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Performance and Sustainability Benefits of Concrete Containing Portland-Limestone Cement

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Performance and sustainability benefits of concrete containing portland-limestone cement

By

Jameson Davis Shannon

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Performance and sustainability benefits of concrete containing portland-limestone cement

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Sustainability and reduction of environmental impacts have continued to increase in importance in the concrete marketplace. Portland-limestone cement (PLC) has been shown to reduce total energy consumed and CO_2 produced during the cement manufacturing process. This material may also have the ability to benefit concrete properties, such as compressive strength and time of set. Other concrete performance measures of potential interest evaluated in this study include durability and modulus of elasticity.

In this dissertation PLC was evaluated for its ability to further increase concrete sustainability, while at the same time providing advantageous properties. This study's focus was to show that PLC can improve concrete mixtures that are similar to commonly used ordinary portland cement (OPC) mixtures. PLC was also evaluated for its ability to increase the amount of total cement replacement (further increasing sustainability). Additionally PLC properties and concrete mixture combinations were evaluated in an attempt to clarify which PLC properties are crucial in performance benefits.

Approximately 2000 concrete specimens were tested along with approximately 1000 cement paste specimens. This dissertation also includes an evaluation of PLC being used in a large scale construction and renovation project on a college football stadium.

The scope of the dissertation included 12 cements from four manufacturing facilities that represent a large portion of the cement industry in the southeast US. Supplementary cementitious materials (SCMs), Class C fly ash, Class F fly ash, and slag cement, were also evaluated in single and dual SCM concrete mixtures at replacement rates up to 70%. Replacement rates of this magnitude are not being used in common practice but may become preferred in some conditions with PLC.

Results indicated that PLC outperformed OPC in areas tested, in almost all cases at up to 50% replacement with single and dual SCMs. PLC also showed considerable advantages at 60% replacement but was often outperformed by OPC at 70% replacement. Aggregate type played a large role at 70% replacement. Elastic modulus, durability, and variability were all similar with PLC and OPC. Combinations of certain SCMs were more advantageous than others, and optimal SCM combinations changed depending on cement source.

Keywords: Concrete, Sustainability, Portland-Limestone Cement

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NOMENCLATURE

ACI	*American Concrete Institute*
Al_2O_3	*Aluminum Oxide*
ASR	*Akali-Silica Reactivity*
ASTM	*American Society for Testing and Materials*
AASHTO	*American Association of State Highway and Transportation Officials*
BTU	*British Thermal Unit*
C	*Celsius*
C_2S	*Di-Calcium Silicat*e
C_3S	*Tri-Calcium Silicate*
C_3A	*Tri-Calcium Aluminate*
C_4AF	*Tetracalcium Alumino Ferrite*
CFC	*Chlorofluorocarbon*
Ca	*Calcium*
$CaCO_3$	*Calcium Carbonate*
CaO	*Calcium Oxide*
Cl	*Chloride*
cm	*Centimeter*
CO_2	*Carbon Dioxide*
COV	*Coefficient of Variation*

CP	*Cement Paste*
CS	*Coarse Sand Fine Aggregate*
CSH	*Calcium Silicate Hydrate*
DOT	*Department of Transportation*
DWS	*Davis Wade Stadium*
eq	*Equivalent*
f_c	*Concrete Compressive Strength*
f_c’	*Design Concrete Compressive Strength*
f_{cp}	*CP Compressive Strength*
Fe_2O_3	*Iron Oxide*
ft	*Feet*
GR	*Gravel Coarse Aggregate*
Hr	*Hour*
in	*Inches*
ITZ	*Interfacial Transition Zone*
K_2O	*Potassium Oxide*
kg	*Kilogram*
kΩ-cm	Kilo-Ohm per Centimeter
L	*Liter*
lb	*Pound*
LEED	*Leadership in Energy and Environmental Design*
LM	*Laboratory Mixed*
LOI	*Loss On Ignition*

LS	*Limestone Coarse Aggregate*
LTRC	*Louisiana Transportation Research Center*
m	*meter*
MCIA	*Mississippi Concrete Institute Association*
MDOT	*Mississippi Department of Transportation*
Mg	*Megagrams*
MgO	*Magnesium Oxide*
MJ	*Megajoule*
ml	*Milliliter*
MPa	Megapascal
MSU	*Mississippi State University*
µm	*Micrometers*
n	*Number of Specimens or Data Points*
N	*Nitrogen*
Na_2O	*Sodium Oxide*
OH	*Hydrogen Oxide*
O_3	*Ozone*
OD	*Oven Dry*
OPC	*Ordinary Portland Cement*
PAB	*Paste-Aggregate Bond*
PG	*Gravel Intermediate Aggregate*
PLC	*Portland-Limestone Cement*
PSD	*Particle Size Distribution*

R_{SI}	*Thermal Resistance*
R^2	*Coefficient of Determination*
SCM	*Supplementary Cementitious Material*
σ_{paste}	*Compressive Strength of Paste Specimens*
S	*Sulfur*
SiO_2	*Silicon Dioxide*
SO_2	*Sulfur Dioxide*
SO_3	*Sulfate*
SSD	*Saturated Surface Dry*
T_c	*Concrete Temperature*
T_{air}	*Air Temperature*
TM	*Truck Mixed*
TTF	*Time Temperature Factor*
US	*United States*
w/cm	*Water to Cementitious Ratio*
XLPE	*Cross Linked Polyethylene*
XRD	*X-ray Diffraction*

CHAPTER I

INTRODUCTION

1.1 Introduction

The concrete industry, as one of the largest construction materials suppliers globally, must consistently evolve to better meet the needs and challenges of the current market. In the US, projects are often heavily time dependent, and pressure is applied to the industry to create products that decrease construction times. Economic and environmental concerns become more influential in marketing products over time, and as such US industries continually face sustainability challenges. Therefore research investigations into new products and manufacturing techniques that support these increasing concerns have become more prevalent.

In concrete materials, one of the most effective ways of reducing CO_2 emissions and decreasing energy costs is to limit the amount of cement, or specifically clinker content, present in mixtures. In the current market this is most often achieved by replacing an amount of cement with an additional cementitious material. Environmental benefits are further enhanced by using byproducts of other industries to fill that role. These byproducts are referred to as supplementary cementitious materials (SCMs).

In most cases when sustainability is increased and environmental impact is decreased, significant drawbacks, either monetary or performance, are present. In the context of reduced clinker content, common issues are lower concrete early strength and longer concrete set times. Monetary costs of using other cementitious materials varies depending on what material is used but is often less expensive than using portland cement. This dissertation shows that in certain cases it is possible to both increase sustainability and improve concrete properties. Instead of sacrificing in other areas to achieve sustainability, which is common, it is possible to gain sustainability and performance benefits at the same time in some situations through the use of portland-limestone cement.

1.2 Objectives and Scope

Portland-limestone cement (PLC) is a relatively new product to US markets manufactured under ASTM C595 (AASHTO M240) as a Type IL cement. This product contains between 5% and 15% ground limestone, essentially replacing that amount of clinker. A clinker reduction of that magnitude would have a meaningful effect on sustainability if PLC was to be used on a large scale. Additionally preliminary investigations have shown that it may be possible to achieve the same or increased concrete properties when using this material, compared to ordinary portland cement (OPC) such as ASTM C150 Type I.

In the current engineering environment, many cases in which sustainability is increased come at the cost of lower performance, higher prices, or both. This research shows that, under the correct conditions, it is possible to both increase sustainability and performance of concrete mixtures. The main objectives of this dissertation are to demonstrate that;

- PLC can be implemented in the concrete marketplace, achieving higher sustainability and increased performance in some cases, without drastic changes to current practices.
- Higher SCM use than what is typical in most projects is not only possible but beneficial and can be increased when utilizing the synergistic effects of PLC
- Relationships between limestone content, fineness, clinker properties, and SCMs can be optimized in order to further increase benefits of PLC
- High SCM replacement concrete mixtures containing PLC can be successfully used in large construction projects.

In this dissertation, a broad collection of cements from multiple manufacturers in the southeastern US were investigated. This investigation served to analyze the differences between PLC and OPC cements in the marketplace both within companies and comparatively between companies and to build a greater understanding of the requirements to achieve potential benefits from PLC. The majority of testing undertaken was based on two of the most critical factors in the present concrete industry, achieving adequate compressive strength and reaching that strength (including initial set) as quickly as possible.

Four cement companies provided 12 cements to be tested (5 OPC and 7 PLC). The study also featured 3 of the most common SCM’s (blast furnace slag, Class C fly ash, and Class F fly ash), multiple aggregates, and multiple admixtures. The study focuses on the need for the most environmentally sustainable concrete mixtures and as such investigated SCM replacement levels by mass mostly varying from 40% to 70%, but some as low as 25%. In total 130 different concrete mixtures (1560 concrete specimens), were tested. This fairly comprehensive data set served to classify a sizable percentage of the concrete market in multiple states in the southeast US.

Additional smaller scale studies that are included in this work are petrography, elastic modulus, chloride ion permeability, and the affect of varying cement contents. Petrography specimens were investigated for differences between OPC and PLC in 0% SCM and 40% fly ash mixtures. Elastic modulus testing using a compressometer was conducted on OPC and PLC specimens of the same mixture at various ages up to 6 months to investigate any potential differences between cement types.

Chloride ion permeability testing was conducted using a resistivity meter. This type of meter is a way of measuring concretes chloride ion resistance that has already begun being used as a part of certain DOT's testing procedures (Rupnow and Icenogle, 2012). This particular method, being relatively new, is governed by the provisional standard AASHTO TP95-11. A round robin style test between 4 labs was also conducted as a part of this evaluation with a single lab using the resistivity meter and 3 labs testing permeability traditionally using ASTM C1202 (Rapid Chloride Ion Penetration).

Field testing was conducted as part of the Davis Wade Stadium (DWS) expansion and renovation project. The project features a 6000 seat increase to the north end of the Mississippi State University (MSU) football stadium and utilizes multiple concrete elements; columns, beams, slabs on grade, elevated slabs, and raker beams. In total over 22,000 yd^3 of concrete was cast in place and over 2,400 yd^3 of that total was PLC. Sampling from concrete mixing trucks at the project site and at the ready mix plant was conducted. Sampling consisted of 50 to 100 cylinders per sample day, sampling multiple trucks each day. PLC and OPC mixes were collected for comparative purposes. Testing on these samples included compressive strength, elastic modulus, and resistivity. Locations of some PLC pours in the project were noted and monitored for finishing characteristics. Several months after the pour, photos were taken to show that there was no meaningful difference in color when PLC was used.

1.3 Organization of Dissertation

This dissertation is organized into 10 chapters. The first 4 chapters lay the groundwork for the study and include an introduction, review of literature and practice, materials tested, and experimental design. The chapters following present test results and findings and are organized according to written works by the author. References for the written works are provided at the beginning of each results chapter.

CHAPTER II

LITERATURE AND PRACTICE REVIEW

2.1 Overview of Literature and Practice Review

This chapter provides a review of literature and practice that focuses on PLC. To facilitate organization, content is divided into the following major sections; 2.2 Concrete Sustainability, 2.3 Portland-Limestone Cement (PLC), 2.4 Supplementary Cementitious Materials (SCMs), 2.5 PLC Synergies, 2.6 and 2.7 PLC Implementation, 2.8 Summary of Literature and Practice Review.

2.2 Concrete Sustainability

The topic of concrete sustainability has recently become more prevalent as environmental concerns involving construction and manufacturing processes have risen. Environmental incentive programs such as LEED (Leadership in Energy and Environmental Design) and Envision have been established to promote more environmentally conscious construction and design practices. However, in some cases these programs may fall short in determining which projects and materials provide the most environmental and economic benefits.

Most environmental and sustainable practice certification programs such as these, base their level of sustainability off of point values in different categories that the project must score to achieve an overall rating. This rating indicates how sustainable, environmentally friendly, or “green” the project is. Possibly due to the widespread use of these terms and unclear definitions, fallacies in the rating system are likely (Denzer and Hedges, 2011). Certain practices or materials that can meaningfully reduce harmful emissions and energy costs may not meet these general certifications while others that provide noticeably less contributions to sustainability may score a lower sustainability rating.

From a research perspective, it may be more pertinent to evaluate a project by other factors than standard “green” certification programs. In concrete materials the most effective way of reducing harmful byproducts, such as CO_2, and decreasing manufacturing energy use is to limit the amount of cement, or specifically clinker content, present in concrete mixtures. Clinker, which is produced by heating multiple raw materials in a kiln, uses a substantial amount of energy and is one of the leading causes of CO_2 emissions, estimated to be approximately 5% of the total CO_2 emissions worldwide (Worrel et al. 2001).

In the current concrete materials market, increased sustainability is most often achieved by replacing an amount of cement with another cementitious material. Environmental benefits are further enhanced by using byproducts of other industries to fill that role. These additional materials are commonly referred to as supplementary cementitious materials (SCMs).

SCM use in concrete mixtures has been increasing recently due to economic and environmental pressures coupled with desirable performance attributes in some areas. Most agencies will allow at least some cement replacement with SCMs, but the level of replacement depends heavily on the project requirements and on standards put forth by local regulatory departments, specifically departments of transportation (DOT's). SCM use in concrete mixtures is still considered relatively new. Therefore some organizations are hesitant to use SCMs or they severely limit SCM usage in certain projects.

Interest in PLC, a product that has been in use in other countries for over 25 years, has increased as it has the potential to provide sustainability benefits. Tennis et al. (2011), in a state-of-the-art report concluded that limestone replacement levels of 5% to 15% were beneficial environmentally and have the potential to also benefit concrete properties. PLC was originally manufactured in the US under the performance cement specification ASTM C1157 as a blended cement product. As of 2012 PLC can now be manufactured under ASTM C595/AASHTO M240 as a Type IL cement. Although there is documented evidence that performance specifications can lead to sustainable practices, an official type designation does facilitate further use (Laker and Smartz 2012; Van Dam et al. 2010).

While PLC has been shown to be beneficial in other countries, due to differing aggregates, SCMs, construction techniques, and other factors that can be unique to the US, performance data on US manufactured PLC is somewhat lacking. PLC gains its sustainability benefits by containing between 5% and 15% ground limestone, according to the new specifications, which reduces the amount of clinker present in the mixture. Ordinary portland cement (OPC) is limited to a maximum of 5% limestone according to ASTM C150, and allowing limestone in C150 cements at 5% is a relatively recent development. The majority of PLC research in the US has been conducted in the last 15 to 20 years, and as such long term data analysis and additional research based on these results can be difficult to acquire.

It has been estimated that even a 5% increase in limestone usage in cement in the US would cause a decrease of 1.6 million tons of raw material, over 11.8 billion BTU's of energy, 2.7 million tons of CO_2 and 190,000 tons of solid waste per year (Cost, 2008). This benefit is achieved by reducing the clinker fraction of a cement, and would be further increased based on additional reduction of clinker. Cost (2011) states that possible increased sustainability benefits may be found by focusing on early age properties for construction purposes, facilitated by performance specifications. A separate study by Bushi and Meli (2014) analyzed an OPC and PLC concrete project from cement production to construction for environmental factors and found roughly a 10% reduction in greenhouse gas emissions (Table 2.1). PLCs have also been shown to provide advantages in the manufacturing stage as they may require up to 10% less raw materials (Goguen 2014).

Table 2.1 Results Summary for OPC and PLC - 1 kg, Absolute Basis, Data Taken from Bushi and Meli (2014)

Impact Category	**Unit**	**OPC**	**PLC**
Global Warming	kg CO_2 eq	0.95	0.85
Total Primary Energy	MJ	6.62	6.02
Non-renewable Energy	MJ	6.27	5.69
Acidification	kg SO_2 eq	4.1E-03	3.7E-03
Eutrophication	kg N eq	1.3E-04	1.2E-04
Smog	kg O_3 eq	0.048	0.043
Ozone Depletion	kg CFC-11 eq	1.1E-11	9.6E-12

An analysis of cement production trends reveals that in major cement manufacturing companies, the percentage of classical OPC cement mixtures has been on the decline (Schneider et al. 2011). The study concluded that from 1995 to 2009, cement produced for use in traditional OPC concrete mixtures declined from 56% to 20%, compared to the total cement market. During the same time period, the percentage of more environmentally friendly, sustainable, and economical mixtures has increased as markets change to accommodate those designs. This serves to also increase the pressure on PLC research as there are many areas that require investigation, such as how PLC will react in US concrete markets, and testing to ensure the product is manufactured and used in a way to achieve its full potential.

Reductions in clinker content are usually associated with decreased concrete performance in some areas such as time of set and early strength gain. However, emerging research has suggested that with PLC and the correct utilization of mixture combinations it may be possible to negate performance loss or even increase performance in certain areas (Cost 2012). Concern with increasing SCM replacement, specifically in the US construction market, hinges on longer set times and decreased early age strengths. With optimized mixture combinations featuring PLC it may be possible to alleviate a considerable amount of these negative affects and further increase the amount of clinker reduction possible.

2.3 Portland-Limestone Cement (PLC)

Some studies have documented that PLC, although lower in clinker content, can exhibit similar compressive strength results to OPC (Tennis et al. 2011) and equivalent or improved durability (Thomas and Hooton 2010). Other studies have shown improved 28 day compressive strengths with PLC compared to OPC (Sata and Beaudoin 2007; De Weerdt et al. 2011; Mounanga et al. 2011; Cost and Bohme, 2012). A more comprehensive study of OPC and PLC produced from 5 facilities, with limestone contents ranging from 6% to 16%, showed no difference in OPC to PLC properties (Cost et al. 2013b). A state-of-the-art review listed PLC as being able to reduce greenhouse emissions, improve workability and pumpability, and have similar mechanical performance, but at the cost of higher susceptibility to sulfate attack and carbonation (Hooton et al. 2007).

It should be noted however that these studies often used OPC with added nano-sized limestone particles instead of manufactured PLC. Currently, in most PLC manufacturing processes, limestone is added to the clinker after it has left the kiln but before the final grinding mill. In this case both the clinker and limestone are ground simultaneously or inter-ground.

Manufacturing differences such as this, as well as different chemical properties of clinker and limestone between plants, can lead to difficulties in accessing perceived PLC benefits. Sources indicating PLC has beneficial properties are available but sources often differ in which properties are enhanced, what level of benefit is achieved, and what makes a PLC mixture optimal. Most sources agree that one or more of three processes are occurring that allow the PLC to achieve similar or enhance properties with less clinker; 1) nucleation site affects, 2) particle packing affects, or 3) enhanced chemical reactions. These processes are described in the sections that follow.

2.3.1 Particle Size Interactions

Limestone is a softer material than clinker, thus when inter-ground the limestone tends to comprise the majority of the smaller particles in the particle size distribution (PSD). Since clinker fineness is directly related to cement performance, an OPC and PLC ground to the same Blaine fineness may have considerably different performance in concrete, because equal overall Blaine fineness would indicate a discrepancy in clinker

Blaine fineness (Voglis et al. 2005). Therefore understanding particle size interactions is likely key in determining optimum PLC design.

Cost et al. (2013a) illustrates the conceptual PSD differences in OPC, separately ground clinker and limestone, and clinker and limestone products ground together. In specimens with similar Blaine fineness, the greatest concentration of smaller particles was found in a sample in which the materials were ground together, compared to an OPC and a 90% OPC plus 10% limestone blend. Although that sample did have the smallest particle sizes it should also be noted that the majority of the small particles are most likely ground limestone, and the PLC mixture may require additional grinding to create clinker particles of similar size to those of OPC (Cost et al. 2013a).

Work done earlier by Schiller and Ellerbrock (1992) supports this position and attempted to quantify PLC inter-grinding relationships. They determined that for a 500 m^2/kg Blaine PLC, the clinker fraction was approximately 350 m^2/kg Blaine while the limestone was 1130 m^2/kg Blaine. These discrepancies further increased to 380 m^2/kg and 1250 m^2/kg at an overall Blaine fineness of 550 m^2/kg.

PLC performance, in particular, appears to be heavily dependent on limestone and clinker finenesses (Tsivilis et al. 2002). This work compared cements with 0% to 35% limestone in cement paste specimens. It was concluded that, in these specimens, cement with limestone addition was able to produce similar strengths to OPC with increased durability and lower water demand. Additionally, optimizing limestone fineness for different limestone contents and clinker combinations could improve clinker reactivity and increase hydraulic potential.

The nucleation site theory assumes that the smaller limestone particles are filling the gaps between the larger clinker particles and facilitate shorter crystallization chains during the cement hydration process (Soroka and Stern 1976). This theory is based on non-reactive or “filler” effects and does not consider an increase in hydration products. The particle packing theory is similar but instead focuses on the increased densities that the intermingling of different particle sizes could cause, and that increased densities effect on compressive strength. Changes in results due to decreased particle sizes or nucleation site effects can be difficult to differentiate between.

PLC fineness’ affect on workability and water demand has been investigated thoroughly. Nedhi et al. (1998) and Vuk et al. (2001) concluded that increased fineness present in PLC can increase workability, add benefit to early age rheological properties, and decrease water demand. Nedhi et al. (1998) used 3 μm to 0.7 μm sized filler particles in high strength concrete mixtures and found that the ultrafine particles combined with commonly used superplastisizing admixtures lowered the flow resistance of the mixture, therefore increasing workability. It is noted, however, that increased surface area may not be the only driving factor behind this trend.

Other studies have documented a decrease in workability and water demand (Bonavetti et al. 2003; Matthews 1994). Bonavetti et al. (2003) used mortar prisms and x-ray diffraction (XRD) to analyze these trends and concluded that concrete with limestone additions always produced lower compressive strengths after 14 days. In the current cement marketplace where admixtures are prevalent in almost all concrete mixtures, these discrepancies tend to be of little importance as any workability reduction due to particles spatial relationships is influenced by water reducers (Siebel and Sprung 1991).

Irassar et al. (2010) developed a study to evaluate composition and milling techniques effect on early age PLC properties. Specimens in these tests were all manufactured from the same clinker grind to limit other variables. Limestone contents varied from 0 to 24% and fineness, as measured by PLC retained on the 45 µm sieve, varied from 5 to 18%. It was found that the PSD was wider with PLC than OPC, meaning that the PLC had greater variation between the largest and smallest particle sizes. Water demand was observed to be slightly reduced when more limestone was added and increased when the materials retained on the 45 µm sieve decreased.

Time of set evaluations for the same study concluded that time of set was decreased with decreased particle sizes. Additionally, the particle size of the PLC was more influential than limestone content on time of set. Compressive strength was found to be dependent on both particle size and limestone content at 7 and 28 days. Of the two variables, at 7 days particle size was more influential than limestone content and the reverse was true at 28 days.

Hawkins et al. (2003) also noted a wider PSD and reduced water demand with PLC. In concrete mixtures it was shown that PLC could produce higher compressive strengths, but in many cases this was only achieved by grinding the PLC finer than the equivalent OPC. It is additionally noted that some chemical reactions may be taking place due to the added limestone, although the main factor influencing the benefits of PLC is believed to be physically related rather than chemically.

2.3.2 Limestone Content and Chemical Reactions

Upper estimates on the amount of limestone addition possible, while still achieving similar or improved properties, vary and are likely dependant on the specific cement chemical properties and mixture design. At lower limestone levels (5 to 8%), individual clinker properties may still be the driving factor in cement performance, but as limestone content increases, additional factors may have considerable influences (Vuk et al. 2001).

Lack of understanding as to how Blaine fineness, chemical composition, and mixture design are interrelated creates difficulty in providing exact solutions as to the most beneficial limestone contents. Likewise, the possibility of enhanced chemical reactions with PLC, can be difficult to ascertain. Chemical reaction differences between PLC and OPC in concrete mixtures have been noted in multiple studies, but their actual impact compared to the impact of limestone as an inert filler is debated.

Ramezanianpour et al. (2009) considered concrete mixtures containing, 0, 5, 10, 15, and 20% limestone addition, and Blaine fineness' of 330 m^2/kg for limestone and 320 m^2/kg for clinker. An increase in slump (reduction in water demand) was found to occur with limestone addition. PLC with 5 and 10% limestone were shown to exhibit similar properties to OPC, while limestone contents of 15 and 20% exhibited poorer properties. It was noted that the optimum amount of limestone for these materials was likely between 10 and 15%.

Moir and Kelham (1999) ascertained that concrete with up to 25% limestone addition could achieve higher early age strengths and similar durability, although late age strengths were lower. This study featured 4 different cement sources. Early activity as expressed by lower time of set and increased early heat release were higher in PLC than in OPC mixtures. Long term performance properties such as carbonation, freeze/thaw, sulfate resistance and chloride penetration were found to be satisfactory and in general agreement with traditional OPCs.

Dhir et al. (2007) conducted a similar study with mortar cubes, and concluded that results equivalent to OPC were only possible with up to 15% added limestone. Additionally, it was determined that for every 10% limestone added above 15% the water to cement ratio needed to be lowered by 0.08 to achieve roughly the same compressive strength as OPC. Lower flexural strength and modulus of elasticity were also noted with limestone addition. In the areas of shrinkage, creep, permeability, and durability, PLC with less than 15% limestone was shown to be similar to OPC or provide slight benefits.

Irasser et al. (2001) used both mortar and concrete testing to evaluate limestone addition's affect on workability, bleeding, initial curing, compressive strength, modulus of elasticity, and durability. Results concluded that up to 10% added limestone could benefit concrete's mechanical properties while having no adverse affect on durability properties. The addition of slag cement further improved PLC long term strength and durability.

Bonavetti et al. (1999) used concrete mixtures containing roughly 0%, 9%, and 18% limestone and showed that the limestone addition increased early age mechanical properties. However the later age strengths at 9% were not improved and the later age strengths at 18% were lower than the comparable OPC mixtures. Flexural strengths and modulus of elasticity testing were also conducted and it was concluded that there was little to no difference in PLC performance compared to OPC in these areas.

Chemically, added limestone levels of less than 35% have been shown to increase the formation of calcium hydroxide ($Ca(OH)_2$) and ettringite at early ages (Hawkins et al. 2003). Heat of hydration was also found to be reduced when limestone was used as an additive. The same study also showed that $CaCO_3$ has the ability to react with C_3A to form monocarboaluminate. Applying Bogue calculations given in ASTM C150 showed that PLC generally produced higher C_3S and lower C_2S values.

Increases in early hydration of cement have been reported for PLCs, but may only exist in the cases of certain pozzolonic factors. Sata et al. (2007) studied PLC at 10% and 20% limestone in the presence of SCMs and concluded that early hydration was significantly increased and further increased with greater limestone addition. Through the use of scanning electron microscopy and calorimetry it was shown that at least some portion of the added limestone was reacting chemically. It was also shown that 28 day strength, modulus of elasticity, and microhardness were improved with limestone addition. The authors suggested that the limestone was responsible for these benefits by acting both chemically and as a filler to facilitate nucleation sites.

Bentz et al. (2012) used mortar cubes, vicat testing, and isothermal calorimetry in mixtures with pozzolans to illustrate chemical reaction differences in PLC compared to OPC. Cement with added limestone was shown to increase early age reactions and decrease initial time of set, with particle size being a key component to these benefits. In the case of constant water volume, the authors also determined a method of relating heat release of specimens to initial set and 1 and 7 day mortar compressive strengths.

Ylmen et al. (2010) used isothermal calorimetry and diffuse reflectance infrared spectroscopy to measure heat emitted and chemical reaction rates during the first 38 hours of cement hydration. In PLC mortar it was concluded that two different calcium silicate hydrate (CSH) products were forming in PLC. One of the two was completely saturated while the other continued to gain saturation throughout the duration of the 38 hour period. It was concluded that the two forms differed in morphology and water content. PLC may be facilitating this second form of CSH, which hydrates much faster than standard CSH and leads to advantageous early age properties. Based on the 38 hour study it was unclear whether the total amount of hydration products increased or if hydration was occurring more rapidly with the same total hydration percentage.

Time of set differences with PLC appear to depend heavily on the specific PLC's properties. Some PLCs have been shown to achieve set times equal or lower than OPC (Bentz, et al., 2012). Bentz (2010) and Bentz and Ferraris (2010) showed that set times up to 5 hours lower could be achieved in cement paste mixtures featuring pozzolons. Gurney et al. (2011) illustrated similar results and concluded that the decrease in set time could be directly related to the limestone's surface area and consequently fineness. A linear relationship was therefore developed to model surface area to initial and final set times; however, the authors noted that this relationship is likely unique to each cement clinker/limestone interaction.

Overall, theories on why some PLC's exhibit lower times of set vary and most often include additional chemical reaction improvements and fineness differences (Cost and Bohme, 2012; Bentz et al. 2012). Other conclusions on why PLC is able to achieve an equal or lower set time than OPC include nucleation site effects and increased early age modulus of elasticity (Sata and Beaudoin, 2007) and larger surface areas (Gurney et al., 2011). In time of set measurements as well as compressive strength data, most studies only consider a few factors (e.g. a single limestone fineness or single clinker source), and as previously noted it is well acknowledged that each clinker/limestone/concrete mixture will exhibit at least somewhat unique results.

2.3.3 Durability of Portland-Limestone Cement

Durability concerns in concrete with added calcium have arisen, especially with regard to the thaumasite form of sulfate attack. This particular form of sulfate attack affects calcium compounds in the concrete (theoretically more calcium compounds would be present in PLC than OPC) and is more likely to occur in areas that are cold or have prolonged moisture exposure (Hobbs and Taylor 1999). Aggressive groundwater or heavy rainfall areas also increase the risk as these can increase the sulfate present in the environment. During this form of attack, the high sulfate environment may cause the calcium carbonate present in the concrete to leech out, thus increasing pores and decreasing concrete durability.

Hartshorn et al. (1999) used cement paste specimens with 0, 5, 15, and 35% limestone to illustrate possible affects of sulfate attack. Mortar specimens wer submerged in a magnesium sulfate solution and thaumasite formation was evaluated using XRD. At a limestone content of 35%, damage and deterioration were shown within one year, and at 15% limestone signs of impending damage due to sulfate attack were observed after the same time period. Compressive strengths in the 35% specimens were approximately 75% of similar unsubmerged specimens.

In additional studies featuring mortar and paste mixtures evaluating thaumasite and magnesium sulfate attack, there was considerable evidence that the rate of attack was increased due to added limestone; although there was little reported change in compressive strength of PLC to control mixtures in these cases (Torres et al. 2003; Borsoi et al. 2000). Also it should be noted that in all of the above mentioned sulfate attack studies that concluded limestone content decreases sulfate resistance, specimens were submerged in sulfate or magnesium solutions to facilitate thaumasite formation. Therefore these environments may be viewed as worst case scenarios and not necessarily equivalent to real world cases.

It has also been shown through multiple studies that increasing limestone did not have a negative effect on durability in both Type II (Hooton 1990) and Type V (Taylor 1998) cements. Field experience in Europe and Canada over a 20 year study with up to 5% added limestone did not produce any known cases in which added limestone contributed to thaumasite sulfate attack (Hooton and Thomas 2002).

General sulfate resistance in PLC mixtures may depend largely on limestone content (Gonzales and Irraser 1998). In this study cement paste specimens were submerged in a sulfate rich solution for 1 year. It was shown that in limestone contents of up to 10% no significant effect on sulfate performance was observed, however at a 20% limestone content detrimental durability effects were found by XRD. The authors concluded that these were most likely caused by changes in hydration, porosity, and type of hydration products.

A separate study by Harsthorn et al. (2001) used paste specimens submerged in a magnesium rich solution and thaumasite was confirmed via XRD. The specimens showed no decreased sulfate resistance at 10% limestone, but considerably decreased resistance at 15% limestone and above, some reaching only 75% of the control mixtures compressive strength. Barker and Hobbs (1999) tested cement paste submerged in both magnesium sulfate and sodium sulfate solutions. Specimens with limestone contents of 15% were shown to have visually severe sulfate attack. In general, sulfate resistance and thaumasite resistance were shown to decrease with limestone content increases in experiments that featured high sulfate conditions (e.g. submerging specimens in solutions), but field studies on actual projects have not found thaumasite sulfate attack to be an issue.

Additional durability studies have shown that PLC is no more vulnerable to akali-silica reactivity (ASR), freezing and thawing, carbonation, and deicer salt scaling, than OPC (Thomas et al. 2013). This study featured PLC with up to 12% limestone compared to OPC mixtures from the same clinker. Tests were conducted on mortar, concrete cylinders, and concrete slabs in mixture designed to replicate common practice. Additional works featuring European produced PLC under EN 197 showed that durability concerns such as shrinkage and permeability are well documented not to have significant differences in PLC compared to OPC (Matthews 1994; Dhir et al. 2007; Tsivilis et al. 2000). These studies utilized mortar and paste mixtures.

2.3.4 Paste-Aggregate Bond

Bond strength between cement paste and aggregates is often crucial in concrete performance as compressive and tensile strengths, modulus of elasticity, and failure modes can all be influenced by weak bonds. Paste-aggregate bonding is most commonly discussed as a function of the properties included in the interfacial transition zone (ITZ), wherein the cement paste's proximity to the aggregate may cause the paste to exhibit different properties. When clinker dilution due to added material (in this case limestone) occurs, the ITZ may undergo additional changes.

The ITZ is formed due to water gradients, or a diffusion process, during early hydration that causes a higher water to cement ratio in the cement paste surrounding the aggregate (Ollivier et al. 1995). Higher water to cement ratios cause the ITZ to be weaker than the surrounding paste and a likely source of failure in concrete mixtures. Elsharief et al. (2003) illustrated that the ITZ could be controlled or its effect diluted by carefully selecting concrete components. This study showed that reducing the water to cement ratio to 0.40 and lowering aggregate size both decreased negative ITZ effects. Furthermore, it was concluded that the ITZ depended heavily on the amount of unhydrated cement grains present; lower amounts of unhydrated grains led to larger porosities.

Kuroda et al. (2000) showed that with the addition of pozzolonic materials, such as fly ash, it was possible to negate some of the negative effects of the ITZ. These effects were more pronounced in high calcium low silicate mixtures. It is expected that the added pozzolonic content leads to greater hydration efficiency at the ITZ. Aggregates may also affect the ITZ size and condition.

Coarse aggregates that are large or have smooth surfaces have been shown to further decrease paste-aggregate bond strength (Akcaogluet al. 2004). In this study multiple aggregate sizes were tested with OPC and high strength OPC. The larger aggregate sizes caused an increasing amount of higher water to cement ratio zones and contributed to lower tensile strengths. This strength reduction was greater in high strength OPC mixtures.

Aggregate properties such as angularity and smoothness can also affect paste-aggregate bond apart from the ITZ. Multiple studies have shown that concrete mixtures with angular aggregates such as limestone can achieve higher compressive strengths than similar mixtures with granite or smooth gravel. Aitcin and Mehta (1990) used OPC with 4 aggregates native to northern California to illustrate this. Diabase, a subvolcanic rock, and limestone aggregates were shown to exhibit higher strengths and elastic modulus compared to granite and river gravel. Likewise other concrete properties, such as modulus of elasticity, are also highly dependent on aggregate properties (Zhou et al. 1995). Six different aggregates were used in concrete mixtures at a constant aggregate volume and concrete modulus of elasticity at 28 days was highly predictable based on aggregate properties.

As mentioned previously, PLC may have the ability to reach greater hydration efficiency than OPC, thus shrinking or improving the characteristics of the ITZ (Kakali et al. 2000). Matchei et al. (2007) found that in cements with added limestone ettringite formation was increased, leading to a greater volume of paste solids. This reaction may serve to enhance space filling properties and lower permeability and porosity. In general, any increase in hydration products or efficiency should lessen any negative effects associated with paste-aggregate bonding. Therefore it may be beneficial to utilize PLC to increase paste-aggregate bonds.

2.3.5 Source Variability

Variability in concrete performance can be difficult to analyze as each cement manufacturing facility produces slightly different products, even of the same cement type. In addition to this, cement from a single source may differ in composition over time due to raw material and operational changes at the manufacturing facility. A recent study, set forth by the Mississippi Department of Transportation (DOT) attempted to clarify how much variability exists in cement products used in local markets (Varner 2013). Interest in the report stems from the fact that the Mississippi DOT considers cements of the same type to be similar enough to not differentiate in design (e.g. Type I cement from one source is equivalent to Type I from a different source, and mixture testing does not require the specific cement source to be used). This procedure is not uncommon among testing facilities.

As this dissertation focused on local Mississippi and Alabama materials, results from the study are particularly of interest. The study featured one Type I cement, five Type II cements, and one Type IL cement, as Type IL cement has recently become a material of interest in the state of Mississippi. The Type II cements were all manufactured at different facilities, and multiple samples were taken of each cement at approximately one month intervals. Mixtures were evaluated considering 100% cement (no SCM replacement), 25% Class C ash replacement, 25% Class F ash replacement, and gravel or limestone coarse aggregate.

Compressive strengths of specimens with gravel aggregate with the same cement type from the same source changed by up to 21.6% at 28 days depending on sample month. Limestone aggregate mixtures changed by up to 12.0%. Different cement sources exhibited up to 31.8% variability on average, also at 28 days. Mixtures with no SCM replacement and gravel aggregates exhibited 67.2% of the compressive strength of similar mixtures with crushed limestone aggregate. With 25% replacement by Class C and F fly ash the gravel mixtures reached only 54.6% and 64.3% of the limestone aggregate mixtures, respectively. In gravel aggregate mixtures, replacement with 25%

fly ash lowered compressive strengths to 88.1% (Class C) and 85.3% (Class F) of the 100% cement mixtures on average.

In limestone aggregate mixtures, 25% Class C fly ash replacement increased compressive strengths in all cements. Crushed limestone mixtures with 25% Class F fly ash replacement still exhibited lower compressive strengths than the 100% cement mixtures. In general, changing cement sample or source with crushed limestone mixtures did not affect results as greatly as in gravel mixtures. Percent change in compressive strength between sources and samples was found to be greater in mixtures with 25% fly ash replacement than in 100% cement mixtures. Acceptable ranges in compressive strength as described in ASTM C39 were exceeded in 18.8% of 100% cement mixtures, 28.6% of 25% Class C fly ash mixtures, and 29.5% of Class F fly ash mixtures.

Type IL mixtures were found to perform similarly to those made with Type I and Type II. Averaging cements of each type, the Type IL cement was found to exhibit the highest compressive strength at 28 days in the 25% replacement with Class C fly ash mixtures. It also proved to have the highest 56 day compressive strengths in all gravel aggregate mixtures. Based on the findings of this report it was concluded that Type IL cements were beneficial in the local Mississippi marketplace due to increased strengths with local aggregates and that there is perhaps more variability in cement source and sample than previously believed.

2.4 Supplementary Cementitious Materials

SCMs also have the ability to reduce clinker content and therefore increase sustainability. However, certain negative performance traits are typically associated with increased SCM use. In this dissertation the SCMs of interest included blast furnace slag (slag cement) and fly ash.

Slag cement, a byproduct of the iron industry, is a commonly used SCM to reduce the amount of cement (OPC or PLC) in concrete and to achieve preferable concrete properties, such as durability, in some cases. Slag cement has been shown to lower permeability, increase late age strength, decrease chloride ion penetration, and increase resistance to sulfate and akali silica reactivity, but can be susceptible to carbonation and scaling (Osborne 1999). Slag cement is classified in ASTM C989 by an activity index of 80, 100, or 120, depending on its strength gain relative to portland cement. Replacement rates for slag cement are usually higher than fly ash with some studies recommending as much as 50% cement replacement by mass (Oner and Akyuz 2007).

Fly ash, a byproduct of the coal industry, has been shown to reduce bleeding, lower water demand, increase late age strength, reduce permeability and chloride ion penetration, and increase resistance to sulfate and alkali reactivity (American Coal Ash Association 1995). Possible disadvantages listed by the same source include slow early strength development, longer time of setting, and seasonal limitations.

Fly ash is classified in ASTM C618 by both an activity index and chemical requirements. Activity index requirements are the same for Class F and C fly ash, but Class F requires a minimum of 70% pozzolans, silicon dioxide (SiO_2) plus aluminum oxide (Al_2O_3) plus iron oxide (Fe_2O_3), while Class C requires only 50%. The difference in chemical composition is usually manifested in additional calcium oxide (CaO) in Class C fly ash.

Early usage of fly ash featured mostly low-calcium ashes from hard bituminous or anthracite coals, but increased fly ash demand has led to wider variations in fly ash properties including some very high calcium contents greater than 25% (Thomas et al. 1999). Higher calcium contents usually equate to higher early reaction rates in concrete and as such the American Concrete Institute (ACI) recommends a maximum of 25% replacement for Class F fly ash and 35% replacement for Class C fly ash (ACI 1996).

Both slag cement and fly ash are most commonly referred to as pozzolanic, being defined in ASTM C595 as siliceous or siliceous aluminous material. In combination with cement these materials react hydraulically and form calcium hydroxide ($Ca(OH)_2$), this can facilitate additional concrete strength. While certain SCM products do contain amounts of calcium (e.g. CaO) to facilitate some hydraulic reactions, this is usually insufficient without cement present (Papadakis and Tsimas 2002).

Replacement of clinker with SCMs is traditionally viewed as potentially problematic due to possible negative impacts on early age compressive strength and time of setting. However, some studies have indicated that replacing one-quarter of the cementitous volume with Class C fly ash and fine limestone improved time of setting, early age compressive strength, and electrical resistivity (Bentz et al. 2015). This study featured Type I and III cements with added limestone and replacement rates of up to 60%. It was shown that some of the negative properties caused by high fly ash replacement could be alleviated with limestone addition.

Field work using 0, 25, 40, and 50% replacement of cement with 2 parts slag to one part fly ash revealed higher compressive strengths at 40% and 50% for OPC and PLC mixtures (Thomas et al. 2010). The PLC used in this work contained approximately 12%

limestone and was ground to 453 m^2/kg Blaine, compared to 373 m^2/kg Blaine for OPC. No consistent compressive strength differences between OPC and PLC were observed.

Mixtures featuring both fly ash and slag cement as SCMs are rare, but some early research has shown possible beneficial effects. Hale et al. (2008) investigated OPC mixtures with 15% fly ash replacement, 25% slag replacement, and a dual SCM system (a total of 40% cement replacement with 15% fly ash and 25% slag cement). Slumps for all mixtures fell within 2.5 to 8.3 cm, and air contents between 5.1% and 6.9%. ASTM C403 time of set varied between 3.3 and 8.1 hours with the fly ash and fly ash plus slag cement mixtures exhibiting the longest times.

Compressive strength and modulus of rupture increased in mixtures with slag cement and slag plus fly ash. The presence of slag cement also increased the modulus of elasticity and reduced shrinkage. This study documented that by combining multiple SCMs it may be possible to increase total replacement levels without sacrificing concrete performance.

2.5 Portland-Limestone Cement Synergies

Cementitious mixtures containing portland cement with fly ash, slag cement, or both (i.e. dual SCM systems), have had recent documented success with PLC. SCM use in concrete, while usually improving workability due to particle size and shape, can also increase time of setting and decrease early age strengths (Hannesson et al. 2012). It has been shown, however, that it is possible to negate at least some of these negative effects with the use of PLC. Therefore PLC synergistic affects, a key element of this dissertation, are defined as benefits to concrete properties when both SCMs and PLC are used.

It has been documented that in PLC mixtures with greater than 10% ground limestone, interactions between the limestone and clinker particles exhibit a more pronounced affect on concrete performance than the individual properties of the two materials (Tsivilis et al. 1999). With large amounts of cement replacement with multiple SCMs these interactions may be further enhanced. Chemical interactions between pozzolons, fine limestone additions, and cement clinker may also be present under certain conditions.

Bentz and Ferraris (2010) used cement paste mixtures to show that the increase in time of setting caused by higher volume fly ash usage could be offset by the addition of 5% calcium hydroxide powder. A chemical study by Matchei et al. (2006) concluded that the added calcium that would be present in PLC did change the cement reaction process, specifically in the way the calcium contents would react with a pozzolonic material. Thus the combination of PLC with SCMs was very likely more beneficial to concrete properties than either material was on its own. Gurney et al. (2011) showed that set times could be further decreased in Class C fly ash mixtures by increasing limestone addition or decreasing limestone particle size. It was found that nano-sized limestone addition at a replacement level of 10% produced equivalent time of setting to OPC.

Cost and Bohme (2012) considered OPC and PLC with 25% fly ash and found synergistic effects present with fly ash and PLC not found in OPC mixtures. In general, it was shown that time of setting decreased and compressive strengths increased when a 10% limestone PLC was used in conjunction with fly ash. The greatest benefit was found in Class C fly ash. Additionally this study showed an apparent connection between limestone fineness and performance of concrete in that the Blaine fineness of PLC appears to be crucial in creating the synergistic effects. This paper also reiterates the difference in performances that can be seen when using pre-ground limestone mixed with OPC compared to inter-ground PLC.

Research by Mounanga et al. (2011) indicated that while additions of slag cement and limestone both decreased time of set, both materials together have a greater effect than either material alone. In the same study, the addition of fly ash increased time of set, but that increase could be lessened with limestone addition. Compressive strength studies by Thomas and Hooton (2010) revealed improved early age compressive strength with PLC in mixtures with fly ash and slag up to 35% replacement. PLC in this study included up to 15% limestone and was ground approximately 100 m^2/kg finer than OPC.

Bonavetti et al. (2001) and De Weedt et al. (2011) noted the synergistic ability of PLC with fly ash and hypothesized that carboaluminates instead of sulphoaluminates were forming due to the increased amount of limestone. This could then indirectly stabilize the ettringite and increase the volume of hydrates while reducing porosity, and lead to an overall increase in concrete strength (Lothenbach et al. 2008). Other sources noted an increase in calcium silicates leading to an accelerating effect on C_3S (Pera et al. 1999).

Cost et al. (2014) used OPC and PLC from four different sources to evaluate the affect of single and dual SCM systems. It was concluded that in concrete mixtures without SCMs, OPC and PLC from four sources produced similar performance. However, with 40% Class C fly ash replacement or 30% slag cement plus 20% Class C fly ash replacement PLC compressive strength benefits were seen with PLC. Mixtures with Class F fly ash replacement showed moderate strength gains with PLC, but less so than Class C. ASTM C403 time of set was shorter with PLC compared to equivalent OPC mixtures. XRD testing of these specimens indicated that PLC strength gains may be due to enhanced calcium carboaluminate formation and stabilization of ettringite. These chemical reactions are likely improving water binding capacity, decreasing porosity, and therefore increasing strength.

Cement with up to 20% limestone and 35% cement replacement by slag cement has been shown to increase compressive strength at 1 and 3 days with similar compressive strengths at 7 to 56 days when compared to OPC (Menendez et al. 2003). This study featured mortar bars and results showed than limestone increased hydration degree, especially at early ages. Also in mortar trials, Carrasco et al. (2005) found that at all ages tested mixtures containing limestone, OPC, and slag cement could produce optimum strength compared to OPC and limestone or OPC and slag cement mixtures. It was noted, however, that the optimum ratio of these three materials was different depending on what test age was used for optimization.

A large portion of the testing protocol featured in this dissertation was based on early work by the author and collaborators published in Cost et al (2013a) and Cost et al. (2013b). Cost et al. (2013a), some of which is included in this results of this dissertation, featured two OPCs and two PLCs, that were used to produce cement paste and concrete specimens. Cements were then evaluated thermally and for compressive strength. Data showed lower heat of hydration and decreases in time of set with PLC compared to OPC and also provided some insight into limestone fineness' affect on PLC performance. Separately added limestone of various Blaine fineness' was also added to OPC specimens to evaluate effects of limestone fineness. In general, PLC was found to perform well in the presence of Class C fly ash, more so than with Class F fly ash, and increasing limestone content increased the synergistic effects. Limestone contents up to approximately 14% were considered. Observations from Cost et al. (2013a) are shown in Figure 2.1. Additional results and discussion from Cost et al. (2013a) are included in Chapter 5 that align directly with the experimental matrix of this dissertation.

Cost et al. (2013b) did not feature any data directly included in this dissertation results, but some of the same material sources used therein are also used in this dissertation's materials. In Cost et al. (2013b), an OPC and PLC sample made with similar clinker were supplied from each of five sources. PLCs were manufactured according to the new Type IL specifications present in ASTM C595. These samples were tested in concrete representative of common structural transportation applications with Class C and F fly ash as well as slag cement. PLCs were found to perform almost identically to the OPC from each source even though limestone values and fineness' varied between sources. Categories tested included compressive strength at various days, time of setting, and chloride ion penetration according to ASTM C1202.

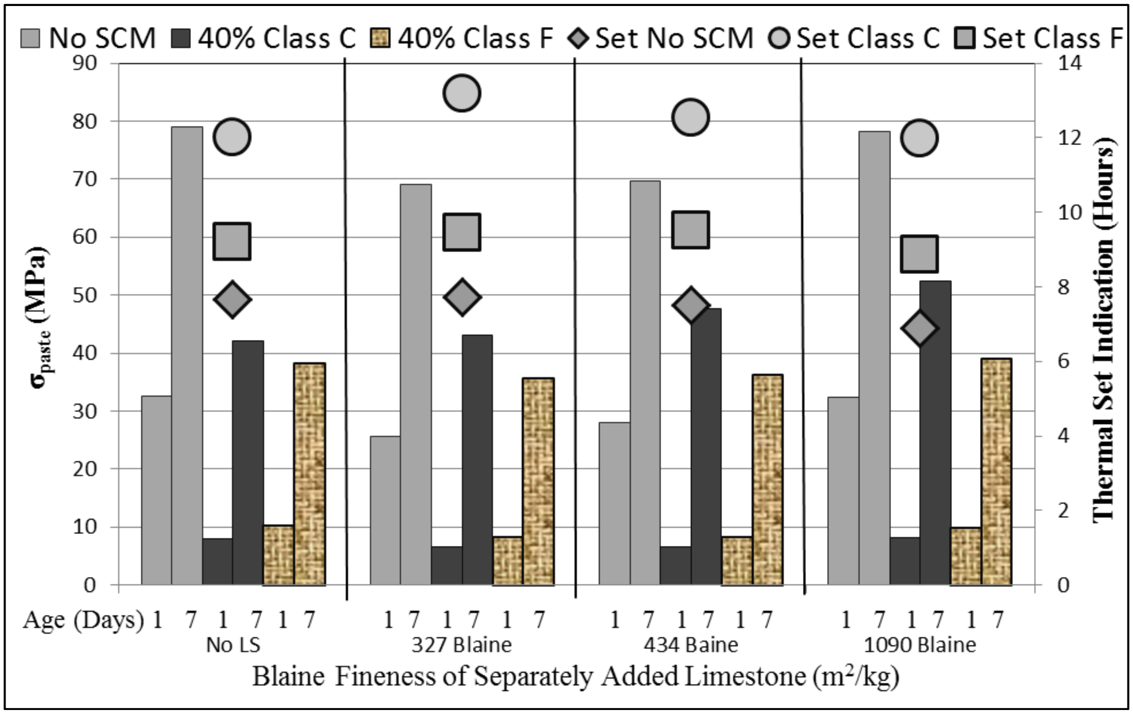


Figure 2.1 Setting and Strength Trends Comparing Limestone Fineness and SCM Type Taken from Cost et al. (2013a)

2.6 Local to Regional Implementation of Portland-Limestone Cement

One objective of this dissertation's body of work was to assist in the implementation of PLC. Therefore some aspects of the study are suited to the state of Mississippi, considering both the Mississippi Department of Transportation (MDOT) and private industry applications, with a focus on providing relatively few protocol changes compared to traditional concrete practices. For this purpose, concrete mixtures made with rounded gravel aggregates and a single SCM (generally fly ash) were evaluated as local aggregate and add to the sustainability focus.

Prior to the work of this dissertation, MDOT specified that cement used in its projects be either Type I, II, or IP, although it is stated that other products may be used if specified in the contract or approved by the engineer (Mississippi Standard Specifications 2004). Rigid pavement specifications from the same source require a minimum of 3500 psi, maximum water to cement ratio of 0.48, and a maximum slump of 3 in. Cement replacement in these mixtures is limited to 25% by fly ash and 50% by slag cement, with no fly ash permitted in blended cements or in combination with slag cement. As mentioned previously, MDOT allowed concrete mixtures to be tested using cement of the same type as the one used in the project, but not necessarily the same source or sample time frame.

Smooth rounded gravel aggregates are not common to all markets, but are heavily used for concrete in Mississippi as well as some other regions of the US. A nationwide review of aggregates production by type (USGS 1999) shows numerous locations of siliceous gravel aggregates mining across the US and suggests that, while use of crushed aggregates is increasing more rapidly than that of natural gravels, there are still similar quantities of each in use today in the US. Thus the data and conclusions from the local and implementable focused sections should also have pertinence outside Mississippi.

Rounded gravel aggregates can cause certain concrete quality challenges that may tend to detract from strength such as entrained air void clustering and inherent difficulties with paste-aggregate bond. Some studies have documented more extreme strength loss when fly ash was used in concrete mixes with rounded gravel aggregates (Holcim (US) Inc 2009; Cost 2008). PLC may have the ability, through synergistic means, to alleviate some of the strength loss caused by these aggregates.

MDOT's Central Materials Laboratory provided information related to concrete practices on MDOT projects from mid fall of 2007 to mid summer of 2014. During that time frame, approximately 1700 structural concrete mixtures were submitted for approval and approximately 96% contained fly ash, 1% contained slag cement, and 93% contained rounded gravel aggregates. As of the summer of 2014 MDOT only allowed up to 25% fly ash replacement of cement in concrete mixtures. As seen in MCIA today special edition (2014) this value was increased in October 2014 to 35% with PLC, as documented in Chapter VIII of this dissertation

2.7 Regional to National Implementation of Portland-Limestone Cement

The recent changes to ASTM C595 to classify PLC as a Type IL cement, and research showing potential benefits of PLC, have led many organizations to consider allowing PLC as a replacement for OPC. Recent work by the Louisiana Transportation Research Center (LTRC) attempted to replicate commonly used mixtures with PLC to determine if the state of Louisiana should allow PLC in its mixture designs (Rupnow and Icenogle 2015). Conclusions indicated that Type IL cement produced similar compressive and flexural strengths, less shrinkage, and similar surface resistivity compared to OPC. The LTRC indicated that type IL mixtures should be allowed for all structural and paving classes of concrete with up to 70% total cement replacement.

The California DOT commissioned a similar project using three cement sources and each source produced a cement with and without limestone (State of California 2008). Base cements (before limestone addition) used in this study were either Type II or Type V and were tested in concrete mixtures containing 25% fly ash replacement. Results concluded that the limestone cements studied were more resistant to electrical conductivity according to ASTM C1202 and achieved higher compressive strengths.

Drying shrinkage was increased with limestone content, but did not reach an unacceptable level.

Over 150 miles of concrete paving, utilizing ASTM C1157 Type GU limestone cement, has been constructed in Utah and Colorado (Laker and Smartz 2013). On all pavements design was achieved using up to 10% limestone and 25% fly ash. Other PLC projects in the area with the same limestone content PLC include buildings of the campus of the University of Utah constructed with 20% fly ash, and a retaining wall featuring 15% fly ash.

Additional PLC use in paving applications was conducted on the main thoroughfare into the Denver International Airport (Mitchell, 2015). A 10 million dollar project, the thoroughfare had been subject to multiple previous repairs due to severe akali-silica damage. Recycled aggregates were used in the project as well as 20% replacement with Class F fly ash. This mixture design was able to meet all requirements for ASR and sulfate durability testing.

Overall, PLC use is increasing in the US as more research regarding its performance is conducted. Laboratory studies have indicated that PLC concrete should be able to achieve similar or more beneficial properties compared to OPC at a decreased environmental impact. Based on these studies, a few field projects have been conducted and were able to replicate these benefits. Future use of PLC is expected to expand exponentially as results of laboratory and field case studies become well known.

2.8 Summary of Literature and Practice Review

This section serves to summarize the findings of the literature review in a concise form. Increases in concrete sustainability are most commonly derived from the reduction of clinker, which serves to lower emissions and energy use in production. The newly amended ASTM C595 allows for the production of PLC with 5% to 15% limestone as a Type IL cement. Lowered emissions, particularly CO_2, and energy costs have been illustrated in multiple studies, both theoretically and in case studies of cement manufacturing facilities producing PLC.

PLC has been shown to be able to achieve similar or improved properties compared to OPC. Benefits of PLC have been reported in both mechanical and durability properties and are likely due to particle packing effects, nucleation site effects, chemical interactions, or a combination of these affects. Due to the PLC manufacturing process the limestone content is usually finer than the clinker, which may lead to inert or filler effects in concrete. The improved PSD has the ability to increase density and decrease porosity, leading to more beneficial concrete properties. Nucleation site effects include the filling in of spaces between clinker particles by the smaller limestone particles, causing shorter and thus stronger crystallization chains.

Chemical reaction differences in PLC concrete may also be contributing to these beneficial properties. Increased hydration products and faster hydration rates have been observed, most likely due to the added calcium present in the concrete. In the case of SCM use, the increased pozzolons tend to further facilitate these reactions, and PLC has been shown to lessen the increased time of set usually associated with SCMs. This may allow an increase in the rate of SCM replacement to be used with PLC, further increasing sustainability.

PLCs benefit to concrete appears to depend heavily on the combination of limestone content and fineness, clinker source, and any SCMs present. Because of this it can be difficult to attempt to optimize PLC mixtures. Multiple sources have concluded, however, that the correct combinations of the materials mentioned can lead to increased compressive strength and reduced time of set.

PLC has been shown to be no more vulnerable to ASR, freezing and thawing, carbonation, deicer salt scaling, or shrinkage than OPC. A potential issue has arisen concerning the thaumasite form of sulfate attack, as high calcium mixtures can be vulnerable to this. Literature is conflicted on if whether this poses additional concern to PLC. In studies where specimens were submitted to high susceptibility conditions (e.g. submerged in a sulfate solution for an extended period), PLC did not perform as well as OPC in regards to sulfate resistance. In field studies and testing under more normal concrete conditions the thaumasite form of sulfate attack was not found to be present in PLC mixtures.

Paste-Aggregate bond issues, specifically with the ITZ, may be improved in PLC due to added hydration. SCMs could also be used with PLC in further increase this benefit. While multiple filler and chemical performance affects would seem to suggest that PLCs may be highly variable, Type IL cements are no more variable that Type I or Type II cements.

Local and national implementation of a new product in the cement industry can be difficult. However, based on observations from this work, the state of Mississippi has already begun PLC testing and the allowance of PLC products. Other studies in Colorado, California, and Utah have likewise shown that PLC can be used effectively in field projects.

Based on literature and practice review findings, there are multiple topics regarding PLC that require additional research. These areas are seen as key points of this dissertation and were the basis of many of the experimental procedures for the data contained herein. While is has been shown that, in general, PLC use can be beneficial, few studies give in depth analysis of the impact that PLC can achieve using local concrete materials and practices.

Potential paste-aggregate bonding ITZ differences in PLC compared to OPC merit further discussion as PLC has shown the ability to improve the ITZ properties, but studies are inconclusive regarding how or to what degree this may occur. Interactions with PLC and SCMs also require additional research. PLC's seemingly synergistic effects with certain SCMs have been documented, however, which cement or SCM properties are the most impactful in achieving the full benefits of these effects have not been clearly shown. These effects could further increase the amount of limestone addition or SCM possible, and in that case higher replacement rates than are currently used in practice also need to be evaluated.

CHAPTER III

MATERIALS TESTED

3.1 Overview of Materials Tested

Materials tested in this work included 12 cements (5 OPCs and 7 PLCs), 3 SCM's (Class C fly ash, Class F fly ash, and slag cement), 4 aggregates (1 fine, 1 intermediate, and 2 coarse), and 5 admixtures (Glenium 7500, RheoTEC Z-60, Pozzolith 322 N, MB AE-90, and Pozzolith NC 534). Descriptions of each material are provided in the subsequent subsections. Cementitious materials were tested by other laboratories and the resultant properties were provided for further use. Most aggregate and admixture data was obtained from manufactures' material certifications.

3.2 Cements

Cements were provided by 4 companies from 4 sources with operations in the southeast U.S. Argos USA, CEMEX, Holcim (US) Inc., and Lehigh Cement Company shipped cements from plants in Calera, Demopolis, Theodore, and Leeds, Alabama respectively. Cements were given a designation (letters A to E) based on plant of origin and then given a number to identify individual materials. Note that originally 5 cement sources were envisioned and letter designations were randomly made by MSU prior to arrival of materials. Testing, however, occurred on only products from 4 sources, therefore there is no source B. Cement was delivered to MSU in either drums (e.g. 55

gallon) or supersacks. Cement that arrived in a supersack was transferred to metal drums after arrival to facilitate sampling. Drums were sealed and stored indoors (mostly in a warehouse type environment) until required for testing.

Sampling from drums was conducted using scoops to transfer material into 5 gallon plastic buckets, which could be more easily used to make specimens. Drums were sealed continuously except for those brief periods where cement was being scooped into plastic buckets. To minimize variability, it was decided that each cement should be tested at a single laboratory (Holcim, Theodore, AL) for common properties to assure uniform comparisons. Cement property results are shown in Table 3.1. Note that each cement shown in Table 3.1 was sampled only one time.

Limestone content measurements are specified by ASTM C150 for OPCs, however, ASTM C595 does not specify a limestone content determination method for PLC's. Limestone content values for PLCs in this work were determined by a type of split-loss method using cement carbon measurements performed with a LECO carbon/sulfur analyzer model no. SC-144DR. Carbon content is converted to CO_2 content, which is then used to calculate theoretical limestone content. Results with this method are an approximation that is usually slightly inflated relative to actual cement limestone contents determined from production data, due to modest levels of carbon content contributed by other cement components. This method also meets the requirement of limestone determination for OPC in ASTM C150 and was seen as the most appropriate for this study. Note that no samples actually exceeded Type IL specifications during manufacturing.

Table 3.1 Cement Properties

	A1	**A2**	**C1**	**C2**	**C3**	**C4**	**C5**	**D1**	**D2**	**D3**	**E1**	**E2**
Cement Type	OPC	PLC	OPC	PLC	PLC	OPC	PLC	OPC	PLC	PLC	OPC	PLC
Al_2O_3 (%)	5.5	5.3	5.0	4.5	4.3	4.9	4.2	4.4	4.2	4.0	4.6	4.0
Cl (%)	0.023	0.021	0.008	0.018	0.011	0.011	0.015	0.007	0.008	0.010	0.010	0.009
CaO (%)	63.9	63.4	64.2	64.3	64.5	63.8	64.9	63.1	63.1	63.1	63.1	63.9
Fe_2O_3 (%)	3.4	3.4	3.5	3.3	3.3	3.5	3.1	3.3	3.2	3.2	3.2	2.9
K_2O (%)	0.65	0.61	0.35	0.43	0.33	0.34	0.34	0.67	0.64	0.71	0.52	0.44
MgO (%)	0.8	0.8	1.0	1.1	1.0	1.1	1.0	2.8	2.7	2.7	3.1	3.1
Na_2O (%)	0.13	0.12	0.18	0.16	0.17	0.18	0.15	0.09	0.09	0.07	0.07	0.07
SiO_2 (%)	19.1	17.8	20.3	19.1	18.5	20.1	17.9	20.3	19.3	17.9	19.0	16.7
SO_3 (%)	3.2	3.9	3.1	3.2	3.3	3.5	3.2	3.2	3.3	3.4	3.3	3.3
C_3S (%)	60.7	---	59.4	---	---	58.3	---	59.1	---	---	59.0	---
C_2S (%)	8.6	---	13.3	---	---	13.7	---	13.6	---	---	9.9	---
C_3A (%)	8.8	---	7.4	---	---	7.0	---	5.9	---	---	6.8	---
C_4AF (%)	10.4	---	10.7	---	---	10.7	---	10.1	---	---	9.6	---
Na eq (%)	0.56	0.52	0.41	0.44	0.39	0.40	0.38	0.52	0.52	0.54	0.41	0.36
Limestone (%)	2.19	8.83	0.10	8.46	10.30	0.35	13.01	0.27	5.23	14.02	4.07	15.69
LOI (%)	2.37	4.71	1.18	4.2	5.08	1.45	6.25	1.54	3.78	6.95	2.63	7.29
Blaine (m^2/kg)	422	522	403	549	482	424	579	421	440	556	407	681
Vicat Initial (min)	95	95	115	105	115	125	95	140	165	100	105	90
Vicat Final (min)	170	160	190	170	220	215	155	250	270	225	205	175
1 Day Strength (MPa)	18.2	19.9	18.0	20.9	16.5	18.0	18.7	15.2	13.7	17.1	15.0	20.1
3 Day Strength (MPa)	29.7	31.8	25.9	30.7	28.1	26.8	29.5	27.0	23.8	27.4	25.8	29.2
7 Day Strength (MPa)	34.6	38.0	31.6	37.9	35.6	34.2	34.1	30.2	28.6	32.3	31.8	35.6
28 Day Strength (MPa)	41.4	42.8	44.0	45.3	42.5	46.1	42.8	39.3	34.8	39.7	42.1	41.2

--Properties as tested by Holcim Theodore Laboratory.
--Strength data was collected using mortar cubes following ASTM C109.
--Limestone (%) was determined according to ASTM C150 for OPC's and with a LECO carbon/sulfur analyzer for PLCs.
--C_3S, C_2S, C_3A, and C_4AF values based on Bogue testing

3.3 Supplementary Cementitious Materials

Three supplementary cementitious materials (SCMs) were used in the study. Class C fly ash was provided by Headwaters in Birmingham Alabama, Class F fly ash provided by Separation Technologies in Crystal River Florida, and slag cement was provided by Holcim (US) in Birmingham Alabama. Each fly ash was only sampled a single time. Slag cement was sampled two times and properties were similar, so they were treated as the same sample. The slag cement evaluated met ASTM specification C989 for Grade 100 and fly ash samples were classified according to ASTM C618.

Additional SCM properties are shown in Table 3.2. All SCM's met specification requirements on original material certifications and aditional testing conducted after the products arrived. A particle size distribution analysis was conducted by the Holcim Theodore laboratory on the SCM's as well as certain cements. Results obtained are shown in Figure 3.1.

Table 3.2 SCM Properties

Property	**Class C Fly Ash**	**Class F Fly Ash**	**Property**	**Slag Cement**
SiO_2 (%)	38.3	54.6	SiO_2 (%)	38.9
Al_2O_3 (%)	20.5	28.2	Al_2O_3 (%)	9.6
Fe_2O_3 (%)	6.3	6.6	Fe_2O_3 (%)	0.4
SO_3 (%)	1.6	0.2	SO_3 (%)	2.1
CaO (%)	22.1	1.2	CaO (%)	36.8
Moisture (%)	0.04	0.2	Air content (%)	4.7
LOI (%)	0.4	3.6	S (%)	0.5
Available Akalies (%)	1.5	0.4	SO_3 (%)	0.8
Fineness (%)	15.7	18.2	Fineness (%)	0.5
Strength Activity Index 7 day (% of control)	101	77.8	Slag Activity Index 7 Day (% of control)	84
Strength Activity Index 28 Day (% of control)	107	80.9	Slag Activity Index 28 Day (% of control)	128
Water Requirement (% control)	95	94	Blaine (m^2/kg)	574
Density (Mg/m^3)	2.63	2.25		

Properties as reported on material certifications or tested by Holcim Theodore Lab.

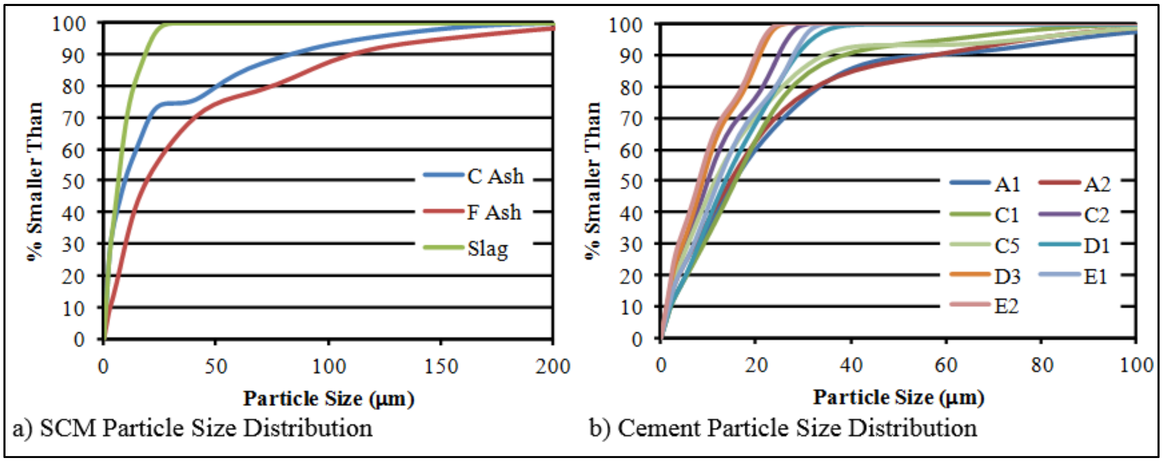


Figure 3.1 Particle Size Distributions

3.4 Aggregates

Aggregates used included a size 57 limestone (LS), size 57 rounded gravel (GR), size 8 rounded gravel (PG), and coarse sand (CS). The size 8 gravel (sometimes informally referred to as pea gravel) and sand were considered uniform, while the size 57 materials may have a tendency to segregate during handling. Material was stored in either large storage bins located outside but protected against rain and wind, or in 5 gallon plastic buckets or barrels stored inside.

Before concrete batching, the size 57 materials were sieved and separated into 3 intermediate sizes and recombined into 5 gallon buckets to ensure material was not segregated prior to batching. The intermediate size fractions of +1.91 cm (3/4 in), -1.91 cm to 0.95 cm (3/8 in), and -0.95 cm were chosen to match the material certifications values as closely as possible. Percent passing each sieve size and additional commonly reported aggregated values are given in Table 3.3. These values are as listed on the material certifications, except for a few verification tests as noted. Aggregates were chosen based on current operations at a local ready mix concrete facility and represented typical aggregates used in the area. Photos of the aggregates used are shown in Figure 3.2. Each aggregate type was sampled more than one time and properties were similar (with exceptions noted in the next paragraph), so they were treated and reported as the same sample.

Table 3.3 Aggregate Properties

Material		**Size 57 Limestone**	**Size 57 Rounded Gravel**	**Size 8 Rounded Gravel**	**Coarse Sand**
Designation		LS	GR	PG	CS
Location		Tuscaloosa, AL	Columbus, MS	Columbus, MS	Columbus, MS
Source		Vulcan	Bacco	Bacco	Bacco
Pit Number		A-34(L)	1-44-49	1-44-49	1-44-49
Bulk Specific Gravity (G_{sb}) - SSD		2.73	2.47	2.46	2.61
Bulk Specific Gravity (G_{sb}) - OD		2.72	2.39	2.39	2.59
Fineness Modulus		7.1	6.82	5.70	2.61
Water Absorption (%)		0.37	3.15	3.08	0.66
Unit Weight (kg/m^3)		1608	1525	---	---
Sand Equivalency		---	---	---	86.8%
Percent Passing	**3.8 cm (1.50 in)**	100	100	---	---
	3.2 cm (1.25 in)	100	100	---	---
	2.5 cm (1.00 in)	96.9	95.4	---	---
	1.9 cm (0.75 in)	74.9	82.4	---	---
	1.3 cm (0.50 in)	28.9	51.7	100	100
	1.0 cm (0.38 in)	11.3	30.3	100	100
	No. 4	2.1	4.3	29.3	99.3
	No. 8	1.6	0.7	0.3	83.1
	No. 16	---	---	0.3	72.8
	No. 30	---	---	---	61.1
	No. 40	---	---	---	44.2
	No. 50	---	---	---	20.9
	No. 100	---	---	---	1.5

--Values based on typical aggregate properties as reported by source. Individual batch values differed insignificantly.

--Some aggregates were tested, for control purposes, at MSU for specific gravity and absorption; results were approximately equal to material certification values.

The size 57 rounded gravel samples, on some occasions, contained a larger amount of fines than the original sample. The original sample had approximately 0.1%

fines or less. The ready mixed concrete facility supplying materials observed fines variations with time, and, in some cases, takes steps at the facility to address this issue.

a) Size 57 Gravel b) Size 57 Limestone

c) Size 8 Rounded Gravel d) Coarse Sand

Figure 3.2 Concrete Aggregates

To account for differing fines contents of size 57 gravel, samples with noticeably more than 0.1% fines were processed before use (up to 1% fines was observed). Note that almost all of the testing presented in this dissertation did not require processing as gravel samples had around 0.1% fines. However, the procedure is presented because a small amount of testing near the end of this work may have used processed gravel. Processed gravels were mostly used for testing not presented herein.

A washing procedure was developed to remove fines down to the level of the original sample. Aggregate was placed in a concrete mixing drum and rotated with a continuous water supply for 3 minutes, allowing excess water with fines to run out of the mixer. After this procedure the aggregate was allowed to air dry and fines content was measured to be less than 0.1%. Figure 3.3 illustrates example gravel before and after washing.

a) Unwashed Sample (Fines of Around 1%) b) Post-Washing Sample (Fines Less Than 1%)

Figure 3.3 Dust Content Control of Size 57 Gravel

3.5 Admixtures

Multiple concrete admixtures were used as described in this section. Pozzolith 322 N and Glenium 7500 are generally classified as type “A” and type “S” water reducers, respectively. RheoTEC Z-60 is a slump and workability retaining admixture. MB AE-90 is an air entraining admixture and was only used in lab mixes that were replicates of field mixes in which air entraining was required. Pozzolith NC 534 is a general purpose retarder that was used under cold weather conditions in some of the field samples and was used in the lab when exact replicates were required. Additional admixture information is presented in Table 3.4 including dosage rate as a function of the entire concrete mixture.

Table 3.4 Admixture Properties

ID	Name	Classification	Type	Dosage Rates (ml/m^3)
A-1	Pozzolith 322 N	ASTM C494 Type A, B, D	Water reducer	275.1 - 507.1
A-2	RheoTEC Z 60	ASTM C494 Type S	Workability-retaining	1027.2 - 1164.7
A-3	Glenium 7500	ASTM C494 Type A, F	Water reducer	515.7 - 1417.3
A-4	MB-AE 90	ASTM C260	Air entrainment	34.4 - 76.3
A-5	Pozzolith NC 534	ASTM C494 Type C	Set retarder	3094.5 - 3481.3

CHAPTER IV

EXPERIMENTAL PROGRAM

4.1 Overview of Experimental Program

Specimens included in this dissertation can be separated into four distinct parts. Part one consists of specimens, discussed in Chapter V, that were not a part of the specimens specifically produced for this dissertation, but were evaluated by the author and contribute to the work as a whole. Parts two and four consist of specimens made as a part of this dissertation, and tested in a laboratory setting. This includes 190 concrete mixtures (2280 specimens) and 134 cement paste (CP) mixtures (2388 specimens). The majority of this testing was conducted between August 2012 and November 2013.

Part two specimens were included in the publications this dissertation is based on, and are discussed in Chapters V, VI, and VII. Part four specimens have not been published as of the date of this dissertation are not discussed herein. Part three specimens consist of field sampled specimens or laboratory specimens designed to complement the field specimens and are discussed in Chapter VIII. Table 4.1 summarizes the number of specimens included in each part.

Table 4.1 Specimens Tested

Part	Laboratory Concrete	Laboratory CP	Field Concrete	Total Specimens
1	112	26	0	138
2	1560	1047	0	2607
3	315	0	495	810
4	720	1341	0	2061

--Specimens tested for part 1 are estimated values

Of the laboratory concrete specimens, the majority were tested for compressive strength, 93 were tested for durability, 144 were used to formulate maturity curves, and 4 were used in petrography testing. Time of set was evaluated for all laboratory mixtures not being tested for maturity. Of the CP specimens, all were tested for compressive strength, and time of set indication was measured for each cement paste mixture. Of the field specimens, the majority were tested for compressive strength, 45 were tested for elastic modulus, and 39 were tested for durability. The majority of field testing was conducted between April 2013 and May 2014.

Specimens tested consisted of high cement replacement with SCM mixtures and comparable no SCM control mixtures. Most cement replacement rates varied from 40% to 70%, but some part one mixtures contained 25%. Field work was conducted at Davis Wade Stadium (DWS) using the same materials to emphasize performance in an actual construction setting, with additional laboratory testing to further investigate observed trends.

4.2 Material Handling and Preparation

Cementitious materials provided in sealed metal drums were stored in those drums. Cementitous materials provided in supersacks were transferred into metal drums and sealed for storage. Identifiers on the cement drums were removed and a new identification system was implemented so that cements were not identified by company. Each drum received a letter (A to E) to identify its company, and a number to identify its product. To facilitate batching, cementitious materials were placed into 5 gallon buckets that were replenished from barrels as needed. Drums were then re-sealed and buckets were sealed until needed for batching.

Aggregates were acquired in one of two ways. When available, an empty concrete mixing truck was filled with aggregates and delivered to the testing facility. When a ready mix truck was not available, aggregates were deposited into a trailer and delivered, using either a front end loader or hand shoveling. Aggregates often were stored in covered bins outside of the testing facility, which facilitated drying of the aggregates before testing. Due to storage issues, it was not possible to acquire all of the aggregates needed at a single time, therefore aggregates were delivered multiple times during the testing process. Deliveries were monitored to ensure that practically equivalent material from the same source was delivered each time. Properties of materials used are provided in Chapter III.

Figure 4.1 (a-d) illustrates a typical aggregate delivery process. The front end loader (Figure 4.1a) was used to place aggregates on the conveyer in the same manner that would occur during concrete production. A clean mixing truck that would normally be filled with concrete was then used to collect the aggregates (Figure 4.1b). Aggregates were deposited by the mixing truck directly into storage bins (Figure 4.1c and 4.1d) until required for testing. In the case that a mixing truck was not available, materials were deposited from the front end loader into a trailer and then hand shoveled into the same storage bins. The size 8 rounded gravel samples were usually collected by the trailer method as this was the least amount of aggregate required.

Moisture contents of aggregates varied considerably upon delivery. Aggregates that were delivered noticeably wet of SSD were dried at an ambient temperature with fans in order to reach a more appropriate moisture content before processing, batching, and testing. When introduced into the concrete mixing drum moisture contents ranged from 0.05% to 0.17% for size 57 limestone, 1.79% to 3.34% for size 57 rounded gravel, 0.46% to 1.93% for size 8 rounded gravel, and 0.27% to 2.95% for coarse sand.

Coarse aggregates (size 57 materials) have the tendency to segregate during handling and as such were sieved to ensure that the material maintained a constant particle size distribution. These materials were sieved into 3 intermediate size fractions, less than 1.0 cm (3/8 in), 1.0 cm to 1.9 cm (3/4 in), and greater than 1.9 cm. The individual sizes were stored in barrels, before being mixed in a pan in 22.7 kg (50 lb) batches of the appropriate size fraction and stored in 5 gallon plastic buckets before testing. Sand and size 8 rounded gravel did not exhibit any segregation tendencies during delivery, drying, or storage, so it was not sieved and recombined. Figure 4.1 (e-h) illustrates the sieving and recombining procedure.

a) Aggregate Sampling b) Aggregate Loading

c) Aggregate Deposited into Bins d) Aggregate Final Storage

e) Aggregate on Sieve f) Aggregate After Sieving

g) Mixing in Pan h) Mixed Aggregate in Bucket

Figure 4.1 Aggregate Delivery, Handling, and Batching Procedures

4.3 Mixture Designs

Part one mixtures were not considered to belong to the dissertation data set and are discussed sparingly. SCM combinations for these mixtures were either 0%, 25% or 40% cement replacement with a single SCM. Mixture designs for part one were based on current practices and literature review findings. The remainder of this section details mixtures included in the dissertation data set (parts one, two, and three).

In general concrete mixture designs and CP proportions were based on typical mixtures used by ready mix suppliers and on mixtures ultimately used at DWS. Saturated surface dry (SSD) aggregate quantities ranged from 845 to 1053 kg/m^3 (1425 to 1775 lbs/yd^3) coarse aggregate (LS and GR), 208 to 111 kg/m^3 (350 to 375 lbs/yd^3) intermediate aggregate (PG), and 684 to 860 kg/m^3 (1153 to 1450 lbs/yd^3) fine aggregate (CS). The w/cm ranged from 0.43 to 0.52 for concrete mixtures, although the vast majority of mixtures were produced at 0.43. CP w/cm values were either 0.40 or 0.50.

Concrete mixtures included in part two and four are illustrated in Table 4.2. Paste mixtures were replicated for each row in Table 4.2 with the exception of rows featuring Class F fly ash. Originally all mixtures shown in Table 4.2 were designed to be a part of the dissertation and publications (part two); however certain mixtures, after being made and tested, were later deemed to not be used (part four). For example, cement D2, was found to be unrepresentative of cement typically produced from that source and was not used in any way in analysis. Some mixtures where excluded only because the mixture has not yet appeared in a publication. Mixtures excluded from analysis are not discussed in results chapters. Part three mixtures included both laboratory (315) and field (495) specimens. All laboratory specimens were made using the same procedure (e.g. part 2 laboratory specimens were made identically to part 3 laboratory specimens).

Admixtures were dosed as a function of cementitous content. A total of 4 admixture blends were used; **1)** 1.30 ml/kg A-1, 3.26 ml/kg A-2, 3.91 ml/kg A-3, **2)** 1.3 ml/kg A-1, 3.26 ml/kg A-2, 3.91 ml/kg A-3, 0.13 ml/kg A-4, **3)** 2.61 ml/kg A-3, and **4)** 1.3 ml/kg A-1, 3.26 ml/kg A-3, 0.13 ml/kg A-4, 9.98 ml/kg A-5. Admixture blend 1 was used in the vast majority of laboratory mixtures, blends 2 and 4 were used when replicating field mixtures, and blend 3 was used in a small group of minimal admixture experiments.

Table 4.2 Concrete Mixtures Tested for Experimental Program Parts Two and Four

f'c (MPa)	CA	w/cm Ratio	Cementitious Content (kg/m^3)	Cementitious Content (%) Cement	Slag	C Ash	F Ash	Cements Incorporated	Admix Dose	Mixtures
31.0	GR, LS	0.43	320.7	100	0	0	0	All	1	24
31.0	GR	0.52	320.7	100	0	0	0	C1, C2, C3, C4	3	4
31.0	GR, LS	0.43	320.7	60	0	40	0	A1,A2,C1,C2,C5,D1,D2,D3,E1,E2	1	20
31.0	LS	0.43	320.7	60	0	0	40	A1,A2,C1,C2,C5,D1,D2,D3,E1,E2	1	10
31.0	GR	0.43	320.7	50	0	50	0	C1, C2	1	2
31.0	GR	0.43	320.7	40	0	60	0	C1, C2	1	2
31.0	GR	0.43	320.7	50	50	0	0	C1, C2	1	2
31.0	GR	0.43	320.7	40	60	0	0	C1, C2	1	2
31.0	GR	0.43	320.7	30	70	0	0	C1, C2	1	2
31.0	GR	0.50	320.7	60	0	40	0	C1, C2, C3, C4	3	4
27.8	GR	0.43	320.7	30	60	10	0	C1, C2, C3, C4, C5	1	5
27.8	GR, LS	0.43	320.7	30	50	20	0	All	1	24
27.8	LS	0.43	320.7	30	50	0	20	A1,A2,C1,C2,C5,D1,D2,D3,E1,E2	1	10
27.8	GR	0.46	320.7	30	40	30	0	C1, C2, C3, C4, C5	1	5
31.0	GR	0.43	320.7	50	40	10	0	C1, C2, C3, C4, C5	1	5
31.0	GR	0.43	376.4	50	40	10	0	C1, C2, C3, C4	1	4
31.0	GR, LS	0.43	320.7	50	30	20	0	All	1,2,4	24
31.0	GR	0.43	376.4	50	30	20	0	C1, C2, C3, C4	1	4
31.0	GR, LS	0.43	320.7	50	30	0	20	A1,A2,C1,C2,C5,D1,D2,D3,E1,E2	1	18
31.0	GR, LS	0.43	320.7	50	25	25	0	C1, C2, C3, C4, C5	1	9
31.0	GR	0.43	376.4	50	25	25	0	C1, C2, C3, C4	1	4
31.0	GR	0.43	320.7	40	40	20	0	C1, C2	1	2
31.0	GR	0.43	320.7	40	30	30	0	C1, C2	1	2
31.0	GR	0.43	320.7	40	50	10	0	C1, C2	1	2

--f'c values were based on psi requirements of 4000 (27.8 MPa) and 4500 (31.0 MPa)

--“CA” represents which coarse aggregates were used in the mixture, gravel (GR) or limestone (LS)

-- “Mixtures” represents the number of unique concrete mixtures fabricated

-- Differing admixtures blends were not considered to be unique mixture

4.4 Laboratory Mixed Specimens

Two types of laboratory mixed specimens were fabricated; 10.2 cm by 20.3 cm (4 in by 8 in) concrete cylinders and 5.1 cm by 10.2 cm (2 in. by 4 in.) CP cylinders. Mixing protocols and procedures for the two types of specimens are provided in subsequent subsections.

4.4.1 Cement Paste Specimens

Ingredients for CP batching included cementitious materials, water, and admixtures. Raw materials were conditioned to room temperature for a minimum of 24 hours prior to batching. Cementitious materials and water were pre-measured in plastic and glass containers, respectively. Admixtures were batched by drawing into 5 ml plastic syringes. After batching, the dry materials (cementitious) were placed into a 2.8 L (3 quart) size bowl, and the wet materials (water and admixtures) were stirred into a glass beaker to assure homogenization before further mixing. The wet materials were then poured into the bowl and mixed into the dry materials using a commercially available handheld kitchen mixer. Mixing was conducted at a low speed for 30 seconds followed immediately by a high speed for 30 seconds. The CP was then poured, using a funnel, into the plastic CP molds leaving approximately 0.6 cm (0.25 in) clearance to facilitate capping. Molds were capped and placed into a curing tank for thermal profile measurements (discussed in section 4.6), or placed on a countertop in a ambient temperature room, in no more than 45 seconds after mixing was completed. Each batch yielded 3 cylinders and a total of 6 batches (18 cylinders) were created for each CP mix. Figure 4.2 illustrates the paste mixing process.

a) Paste Mixing Tools b) Mixing

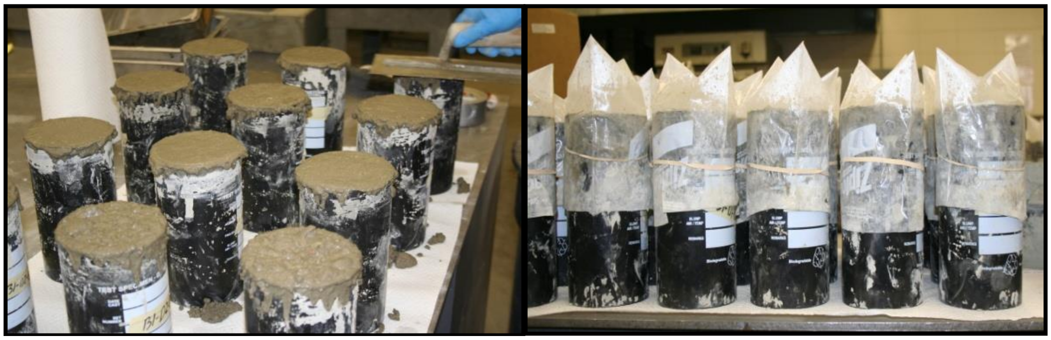
c) Mixing of Combined Materials d) Forming Cylinders

Figure 4.2 Cement Paste Mixing

4.4.2 Laboratory Concrete Specimens

Concrete mixing was performed in accordance with ASTM C192. Concrete was mixed in batches of either 0.05 m^3 (1.5 ft^3) or 0.06 m^3 (1.75 ft^3), indoors, in a typical laboratory concrete mixing drum (Figure 4.3a). Each batch produced between 12 and 20 concrete cylinders. Immediately after mixing, concrete was tested for slump, air content, and unit weight in accordance with ASTM C143, C231, and C138 respectively. A portion of the batch was used to conduct concrete set time testing in accordance with ASTM C403 using a standard handheld penetrometer. Each cylinder was formed in two layers with each layer being rodding approximately 25 times. Cylinder fabrication began adjacent to the mixer (Figure 4.3b) and then cylinders were carefully transferred into an adjacent ambient temperature room for finishing (Figure 4.3c). Cylinder capping was accomplished using plastic bags and rubber bands, in order to meet specifications and to provide for smooth concrete surfaces. Cylinders were then stored in plastic molds at the same location where they were finished for the first 24 ± 8 hours (Figure 4.3d).

a) Mixing Drum b) Cylinder Fabrication



c) Finishing Cylinders d) Final Location

Figure 4.3 Concrete Mixing

4.4.3 Davis Wade Stadium Field Specimens

Field specimens were collected on seven days using two different methods. In some cases, field testing was conducted at the project site directly from the mixing truck. As the truck entered the site but before concrete pouring began, concrete was sampled directly from the truck using a wheelbarrow. Due to factors such as space restrictions on the construction site, sampling also occurred at the ready mix facility. Concrete mixing trucks were allowed to mix at the facility for a specified amount of time similar to the driving distance from the facility to the final location, to minimize any variability between sampling and to assure that the concrete was properly mixed.

The same sampling procedure was used at both sites. The concrete was taken directly from the wheelbarrow and used for the fresh mixed concrete tests listed in Section 4.4.2, followed immediately by cylinder fabrication. For field samples, approximately 25 cylinders were fabricated from each truck, with 2 to 4 trucks tested each day. Cylinders were fabricated in the same method as lab mixed specimens, with the exception of being left at location to cure for the first 24 to 30 hours and having thermocouples inserted in 2 of the specimens to measure internal temperature. Specifications limit the moving of specimens until the initial cure time ends, therefore field test temperatures exhibited a wider range than lab mixed specimens during the initial 24 to 30 hour cure. Thermocouples inserted into the specimens recorded internal temperature which was later used to adjust the compressive strength data to more accurate values based on maturity. Figure 4.4 illustrates the field sampling procedure.

a) Concrete Sampling b) Field Concrete Specimens

Figure 4.4 Concrete Field Sampling

4.5 Curing

Curing protocols differed depending on specimen type and test. CP specimens that were tested for compressive strength at times over 24 hours were cured in the plastic capped mold for the first 18 to 30 hours in a room temperature environment, then removed from molds and moved to a curing room. CP specimens to be tested at 24 hours were cured in foam blocks in a temperature controlled tank to test for set time indication. After that time the specimens were removed and tested.

Concrete (with the exception of maturity adjustment specimens) was cured according to ASTM C192. Concrete was allowed to cure in covered molds for the first 18 to 30 hours in a room temperature environment. Concrete was then removed from molds and transported to a curing room. Some maturity adjustment specimens were cured differently in order to reach higher and lower curing temperatures. These specimens were cured in tanks at varying temperatures; damp towels were used to assure 100% humidity.

At one point during the course of this study, maintenance was necessary on the curing room and all specimens currently in the room were moved to lime water filled tanks. Specimens were fully submerged in the tanks according to specifications. No data related issues are believed to have occurred; this was noted only for completeness of protocols. Figure 4.5 illustrates the curing protocols used. Figure 4.5a shows the curing tank with foam blocks used for 24 hour paste curing. Further details on the block can be found in Section 4.6. The same type of tank shown in Figure 4.5 was also used for temperature adjusted maturity specimens and for submerged storage of all samples during curing room maintenance. Figure 4.5b shows the curing room that was used for all remaining curing.

The curing room was maintained at 100% humidity with an Aquafog fan. Temperature was monitored continuously with a hand held datalogger. Due to inconstant temperatures in the building present from October 2012 to May 2013, additional measures were required to maintain stable temperatures. A small area immediately outside the curing room was partitioned and could be heated or cooled to change temperatures within the curing room. Figure 4.6 illustrates the temperatures in the room during the time period in which the vast majority of cylinders were tested, August 2012 to May 2014. Each bin represents a one degree Celsius range with the bin label as the highest value (e.g. bin 25 shows the frequency of temperatures from 24.1 ˚C to 25.0 ˚C). The dotted lines on the figure bracket the target temperature values specified in ASTM C192. Note that the vast majority of temperatures exceeding those values occurred between October 2012 and May 2013; before the additional temperature control methods were applied.

a) Tank with Foam Blocks b) Curing Room

Figure 4.5 Curing Protocols

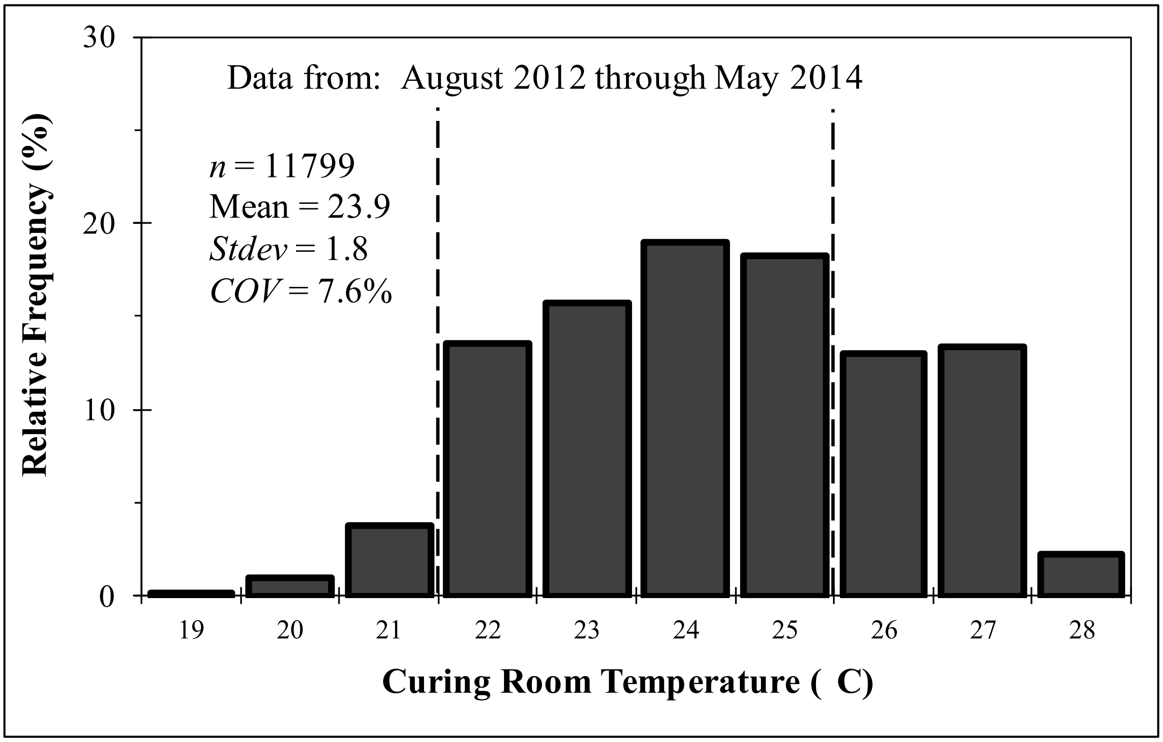


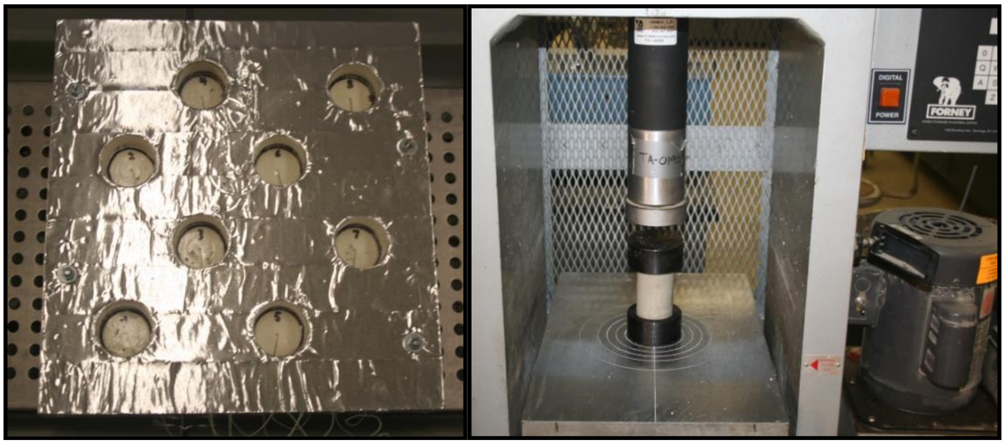
Figure 4.6 Temperatures in Curing Room

4.6 Cement Paste Specimen Testing

CP testing consisted of compressive strength and time of set indication tests. Compressive strength (f_{cp}) tests were performed at 1, 7, 14, 28, 56, and 180 days with three replicates each. Compressive tests were performed using a standard concrete testing hydraulic load frame which could apply a maximum load of 272 Mg (600,000 lbs). Unbonded capping with 70 durometer pads and a load head extender were utilized with the load frame to accommodate specimen dimensions. CP set time indication was tested using thermal profile blocks with thermocouples placed in a temperature controlled tank (Figure 4.5a).

The blocks were manufactured of Cross Linked Polyethylene (XLPE) which had an approximate R_{SI} value of 0.56. An exact R_{SI} value for the block was unavailable. Blocks measured 40.64 cm (16 in) by 38.10 cm (15 in) with a depth of 7.62 cm (3 in) and were covered with aluminum tape to protect the foam in the humid environment. Each block had 8 locations for CP specimens to be tested. These locations were 2.54 cm (1 in) deep cylindrical holes that the specimens would fit in snuggly, and were spaced at least 2.54 cm (1 in) away from other cylinders and the side of the block.

Thermocouple ends were placed in the center of each hole and covered with clear packing tape to prevent movement. The thermocouples measured non-contact temperature changes under each specimen using Pico dataloggers and a laptop computer. Temperatures were monitored for a minimum of 24 hours. Specimens were placed into thermal profile blocks in less than 45 seconds after pouring into plastic molds, and a single cylinder filled with coarse sand was used to provide a reference temperature. Temperature data was recorded once a minute using the Pico datalogger software. The thermal profile block and compressive test frame with CP attachments are shown in Figure 4.7.



a) Thermal Profile Block b) CP Compressive Strength Testing

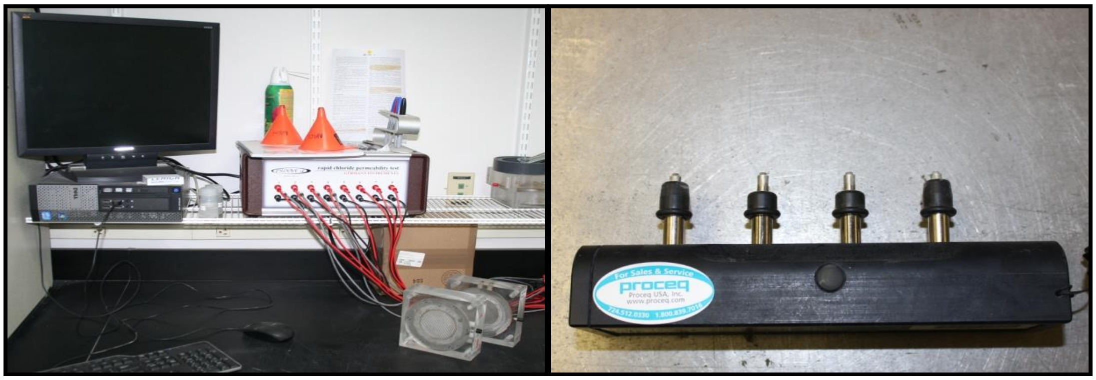
Figure 4.7 Cement Paste Testing

4.7 Concrete Specimen Testing

Concrete testing included fresh mixed properties discussed in Section 4.4.2, compressive strength, set time, chloride ion resistivity, elastic modulus, maturity adjustments, and petrography. Compressive strength (f_c) was tested in accordance with ASTM C39 and was conducted with the same load frame used for CP compression testing, with unbonded capping using 70 durometer pads appropriate for the cylinder's dimensions as per ASTM C1231. Concrete compressive strength tests were conducted at 7, 14, 28, and 56 days for laboratory mixtures.

Set time was tested on laboratory mixtures in accordance with ASTM C403. Set time specimens were collected immediately after concrete cylinders were fabricated, placed next to the concrete specimens at room temperature, and were tested every 30 minutes starting at 3 hours after mixing. Testing continued until the specimen reached the required penetration resistance. Set time was not tested on field sampled mixtures.

Concrete durability was tested using 2 methods; ASTM C1202 Rapid Chloride Ion Permeability and AASHTO TP95-11 Surface Resistivity Indication. ASTM C1202 testing occurred at 4 laboratories not associated with MSU's laboratory (i.e. MSU performed no C1202 testing). AASHTO TP95-11 testing occurred at MSU's laboratory, testing was accomplished with a Resipod Surface Resistivity Meter. A total of 8 measurements were taken on each cylinder, two on each quarter, and a minimum of 2 cylinders were used for each specimen type. Specimens tested at 180 days had half the minimum number of measurements (one on each quarter, four measurements per specimen). Figure 4.8a and b show the two types of equipment used.

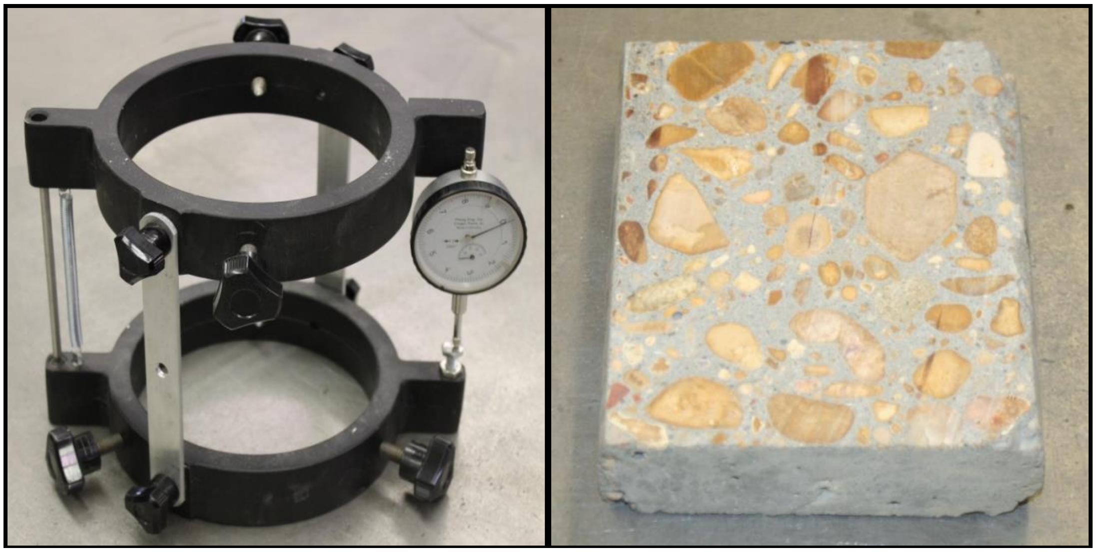


a) ASTM C1202 Equipment b) AASHTO TP95 Equipment

Figure 4.8 Resistivity Testing

Elastic modulus testing was performed in accordance with ASTM C469 using a compressometer collar (Figure 4.9a) with dial gauges. Duplicate specimens from the same concrete batch were first tested to determine compressive strength. The elastic modulus specimen was then fitted with the collar and preloaded to 40% of the maximum compressive strength before testing.

Petrography testing was conducted on 4 samples at a separate laboratory. Specimens had already undergone compressive strength testing and were prepared by removing any damaged sections and, using a standard block saw, cutting each specimen into rectangular pieces 9.5 cm (3.75 in) by 12.7 cm (5 in) with a thickness of 2.5 cm (1 in). Each specimen was then prepared according to ASTM C856 and observed using a digital microscope with magnification up to 200X. A sample of a cut specimen pre-testing is shown in Figure 4.9b.



a) Compressometer Collar b) Petrography Sample

Figure 4.9 Elastic Modulus and Petrography Testing

Maturity testing was conducted with laboratory mixed concrete specimens in order to equate field data to lab data due to differing field temperatures. Specimens were cured in the curing chamber at temperature settings of 7 ˚C or 35 ˚C, or in the curing room at approximately 23 ˚C. Temperature was monitored by a thermocouple inside the specimen (T_c) and one in the surrounding air (T_{air}). Concrete specimen temperature for maturity testing (T_α) was taken as an average of T_c and T_{air}, as this was seen as a more accurate representation of the actual temperature compared to the temperature setting of the environment. Specimens were tested according to ASTM C1074 at intervals of 250, 500, 1000, 1500, 2500, and 5000 Maturity (˚C-hr).

CHAPTER V

SINGLE SCM MIXTURE EVALUATIONS WITH A FOCUS ON IMPLEMENTATION

5.1 Overview

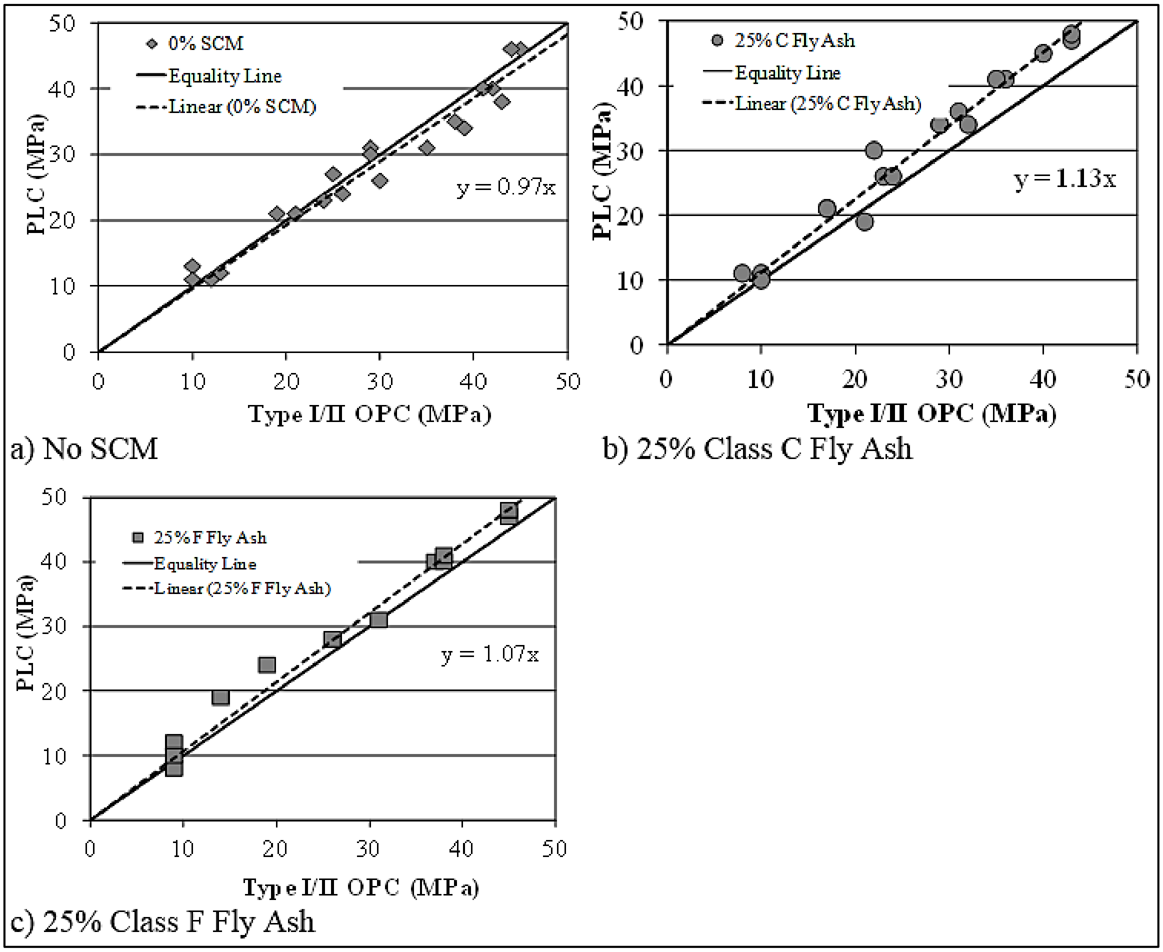
This chapter focuses on PLC used in mixtures with a single SCM, largely from an implementation standpoint, featuring the use of local aggregates and mixture designs similar to those being used in current practice. Data from this chapter has been published in Cost et al. (2013a) and Shannon et al. (2015a). Cost et al. (2013a) features data from specimens not included in this dissertation's primary experimental matrix, but that were important in early stages of the overall effort; however, the author of the dissertation was involved with data reduction and publishing of this document. Cost et al. (2013a) was the basis for some of the larger testing programs included in this dissertation; therefore it is discussed briefly in the results. Results from Cost et al. (2013a) are discussed in section 5.2, and results from Shannon et al. (2015a) are discussed in Section 5.3.

5.2 Single SCM Results Published in Cost et al. 2013a

This portion of the study featured concrete and CP specimens from two different cement manufacturing facilities. PLC's tested were inter-ground with 5% to 10% limestone content. SCMs used included Class C fly ash, Class F fly ash, and slag cement. Limestone powder at various Blaine fineness' was also tested in its capacity to be mixed with OPC, forming separately ground PLC. Cements were manufactured from March 2011 to December 2011.

Concrete mixtures were evaluated with 25% Class C and F fly ash replacement. Data from these specimens are shown in equality plots in Figure 5.1. Equality plots compared the average of 3 OPC specimens on the x-axis with 3 PLC specimens on the y-axis to form each data point. An equality line (thick black line in the figures) was then drawn to better illustrate trends. Data points above the equality line indicate higher strengths for PLC and data points below indicate higher strengths for OPC.

Linear trend lines were created with slopes to indicate performance. A slope of 1.00 would indicate equal OPC and PLC strengths, and slopes to the PLC or OPC side serve to illustrate compressive strength differences. Data shown in Figure 5.1 includes 1 to 56 day compressive strengths. In all cases PLC followed OPC strength trends fairly closely. In cases with fly ash present, PLC performed slightly better than in the no SCM mixtures. This effect was more pronounced with Class C fly ash than with Class F fly ash. The fact that PLC tracked closely with OPC and performed slightly better in the presences of SCMs, concurs with trends seen in the literature and practice review for products manufactured in the US within the past decade.



a) No SCM

b) 25% Class C Fly Ash

c) 25% Class F Fly Ash

Figure 5.1 No SCM and 25% Fly Ash Equality Plots

5.2.1 Cement Paste with Varying Limestone Fineness’

To evaluate the effect of limestone fineness on PLC performance, CP specimens were evaluated using OPC and 10% ground limestone of either 327, 434, or 1090 m^2/kg Blaine fineness. All mixtures used the same water to cement ratio (0.32) and admixture dose (9.1 ml/kg A-3), and were tested with no SCM, 25% Class C fly ash, and 25% Class F fly ash.

In general, compressive strengths at 1 and 7 days increased with limestone fineness, especially in the no SCM mixtures. Strengths were further enhanced by Class C fly ash. Synergistic effects of Class F fly ash were less pronounced. Time of set indication was conducted with thermal methods, and the coarsest limestone (327 m^2/kg Blaine) was found to increase time of set with Class C fly ash. Increasing Blaine fineness resulted in similar time of set indications as seen in OPC. Time of set retardation with Class F fly ash and coarse limestone was less severe than with Class C fly ash.

The best performing limestone, 1090 m^2/kg Blaine, was then used to compare the effects of 10% and 15% limestone in CP mixtures with higher replacement rates. SCM replacement rates included in this group of specimens were no SCM, 40% Class C fly ash, 40% Class F fly ash, and 40% slag cement. Results are shown in Figure 5.2. Time of set indication continued to decrease as more limestone was added, and compressive strengths were not substantially different in 10% and 15% limestone mixtures.

Another data subset featured in this portion of the study was the difference between inter-ground PLC compared to OPC with added limestone. Figure 5.3 illustrates the results of this data set. Two inter-ground 10% limestone PLCs were manufactured at 497 and 549 m^2/kg Blaine fineness. These were compared to a sample of 90% OPC (363 m^2/kg Blaine) with 10% limestone (1090 m^2/kg Blaine). All of these materials were manufactured at the same plant during the same general timeframe.

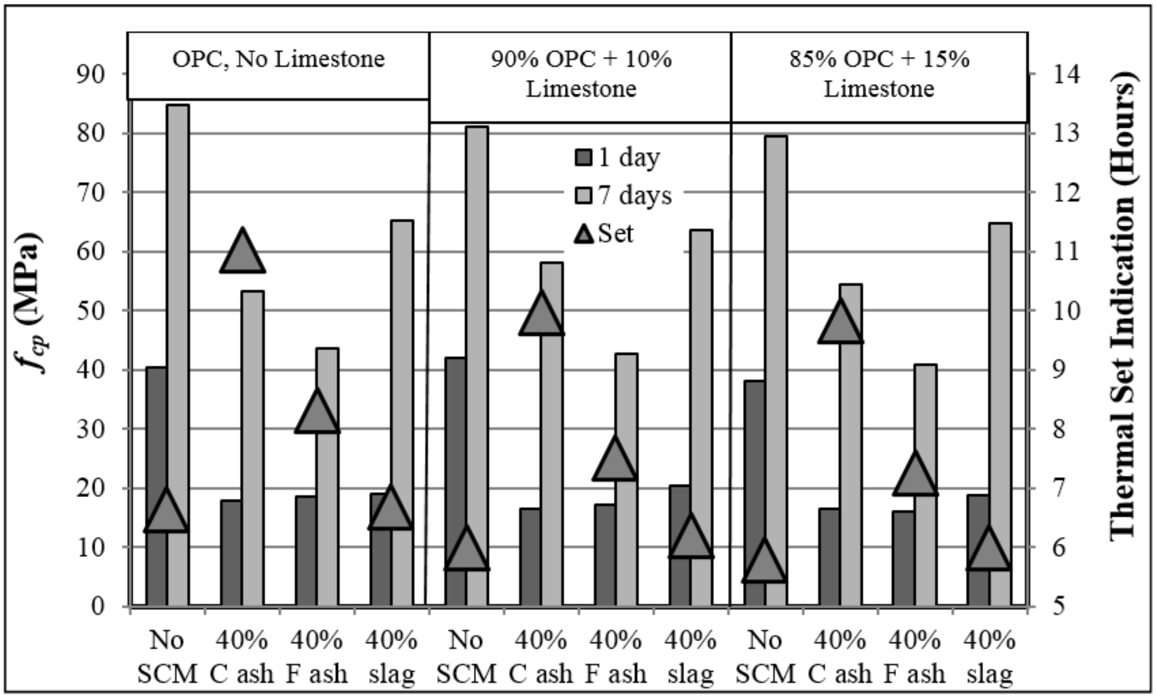


Figure 5.2 10% and 15% Limestone Compressive Strength and Time of Set Results

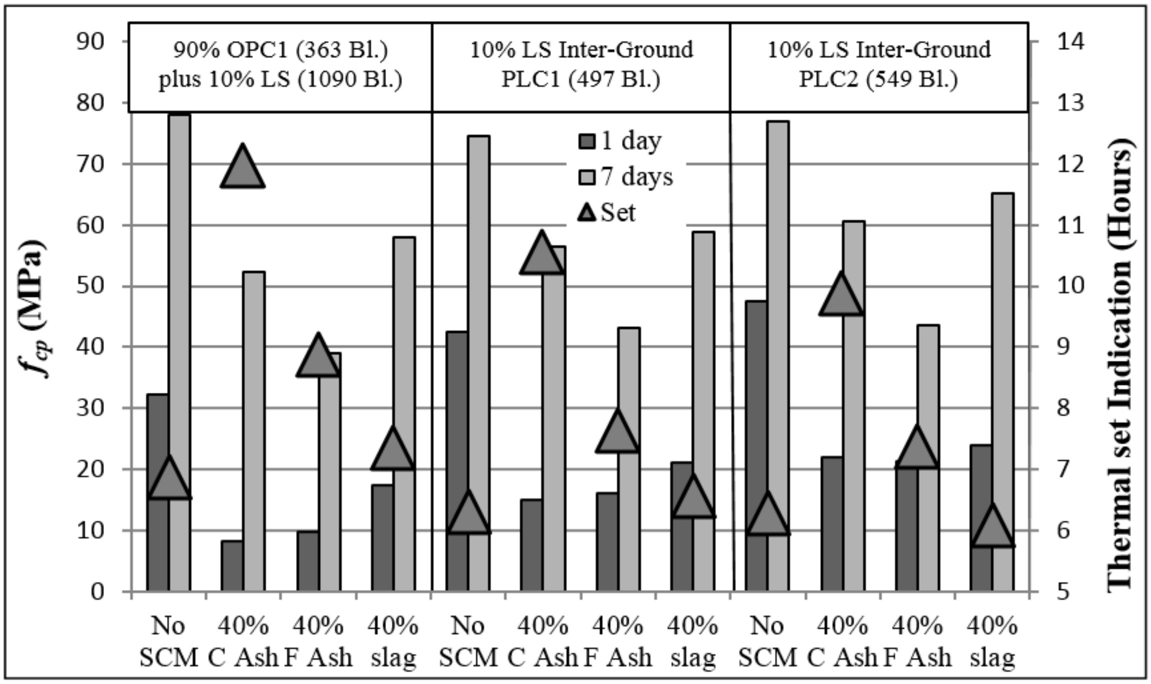


Figure 5.3 Inter-Ground Versus Added Limestone Compressive Strength and Time of Set Results

Inter-ground PLCs exhibited lower time of set and increased compressive strengths, with the exception of compressive strength in the no SCM mixtures. The finer inter-ground PLC seemed to achieve more added benefits that the coarser inter-ground PLC. Since increasing fineness has been shown to increase concrete performance, it could be theorized that the inter-ground PLC product at 497 m^2/kg Blaine may have a higher limestone fineness than the 1090 m^2/kg Blaine added limestone in the OPC specimen. Thus inter-grinding effects may be separating the Blaine fineness of the limestone and clinker further apart than previously thought.

To investigate this possibility, a PSD analysis was performed using a laser diffraction particle size analyzer on the OPC plus limestone sample and the PLC sample at 497 m^2/kg Blaine. Results of this analysis are shown in Figure 5.4. As expected the

OPC with added 1090 m^2/kg Blaine limestone had a higher concentration of finer particles (< 10 μm) than a 100% OPC mixture. However, the inter-ground PLC had an even higher number of fine particles than the OPC plus limestone cement.

From literature and concurrent research it has been shown that when clinker and limestone are inter-ground, the limestone particles make up the finest particles in the mixture. Therefore, it is likely that the inter-ground PLC contains a limestone fraction finer than 1090 m^2/kg Blaine and that limestone fineness in a PLC mixture may be the most influential property of PLC. It should be noted that during this section of the study all materials were produced at the same cement manufacturing plant (i.e. same or similar grinding mills) and grinding trends likely differ between facilities.

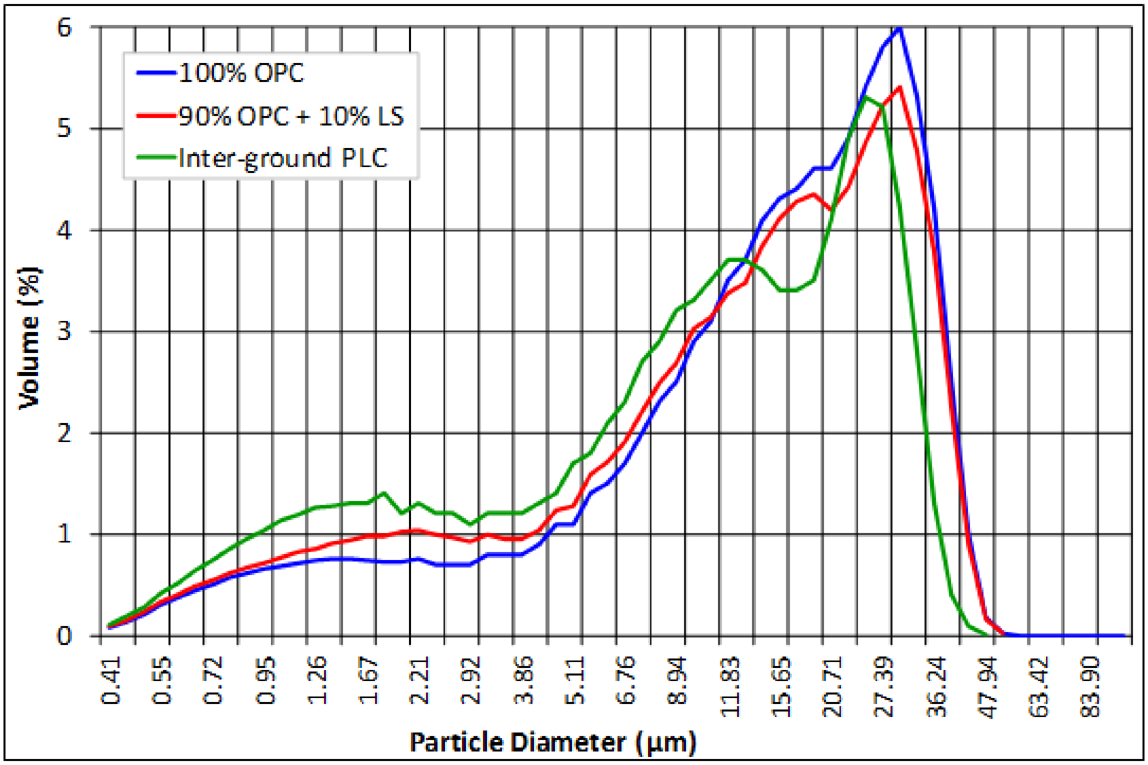


Figure 5.4 Particle Size Analysis for Inter-Ground and Separately Combined Samples

5.3 Single SCM Results Published in Shannon et al. 2015a

This portion of the study also featured both concrete and CP specimens. All concrete specimens included in this section featured size 57 gravel coarse aggregate (GR), size 8 intermediate aggregate (PG), and coarse sand (CS). One OPC and one PLC were tested from each source. In the event that more than one PLC or OPC was provided from a single source, the source indicated which cement was more representative of their production and that cement was used. Cementitious materials included in these specimens were A-1, A-2, C-1, C-2, D-1, D-3, E-1, E-2, slag cement, and Class C fly ash. Admixture blend 1 was used in the majority of specimens with a small number tested using admixture blend 2. Water to cement ratios were either 0.43 or 0.52 for concrete specimens and 0.50 for CP specimens.

Source C (OPC and PLC) was used to evaluate replacement rates of 40%, 50%, and 60% with Class C fly ash, as well as 50%, 60%, and 70% with slag cement. All cements were then compared using 40% Class C fly ash replacement, as this replacement rate was considered the most implementable. CP specimens were evaluated for compressive strength and time of set. Concrete specimens were evaluated for compressive strength, time of set, slump, air content, and petrography.

5.3.1 Fresh Mixed and Time of Set

In total, 15 matched pairs were used to evaluate fresh mixed properties via t-tests. These pairs evaluated OPC to PLC changes and did not take into account differing sources, SCM replacement levels, and admixture dosages. Target values for slump and air content were 20.3 cm (8.0 in) and 2.0%, respectively. Mean values of slump tests were 20.5 cm for OPC and 20.1 cm for PLC. A p-value of 0.3280 indicated that these slumps were not statistically different. Mean air contents were 2.53% for both types of cements.

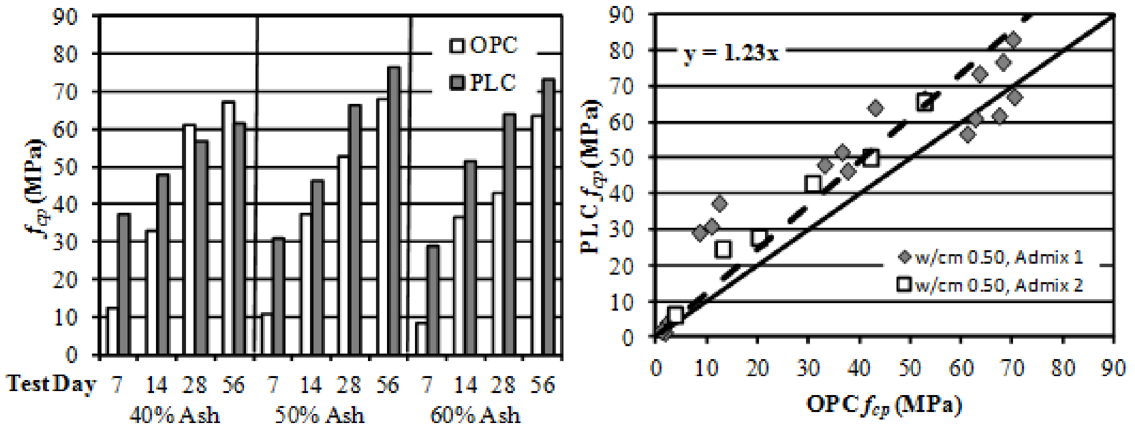
Time of set indication used the same 15 concrete pairs with an additional 14 CP pairs. Mean time of set in concrete was 6.56 hr for OPC and 5.87 hr for PLC. A p-value of 0.0003 indicated that the set times were statistically different. Mean CP time of set indication values were 15.57 hr for OPC and 12.89 hr for PLC. A p-value of 0.0092 indicated that CP time of set indications were statistically different.

5.3.2 Single Source Results with Multiple Replacement Rates

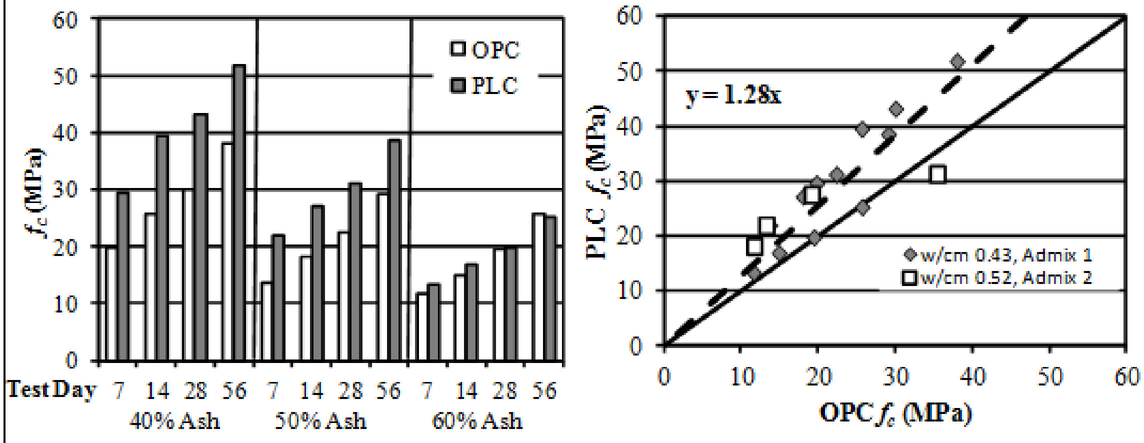
This section features results from a single cement source (C) with 6 replacement rates. In total 14 concrete mixtures (168 specimens) and 14 CP mixtures (252 specimens) are shown in the Figure 5.5 and 5.6. Figure 5.5 illustrates concrete and CP results with fly ash replacement. Parts (a) and (c) show differences between replacement rates at test days of 7, 14, 28, and 56, and parts (b) and (d) show equality plots.

It should be noted that the equality figures contain more data than is shown in the bar charts in the form of additional admixture blends, water to cement ratios, and in CP specimens early test days. Admixture and water to cement ratio differences are noted in the figures.

In the equality plots illustrated in Figure 5.5(b) and (d) it is shown that all 3 fly ash replacement rates exhibited higher compressive strengths with PLC compared to OPC. The overall percent increases (as noted in the slopes of 1.23 and 1.28) were similar in both concrete and CP specimens. It should be noted, however, that there are different trends in concrete to CP performance based on different replacement rates as seen in Figure 5.5 (a) and (c). In concrete mixtures the greatest compressive strength values and ratio of PLC to OPC compressive strength occurred in 40% fly ash mixtures. Increasing replacement rates caused both the compressive strength and the PLC to OPC compressive strength ratio to decrease. CP mixture trends were the opposite with higher replacement mixtures exhibiting larger compressive strengths. This may suggest paste-aggregate bond issues that could be present in the concrete, but would not be in CP.



a) CP f_{cp} b) CP Equality



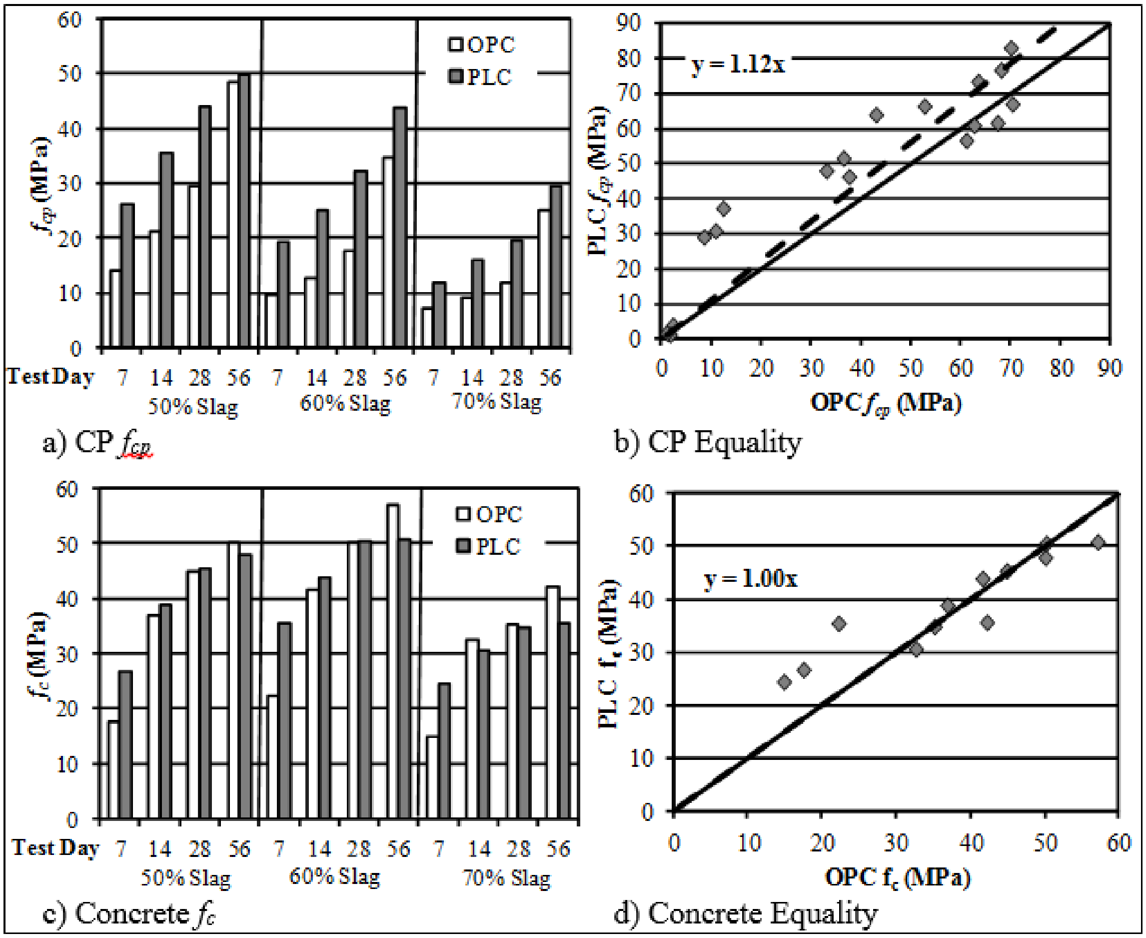
c) Concrete f_c d) Concrete Equality

Figure 5.5 Concrete and CP with Fly Ash Test Results

Figure 5.6 shows the same general layout as Figure 5.5, but with slag cement replacement mixtures. All mixtures were made with a single water to cement ratio (0.43) and admixture blend 1. This section focuses more on fly ash, as it is generally more used than slag cement, but slag cement replacement testing may be helpful in determining PLC performance trends due to chemical and fineness effects.

Both concrete and CP mixtures with slag cement showed increased compressive strengths with PLC at 7 days. Later age strengths, however, converged to strengths similar to OPC. Concrete performance specifically was very similar in PLC and OPC past 7 days. On average, concrete strengths were greater with slag cement mixtures than fly ash mixtures, especially at higher replacement rates. However, CP strengths showed the opposite trend. This may suggest higher paste-aggregate bond strengths with slag cement than fly ash, possibly due to increased fineness present in slag cement. These differences appear to be mitigated in PLC mixtures, likely because of the added cement fineness.

When all test days and mixtures combinations were considered neither fly ash mixtures nor slag cement mixtures exhibited statistically significantly different compressive strengths with PLC than with OPC (p-values of 0.08 and 0.73 for fly ash and slag cement specimens, respectively) in concrete mixtures. Mean values, however, were practically different in fly ash mixtures (29.8 MPa compared to 22.3 MPa), but not so in slag cement mixtures (38.7 Mpa compared to 37.1 MPa).



a) CP f_{cp}

b) CP Equality

c) Concrete f_c

d) Concrete Equality

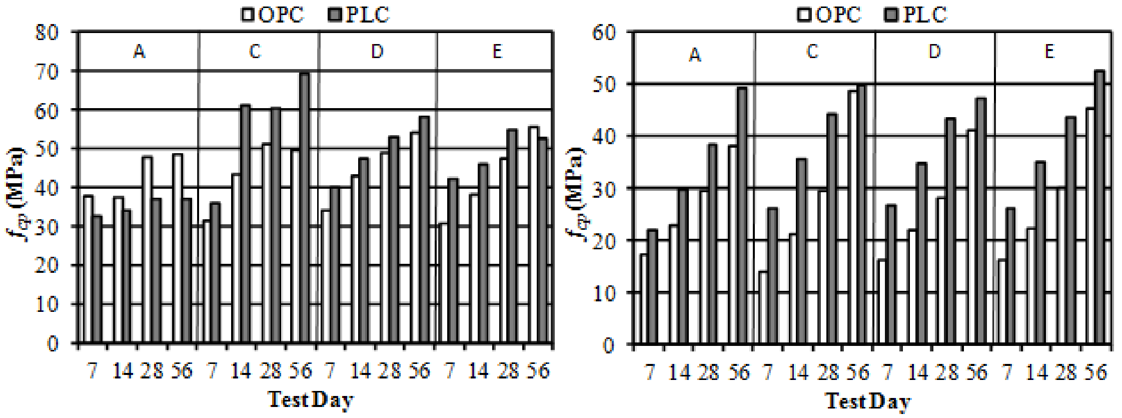
Figure 5.6 Concrete and CP with Slag Cement Test Results

5.3.3 Multiple Source Results with 40% Fly Ash Replacement

Potential benefits of PLC, especially in the 40% fly ash replacement mixtures, have been shown in the previous section. This section shows that these benefits may be achieved in cements from multiple sources. Figure 5.7 shows OPC and PLC data from each source with No SCM (cement is the only cementitious material) and 40% fly ash replacement in both concrete and CP mixtures. This figure was formed using 16 concrete mixtures (192 specimens) and 16 CP mixtures (288 specimens). All mixtures were made at the same water to cement ratio (0.43) and used admixture blend 1.

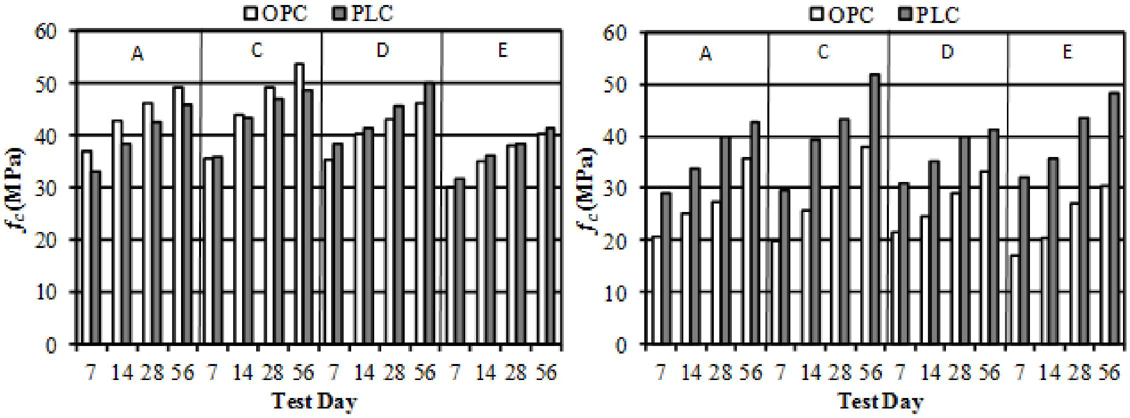
In concrete with no SCMs (Figure 5.7c), OPC mixtures exhibited slightly higher compressive strengths than PLC mixtures for sources A and C. However, PLC mixtures were slightly higher in sources D and E. Generally, OPC and PLC compressive strength differences in no SCM mixtures were virtually negligible, which coincides with current literature. CP mixtures with no SCM tended to favor OPC for source A, PLC for source C, and slightly favored PLC for sources D and E. In 40% fly ash mixtures PLC exhibited higher compressive strengths in all CP and concrete mixtures, in most cases by substantial margins. As in previous figures, CP data tends to show more variability than concrete data, though overall differences do not appear to be especially meaningful.

Figure 5.8 represents the equality plots associated with the mixtures shown in Figure 5.7. Results from all sources are shown without differentiation. CP mixtures with no SCMs exhibited little to no difference in compressive strength between OPC and PLC. Concrete with no SCM showed a moderate advantage with PLC. However, considering variability it does not appear to be substantial. Both concrete and CP mixtures with 40% fly ash indicated compressive strength advantages with PLC relative to OPC. Concrete mixtures especially exhibited this trend with a slope of 1.46, and each data point in the concrete set favored PLC over OPC. This is believed to be related to enhanced particle size distributions or improvements in the paste-aggregate bond. A two-way analysis of variance was conducted and it was found that there was a statistically significant difference between No SCM and 40% replacement mixtures (p-value of 2.4E-7), OPC and PLC mixtures (p-value of 0.0004), and combinations thereof (p-value of 0.0002).



a) CP No SCM

b) CP 40% Fly Ash



c) Concrete No SCM

d) Concrete 40% Fly Ash

Figure 5.7 Multiple Source Compressive Strength Test Results

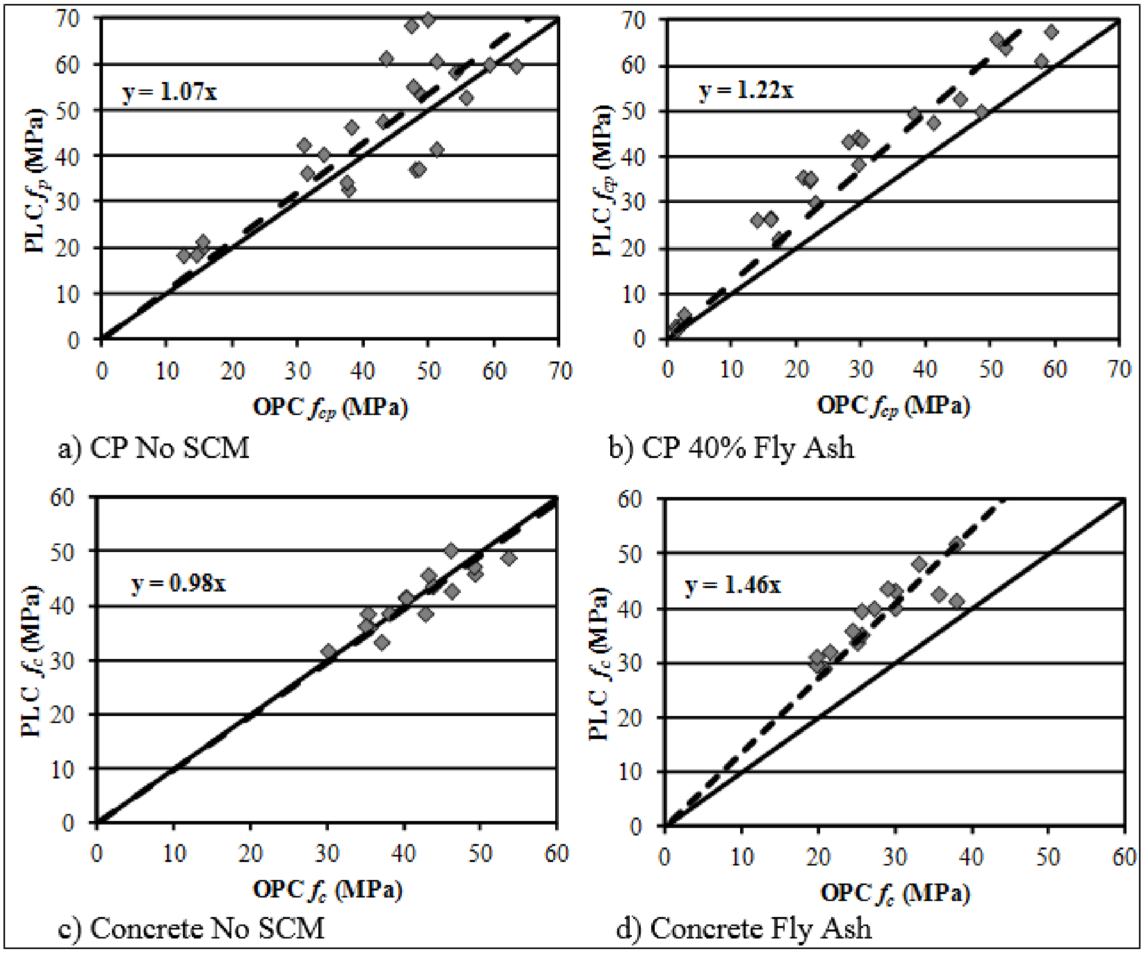
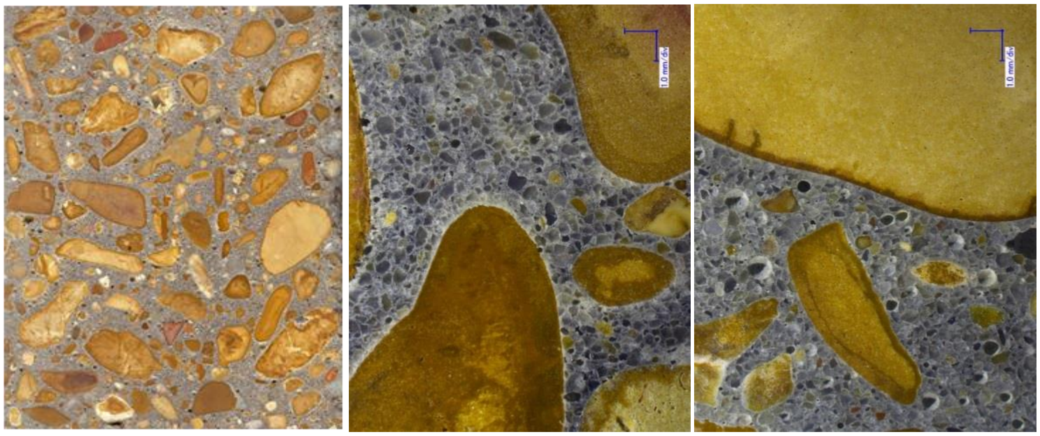


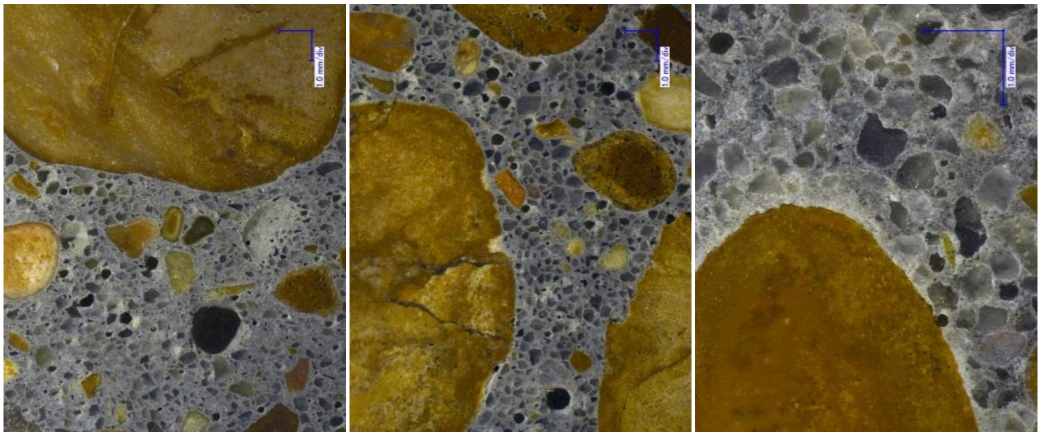
Figure 5.8 Multiple Source Equality Plots

5.3.4 Petrography Results

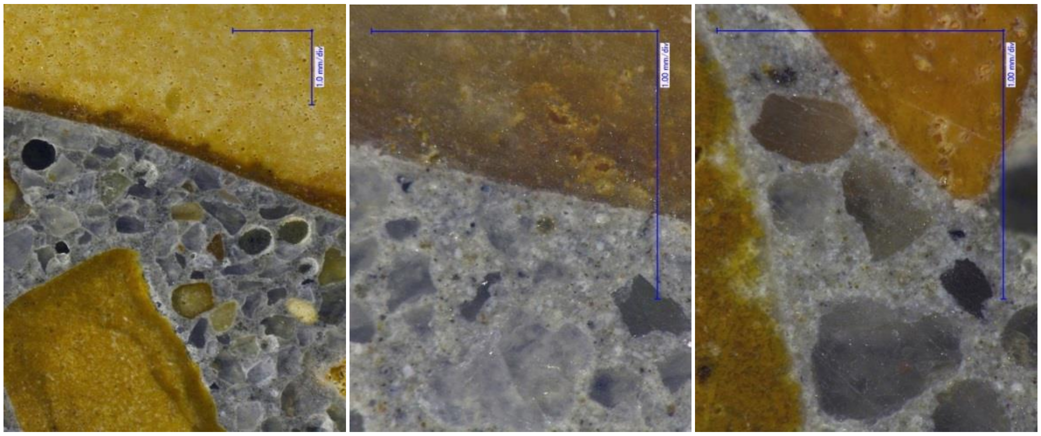
Petrography was performed on 4 concrete specimens from cement source C (No SCM OPC, No SCM PLC, 40% fly ash OPC, 40% fly ash PLC). The analysis was thought to be useful in determining any differences in paste-aggregate bond as well as any relation between paste-aggregate bonds and compressive strength. Results of the petrography analysis are shown in Figure 5.9 with an example of a full size processed specimen in Figure 5.9a.



a) Example Specimen b) No SCM OPC 20X c) No SCM PLC 20X



d) 40% Ash OPC 20X e) 40% Ash PLC 20X f) No SCM OPC 50X



g) No SCM PLC 50X h) 40% Ash OPC 200X i) No SCM PLC 50X

Figure 5.9 Petrography Images

In no SCM mixtures with OPC, the paste portion was generally darker in color and less uniform than the PLC paste portion. OPC paste also appeared to be coarser with a medium texture, compared to the PLC, which appeared finer with a medium fine texture (parts (b) and (c)). Mixtures with fly ash appeared to have a finer and chalkier paste texture compared to no SCM mixtures (parts (d) and (e)). White to translucent irregularly shaped particles were present in both OPC and PLC fly ash mixtures and appeared to have a higher content in OPC fly ash mixtures, but were not identified in this testing.

The no SCM OPC specimen exhibited notably lighter colors than in the no SCM PLC specimen near the paste aggregate interfacial transition zone or ITZ, (parts (f) and (g)). This serves to indicate higher water to cement ratios. These color variations were less pronounced in OPC with 40% fly ash replacement. In general differences in the ITZ between OPC and PLC were less obvious in fly ash replacement mixtures than no SCM mixtures. The volume of unhydrated fly ash particles appeared to be increased in the OPC specimen relative to the PLC specimen (parts (h) and (i)). This would suggest a more uniform or greater cementitious hydration present in PLC mixtures.

CHAPTER VI

SYNERGYSTIC EVALUATION OF FLY ASH TYPES

6.1 Overview

This chapter focuses on PLC interactions with commonly used SCMs. Emphasis is placed on differences between Class C and Class F fly ash. SCM replacement rates evaluated were higher than those most often used in practice to further investigate possible synergistic effects of SCMs with PLC. The test matrix was formatted to accommodate these comparisons by utilizing 32 pairs of mixtures (each pair consisting of Class C and Class F fly ash mixtures). Approximately 768 specimens were included in this analysis. Data presented in this chapter is scheduled for submission to a peer reviewed journal (Shannon et al. 2015c).

6.2 Mixtures Evaluated

Mixtures evaluated are shown in Table 6.1. Group numbers were given to similar mixtures based on SCM content (Group 1 = 50% slag cement/20% fly ash, Group 2 = 30% slag cement/20% fly ash, Group 3 = 40% fly ash, Group 4 = 30% slag cement/20% fly ash). Note that groups 2 and 4 had the same SCM rates but were separated based on aggregate type. Groups 1-3 had LS coarse aggregate while group 4 had GR. All mixtures included aggregates PG and CS. All mixtures featured the same admixture dosage rates of 1.30 ml/kg A-1, 3.26 ml/kg A-2, and 3.91 ml/kg A-3.

Table 6.1 Concrete Mixture Proportions

Group	Pair Number	Type-Cement	SSD Aggregates (kg/m^3)				Cementitious Materials (kg/m^3)		
			GR	LS	PG	CS	Cement	Slag	Fly Ash
1	1	OPC-A1	---	890	222	804-818	96 (30%)	160 (50%)	64 (20%)
	2	PLC-A2	---	890	222	803-817	96 (30%)	160 (50%)	64 (20%)
	3	OPC-C1	---	890	222	804-818	96 (30%)	160 (50%)	64 (20%)
	4	PLC-C2	---	890	222	805-817	96 (30%)	160 (50%)	64 (20%)
	5	OPC-D1	---	890	222	804-818	96 (30%)	160 (50%)	64 (20%)
	6	PLC-D3	---	890	222	805-817	96 (30%)	160 (50%)	64 (20%)
	7	OPC-E1	---	890	222	804-818	96 (30%)	160 (50%)	64 (20%)
	8	PLC-E2	---	890	222	805-817	96 (30%)	160 (50%)	64 (20%)
2	9	OPC-A1	---	890	208	829-843	160 (50%)	96 (30%)	64 (20%)
	10	PLC-A2	---	890	208	827-841	160 (50%)	96 (30%)	64 (20%)
	11	OPC-C1	---	890	208	829-843	160 (50%)	96 (30%)	64 (20%)
	12	PLC-C2	---	890	208	827-841	160 (50%)	96 (30%)	64 (20%)
	13	OPC-D1	---	890	208	829-843	160 (50%)	96 (30%)	64 (20%)
	14	PLC-D3	---	890	208	827-841	160 (50%)	96 (30%)	64 (20%)
	15	OPC-E1	---	890	208	829-843	160 (50%)	96 (30%)	64 (20%)
	16	PLC-E2	---	890	208	827-841	160 (50%)	96 (30%)	64 (20%)
3	17	OPC-A1	---	890	208	812-841	192 (60%)	---	128 (40%)
	18	PLC-A2	---	890	208	809-838	192 (60%)	---	128 (40%)
	19	OPC-C1	---	890	208	812-841	192 (60%)	---	128 (40%)
	20	PLC-C2	---	890	208	809-838	192 (60%)	---	128 (40%)
	21	OPC-D1	---	890	208	812-841	192 (60%)	---	128 (40%)
	22	PLC-D3	---	890	208	809-838	192 (60%)	---	128 (40%)
	23	OPC-E1	---	890	208	812-841	192 (60%)	---	128 (40%)
	24	PLC-E2	---	890	208	809-838	192 (60%)	---	128 (40%)
4	25	OPC-A1	890	---	208	740-754	160 (50%)	96 (30%)	64 (20%)
	26	PLC-A2	890	---	208	737-752	160 (50%)	96 (30%)	64 (20%)
	27	OPC-C1	890	---	208	740-754	160 (50%)	96 (30%)	64 (20%)
	28	PLC-C2	890	---	208	737-752	160 (50%)	96 (30%)	64 (20%)
	29	OPC-D1	890	---	208	740-754	160 (50%)	96 (30%)	64 (20%)
	30	PLC-D3	890	---	208	737-752	160 (50%)	96 (30%)	64 (20%)
	31	OPC-E1	890	---	208	740-754	160 (50%)	96 (30%)	64 (20%)
	32	PLC-E2	890	---	208	737-752	160 (50%)	96 (30%)	64 (20%)

--All mixtures had a constant total cementitious content of 320 kg/m^3 and w/cm of 0.43.

--Each mix pair listed was made with Class C and Class F fly ash.

--Cement column indicates whether OPC or PLC was used and the specific cement utilized.

--Range of CS content was due to differing specific gravities (shown as C ash value- F ash value).

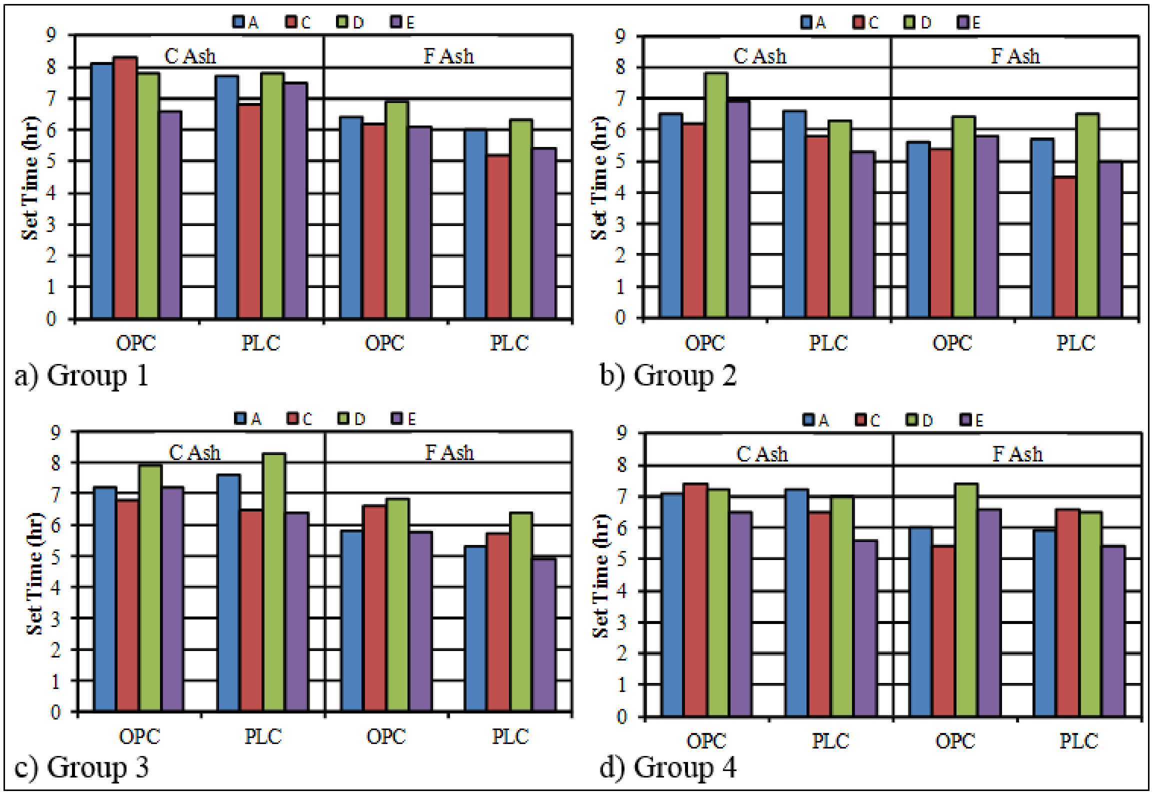
--Groups 1-4 were 70% replacement LS, 50% replacement LS, 40% replacement LS, and 50% replacement GR, respectively.

6.3 Fresh Mixed Properties and Time of Set

Concrete slump was 20.6 cm on average for OPC mixtures and 20.8 cm for PLC mixtures. Average air content was 2.6% for both OPC and PLC mixtures. Unit weights were, on average, 2387 kg/m^3 for LS aggregate mixtures and 2291 kg/m^3 for GR aggregate mixtures. Paired t-tests were conducted with an alpha value of 0.05 and indicated that there was no significant difference in slump, air content, or unit weight between OPC and PLC. Using the same alpha value and comparing C ash to F ash pairs, there was a statistically significant difference in air content. Class C ash produced slightly lower average air contents (2.4%) than Class F (2.7%).

Time of set results obtained according to ASTM C403 are shown in Figure 6.1. In group 1 mixtures with C ash, OPC and PLC exhibited similar time of set. However, F ash mixtures showed lower time of set than C ash, and all PLC mixtures with F ash showed lower time of set than OPC mixtures with F ash. Similar trends were observed in group 3 mixtures, with inconclusive OPC to PLC comparisons in C ash, but F ash having faster set than C ash, and PLC outperforming OPC in F ash.

In group 2 and 4 mixtures, PLC showed the same to slightly decreased time of set compared to OPC in C ash mixtures. In these groups with F ash mixtures, the advantage of PLC over OPC was not as pronounced. The lowest average time of set, considering all cements was observed in group 2 F ash mixtures.



a) Group 1

b) Group 2

c) Group 3

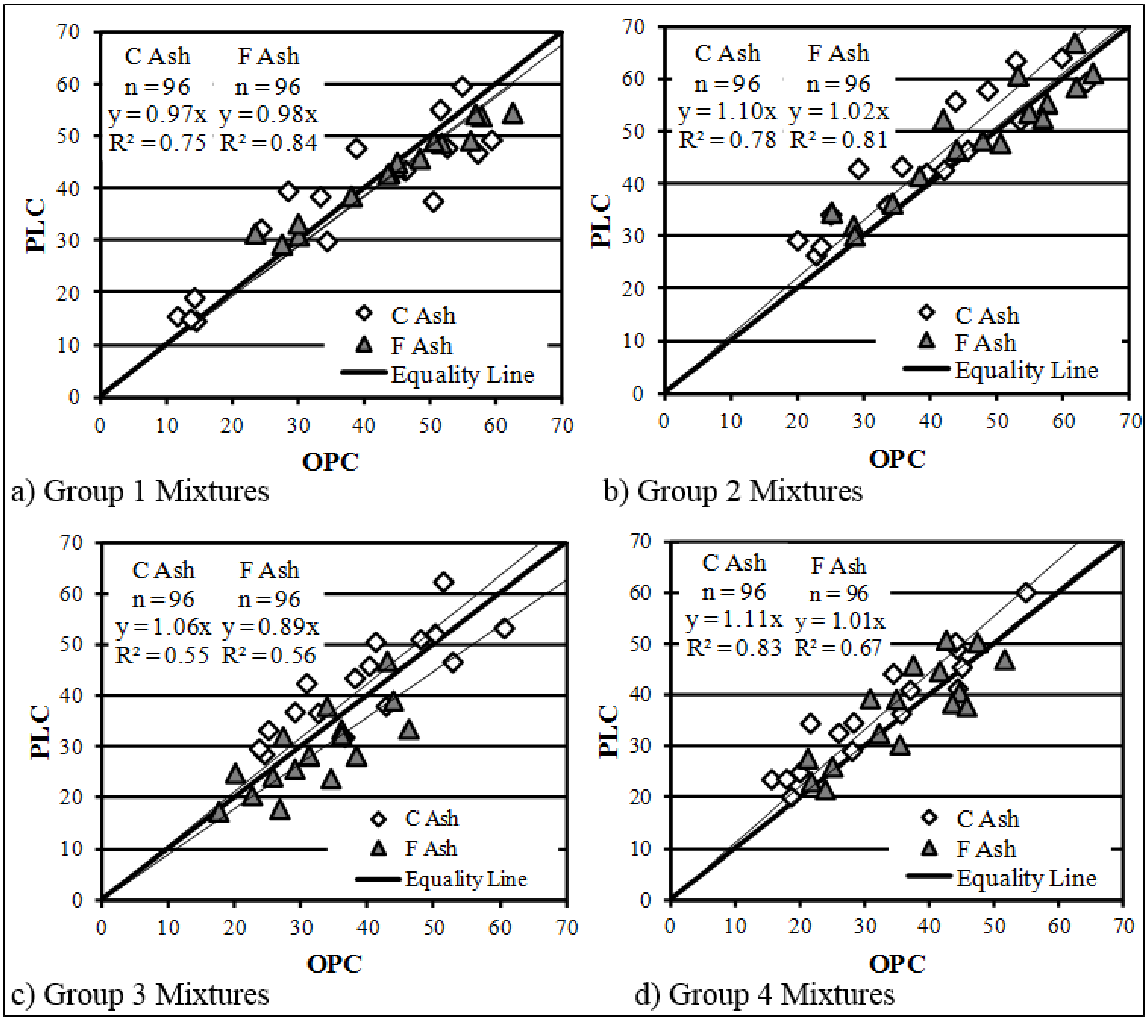
d) Group 4

Figure 6.1 Time of Set Results

6.4 Compressive Strength

Concrete compressive strengths are shown via equality plots in Figure 6.2. Plots were created in the same manner as described in Chapter V. Group 1 mixtures showed roughly equivalent performance considering both ash types with a slight advantage to OPC (slopes of 0.97 and 0.98). Early age compressive strengths with C ash were generally lower than with F ash in both OPC and PLC specimens. On average strengths were 14.7 MPa lower at 7 days and 10.2 MPa lower at 14 days. Differences of these magnitudes were not seen in 28 and 56 day tests.

In group 3 mixtures with C ash, compressive strengths were on average 10.4 MPa higher than F ash considering all test days. Compressive strength results with C ash were, in general, similar to slightly improved with PLC (slope of 1.06). In F ash specimens higher strengths were observed in OPC mixtures (slope of 0.89).



a) Group 1 Mixtures

b) Group 2 Mixtures

c) Group 3 Mixtures

d) Group 4 Mixtures

Figure 6.2 PLC Versus OPC Equality Plot

Group 2 mixtures with F ash were similar with a slight advantage to PLC (slope of 1.02). Mixtures with C ash were noticeably higher with PLC (slope of 1.10). Differences in F ash and C ash strengths were less pronounced than in groups 1 and 3 mixtures. In group 4 mixtures, similar trends were seen as in group 2 with generally decreased compressive strengths (9.5 MPa lower on average). This was expected considering aggregate properties.

To further evaluate differences between paired mixtures, a series of t-tests were conducted and are shown in Table 6.2. Variables considered in each test are shown in the table as y_1 and y_2 (e.g. row 3 in the table considers group 1 mixtures with OPC, variables C ash and F ash, and significant differences were found at 7 and 14 days and in time of set). Group 1 mixtures had slightly higher 7 day strengths with OPC compared to PLC but no other significant differences between the two cement types. All group 1 pairings comparing C ash to F ash showed higher strengths with F ash at 7 and 14 days and lower time of set. However, at 56 days there was very little difference between ash types.

Group 2 mixtures exhibited significantly higher strengths in PLC at 7 and 14 days and lower time of set. In mixtures with F ash, compressive strengths were significantly higher at 7 days and, when considering both PLC and OPC mixtures, at 14 days. Time of set was significantly lower in F ash mixtures except when only considering PLC data. Based solely on mean differences, in each of the cases in this group, F ash provided higher strengths and lower set times. In general, considering PLC data, F ash mixtures performed better with slag cement, while the most advantageous PLC mixtures with C ash were 40% C ash with no slag cement. With these findings it appears that PLC mixtures benefit from large amounts of CaO, and large amounts of CaO with the added aluminates found in Class F fly ash.

In group 3 mixtures there was no statistically significant difference in any of the OPC versus PLC results. C ash mixtures exhibited higher compressive strengths in PLC, OPC, and both combined at all test days, with the exception of OPC only at 14 days. These mixtures also all had significantly lower time of set with F ash. Overall, group 4 mixtures showed patterns similar to group 2 with the exception of statistically insignificant time of set differences. It should be noted, however, that individual mixtures within groups 2 and 4 do not necessarily follow consistent trends.

When considering LS mixtures (groups 1 to 3), few significant differences were seen in compressive strengths, but all groups showed lower set times with F ash. LS versus GR mixture results were expected with LS mixtures producing higher compressive strengths at all test days and little difference in time of set.

Figure 6.3 illustrates the compressive strength of each individual mixture based on source. In group 1 mixtures, F ash mixtures showed noticeably higher compressive strengths at 7 and 14 days compared to C ash, but similar strengths at 28 and 56 days. Group 1 OPC mixtures with C ash appeared to exhibit no clear advantages of one cement source over another. However, in the PLC versions of these mixtures, sources A and C had apparent advantages over sources D and E at 14, 28, and 56 days. In group 1 mixtures with F ash, source E exhibited the lowest compressive strengths in OPC at 14, 28, and 56 days, and in PLC at all test days.

Table 6.2 Results of t-test Evaluation

Groups				7 Day f_c (MPa)		14 Day f_c (MPa)		28 Day f_c (MPa)		56 Day f_c (MPa)		Set Time (hr)	
	y_1	y_2	n	$\mu(y_1\text{-}y_2)$	p-value	$\mu(y_1\text{-}y_2)$	p-value	$\mu(y_1\text{-}y_2)$	p-value	$\mu(y_1\text{-}y_2)$	p-value	$\mu(y_1\text{-}y_2)$	p-value
1	OPC	PLC	8	-2.8	0.017	-2.2	0.276	3.1	0.195	3.8	0.104	0.5	0.107
1	C Ash	F Ash	8	-14.7	0.000	-10.2	0.001	-3.4	0.209	-0.0	0.984	1.5	0.000
1 OPC	C Ash	F Ash	4	-14.2	0.006	-12.7	0.034	-3.5	0.550	-0.7	0.885	1.3	0.038
1 PLC	C Ash	F Ash	4	-15.2	0.001	-7.6	0.009	-3.3	0.071	0.6	0.812	1.7	0.001
2	OPC	PLC	8	-5.2	0.003	-4.9	0.025	-2.8	0.217	-0.5	0.795	0.6	0.043
2	C Ash	F Ash	8	-5.1	0.000	-6.9	0.017	-5.1	0.098	-3.9	0.270	0.8	0.003
2 OPC	C Ash	F Ash	4	-6.2	0.003	-7.9	0.135	-7.7	0.140	-5.8	0.312	1.1	0.004
2 PLC	C Ash	F Ash	4	-3.9	0.029	-5.9	0.111	-2.4	0.550	-1.5	0.743	0.6	0.180
3	OPC	PLC	8	-0.7	0.744	-0.8	0.769	-0.1	0.963	1.3	0.636	0.4	0.084
3	C Ash	F Ash	8	8.2	0.001	8.3	0.002	11.4	0.001	13.5	0.000	1.3	0.001
3 OPC	C Ash	F Ash	4	5.7	0.041	4.7	0.085	8.2	0.050	10.3	0.025	1.0	0.038
3 PLC	C Ash	F Ash	4	10.7	0.005	12.0	0.001	14.6	0.005	16.7	0.003	1.6	0.015
4	OPC	PLC	8	-3.2	0.035	-4.3	0.066	-2.5	0.217	-0.8	0.711	0.4	0.233
4	C Ash	F Ash	8	-3.2	0.015	-5.0	0.008	-1.9	0.298	1.5	0.469	0.6	0.077
4 OPC	C Ash	F Ash	4	-4.9	0.022	-7.4	0.009	-4.0	0.086	0.2	0.887	0.7	0.274
4 PLC	C Ash	F Ash	4	-1.5	0.305	-2.7	0.258	0.2	0.939	2.8	0.521	0.5	0.212
1-3	OPC	PLC	24	-2.9	0.004	-2.6	0.040	0.1	0.956	1.5	0.246	0.5	0.001
1-3	C Ash	F Ash	24	-3.9	0.072	-2.9	0.157	1.0	0.627	3.3	0.122	0.5	0.001
1-3 OPC	C Ash	F Ash	12	-4.9	0.086	-5.3	0.081	-1.0	0.746	1.3	0.668	1.1	0.000
1-3 PLC	C Ash	F Ash	12	-2.8	0.041	-0.5	0.854	3.0	0.315	5.3	0.095	1.3	0.000
2&4	LS	GR	16	6.5	0.000	9.8	0.000	10.5	0.000	11.3	0.000	-0.5	0.007
2&4 OPC	LS	GR	8	5.5	0.006	9.4	0.002	10.4	0.005	11.4	0.003	-0.4	0.149
2&4 PLC	LS	GR	8	7.5	0.000	10.1	0.001	10.6	0.001	11.1	0.007	-0.6	0.029

-- $\mu(y_1\text{-}y_2)$ is equal to the difference in means of y_1 and y_2 (y_1 - y_2), positive values indicate y_1 is higher and vice versa.

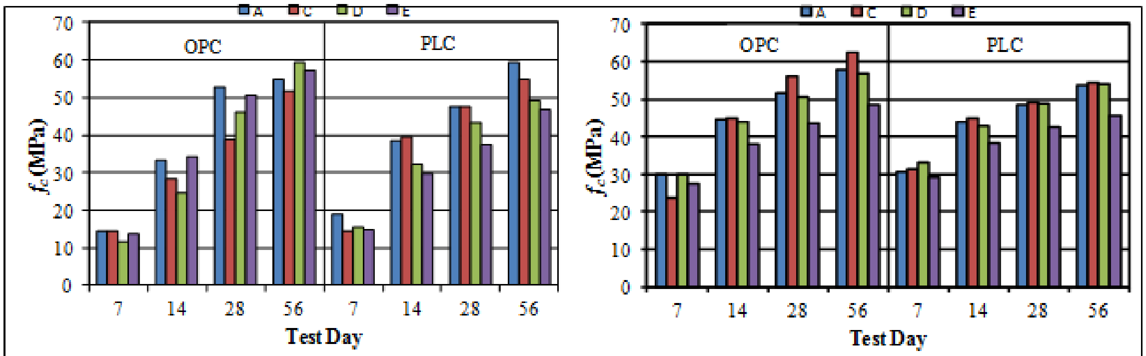
-- p-value of 0.05 or below indicates a statistically significant difference between variables.

--n indicates the number of mixture pairs in each row.

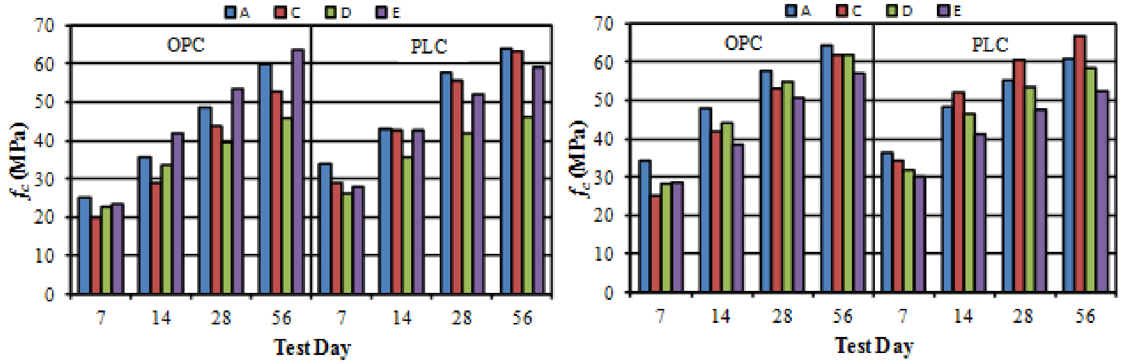
Group 2 mixtures with C ash showed source D lagging behind other sources in OPC specimens at 28 and 56 days and in PLC specimens at all test days. Group 2 mixtures with F ash showed similar results to group 1 with F ash, with source E being the lowest performer in 7 of 8 cases. Group 3 mixtures with C ash showed source D OPC and source C PLC clearly outperforming other sources in their respective categories. These trends were also seen in group 3 with F ash mixtures although not as substantially. However, all of these mixtures recorded relatively low compressive strengths, so it is expected that individual trends would not be as pronounced. Additionally group 3 mixtures with F ash continued to show source E exhibiting lower strengths than other sources, although source D PLC was also low.

In group 4 mixtures (gravel aggregates) with C ash, source C in OPC and PLC showed meaningful advantages over other sources. This advantage was less apparent in F ash with OPC and did not appear in F ash with PLC. Comparatively source E showed its best F ash performance in group 4 OPC specimens, but still was at a disadvantage in PLC specimens.

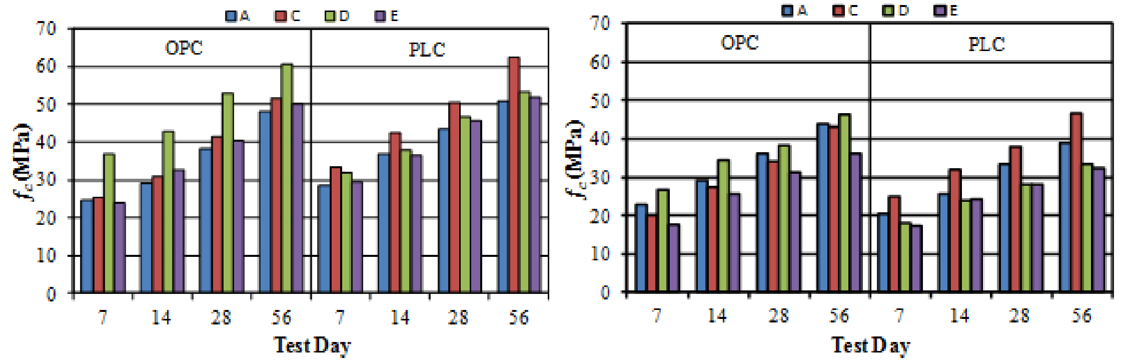
Data in Figure 6.3 was repurposed with all PLC compressive strengths normalized to their respective OPC compressive strength value (e.g. PLC compressive strength minus OPC compressive strength for each source). This data is presented in Figure 6.4. Positive values would then indicate that PLC exhibited higher compressive strengths and would indicate the opposite for negative values. The figure also serves to show to what degree PLC performance is different than OPC.



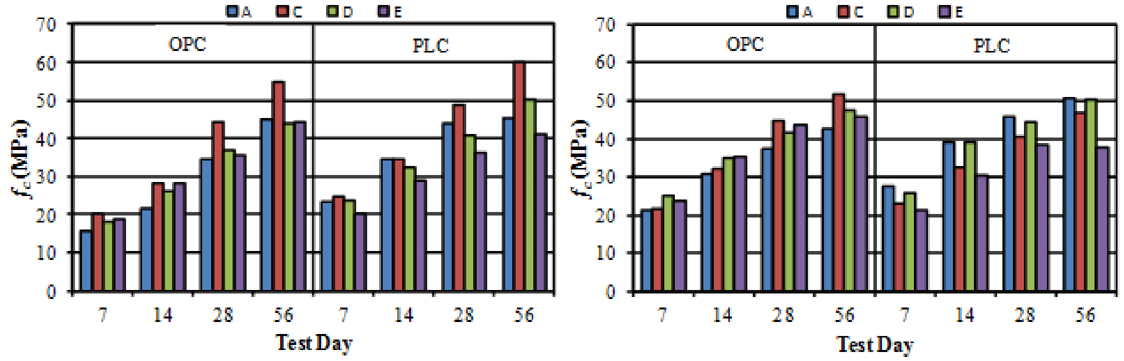
a) Group 1 with C Ash b) Group 1 with F Ash



c) Group 2 with C Ash d) Group 2 with F Ash



e) Group 3 with C Ash f) Group 3 with F Ash



g) Group 4 with C Ash h) Group 4 with F Ash

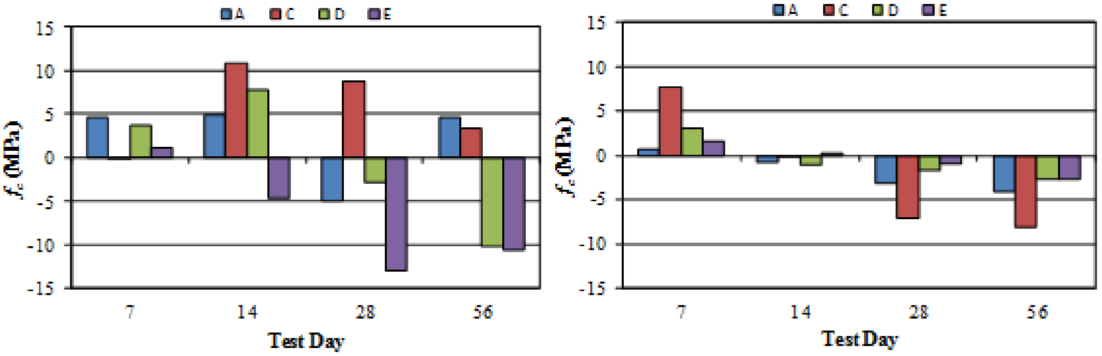
Figure 6.3 Compressive Strengths by Source

Group 1 data in Figure 6.4 was erratic with regard to each source's performance. In general PLC performed better at early age strengths with respect to OPC. It was observed, however, that in F ash mixtures PLC to OPC performance was more similar. In group 2 mixtures, PLC outperformed OPC in most cases with C ash, specifically in source A and B products. In group 2 with F ash, performance of PLC diminished at later age strengths. In those mixtures only source C PLC was consistently better than its OPC.

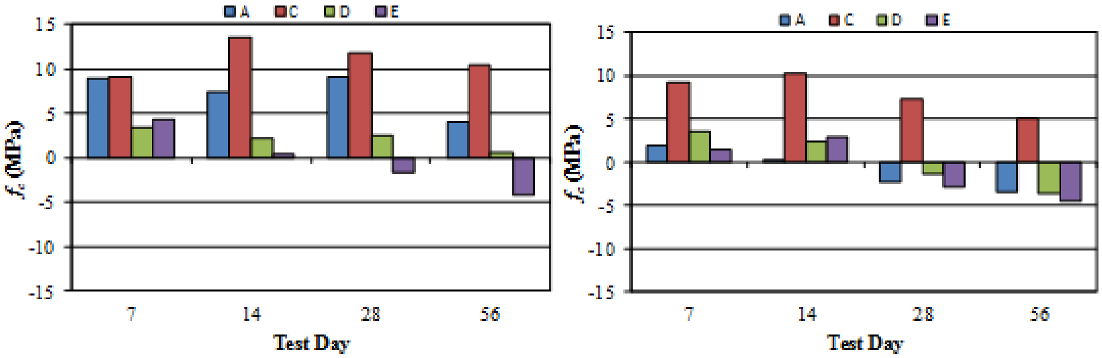
Group 3 mixtures with C ash showed all sources except source D to be substantially better with PLC than OPC. In F ash mixtures, only source C PLC had higher strengths than its OPC. Group 4 with C ash showed similar results to group 2 with C ash; all sources except source E performed better with PLC. In group 4 with F ash, source A noticeably outperformed other sources in PLC to OPC relationship.

Factors contributing to differences in PLC versus OPC performance observed in limestone and gravel aggregate mixtures are unknown at the present. Possibilities for these differences may include PSD variations between C ash and F ash, calcium content (limestone aggregate would add additional calcium), and smooth versus crushed faces. Any differences in PAB or ITZ properties would be more apparent in gravel mixtures due to the smooth and rounded nature of the aggregates.

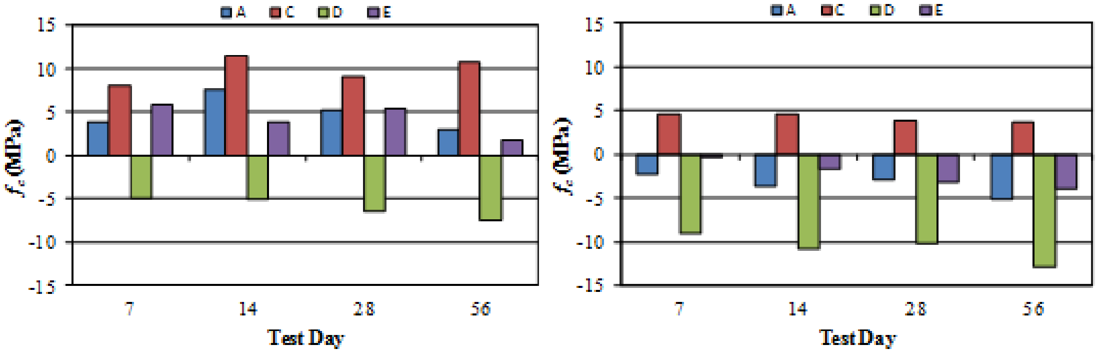
Figure 6.5 shows the same data in a slightly different formant than Figure 6.4. Figure 6.5 may be a more practical representation of PLC to OPC differences as values were based on percentage differences in compressive strength rather than compressive strength values alone (e.g. the figure correctly shows that a 5 MPa difference at 7 days is more indicative of performance benefits than a 5 MPa difference at 56 days).



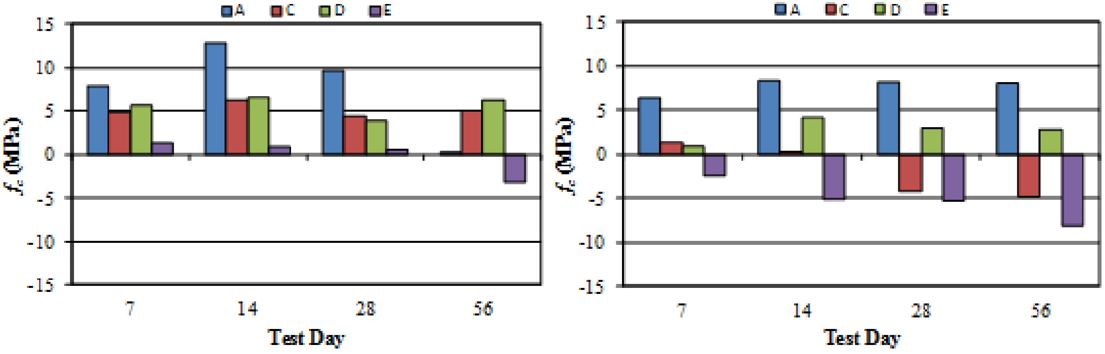
a) Group 1 with C Ash   b) Group 1 with F Ash



c) Group 2 with C Ash   d) Group 2 with F Ash

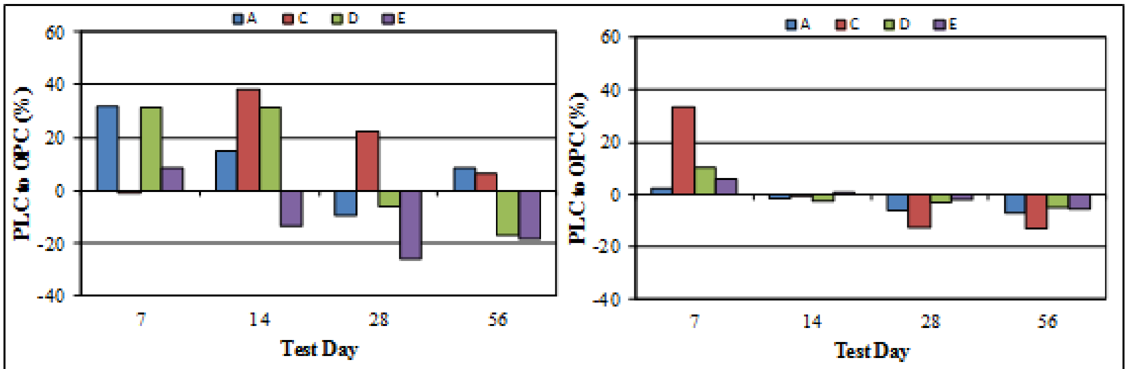


e) Group 3 with C Ash   f) Group 3 with F Ash

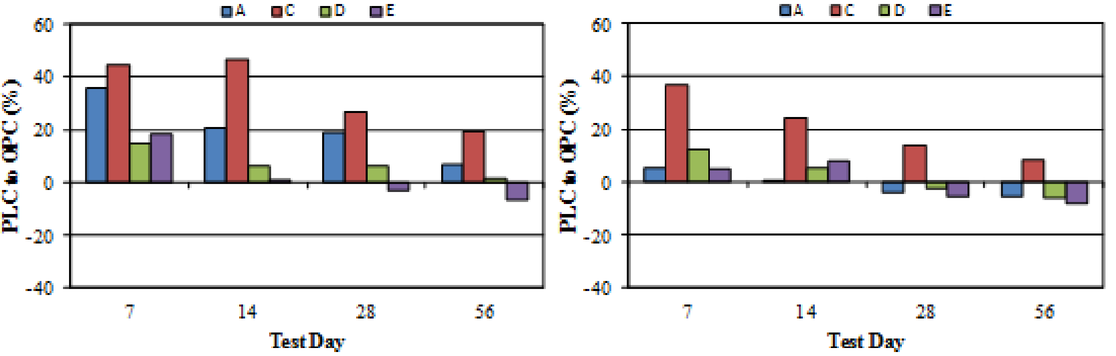


g) Group 4 with C Ash   h) Group 4 with F Ash

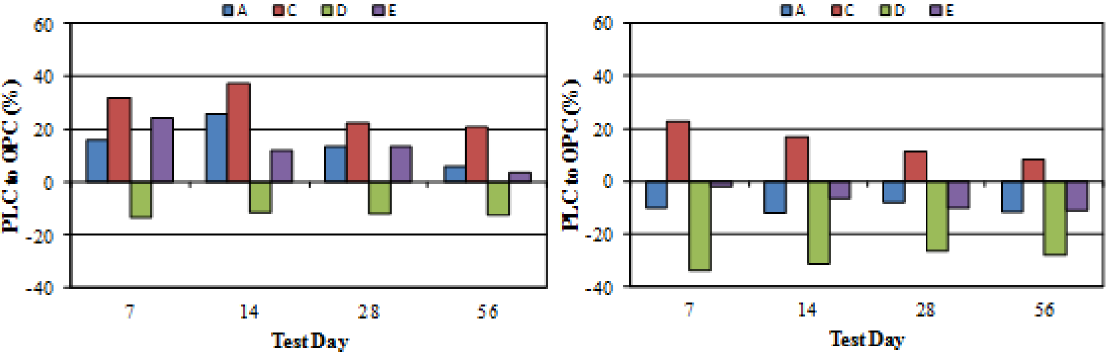
Figure 6.4 PLC Performance Normalized to OPC



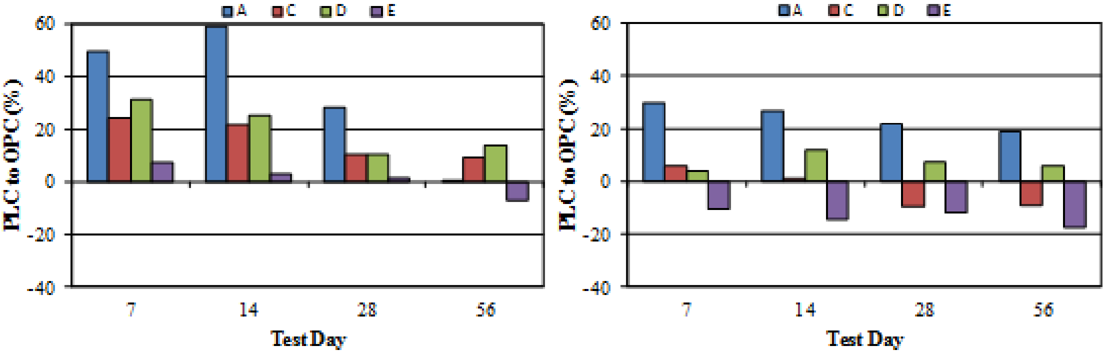
a) Group 1 with C Ash b) Group 1 with F Ash



c) Group 2 with C Ash d) Group 2 with F Ash



e) Group 3 with C Ash f) Group 3 with F Ash



g) Group 4 with C Ash h) Group 4 with F Ash

Figure 6.5 PLC Performance Normalized to OPC (% Difference)

6.5 Variability

A variability analysis was conducted to evaluate any substantial differences in OPC to PLC or source to source compressive strength variations. All sources were compared to source A (e.g. a variability of 1.00 would indicate the same strength as source A, less than 1.00 indicates source A is higher, greater than 1.00 indicates source A is lower). For example the group 1 OPC, source C, 7 day value of 1.02 was obtained by dividing the group 1 OPC, source C, 7 day compressive strength by the group 1 OPC source A, 7 day compressive strength, and indicates that source C was 2% higher. Variabilities on each test day and an average of all days are given in Table 6.3 and Table 6.4.

In C ash mixtures (Table 6.3), the lowest and highest variabilities were 0.73 and 1.49, indicating approximate differences of -27% and +49%, respectively. Both of these occurred in OPC mixtures. Averaging all test days, the lowest and highest variabilities were 0.78 and 1.40. The lowest occurred in PLC and the highest occurred in OPC. On average, group 1 exhibited a range of variabilities of 0.88 to 1.00 in PLC and 0.78 to 0.93 in OPC. This appears to indicate PLC was less variable (range of 0.12) compared to OPC (range of 0.15). Using the same procedure ranges were as follows: 0.22 (group 2 OPC), 0.19 (group 2 PLC), 0.35 (group 3 OPC), 0.15 (group 3 PLC), 0.17 (group 4 OPC), 0.26 (group 4 PLC). Therefore in 3 of the 4 groups PLC had lower variability than OPC, the one outlying group being the only gravel aggregate group.

In F ash mixtures (Table 6.4), the opposite trend was observed with groups 2, 3, and 4 mixtures being more variable with PLC than OPC. Average lowest and highest values in these mixtures were 0.78 and 1.20, a considerably smaller range than the C ash average variabilities. Both extremes occurred in PLC. Based on literature review findings the variabilities determined appear to be within expected values.

Table 6.3 Compressive Strength Variability with Class C Fly Ash

Group (Cement)	Source	Compressive Strength Variability				Source Avg.
		7 Day	14 Day	28 Day	56 Day	
1 (OPC)	C	1.02	0.85	0.74	0.94	0.89
	D	0.82	0.73	0.88	1.08	0.88
	E	0.96	1.03	0.96	1.04	1.00
1 (PLC)	C	0.77	1.03	1.00	0.92	0.93
	D	0.81	0.84	0.91	0.83	0.85
	E	0.79	0.78	0.79	0.78	0.78
2 (OPC)	C	0.80	0.82	0.90	0.88	0.85
	D	0.91	0.94	0.81	0.76	0.86
	E	0.94	1.18	1.10	1.06	1.07
2 (PLC)	C	0.85	0.99	0.96	0.99	0.95
	D	0.77	0.83	0.73	0.72	0.76
	E	0.82	0.98	0.90	0.93	0.91
3 (OPC)	C	1.03	1.06	1.08	1.07	1.06
	D	1.49	1.47	1.39	1.26	1.40
	E	0.97	1.12	1.06	1.05	1.05
3 (PLC)	C	1.17	1.15	1.16	1.22	1.18
	D	1.12	1.03	1.07	1.04	1.07
	E	1.04	1.00	1.06	1.02	1.03
4 (OPC)	C	1.28	1.31	1.29	1.22	1.27
	D	1.15	1.20	1.08	0.98	1.10
	E	1.19	1.30	1.04	0.99	1.13
4 (PLC)	C	1.06	1.00	1.11	1.32	1.12
	D	1.00	0.94	0.93	1.11	1.00
	E	0.85	0.84	0.82	0.91	0.86

--Variability calculation was based on comparison to source A (e.g. Group 1 (OPC) source C 7 day value was calculated as (Group 1 (OPC) source C 7 day value divided by Group 1 (OPC) source A 7 day value)

Table 6.4 Compressive Strength Variability with Class F Fly Ash

Group (Cement)	Source	Compressive Strength Variability				Source Avg.
		7 Day	14 Day	28 Day	56 Day	
1 (OPC)	C	0.78	1.01	1.08	1.08	0.99
	D	1.00	0.98	0.98	0.98	0.99
	E	0.92	0.85	0.84	0.84	0.86
1 (PLC)	C	1.01	1.02	1.01	1.01	1.01
	D	1.08	0.97	1.01	1.01	1.02
	E	0.95	0.87	0.88	0.85	0.89
2 (OPC)	C	0.73	0.88	0.92	0.96	0.87
	D	0.83	0.92	0.95	0.96	0.92
	E	0.83	0.80	0.88	0.88	0.85
2 (PLC)	C	0.95	1.08	1.10	1.10	1.06
	D	0.88	0.96	0.97	0.96	0.94
	E	0.83	0.86	0.86	0.86	0.85
3 (OPC)	C	0.89	0.94	0.94	0.98	0.94
	D	1.18	1.19	1.06	1.05	1.12
	E	0.78	0.88	0.86	0.82	0.84
3 (PLC)	C	1.22	1.25	1.13	1.20	1.20
	D	0.87	0.93	0.84	0.86	0.88
	E	0.85	0.94	0.85	0.83	0.87
4 (OPC)	C	1.03	1.04	1.19	1.21	1.12
	D	1.18	1.13	1.11	1.11	1.13
	E	1.13	1.15	1.16	1.08	1.13
4 (PLC)	C	0.83	0.83	0.89	0.93	0.87
	D	0.94	1.00	0.97	0.99	0.98
	E	0.78	0.77	0.84	0.74	0.78

--Variability calculation was based on comparison to source A (e.g. Group 1 (OPC) source C 7 day value was calculated as (Group 1 (OPC) source C 7 day value divided by Group 1 (OPC) source A 7 day value)

Varner (2013) found variability at 28 days by cement source ranged by up to 21.6% with gravel aggregates and 12.0% with limestone aggregates. Variabilities at the same test day in this study ranged up to 27% with gravel and 29% with limestone. However, this study considered much higher SCM contents than Varner (2013) so higher variability would be expected.

CHAPTER VII

PLC WITH HIGH SCM REPLACEMENT RATES

7.1 Overview

This chapter investigates PLCs ability to increase the total amount of SCM replacement possible in concrete mixtures, while simultaneously benefiting concrete properties. This section features concrete with 50% to 70% cement replacement with dual SCMs. SCMs considered were slag cement and Class C fly ash, and multiple SCM combinations were considered for each cement replacement rate. Four cements were used in these mixtures, all from cement source C, to minimize any effects of different manufacturing facilities. Results from this section are currently in peer review at a journal (Shannon et al. 2015b).

7.2 Results

Concrete mixtures evaluated in this section are shown in Table 7.1. Mixtures were given an ID beginning with either “G” or “L”, which designated whether the coarse aggregate was gravel (GR) or limestone (LS). The first 28 mixtures were evaluated as a set of 3 PLCs (C2, C3, and C5) compared to an OPC (C1). CP specimens were also created and tested for compressive strength for each of the 34 mixtures.

Table 7.1 Properties of Mixtures Evaluated

Mix	**Cement**	**Cement**	**SSD Aggregates (kg/m^3)**				**Cementitious Materials (kg/m^3)**			**w/cm**
ID	**ID**	**Type**	**GR**	**LS**	**PG**	**CS**	**Cement**	**Slag**	**C Ash**	
G1	C1	OPC	845	0	208	818	321 (100%)	0 (0%)	0 (0%)	0.43
G2	C2	PLC	845	0	208	814	321 (100%)	0 (0%)	0 (0%)	0.43
G3	C3	PLC	845	0	208	814	321 (100%)	0 (0%)	0 (0%)	0.43
G4	C5	PLC	845	0	208	814	321 (100%)	0 (0%)	0 (0%)	0.43
G5	C1	OPC	890	0	222	732	96 (30%)	192 (60%)	32 (10%)	0.43
G6	C2	PLC	890	0	222	730	96 (30%)	192 (60%)	32 (10%)	0.43
G7	C3	PLC	890	0	222	730	96 (30%)	192 (60%)	32 (10%)	0.43
G8	C5	PLC	890	0	222	730	96 (30%)	192 (60%)	32 (10%)	0.43
G9	C1	OPC	890	0	222	729	96 (30%)	160 (50%)	64 (20%)	0.43
G10	C2	PLC	890	0	222	727	96 (30%)	160 (50%)	64 (20%)	0.43
G11	C3	PLC	890	0	222	727	96 (30%)	160 (50%)	64 (20%)	0.43
G12	C5	PLC	890	0	222	728	96 (30%)	160 (50%)	64 (20%)	0.43
G13	C1	OPC	890	0	222	706	96 (30%)	128 (40%)	96 (30%)	0.46
G14	C2	PLC	890	0	222	705	96 (30%)	128 (40%)	96 (30%)	0.46
G15	C3	PLC	890	0	222	705	96 (30%)	128 (40%)	96 (30%)	0.46
G16	C5	PLC	890	0	222	705	96 (30%)	128 (40%)	96 (30%)	0.46
G17	C1	OPC	845	0	208	803	160 (50%)	128 (40%)	32 (10%)	0.43
G18	C2	PLC	845	0	208	802	160 (50%)	128 (40%)	32 (10%)	0.43
G19	C3	PLC	845	0	208	802	160 (50%)	128 (40%)	32 (10%)	0.43
G20	C5	PLC	845	0	208	802	160 (50%)	128 (40%)	32 (10%)	0.43
G21	C1	OPC	845	0	208	801	160 (50%)	96 (30%)	64 (20%)	0.43
G22	C2	PLC	845	0	208	799	160 (50%)	96 (30%)	64 (20%)	0.43
G23	C3	PLC	845	0	208	799	160 (50%)	96 (30%)	64 (20%)	0.43
G24	C5	PLC	845	0	208	752	160 (50%)	96 (30%)	64 (20%)	0.43
G25	C1	OPC	845	0	208	800	160 (50%)	80 (25%)	80 (25%)	0.43
G26	C2	PLC	845	0	208	797	160 (50%)	80 (25%)	80 (25%)	0.43
G27	C3	PLC	845	0	208	797	160 (50%)	80 (25%)	80 (25%)	0.43
G28	C5	PLC	845	0	208	797	160 (50%)	80 (25%)	80 (25%)	0.43
G29	C1	OPC	845	0	208	799	128 (40%)	128 (40%)	64 (20%)	0.43
G30	C2	PLC	845	0	208	797	128 (40%)	128 (40%)	64 (20%)	0.43
G31	C1	OPC	845	0	208	796	128 (40%)	96 (30%)	96 (30%)	0.43
G32	C2	PLC	845	0	208	794	128 (40%)	96 (30%)	96 (30%)	0.43
G33	C1	OPC	845	0	208	801	128 (40%)	160 (50%)	32 (10%)	0.43
G34	C2	PLC	845	0	208	799	128 (40%)	160 (50%)	32 (10%)	0.43
L1	C1	OPC	0	890	208	860	321 (100%)	0 (0%)	0 (0%)	0.43
L2	C2	PLC	0	890	208	856	321 (100%)	0 (0%)	0 (0%)	0.43
L4	C5	PLC	0	890	208	856	321 (100%)	0 (0%)	0 (0%)	0.43
L9	C1	OPC	0	890	222	818	96 (30%)	160 (50%)	64 (20%)	0.43
L10	C2	PLC	0	890	222	817	96 (30%)	160 (50%)	64 (20%)	0.43
L12	C5	PLC	0	890	222	817	96 (30%)	160 (50%)	64 (20%)	0.43
L21	C1	OPC	0	890	208	843	160 (50%)	96 (30%)	64 (20%)	0.43
L22	C2	PLC	0	890	208	841	160 (50%)	96 (30%)	64 (20%)	0.43
L24	C5	PLC	0	890	208	841	160 (50%)	96 (30%)	64 (20%)	0.43

-- All mixtures were made with 320 to 321 kg/m^3 of cementitious material (5.75 sacks).

Note that the first set of four mixtures are 0% replacement (100% cement) control mixtures for comparison purposes. Mixtures with 60% cement replacement were conducted on a smaller scale with a single PLC (C2) and OPC (C1). Limestone mixtures were made with cements C1, C2, and C5, due to material shortages. Limestone mixtures were numbered the same as their equivalent gravel mixtures (e.g. G21 and L21 are essentially the same proportions with different coarse aggregate).

7.2.1 Fresh Mixed Properties and Time of Set

Concrete slump averaged 29.8 cm for OPC mixtures and 20.8 cm for PLC mixtures. Air contents averaged 2.4% for OPC mixtures and 2.3% for PLC mixtures. Paired t-tests revealed that there was not a significant difference between air contents, but there was a significant difference between slumps. However, the mean slump difference was approximately 1 cm, which is not perceived as being very meaningful practically. Unit weights varied from 2259 to 2323 kg/m^3 in GR mixtures and 2339 to 2419 kg/m^3 in LS mixtures.

Concrete time of set results, conducted according to ASTM C403, are shown in Figure 7.1. In 0% replacement mixtures with GR aggregate, OPC time of set was recorded at 4.4 hr, while PLCs exhibited set times of 4.0 to 4.2 hr. The same mixtures with LS aggregates had set times of 5.6 hr for OPC and 4.6 to 4.9 hr for PLC. Note that for LS mixtures there were two PLCs while in GR mixtures there were three. In both GR and LS mixtures, PLC exhibited lower time of set than OPC in 0% replacement mixtures. Paired t-test were used to investigate differences between GR and LS mixtures. On average GR mixtures had a time of set of 6.1 hr while LS mixtures a time of 6.2 hr.

However, a difference of 0.1 hr is not seen as a meaningful difference and t-tests concur that the times were not significantly different.

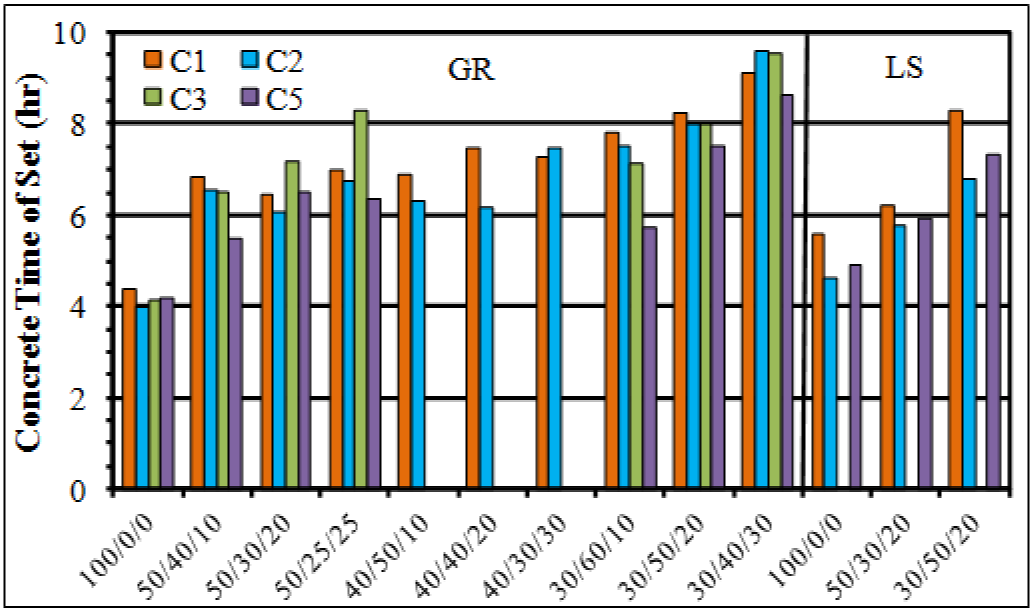


Figure 7.1 Concrete Time of Set Results

In GR mixtures with 50% replacement, C3 time of set was slower than C1 in two cases, and C5 was equal to C1 in one case. In the other 6 of 9 PLC to OPC comparisons, PLC showed faster time of set than OPC. Considering LS mixtures, C2 and C5 both had faster time of set measurements than OPC. Five matched pairs exist in 50% replacement mixtures with GR and LS aggregates, and t-tests were performed to evaluate differences between C1 and C2 and between C1 and C5. For these cases the average time of set for C1 was 7.0 hr, C2 was 6.4 hr, and C5 was 6.3 hr.

While PLC set was faster based on these averages, t-tests revealed no statistically significant difference (p-values were 0.07 for C2 and 0.06 for C5). Overall in the 50% replacement mixtures, PLC was shown to achieve, on average, faster time of set values.

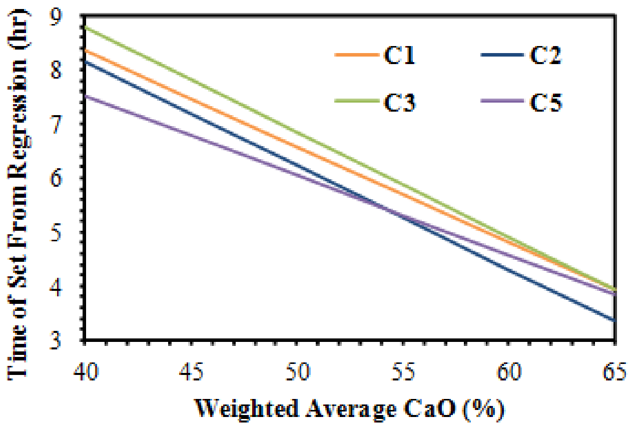
Although these values were not statistically significant, a decrease in time of set by 0.6 to 0.7 hr may have practical benefits. There were no meaningful differences observed between PLCs C2 and C5.

Some potentially interesting trends were observed relating to Class C fly ash's impact on time of set. As fly ash content was increased from 10% to 25% and slag cement content was decreased from 40% to 25%, only cement C3 exhibited a progressive increase in time of set. Normalizing the data relative to the lowest fly ash content and applying regression through the origin (RTO), it was found that C3 time of set increased approximately 1 hr for each 10% increase in Class C fly ash (R^2 of 0.89).

In 60% replacement mixtures (40% cement) only the OPC and a single PLC (C2) were evaluated. C2 averaged 0.7 hr faster time of set, ranging from 0.2 hr slower to 1.3 hr faster. Time of set was slightly longer for these mixtures than C1 and C2 in 50% replacement mixtures, which is expected, and no obvious fly ash trends were observed. Overall, 60% replacement mixtures exhibited no unexpected behaviors.

In 70% replacement mixtures with GR aggregates, PLC time of set was slower than the OPC in two cases, but the remaining 7 cases showed faster time of set with PLC. Interesting fly ash trends were observed again in this data set. RTO was performed in the same manner as described above and showed that time of set increased by approximately 1.1 hr for every 10% increase in Class C fly ash (R^2 of 0.81). Time of set increase per 10% fly ash increase was found to be 0.7, 0.9, 1.1, and 1.5 hr for cements C1, C3, C3, and C5, respectively.

To further investigate SCM impact on time of set, CaO contents for each cementitious material were used to calculate approximate CaO values for the mixture (e.g. a mixture containing a 50/30/20 cementitious blend with cement C1 was calculated as 64.2(0.5) plus 36.8(0.3) plus 22.1(0.2) for a total CaO content of 47.6%). Note that this does not consider different CaO compositions, but attempts to show general trends. Time of set for each mixture compared to CaO content utilizing linear regression is shown in Figure 7.2.



Cement	Slope	Intercept	R^2
C1	-0.177	15.44	0.88
C2	-0.192	15.85	0.76
C3	-0.194	16.54	0.83
C5	-0.147	13.42	0.70

Note: Linear Regression Was Used

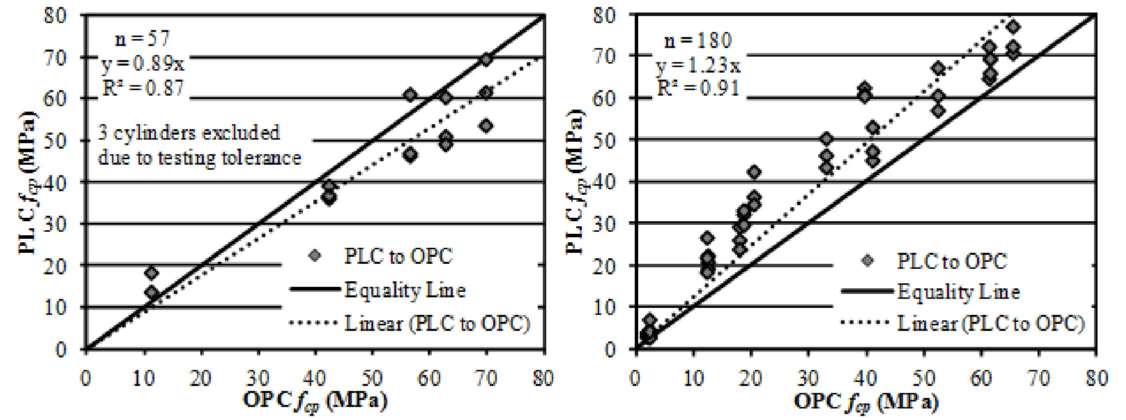
Figure 7.2 Time of Set Compared to Weighted CaO Content

As seen in Figure 7.2, cement C3 shows the longest time of set of all cements regardless to fly ash content. Based on Blaine fineness and limestone content, C3 was expected to perform the worst of the PLCs, which was confirmed by this data. Cements C2 and C5 both perform better than the OPC C1, however there is a transition in which C2 and C5 PLCs swap performance trends. At higher CaO contents C2 exhibited the lowest time of set, but at lower CaO contents C5 exhibits the lowest time of set. In general, this section agrees with expectations that PLC products are suitable for very high replacement mixtures.

7.2.2 Cement Paste Compressive Strengths

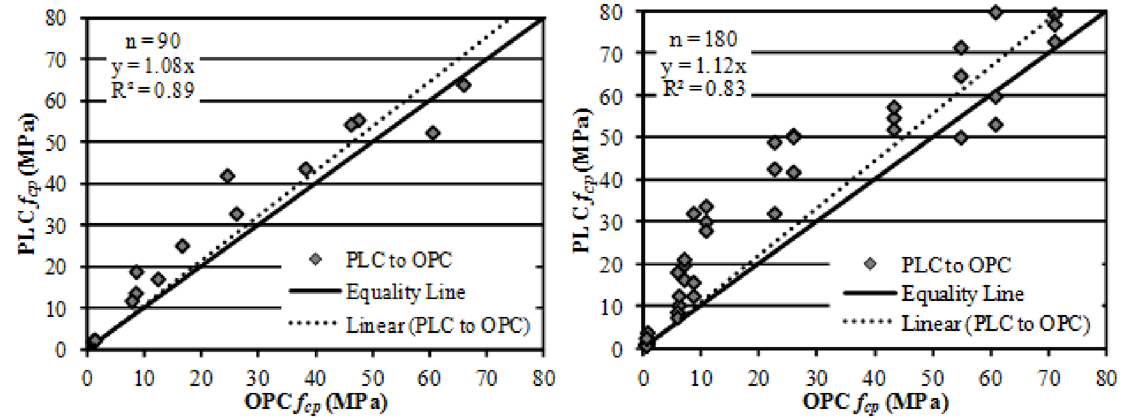
CP compressive strengths are shown in Figure 7.3. Each data point illustrates an average of 3 OPC specimens with 3 PLC specimens and the total number of specimens on each plot (n) is provided. Slopes and R^2 values were obtained in the same manner as discussed in Chapter V. In all mixtures with SCMs, CP specimens with PLC exhibited higher compressive strengths than with OPC up to strengths of 50 MPa. Results of mixtures between 50 MPa and 70 MPa varied depending on replacement rate. In 50% replacement mixtures, PLC was noticeably beneficial at higher strengths (above 50 MPa), but at 60% and 70% replacement OPC was greater in some cases.

PLC exhibited the lowest compressive strengths in 0% replacement mixtures and the highest compressive strengths in 50% replacement mixtures, when compared to OPC. At 50% replacement PLC produced higher compressive strengths than OPC in all 45 data pairings, and at 60% and 70% replacement, in 14 out of 18 (78%) and 40 out of 45 (89%) parings, respectively. It should be noted that in the 70% replacement mixtures, different patterns were observed below and above approximately 40 MPa. Below 40 MPa a slope of 1.94 (R^2 of 0.88) was observed and above 40 MPa a slope of 1.05 (R^2 of 0.30). In general terms this would indicate that PLC strengths were approximately twice that of OPC at compressive strengths under 40 MPa but essentially the same at higher strengths.



a) 0% Replacement

b) 50% Replacement



c) 60% Replacement

d) 70% Replacement

Figure 7.3 CP Compressive Strength Equality Plots

Considering testing age in 0% replacement mixtures, PLC had higher compressive strengths at 1 day in all parings, but then only 2 of the remaining 14 pairings tested after 1 day. In 50% replacement mixtures, PLC outperformed OPC on all test days. In 60% and 70% replacement mixtures, PLC mixtures had lower compressive strengths in a single 1 day and multiple 28 and 56 day tests.

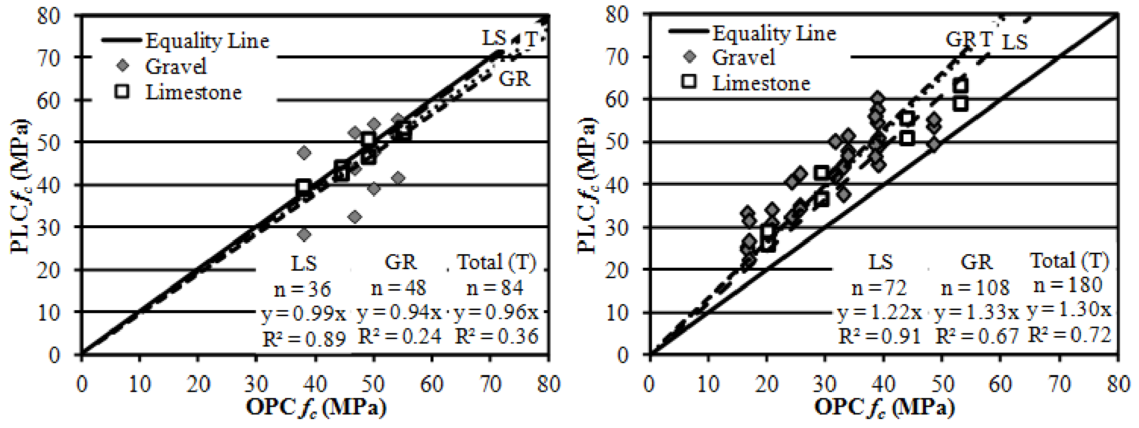
7.2.3 Concrete Compressive Strength

Concrete compressive strength results are shown in equality plots in Figure 7.4. Data is represented in the same manner as the CP equality plots presented in the previous section with the exception of multiple aggregate types being used. Trend lines were determined for each aggregate separately (GR and LS) and for the total data (T) which contains both aggregate types. Results of the equality plots are further summarized for quick comparisons in Table 7.2. Results for individual mixture comparisons are shown in Figure 7.5 and Figure 7.6.

7.2.3.1 Gravel Aggregates

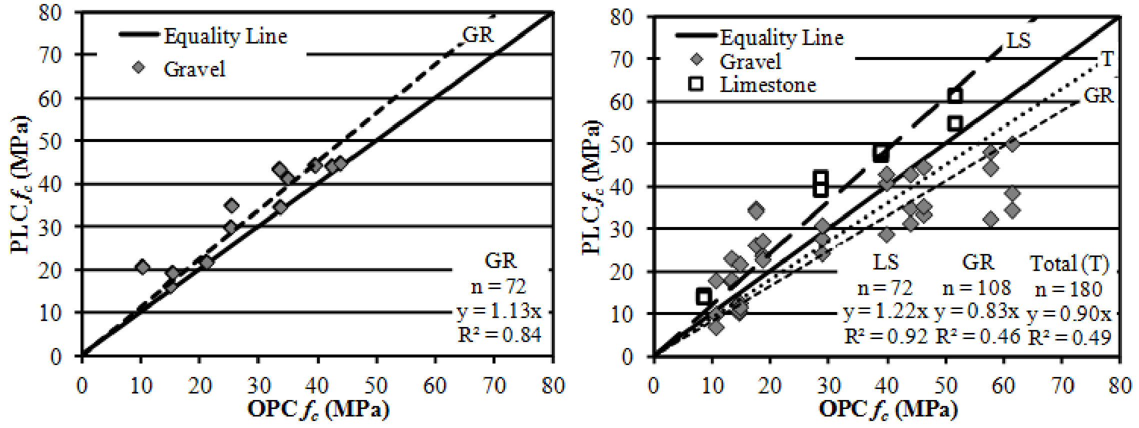
In mixtures with 0% replacement, CP and concrete equality plot slopes rank the three PLCs in the same order or performance, from best to worst, C2, C5, and C3. CP slopes show that C1 and C2 perform essentially the same, but concrete data shows C2 outperforming C1 (Table 7.2 and Figure 7.5b). In Figure 7.5a, C2 always exceeded C1 in compressive strength while C3 and C5 did not.

In mixtures with 50% replacement, CP specimens show C2 and C3 with approximately equivalent performance and C5 performing slightly below C2 and C3. Concrete data does not agree with this and shows C2 performing moderately better than C3, which performed moderately better than C5. In these mixtures all three PLCs exhibited higher compressive strengths than OPC at all test days. Mixtures with GR aggregates performed exceptionally better with PLC than with OPC.



a) 0% Replacement

b) 50% Replacement



c) 60% Replacement

d) 70% Replacement

Figure 7.4 Concrete Compressive Strength Equality Plots

In 70% replacement mixtures, CP equality plot slopes were over 1.00 in all cases which would indicate PLC outperforming OPC. However, in concrete equality plots slopes were all well below 1.00 which would indicate OPC exhibiting higher strengths than all three PLCs. Compressive strength advantages seen in PLC concrete at 50% replacement appear to be almost as equally disadvantageous in 70% replacement mixtures. Figure 7.5d shows that out of 36 pairings, 22 (61%) indicate OPC outperforming PLC. Considering that this decrease was not observed in CP mixtures it may be likely that paste-aggregate bond (PAB) or interfacial transition zone (ITZ) properties may have contributed to this decrease in strength.

In 60% replacement mixtures, C2 was the only PLC tested and performed similarly in both CP and concrete. C2 outperformed C1 at every cementitious blend and test day, which is the same case as that for the 50% replacement mixtures (Figure 7.5c). In both 50% and 60% replacement, the compressive strength differences appear to be practically relevant.

Table 7.2 CP and Concrete Equality Plot Slopes

Replacement Rate	**Cement**	**CP**		**Concrete GR Agg.**		**Concrete LS Agg.**	
		Slope	**R^2**	**Slope**	**R^2**	**Slope**	**R^2**
70%	C2	1.07	0.81	0.71	0.34	1.17	0.90
70%	C3	1.13	0.89	0.80	0.57	---	---
70%	C5	1.15	0.80	0.74	0.87	1.26	0.95
60%	C2	1.08	0.89	1.13	0.84	---	---
50%	C2	1.24	0.89	1.43	0.44	1.27	0.91
50%	C3	1.26	0.95	1.31	0.89	---	---
50%	C5	1.18	0.90	1.23	0.73	1.16	0.97
0%	C2	1.00	0.94	1.10	0.43	0.97	0.89
0%	C3	0.86	0.97	0.75	0.91	---	---
0%	C5	0.94	0.80	0.97	0.91	1.00	0.91

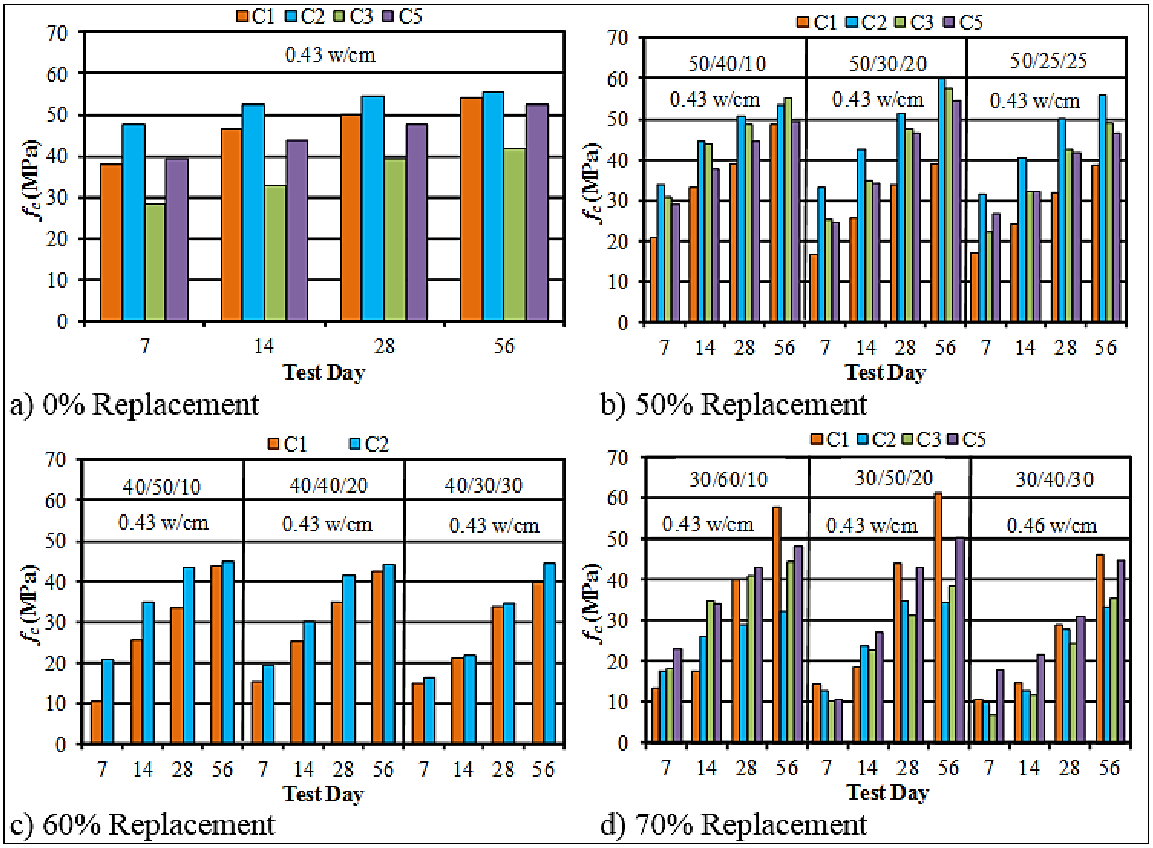


Figure 7.5 Concrete Compressive Strength with GR Aggregate Results

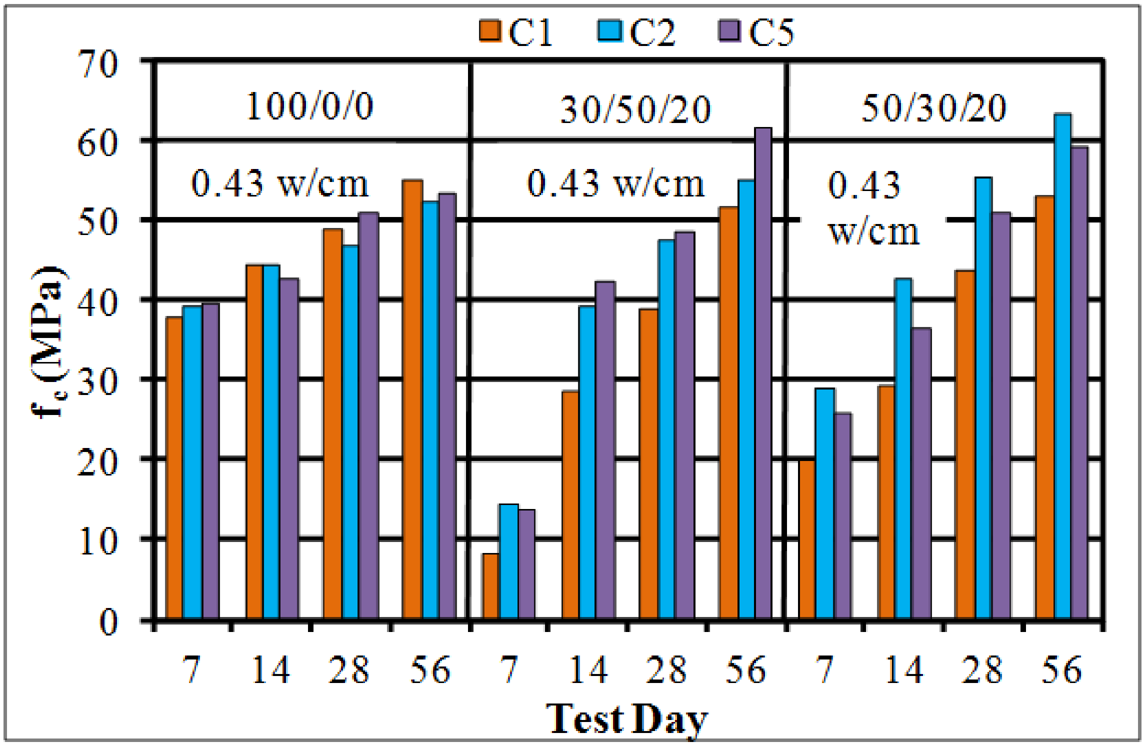


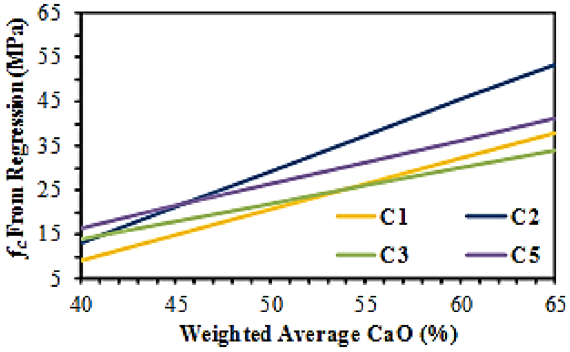
Figure 7.6 Concrete Compressive Strength with LS Aggregate Results

Further investigation featuring GR aggregates and focusing on test day and CaO content is shown in Figure 7.7 and Table 7.3. Figure 7.7 was created utilizing the same methods as Figure 7.2. Table 7.3 list paired t-tests for concrete specimens performed in the same manner as CP. In the majority of concrete cases, the weighted average of CaO values did not appear to produce data that was especially useful. Cements C2 and occasionally C3 linear regressions shown in Figure 7.7 over predicted compressive strengths at high CaO contents. This is most likely due to better than expected behavior in 50% replacement mixtures.

Considering 7 day test results, C2 and C5 had statistically significantly higher compressive strengths than C1 (average strengths were 5.8 MPa to 7.1 MPa higher).

These PLCs exhibited higher strengths, compared to OPC, in 80% to 86% of the Figure 7.5 cases. C3 also exhibited higher strengths than C1 (1.6 MPa to 3.5 MPa higher), but the difference was not statistically significant. Figure 7.7a further illustrates these 7 day observations and shows that the general expectations of 7 day performance were in most cases observed.

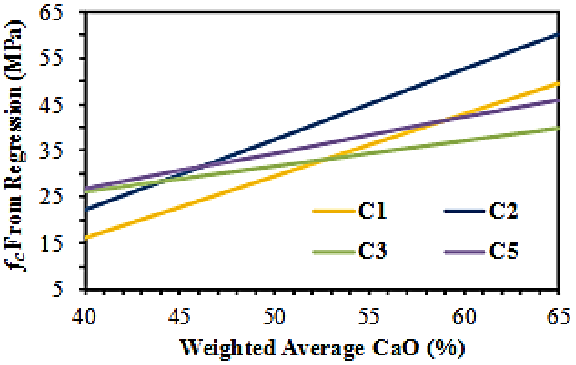
Considering 14 day test results, C2 and C5 again show statistically significantly higher compressive strengths than C1 (average strengths were 7.2 MPa to 8.9 MPA higher). These PLCs exhibited higher strengths, compared to OPC, in 86% to 100% of the cases considered. C3 showed better performance at 14 days (4.6 MPa to 7.8 MPa higher than C1 on average), and was statistically significantly higher when the 0% replacement mixtures where not included in the analysis. Similar to 7 day results, general 14 day strength expectations were observed in most cases.



Cement	Slope	Intercept	R^2
C1	1.143	-36.44	0.90
C2	1.616	-51.54	0.83
C3	0.806	-18.29	0.51
C5	0.987	-22.98	0.80

Note: Linear Regression Was Used

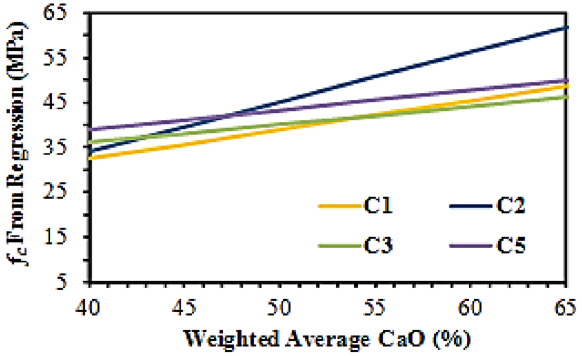
a) 7 Day



Cement	Slope	Intercept	R^2
C1	1.336	-37.34	0.93
C2	1.523	-38.73	0.69
C3	0.554	3.90	0.18
C5	0.767	-3.84	0.76

Note: Linear Regression Was Used

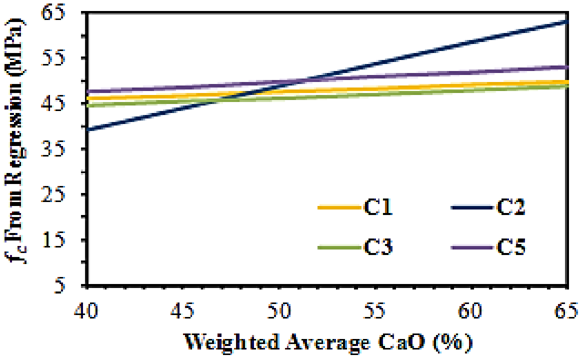
b) 14 Day



Cement	Slope	Intercept	R^2
C1	0.644	6.77	0.45
C2	1.098	-9.73	0.55
C3	0.400	20.10	0.13
C5	0.435	21.59	0.40

Note: Linear Regression Was Used

c) 28 Day



Cement	Slope	Intercept	R^2
C1	0.150	40.10	0.01
C2	0.961	0.80	0.40
C3	0.165	38.00	0.03
C5	0.220	38.80	0.28

Note: Linear Regression Was Used

d) 56 Day

Figure 7.7 Concrete Compressive Strength Compared to Weighted CaO Content

In 28 day tests, only C5, without considering the 0% replacement mixtures, was statistically significantly higher than C1. On average PLC was still the stronger than OPC 57% to 71% of the time, this equated to overall strength increases of 1.0 MPa to 5.4 MPa. On average, C2 and C5 still continued to outperform C3. C3 strength increase compared to OPC was 1.0 MPa to 3.1 MPa, while C2 and C5 show increases of 4.3 MPa to 5.4 MPa.

Table 7.3 Statistical Analysis of GR Aggregate Mixtures by Test Day

100% Cement Included	Test Day	V_2	M_1 (MPa)	M_2 (MPa)	M_2 - M_1 (MPa)	p-value	Cases Where PLC > OPC
Yes	7	C2	17.1	24.2	7.1	0.007	8 of 10, 80%
		C3	18.7	20.3	1.6	0.580	4 of 7, 57%
		C5	18.7	24.4	5.8	0.025	6 of 7, 86%
No	7	C2	14.8	21.6	6.8	0.017	7 of 9, 78%
		C3	15.4	18.9	3.5	0.211	4 of 6, 67%
		C5	15.4	22.0	6.5	0.027	5 of 6, 83%
Yes	14	C2	25.2	32.9	7.7	0.003	9 of 10, 90%
		C3	25.8	30.4	4.6	0.280	5 of 7, 71%
		C5	25.8	33.0	7.2	0.017	6 of 7, 86%
No	14	C2	22.8	30.7	7.9	0.006	8 of 9, 89%
		C3	22.3	30.0	7.8	0.038	5 of 6, 83%
		C5	22.3	31.2	8.9	0.003	6 of 6, 100%
Yes	28	C2	36.9	41.7	4.8	0.165	7 of 10, 70%
		C3	38.2	39.2	1.0	0.800	4 of 7, 57%
		C5	38.2	42.5	4.3	0.084	5 of 7, 71%
No	28	C2	35.5	40.3	4.8	0.211	6 of 9, 67%
		C3	36.2	39.2	3.1	0.497	4 of 6, 67%
		C5	36.2	41.6	5.4	0.049	4 of 6, 67%
Yes	56	C2	47.1	45.8	-1.3	0.808	7 of 10, 70%
		C3	49.3	46.0	-3.4	0.579	3 of 7, 43%
		C5	49.3	49.3	0.0	0.997	3 of 7, 43%
No	56	C2	46.3	44.8	-1.6	0.787	6 of 9, 67%
		C3	48.5	46.7	-1.9	0.786	3 of 6, 50%
		C5	48.5	48.9	0.3	0.942	3 of 6, 50%

--Variable 1 (V_1) was OPC (C1) in all cases, and Variable 2 (V_2) is shown.
--M_1 and M_2 are mean (or average) values for V_1 and V_2, respectively.
--Statistical analysis was paired *t*-test with alpha of 0.05, two tailed, null hypothesis of zero mean difference.

At 56 days there were no statistically significant differences between PLC and OPC when all PLCs where considered. On average PLC performed from 3.4 MPa weaker to 0.3 MPa stronger than OPC. PLC outperformed OPC in 43% to 70% of cases, with C3 continuing to be the lowest performing PLC. It should be noted that the 28 and 56 day data represents the overall PLC to OPC trends, and does not indicate that PLC was outperformed in all cementitious combinations. For example at 50% replacement PLC performed better in all cases, but results at 70% replacement (in which PLC did not perform as well as OPC with GR aggregate) cause the average PLC to OPC trends to not be statistically significant.

7.2.3.2 Limestone Aggregates

Cement C3 and 60% replacement mixtures were not tested with LS aggregate. CP and concrete equality plots for LS mixtures were more agreeable than with GR mixtures. One exception to this is in the 0% replacement mixtures, in which C2 was shown to be slightly outperformed by C1 (slope of 0.97) while CP data showed a slope of 1.00. Also in these mixtures C5 concrete appeared to be equal to C1 (slope of 1.00) while CP mixtures showed a slope of 0.97. Considering that CP and concrete strengths agree so closely for LS mixtures but not for GR mixtures, it appears likely that GR mixtures are being affected by PAB or ITZ behaviors (especially at 70% replacement).

As observed in Figure 7.6, at 0% replacement C1, C2, and C5 showed similar performance, with mixtures slightly favoring OPC. In 50% replacement mixtures, C2 and C5 outperformed C1 by a noticeable margin. C1 exhibited higher strengths than C5, but strength increases with C2 compared to OPC in LS mixtures were not as impressive as in GR mixtures. At 70%, interestingly, the slope coefficients were approximately mirrored compared to 50% replacement. For example, at 70% replacement C5 and C2 exhibited slopes of 1.26 and 1.17, respectively, while at 50% replacement these slopes were 1.16 and 1.27, respectively. Excluding the 0% replacement mixtures, in which PLC to OPC trends were roughly equivalent, PLC outperformed OPC with LS aggregates at both 50% and 70% replacement rates. It should be noted, however, that only C2 and C5 PLCs were tested with LS aggregates, and based on GR aggregate results these were the top performing PLCs.

Paired t-tests were conducted on LS aggregate mixtures in the same manner as GR aggregate mixtures. Data was not separated by test day as there were considerably less data points than the GR data set. C2 and C5 were both found to be statistically significantly stronger than C1. Average strength increases were 5.9 MPa and 5.5 MPa with p-values of 0.005 and 0.002 for C2 and C5, respectively.

CHAPTER VIII

DAVIS WADE STADIUM EXPANSION AND RENOVATION PROJECT

8.1 Overview

This chapter includes results from field and concurrent laboratory testing associated with the Davis Wade Stadium (DWS) expansion and renovation project. Results have been published in Howard et al. (2015). The primary objective of this chapter is to document successful use of PLC with 50% replacement of cement using dual SCMs. Approximately 1900 m^3 of PLC concrete was used in the project

This section includes documentation of project site activities from November 2012 to May 2014 with most testing occurring between April 2013 and March 2014. The main expansion areas were a north end zone plaza with concessions, jumbotron and approximately 6000 additional seats (traditional, club, and box seats). Renovations also occurred to the west side concourse. Overall project costs were estimated at 75 million dollars.

8.2 Field Materials

SCMs incorporated in the mixtures were 30% Class C fly ash and 20% slag cement, from the same sources used in laboratory testing as described in Chapter III and of similar properties. Three cements were used in the project, ASTM C150 OPC and C1157 PLC supplied by Holcim (US) Inc. from Theodore, AL, and ASTM C150 OPC supplied by CEMEX from Demopolis, AL. A fourth cement, ASTM C1157 PLC from CEMEX was also supplied for laboratory testing for consistent OPC to PLC pairs. Holcim (US) Inc. cements comprised the majority of field samples and cement properties for those samples are shown in Table 8.1. The table represents averages of multiple daily samples between April 2013 and April 2014.

Aggregates used in concrete mixtures included coarse aggregate LS, intermediate aggregate PG, and fine aggregate CS. Admixtures A-1, A-3, and A-4 were used in all mixtures. Either admixture A-2 (retardant) or A-5 (accelerant) was used in each mixture depending on weather conditions. Aggregate properties and admixture dosage was consistent with Chapter III.

Table 8.1 Summary of Holcim (US) Inc. PLC Properties Supplied to DWS with Parallel OPC Properties for Comparison

Cement		Blaine	Limestone Content	Initial Vicat	Final Vicat	Mortar Cube Strengths (MPa)		
						1 day	3 day	28 day
C1157 (PLC)	Avg.	557 m^2/kg	9.9%	111 min	195 min	19.7	30.0	43.8
Type GU	COV	1.6%	0.1%	10.7%	10.3%	9.0 %	7.5 %	4.3 %
C150 (OPC)	Avg.	407 m^2/kg	3.8%	102	190 min	16.7	27.3	42.4
Type I/II	COV	1.4%	10.5%	12.0%	12.0%	8.8 %	6.4%	2.7%

--Avg. = average value.
--COV = coefficient of variation (standard deviation divided by mean).
--Limestone contents calculated from CO_2 contents of cement and limestone as in ASTM C150.
--Blaine fineness determined via ASTM C204.
--Initial and final Vicat determined via ASTM C191.
--Mortar cube strength determined via ASTM C109.

8.3 Field Sampling

Approximately 17000 m^3 of cast in place concrete was used during the project for various structural components. Table 8.2 illustrates concrete mixture designs from the project categorized by typical use, design strength, cement type, replacement rate, and cementitious content. For the purpose of this research mixtures F and G were sampled to evaluate any differences between the two cement types.

Table 8.2 DWS Cast in Place Concrete Design Properties and Quantities

Mix	Typical Use	f_c' (MPa)	Cement Type	Cement/Slag/C Ash (%)	Design Total Cementitious Content (kg/m^3)	Total Quantity (m^3)
A	Beams, Footings	25.6	C150 Type I	80/0/20	363	765
B	Drilled Piers	25.6	C150 Type I	30/50/20	321	956
C	Walls	25.6	C150 Type I	50/25/25	335	2485
D	Flatwork	31.0	C150 Type I	50/30/20	390	1911
E	Flatwork	31.0	C150 Type I	50/25/25	349	5925
F	Flatwork	31.0	C150 Type I	50/30/20	349	573
G	Flatwork	31.0	C1157 Type GU	50/30/20	349	1911
H	Columns	34.5	C150 Type I	50/25/25	349	765
I	Columns	34.5	C150 Type I	70/15/15	390	573
J	Columns	34.5	C150 Type I	50/30/20	390	191
K	Raker Beams	41.4	C150 Type I	100/0/0	363	956

-- Beams (A) were grade beams. Walls (C) included foundation, retaining, and basement. Flatwork (D through G) included slabs on grade, elevated slabs, housekeeping pads, aisle steps, risers, topping slabs, and elevator walls.

-- f_c'= specified design compressive strength, values were at 28 days, except for Mix A (56 Days).

-- Mixes F and G are of primary interest to this paper and had design *w/cm* ratios of 0.43 and were air entrained (4.5%).

-- There were 17,011 m^3 (22,250 yd^3) of documented concrete when individual mixes were rounded to the nearest 250 yd^3.

--There was an additional 765 m^3 (1,000 yd^3) besides mixes A to K where less than 250 yd^3 was used per mix type.

Field specimens were made with concrete sampled directly from a concrete mixing truck on 7 days. Truck mixed (TM) samples were given the designation TM1-TM21. On each day the same concrete mixture was sampled from each truck, with the exception of day 7 on which two different mixtures were sampled. Mixture F (OPC) was sampled on day 2 with Holcim (US) Inc. OPC, and on day 7a with CEMEX OPC. Mixture G (PLC) was sampled on days 1, 3, 4, 5, 6, and 7b. Details of sampling are shown in Table 5.3. Laboratory mixtures (LM) were created to match and compliment field data. Detailed proportions of all TM and LM specimens are given in tables 8.4 and 8.5.

Table 8.3 Summary of Concrete Sampling During Davis Wade Stadium Construction

Day ID	Date and Time Began	Truck ID’s	Mix ID	Cement	Quantity (m^3)	Application and Placement Location
1	04/17/2013 2:30 AM	TM 1 to TM 4	G	Holcim PLC	212.5	Renovation: Exterior Slab on Grade, lower west concourse - sections 03 and 04
2	05/09/2013 11:15 AM	TM 5 to TM 7	F	Holcim OPC	24.5	Renovation: Exterior Slab on Grade
3	08/30/2013 10:30 AM	TM8 to TM 10	G	Holcim PLC	30.5	Expansion: Exterior Slab on Grade, west side of stadium
4	09/05/2013 9:20 AM	TM11 to TM13	G	Holcim PLC	32.5	Expansion: Exterior Slab on Grade, service corridor and main field level telecom room
5	09/26/2013 4:00 AM	TM14 to TM16	G	Holcim PLC	172.0	Expansion: Elevated Slab, third story in northeast corner
6	11/21/2013 4:00 PM	TM17 to TM 19	G	Holcim PLC	137.5	Expansion: Slab on Grade
7a	03/12/2014 10:15 AM	TM 20	F	CEMEX OPC	6.0	Expansion: Exterior Slab on Grade, field level loading dock
7b	03/12/2014 9:25 AM	TM 21	G	Holcim PLC	12.0	Expansion: Exterior Slab on Grade, field level loading dock

--All sampled mixes contained 50% cement (OPC or PLC), 30% slag cement, and 20% C ash.

--Truck IDs correspond to Table 8.4 Mix IDs.

Table 8.4 Properties of Truck Mixed Concrete Tested

Mix	SSD Aggregates (kg/m³)			Cementitious Materials (kg/m³)				*w/cm*	Admixtures (ml/m³ Concrete)				
ID	LS	PG	CS	Cement	Slag	C Ash	Total		A-1	A-2	A-3	A-4	A-5
TM 1	919	181	708	173 (50% Holcim PLC)	104 (30%)	70 (20%)	347	0.447	507	1160	765	58	0
TM 2	921	183	708	174 (50% Holcim PLC)	104 (30%)	70 (20%)	348	0.447	507	1156	769	58	0
TM 3	920	181	708	174 (50% Holcim PLC)	104 (30%)	70 (20%)	348	0.447	503	1160	769	58	0
TM 4	919	181	708	173 (50% Holcim PLC)	104 (30%)	70 (20%)	347	0.450	503	1165	774	76	0
TM 5	920	183	693	181 (50% Holcim OPC)	108 (30%)	73 (20%)	362	0.413	438	1032	688	60	0
TM 6	920	181	692	180 (50% Holcim OPC)	108 (30%)	73 (20%)	361	0.417	447	1032	683	60	0
TM 7	920	181	693	181 (50% Holcim OPC)	108 (30%)	72 (20%)	361	0.417	447	1032	683	69	0
TM 8	918	181	708	173 (50% Holcim PLC)	105 (30%)	62 (20%)	340	0.447	447	1027	683	60	0
TM 9	918	181	708	173 (50% Holcim PLC)	104 (30%)	62 (20%)	339	0.438	451	1027	683	34	0
TM 10	918	181	709	173 (50% Holcim PLC)	104 (30%)	63 (20%)	340	0.438	443	1032	683	34	0
TM 11	918	181	709	173 (50% Holcim PLC)	104 (30%)	62 (20%)	339	0.431	456	1027	688	43	0
TM 12	920	181	709	174 (50% Holcim PLC)	104 (30%)	62 (20%)	340	0.431	443	1032	688	43	0
TM 13	924	181	708	174 (50% Holcim PLC)	103 (30%)	62 (20%)	339	0.430	451	1032	692	43	0
TM 14	931	181	708	173 (50% Holcim PLC)	104 (30%)	70 (20%)	347	0.431	499	1160	572	57	0
TM 15	920	181	708	174 (50% Holcim PLC)	105 (30%)	70 (20%)	349	0.432	494	1165	787	57	0
TM 16	923	181	708	175 (50% Holcim PLC)	105 (30%)	70 (20%)	350	0.430	503	1160	769	48	0
TM 17	921	181	709	175 (50% Holcim PLC)	104 (30%)	70 (20%)	349	0.411	507	1160	572	49	0
TM 18	919	184	708	173 (50% Holcim PLC)	104 (30%)	70 (20%)	347	0.437	507	1160	576	48	0
TM 19	921	181	710	174 (50% Holcim PLC)	104 (30%)	70 (20%)	348	0.433	503	1156	576	48	0
TM 20	923	183	711	174 (50% CEMEX OPC)	104 (30%)	70 (20%)	348	0.389	275	0	516	70	3095
TM 21	923	183	709	173 (50% Holcim PLC)	104 (30%)	62 (20%)	339	0.422	275	0	688	51	3095

Indicated proportions shown for each mixture are based on 1 m^3 volume, regardless of batch size

Table 8.5 Properties of Laboratory Mixed Concrete Tested

Mix ID	SSD Aggregates (kg/m³)			Cementitious Materials (kg/m³)				w/cm	Admixtures (ml/m³ Concrete)				
	LS	PG	CS	Cement	Slag	C Ash	Total		A-1	A-2	A-3	A-4	A-5
LM 1	920	178	710	174 (50% Holcim OPC)	104 (30%)	70 (20%)	348	0.446	454	1137	1366	35	0
LM 2	920	178	708	174 (50% Holcim PLC)	104 (30%)	70 (20%)	348	0.446	454	1137	1366	35	0
LM 3	920	178	698	182 (50% Holcim OPC)	109 (30%)	72 (20%)	363	0.429	473	1181	1417	35	0
LM 4	920	178	695	182 (50% Holcim PLC)	109 (30%)	72 (20%)	363	0.429	473	1182	1417	35	0
LM 5	920	178	742	174 (50% Holcim OPC)	104 (30%)	70 (20%)	348	0.410	454	1137	1366	35	0
LM 6	920	178	740	174 (50% Holcim PLC)	104 (30%)	70 (20%)	348	0.410	454	1137	1366	35	0
LM 7	920	178	759	174 (50% CEMEX OPC)	104 (30%)	70 (20%)	348	0.391	454	0	1366	35	3481
LM 8	920	178	756	174 (50% CEMEX PLC)	104 (30%)	70 (20%)	348	0.391	454	0	1366	35	3481
LM 9	890	208	860	321 (100% Holcim OPC)	0 (0%)	0 (0%)	321	0.429	454	1137	1366	35	0
LM 10	890	208	856	321 (100% Holcim PLC)	0 (0%)	0 (0%)	321	0.429	454	1137	1366	35	0
LM 11	890	208	844	160 (50% Holcim OPC)	96 (30%)	64 (20%)	320	0.430	454	1137	1366	35	0
LM 12	890	208	841	160 (50% Holcim PLC)	96 (30%)	64 (20%)	320	0.430	454	1137	1366	35	0
LM 13	920	178	721	174 (50% Holcim OPC)	104 (30%)	70 (20%)	348	0.437	454	1137	1366	35	0
LM 14	920	178	721	174 (50% Holcim PLC)	104 (30%)	70 (20%)	348	0.437	454	1137	1366	35	0

--Indicated proportions shown for each mixture are based on 1 m^3 volume, regardless of batch size.

--LM 1 to 8 were produced to reasonably match sample days 1, 2, 6, and 7a.

--LM 9 to 12 were produced to evaluate chloride ion resistance.

--LM 13 and 14 were produced to evaluate maturity.

8.4 DWS Results

A member of the research team spoke to the concrete finishing group informally to determine their thoughts on the PLC concrete. Perception was that the PLC mixture with 50% replacement was similar to a mixture of essentially the same proportions with OPC and that there were no concrete related finishing problems. Informal discussion with representatives of the prime contractor also indicated no negative observed finishing distinctions between the PLC and OPC products.

8.4.1 Fresh Mixed Properties and Time of Set

Slump was the primary fresh mixed property evaluated as concrete was required to be pumped multiple stories high for some of the slabs. Air content and unit weight were recorded and found to be on average 4.3% and 2340 kg/m^3, respectively, for the field sampled mixtures. Initial temperatures ranged from 19 to 32 ºC. Concrete samples from days 1 and 3 to 6 were relatively similar. These mixtures (Mix G, PLC) exhibited an average slump of 19.6 cm, with a range of 14.0 to 22.9 cm. Samples from the OPC Mix F on day 2 exhibited an average slump of 21.6 cm, with a range of 20.3 to 22.9 cm. Samples from day 7 mixtures differed with a slump of 5.1 cm for Mix F OPC (TM 20) and 11.4 cm for Mix G PLC (TM 21).

Laboratory mixtures were proportioned to create seven matched pairs to be evaluated statistically. At a five percent level of significance, OPC and PLC slumps were not statistically different (p-value of 0.121). Taking into account laboratory and field mixtures, PLC appeared to reduce slump, on average, by approximately 2 cm or around 10% of the total slump.

Time of set results for laboratory concrete mixtures are shown in Figure 8.1. PLC mixtures exhibited lower times in each mixture pairing. Note that pairing LM 7 and 8 used a different admixture than LM 1 to 6 and results were less intuitive than what was expected. On average PLC concrete mixtures recorded lower time of set by 1.3 hr with all data considered or 0.9 hr in mixtures LM 1 to 6

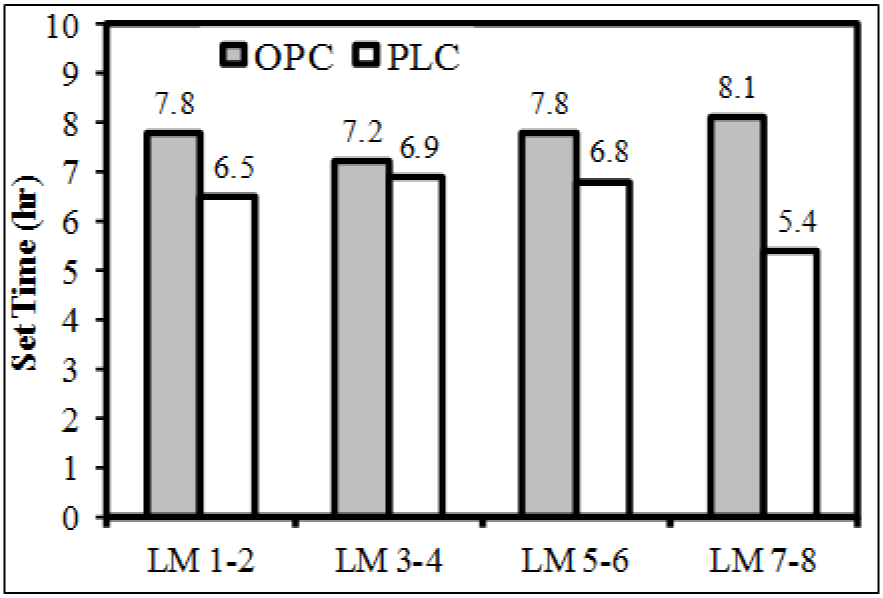


Figure 8.1 Laboratory Mixtures Time of Set

8.4.2 Compressive Strength

Due to cylinders being left on site for the first 24 ± 8 hr and differences in temperature on sample days, compressive strength results at 1, 3, and 7 days were adjusted using maturity data. Concrete maturity specimens of similar proportions to that sampled from the field were tested for compressive strength and plotted as a function of a time temperature factor (TTF) in units of ˚C-hr. Maturity results are shown in Figure 8.2.

An exponential line of best fit was applied to the figure and its equation used to adjust data points. (e.g. if a PLC specimen was tested at a 1 day TTF of 700 and found to have a compressive strength of 12 MPa, that strength would be adjusted using the equation on part (b) of Figure 8.2 to 9.23 MPa). This provides the predicted compressive strength that the specimen would achieve at a true 1 day test (approximately 550 TTF).

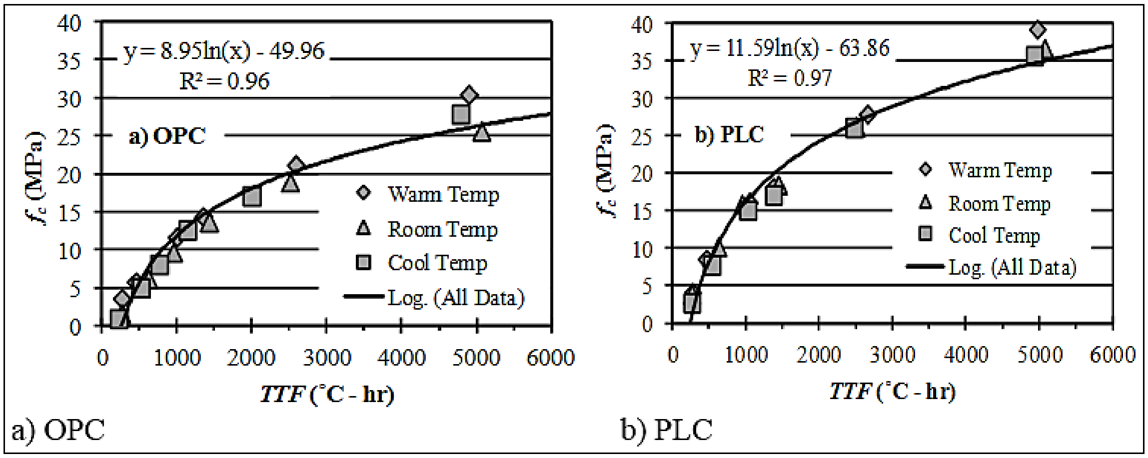


Figure 8.2 Maturity Adjustment Data

In order to compare OPC to PLC results in a meaningful way, truck samples were divided into six groups of similar properties. Note that TM 5 to 7 contained OPC from the same source as the PLC in TM 1 to 4, 8 to 19, and 21. TM 20 was the single sample obtained with CEMEX OPC. Compressive strengths are presented in Table 8.6 as an average of the specimens included in each group on each test day. The number of specimens included in each averaged compressive strength value is provided.

Groups 2, 5, and 6 were single truck samples not similar to other mixtures tested. Compressive strengths for these groups are provided in the table but are not the focus of the analysis. In general, group 1 mixtures (OPC control) were compared to groups 3 and

4 mixtures (PLC mixtures with different w/cm). Maturity adjusted strengths were 26 to 71% (1 day), 7 to 21% (3 day), and 4 to 25% (7 day) higher for PLC compared to OPC. Beginning at 14 days and continuing to 180 days, strengths did not portray as substantial differences between OPC and PLC. During that time period, PLC ranged from 11% higher to 7% lower in compressive strength. At 14 days all three groups had already surpassed the required mix design compressive strength, and by 28 days were 38 to 53% higher than the required value.

Table 8.6 Truck Mixed Concrete Strengths

Group	1	2	3	4	5	6
n_{trucks}	3	1	10	5	1	1
Trucks Included	TM 5-7	TM 17	TM 9-16, 18, 19	TM 1-4, 8	TM 20	TM 21
Mix and Cement	F Holcim OPC	G Holcim PLC	G Holcim PLC	G Holcim PLC	F CEMEX OPC	G Holcim PLC
w/cm	0.41-0.42	0.41	0.43-0.44	0.44-0.45	0.39	0.42
Cementitious content (kg/m^3)	361-362	349	339-350	340-348	348	339
Age	*Shown: Average Compressive Strength in MPa [n]*					
1 day	6.1 [9]	10.0 [3]	7.7 [30]	10.4 [12]	---	---
3 day	18.0 [9]	19.6 [3]	19.3 [30]	21.7 [15]	25.8 [5]	22.6 [5]
7 day	28.0 [9]	32.7 [3]	29.0 [30]	35.5 [15]	38.5 [5]	33.9 [5]
14 day	42.0 [9]	---	41.5 [24]	46.6 [15]	---	---
28 day	55.8 [9]	60.7 [3]	54.3 [30]	60.0 [15]	66.7 [6]	63.6 [6]
56 day	66.9 [9]	68.0 [3]	62.5 [30]	66.6 [15]	77.6 [5]	73.5 [5]
90 day	70.4 [3]	71.3 [3]	70.2 [21]	69.6 [7]	---	---
180 day	74.0 [8]	74.0 [3]	70.2 [31]	73.4 [14]	---	---

-- 1 to 7 day data shown are the equivalent test day strengths for specimens cured at 23 °C, where measured values were adjusted using maturity relationships. Actual equivalent 23 °C ages prior to adjustment were 0.8 to 1.6, 2.6 to 3.5, and 6.4 to 7.8 days.
-- 14 to 180 day strength data are measured values according to C39, without adjustment.
-- n_{trucks} = number of trucks sampled, n = number of cylinders tested

Taking into account the lower *w/cm* and higher cement content of OPC mixtures, it should not be interpreted that PLC did not perform as well as OPC after 14 days. LM mixtures based on TM mixtures are shown in Figure 8.3 to provide a more controlled analysis of compressive strength trends. In all pairs, PLC exhibited higher compressive strengths than OPC at 7 and 14 days, and in three of the four pairs at 28 and 56 days. In pair LM 3-4 PLC and OPC were approximately equal at 28 days, and OPC showed higher compressive strengths at 56 days.

When each pair was averaged together, PLC compressive strengths exceeded OPC strengths by 25% (7 day), 19% (14 day), 10% (28 day) and 5% (56 day). Data suggests that PLC gains early strength at a faster rate than OPC, but may not differ substantially in ultimate strength. However, early age strength gain is more meaningful in many construction practices.

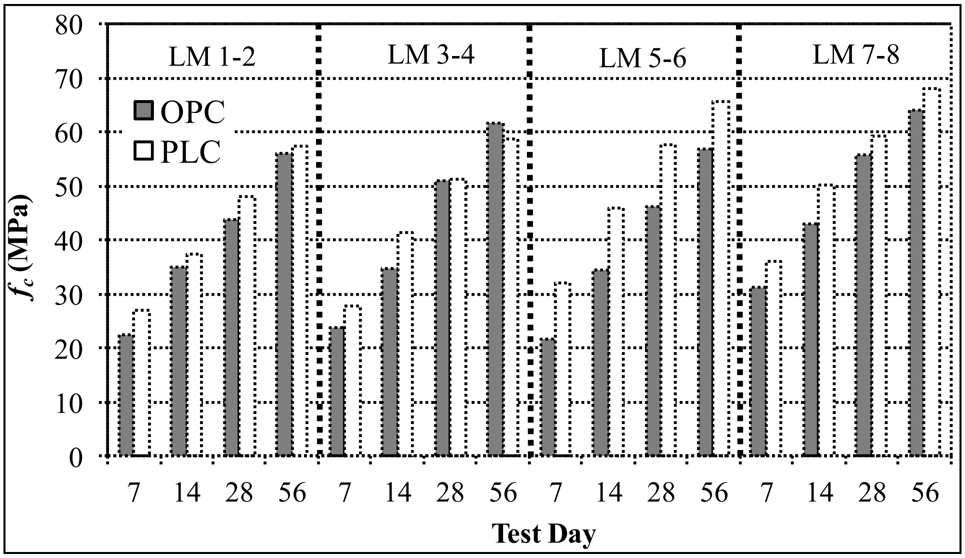


Figure 8.3 Laboratory Mixtures Compressive Strength

8.4.3 Elastic Modulus

Elastic modulus results are shown in Figure 8.4 with each data point based on an average of either three or four specimens. Test days varied between 3 and 180 days. No noticeable differences were observed in compressive strength to elastic modulus relationships between OPC and PLC. The elastic modulus to compressive strength design relationship as described in ACI-318 (4700 multiplied by the square root of the compressive strength) is shown on the figure. Also indicated in the figure are versions of the equation with constants of 5700 and 6700, which fit more closely with the specimens tested. In general it appears that the ACI-318 equation provides a conservative estimate of elastic modulus.

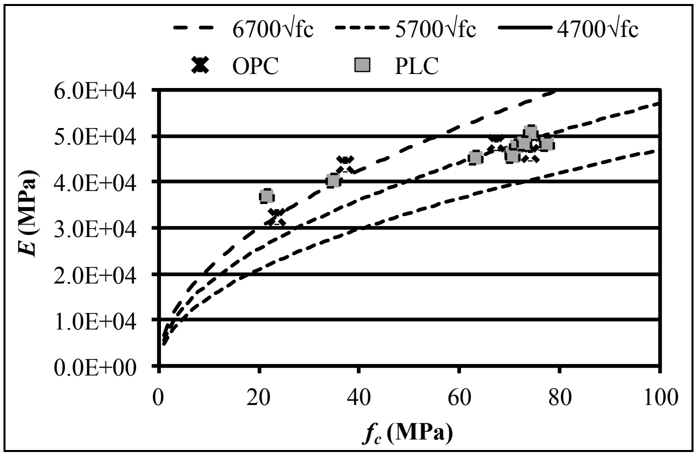


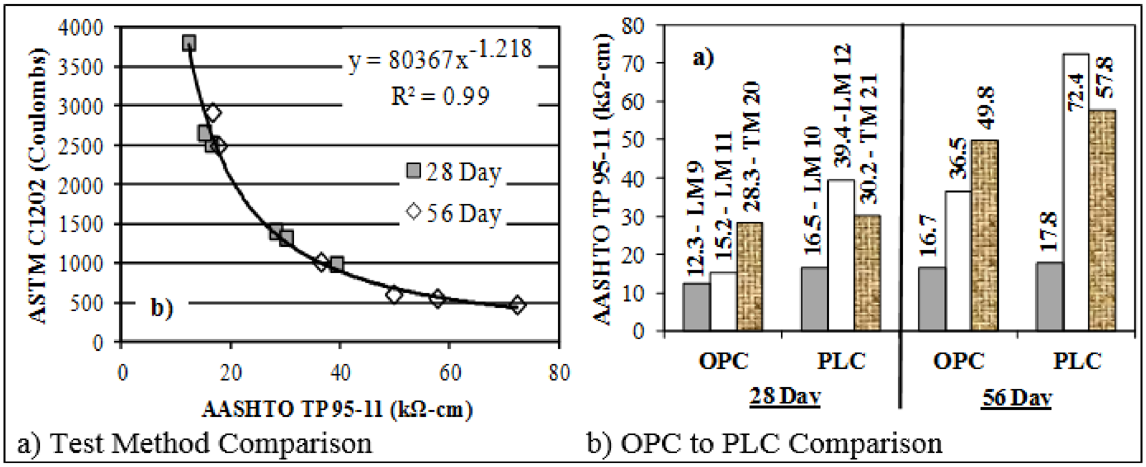
Figure 8.4 Elastic Modulus Test Results

8.4.4 Resistivity and Chloride Ion Permeability

Resistivity and chloride ion permeability results are shown in Figure 8.5. Specimens tested included LM 9 to 12 and TM 20 and 21. Part (a) of the figure illustrates that the results for ASTM C1202 and AASHTO TP 95-11 are essentially equivalent. Part (b) shows an OPC to PLC comparison of the same data with only AASHTO TP 95-11 results. According to TP 95-11 categories LM 9 (OPC) and LM 10 (PLC) both exhibited moderate chloride ion penetration at 28 and 56 days, with slight advantages in the PLC mixture. LM 11 (OPC) also showed moderate penetration, but

LM 12 (PLC) achieved the very low penetration category and was greater than twice as resistant as LM 11. TM 20 (OPC) had the lowest *w/cm* (0.389) of all TM samples, which would increase resistivity. However, TM 21 (PLC, *w/cm* 0.422) still produced higher resistivity values at both test days.

TM samples 1 to 19 were also tested for resistivity at 180 days. OPC samples averaged 117 kΩ-cm with a range of 115 to 119 kΩ-cm, and PLC samples averaged 142 kΩ-cm with a range of 117 to 171 kΩ-cm. Two of the sixteen PLC TM samples fell into the OPC range, with the remaining fourteen having higher resistivities. It should be noted that the OPC mixtures had higher cementitious contents than comparative PLC mixtures.



a) Test Method Comparison b) OPC to PLC Comparison

Figure 8.5 Resistivity and Chloride Ion Permeability Test Results

CHAPTER IX

CONCLUSIONS AND RECOMMENDATIONS

9.1 Overview

The main objectives of this dissertation as outlined in the introduction were to evaluate PLC focusing on implementation, synergistic SCM interactions, and optimizing PLC properties and to document successful use of PLC in a large construction project. Details of each investigation were provided in Chapters V to VIII. Conclusions based on the data in those chapters are given in the following subsections as well as recommendations for future research.

9.2 Highly Implementable Single SCM Concrete with PLC

PLC with up to 15% limestone has been shown to potentially significantly improve concrete sustainability and performance compared to OPC. PLC performance is likely dependant on particle size distribution, and synergistic effects of the PLC appear to be enhanced in the presence of certain SCMs. Higher than traditionally seen replacement rates with some SCMs may be possible.

In concrete mixtures with materials and proportions common to Mississippi and other areas, PLC has been shown to produce higher compressive strengths and lowertime of set with Class C fly ash at up to 40% replacement. Mixtures with slag cement exhibited higher strengths overall than with fly ash, but distinctions between PLC and

OPC mixtures were less apparent. Concrete and CP specimens sometimes showed different trends in PLC to OPC performance.

Comparing cements from four sources, CP results for 0% replacement mixtures varied by source on whether OPC or PLC had better performance. Concrete results from these mixtures agreed with CP data with 2 sources favoring OPC and two favoring PLC. In mixtures with 40% Class C fly ash, PLC produced noticeably higher mixtures in both CP and concrete specimens.

Slump and air content were found to not be statistically different in PLC and OPC mixtures. However, time of set measurements were found to be statistically different with PLC producing faster times by 0.7 hr in concrete and 2.7 hr in CP. Petrography results indicated that there may be a greater percentage of cement hydration in PLC mixtures. OPC mixtures also showed signs of higher w/cm at the paste-aggregate ITZ. Differences in PLC to OPC paste portions appeared to decrease in 40% fly ash mixtures. Petrography suggests that PAB may be of high influence in strength differences between OPC and PLC, which in turn may be a factor of particle size distribution effects.

In September of 2014 the Mississippi DOT issued a special provision allowing the use of Type IL PLC in concrete mixtures. The provision also increases the maximum allowed amount of fly ash replacement from 25% to 35% when PLC is used. A large portion of the basis of this provision was based on data featured in this dissertation. As of 2015 PLC is being used in mix designs submitted to the DOT and a sizable portion of the private concrete market in the Jackson, Mississippi metropolitan area.

9.3 Synergistic Evaluation of Fly Ash Types with PLC

Class C and Class F fly ash were found to be beneficial in concrete with both single and dual SCM mixtures, and both LS and GR aggregates. PLC was able to increase compressive strength and decrease time of set in certain cases. In 50% replacement mixtures with 30% slag cement, 20% fly ash, and LS aggregates, PLC generally outperformed OPC in the majority of sources and test ages. Greater strength differences between PLC and OPC were observed in C ash mixtures compared to F ash mixtures. At 40% replacement, C ash mixtures performed slightly better with PLC than OPC, while F ash mixtures were noticeably better with OPC. In 70% replacement mixtures OPC held a slight advantage over PLC with both fly ash types. The 50% replacement mixtures were reproduced with GR aggregates and similar trends were observed compared to 50% replacement with LS aggregates.

Considering all sources and mixtures, PLC was more beneficial to compressive strength at early test days. Time of set was decreased in most cases by PLC use compared to OPC, and by F ash use as compared to C ash. Advantages in time of set were more apparent in C ash mixtures than in F ash mixtures.

Many differences were observed in how cements from each source reacted to each SCM replacement rate. In some cases certain cements exhibited greatly beneficial or reduced properties in a specific replacement rate (i.e. 40% replacement) or in specific mixture (i.e. 40% replacement with C Ash). No source of cement was the best or worst in all cases evaluated, but some cements were more beneficial than others (i.e. PLC provided benefits in 80% of mixtures for one source and in 30% of mixtures for another). This may indicate that specific Blaine fineness', limestone contents, or even clinker compositions are affecting which SCM replacement rates are the most beneficial. In general, PLC was more advantageous in C ash mixtures compared to F ash, although there were some cases with increased strengths in F ash mixtures.

Compressive strength variability in mixtures with C ash was higher than in mixtures with F ash. Interestingly OPC mixtures contributed to the highest variations in C ash, while PLC mixtures were the most variable in F ash. Mixtures tested with 40% replacement with a single SCM exhibited by far the highest variation between cement sources. Based on the variability of the high replacement rate mixtures tested and current literature, it appears that PLC is not more variable than OPC.

9.4 PLC with High SCM Replacement Rates

Concrete mixtures with PLC and higher SCM replacement rates would be able to further increase concrete sustainability, and because of synergistic effects of PLC with SCMs, these higher replacement rates appear to be more achievable. The sustainability benefits are additionally increased by using local aggregates. This data set shows clearly that PLC can improve performance of concrete with gravel aggregates at replacement rates up to 50% with dual SCMs. In a large number of cases, PLC mitigated the delayed setting associated with high SCM use, and increased early strength gains.

Expectations of PLC performance based on limestone content and Blaine fineness generally agreed with test results. In fresh mixed properties, slumps were within 1 cm and air contents were not statistically significant. Both PLCs evaluated with favorable limestone content to Blaine fineness relationships exhibited lower times of set than OPC. Overall times were faster by 0.6 hr to 0.7 hr, and this difference was seen as practically relevant to construction. The PLC evaluated with a less favorable limestone content to

Blaine fineness relationship had, on average, a higher time of set than the OPC or other PLC mixtures.

In mixtures with PLC, 50% SCM replacement, and gravel aggregates, performance was exceptional compared to equivalent OPC mixtures. Compressive strengths were noticeably higher at all test days evaluated. Trendlines showed PLC outperforming OPC by 33%, and measured strength differences of 10 MPa or higher were common. CP specimens were able to correctly predict concrete results in some cases, but were not representative at 70% replacement. This likely indicates issues with the PAB or ITZ. Increasing the replacement rate from 60% to 70% caused sharp decreases in performance trends in gravel aggregates. OPC often outperformed PLC by 10 MPa or more at later test days in these cases. Based on these findings it is not advised to use PLC in mixtures with cement contents below 40% to 50% without further investigation.

In limestone aggregate mixtures, CP adequately predicted concrete performance trends. Mixtures with 0% replacement did not show any substantial differences between OPC and PLC. However, in mixtures with SCMs, both PLCs with favorable limestone content to Blaine fineness relationships outperformed OPCs in all replacement rates tested. Strength increases on average were 5.5 MPa to 5.9 MPa for PLC relative to OPC.

9.5 Davis Wade Stadium Construction and Renovation Project

During the DWS expansion and renovation project PLC was used in concrete mixtures with 50% SCM replacement. No problems were reported for finishing of PLC concrete slabs, either on grade or elevated. PLC reduced slump by approximately 2 cm on average when compared to similar OPC mixtures used at the project. Time of set with

PLC was reduced by approximately 1 hr, compared to the same OPC samples. Based on field samples, PLC mixtures' compressive strengths were higher than OPC mixtures' at test times up to 9 equivalent days at 23 ˚C. This successful use of PLC should increase the confidence of the US marketplace to use PLC in future applications.

Additional evaluations concluded that there was no difference in elastic modulus between OPC and PLC, and that ACI-318's elastic modulus to compressive strength relationship could be used in both cases. PLC improved chloride ion resistance, based on ASTM C1202 and the relatively new AASHTO TP95-11. There was also found to be no difference in results between the more time consuming C1202 and the newer TP95-11.

9.6 Recommendations for Future Research

In general, there should be no concern in using PLC with replacement rates up to 50%, but there are some areas that do merit additional investigation. Mixtures featuring higher SCM rates may be beneficial, but further research is needed to expand on observed decreases in PLC performance relative to OPC in 60% to 70% replacement mixtures, in particular with gravel aggregates. This likely is caused by PAB or ITZ behaviors and as such it is recommended that these be evaluated in depth. Overall, PLC performance benefits seem to rely, at least in part, on PAB and it is recommended that further research be conducted on how PAB affects concrete performance. Also recommended is a more rigorous statistical evaluation of the entire data set collected in this study.

In the fly ash variability data it was shown that each PLC performed differently compared to the other PLCs dependant on SCM replacement rates. This may indicate that there are factors influencing PLC performance that are not fully understood, and could be used to potentially further increase benefits. Research that includes additional constants may be able to isolate these values. For example, testing multiple PLCs of different Blaine fineness' from the same source, same clinker grind, and same limestone content could prove advantageous.

In general, there are several areas of PLC implementation, not associated with performance that could be evaluated. Implementation of PLC may be hindered by limitations on production or facilities. Production of an additional cement type may cause storage issues due to insufficient silo space. Facilities that are grinding mill limited would also face limitations on PLC production as it requires more grinding time compared to OPC. Niche markets such as those catering to high amounts of 100% cement concrete may not prefer PLC, as the majority of PLC benefits are observed in the presence of SCMs.

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