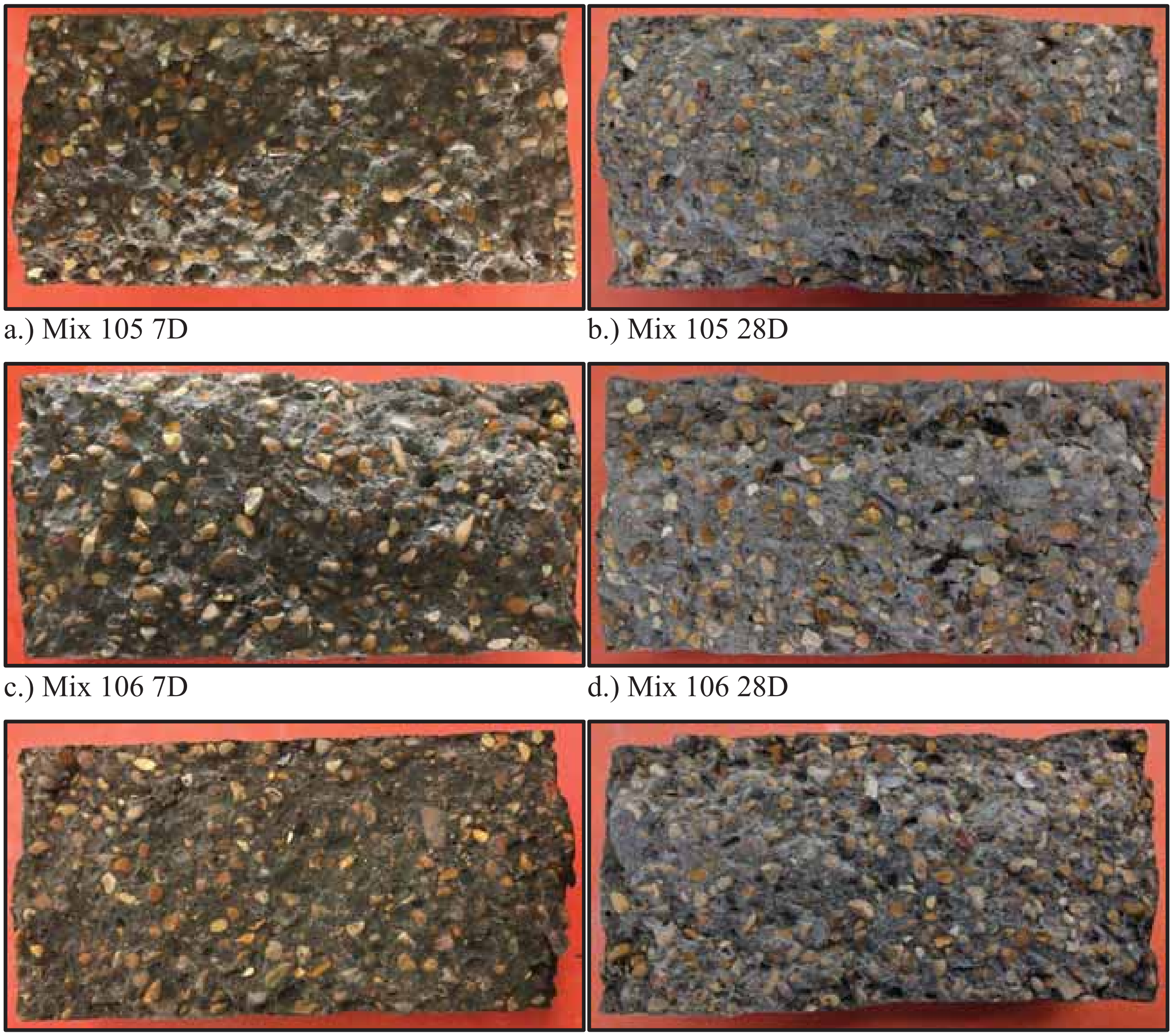
f.) Mix 101 28D

Figure A.27. Mixes 99-101



a.) Mix 102 7D
b.) Mix 102 28D
c.) Mix 103 7D
d.) Mix 103 28D
e.) Mix 104 7D
f.) Mix 104 28D

Figure A.28. Mixes 102-104



a.) Mix 105 7D
b.) Mix 105 28D
c.) Mix 106 7D
d.) Mix 106 28D
e.) Mix 107 7D
f.) Mix 107 28D

Figure A.29. Mixes 105-107


a.) Mix 108 7D


b.) Mix 108 28D


c.) Mix 109 7D


d.) Mix 109 28D


e.) Mix 110 7D


f.) Mix 110 28D

Figure A.30. Mixes 108-110


a.) Mix 111 7D


b.) Mix 111 28D


c.) Mix 112 7D


d.) Mix 112 28D


e.) Mix 113 7D


f.) Mix 113 28D


g.) Mix 114 7D


h.) Mix 114 28D

Figure A.31. Mixes 111-114