TRC0405

Ground Granulated Blast Furnace Slag and Fly Ash in Concrete Mixtures

Natalie Peterson Becknell, Micah Hale

Final Report

2006

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Ground Granulated Blast Furnace Slag and Fly Ash in Concrete Mixtures		5. Report Date March 2006 6. Performing Organization Code
7. Authors Natalie Peterson Becknell and Micah Hale		8. Performing Organization Report No. AHTD TRC 0405
9. Performing Organization Name and Address University of Arkansas 4190 Bell Engineering Center Fayetteville, AR 72701		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address Arkansas Highway and Transportation Department P. O. Box 2261 Little Rock, AR 72203		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code

15. Supplementary Notes
Supported by a grant from the Arkansas Highway and Transportation Department

16. Abstract

Currently, the Arkansas State Highway and Transportation Department limits cementitious materials in concrete mixtures to portland cement, ground granulated blast-furnace slag (GGBFS), and fly ash. GGBFS is limited to cement replacement rate of 25% by weight and fly ash is limited to a cement replacement rate of 20% by weight. A body of knowledge on concrete mixtures containing both GGBFS and fly ash needs to be developed before the use of both materials is allowed in state projects. The experimental program focuses on the fresh and hardened concrete properties of a range of replacement rates for GGBFS, fly ash, and ternary mixtures without chemical admixtures. The research shows that: different cement sources, up to 40% GGBFS, up to 40% fly ash, up to 20% of each for ternary mixtures, and both grade 100 and grade 120 GGBFS can be used in concrete mixtures in Arkansas.

17. Key Words Slag cement, fly ash, ternary concrete mixtures	18. Distribution Statement NO RESTRICTIONS. THIS DOCUMENT IS AVAILABLE FROM THE NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD, VA. 22161		
19. Security Classif. (of this report) UNCLASSIFIED	20. Security Class. (of this page) UNCLASSIFIED	21. No. of Pages	22. Price N/A

Abstract

Currently, the Arkansas State Highway and Transportation Department limits cementitious materials in concrete mixtures to portland cement, ground granulated blast-furnace slag (GGBFS), and fly ash. GGBFS is limited to cement replacement rate of 25% by weight and fly ash is limited to a cement replacement rate of 20% by weight. A body of knowledge on concrete mixtures containing both GGBFS and fly ash needs to be developed before the use of both materials is allowed in state projects. The experimental program focuses on the fresh and hardened concrete properties of a range of replacement rates for GGBFS, fly ash, and ternary mixtures without chemical admixtures. The research shows that: different cement sources, up to 40% GGBFS, up to 40% fly ash, up to 20% of each for ternary mixtures, and both grade 100 and grade 120 GGBFS can be used in concrete mixtures in Arkansas.

Table of Contents

List of Tables

List of Figures

List of Charts

Chapter 1 INTRODUCTION

1.1 General

Currently, the Arkansas State Highway and Transportation Department (AHTD, 2003) limits cementitious materials in concrete mixtures to portland cement, ground granulated blast furnace slag (GGBFS), and fly ash (FA). In the AHTD's Standard Specifications for Highway Construction 2003 (Specifications) (AHTD, 2003) GGBFS is limited to a cement replacement rate of 25% by weight and FA is limited to a cement replacement rate of 20% by weight, as described in Section 3.2 and Section 3.3. The Specifications also do not allow the use of ternary mixture designs (mixture designs where more than one supplementary cementitious material is combined with cement). Previous research has shown that GGBFS and FA can have beneficial effects on the fresh and hardened concrete properties at replacements of 40% and beyond and the benefits are also present in ternary mixtures (ACI Committee 233). Before changes can be made to AHTD's Specifications, the effects of GGBFS, FA, or both materials on concrete mixtures incorporating native Arkansas materials should be examined.

1.2 Objectives

The purpose of this research was to examine the fresh and hardened properties of concrete mixtures containing GGBFS, FA, and a combination of both materials. Due to different grades of GGBFS and sources of Type I cement available in the state of Arkansas, the following variables were investigated:

1. Source of Type I cement,
2. GGBFS and FA replacements of cement by weight, and

3. Grade of GGBFS.

The information collected through the study allowed the investigators to draw conclusions on the allowances of GGBFS and FA in concrete mixtures in the state of Arkansas. These conclusions were used to form recommendations to AHTD in the matter of updating the Specifications to include the new findings from this study. The change in specifications could benefit the construction industry and AHTD. The construction industry would benefit by having more options in mixture design. AHTD would benefit by promoting better economy and materials for construction projects; and the public would benefit from longer lasting concrete structures which would reduce the amount of tax dollars needed for repair.

1.3 Scope

Mixture designs with varying quantities of GGBFS, FA, and ternary mixtures were examined in the research programs. The mixture designs were created to range from the current replacement rates allowed to replacement rates greater than recommended in the literature from previous research. Type I cement from two different sources, two grades of GGBFS, and Class C FA were used in the study. The materials are common in Arkansas, and they were chosen to accurately represent typical mixture designs. The same coarse and fine aggregates were used throughout the project and were also chosen to represent typical concrete in Arkansas. The water-to-cementitious materials ratio (w/cm) was held constant for all mixtures tested. No admixtures such as air entraining and water reducing admixtures were employed in the mixtures so that changes in the concrete properties would be properly attributed to the experimental variables. The project was limited to the effects of varying replacements of GGBFS, FA, or both on the fresh and hardened properties of concrete.

Chapter 2 LITERATURE REVIEW

2.1 General

Environmental concerns and the current stress on the cement producing industry have fueled the interest in alternative mixture design strategies. One strategy that fulfills both environmental concerns and cement shortage is the replacement of part of the cement with waste materials. Ground granulated blast-furnace slag and fly ash are the two materials allowed in the state of Arkansas. These materials are industrial by-products and, when not used as a construction material, are discarded as waste in large amounts. Other studies have shown the benefits and drawbacks of using either material or both together in portland cement concrete mixtures. The following sections describe those studies, their results, and the impact of the research.

2.2 Ground-Granulated Blast-Furnace Slag

GGBFS used in concrete is created from pulverizing waste products created during the refining of iron ore. The by-products from other metallurgical processes, such as refining iron to steel or producing nickel, are iron-rich and not suitable for concrete (Mindess et. al. 2003). Lime-based inorganic fluxes are used in iron ore refining to remove the impurities to create useable iron (Mindess et. al. 2003). The ore, fluxes, and energy source-coke are heated in a blast furnace until the molten iron is extruded. The waste product, blast furnace slag, is screened from the iron. Typically blast furnace slag consists of about 20 percent by mass of iron production (Blast Furnace Slag-Material Description).

Several different structures of blast furnace slag (BFS) can be formed depending on the cooling process used between the removal of the slag from the furnace and storage. Most of the BFS produced in the United States is in the form of air-cooled blast furnace slag (Blast Furnace Slag-Material Description). The air-cooling process is less expensive because it does not use water to cool and heat to dry the pellets created by the water. The air-cooled products are usually crystalline without cementitious properties when ground and the larger sizes require a more arduous grinding process (ACI Committee 233). The air-cooled pellets are used as aggregates because of their hardness (Blast Furnace Slag-Material Description). However, the amount of BFS being used in a cementitious form is growing because of the advances in pelletizing which reduce costs from quenching processes.

The preferred cooling process which produces the highest quality cementitious material is pelletizing (Blast Furnace Slag-Material Description). During the pelletizing process, the molten slag is quickly cooled by water and a glassy granule of calcium aluminosilicate is formed without crystallization. Water is administered to the hot blast furnace slag with spray jets while the slag is dropped into a collecting bin. Before pelletizing, quenching was the preferred water method. Quenching involves immersing the hot blast furnace slag into a bath of water. Quenching requires a large amount of water for the bath and also requires more energy for a more strenuous drying process (ACI Committee 233). After cooling, the BFS is ground to less than 4mm and then is further ground to a size that is similar to cement size 10-15 μm (Mindess et. al. 2003). When crushed or milled very finely, GGBFS has cementitious properties because of its silica and calcium content (Mindess et. al. 2003).

The slag created in iron refining is rich in lime, silica, and alumina which allow it to be suitable for use in concrete as a SCM (Mindess et. al. 2003). The grade of GGBFS is based on the reactivity of the GGBFS. The reactivity is measured by comparing seven and twenty-eight day compressive strength of mortar cubes made from 100% portland cement to mortar cubes containing 50% GGBFS and 50% cement. The slag activity index is calculated by dividing the compressive strength of the GGBFS/cement mortar cubes by the compressive strength of the cement only mortar cubes. The resulting number is multiplied by 100 resulting in a “grade” (ASTM C989, AASHTO) of GGBFS.

$$activity-index=\frac{7(or28)day}{7(or28)day}\frac{compressive}{compressive}\frac{strength}{strength}\frac{slag/cement-cubes}{cement-only-cubes}\times 100$$

Three grades of GGBFS are used to identify the cementitious nature of the slag: GR 80, GR 100, and GR 120. Table 1 shows the test requirements for ASTM C989 (Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars).

Table 2.1 Physical Requirements (ASTM C989)

Slag activity index, min %	**Average of last five consecutive samples**	**Any individual sample**
7-day index		
GR 80	---	---
GR 100	75	70
GR 120	95	90
28-Day Index		
GR 80	75	70
GR 100	95	90
GR 120	115	110

2.3 Fly Ash

Fly ash (FA) is a by-product of burning coal. Fly ash is collected from the flue gases (Coal Fly Ash-Material Description). The source of coal used to produce FA is divided into two classes; Class C and Class F. Class F is normally produced from anthracite or bituminous coal with pozzolanic properties and Class C is produced from subbituminous coal and lignite with pozzolanic and cementitious properties (ASTM C618 Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete). Class F FA is generally found east of the Mississippi River and Class C FA is generally found on the western side of the Mississippi River in the United States. Some coal sources from the western states are not suitable for FA used in concrete and their use should be heavily monitored (Mindess et. al. 2003). Typically, three types of coal-fired plants are used in producing electricity: dry-bottom boilers, wet-bottom boilers, and cyclone furnaces. A dry-bottom boiler is best for collecting FA because about 80% of the FA will leave with the separation of the flue gas and is easily collected. A wet-bottom boiler will trap about 50% FA within the furnace and a cyclone furnace only allows 20-30% to leave with the flue gas (Coal Fly Ash-Material Description). Care must be taken to avoid chemicals, such as scrubber products, from removing sulfur dioxide from gases that escape from the energy process (Mindess et. al. 2003). FA must conform to the standards in ASTM C618.

Class F FA that is good for concrete mixtures has 70-90% glass. The high glass content signifies the useful nature of Class F FA in concrete as described in Section 2.4. Some Class C FA contains free lime (CaO) and anhydrite ($CaSO_4$). Class C FA may also contain C_3A (the most reactive cementitious compound) which can cause high water demand, early stiffening, or rapid setting all of which are undesirable in concrete. The compound C_3A forms ettringite when enough sulfate is available and monosulfoaluminate when not enough sulfate is present during hydration. When the monosulfoaluminate comes into contact with sulfate ions, ettringite is formed again and is referred to as sulfate attack (Mindess et. al. 2003).

2.4 Pozzolanic Reaction

The SCMs, GGBFS and FA, contain amorphous or glassy silica which reacts with calcium hydroxide (CH) formed from the hydration of calcium silicates (C_2S and C_3S). This is a secondary reaction during the hydration process (further discussed in Section 2.7.3) and often will allow benefits such as lower heat of hydration and a denser, and less permeable, concrete (Mindess et. al. 2003). This secondary reaction can also hinder the early strength gain of the concrete if used to excess. Two hydration reaction equations and the principal pozzolanic reaction equations are as follows (Mindess et. al. 2003):

$$2C_3S + 11H \rightarrow C_3S_2H_8 + 3CH$$

$$2C_2S + 11H \rightarrow C_3S_2H_8 + 2CH$$

$$CH + S + H \rightarrow CSH \quad .$$

One of the products of cement hydration and the SCM reaction, CSH (calcium silicate hydrate), is 50% of the volume of concrete paste. Another product, CH (calcium hydroxide), is about 25% of the volume of concrete paste. The CSH is the product that binds cement particles together and gives concrete strength. CH crystals grow in the void space left by the hydration process (Mindess et. al. 2003).

2.5 Common Use of Ground Granulated Blast-Furnace Slag and Fly Ash

Combinations of cement-FA, cement-GGBFS, and cement-FA-GGBFS have been used in concrete successfully in various areas around the world (ACI Committee

233). GGBFS was used as a separate product to combine with portland cement in the late 1970's in the United States even though intergrinding slag and portland cement clinker was done thirty years earlier. The United States Department of Transportation and the Federal Highway Administration suggest that substitutions for cement by weight with GGBFS be limited to 50% when not exposed to deicing salts and 25% when exposed to deicing salts. They also state that while replacements of up to 70% have been used successfully for specific projects, a more optimum replacement rate is approximately 50% (Ground Granulated Blast-Furnace Slag-Materials Group). Research suggests that 25% is optimum for scaling resistance but that concrete with up to 50% GGBFS has comparable scaling resistance to 100% portland cement concrete (ACI Committee 233). Fly ash has been used in portland cement concrete for over 60 years in the United States (Coal Fly Ash-Material Description). A 1992 survey indicated that 44 states out of 50 in the United States used FA with portland cement in concrete but is generally avoided in bridge decks (Coal Fly Ash-User Guideline). FA is generally avoided because of variable composition, negative impact on early strength for stripping forms, and negative impact on air content (Fly Ash-Materials Group).

2.6 "Green" Concrete

An increasingly popular trend in construction is the ability to produce "Green" projects. The force behind the green movement is to design and build structures that are more environmentally friendly and conservative. Buildings can be certified as a Leadership in Energy and Environmental Design (LEED) building (Leadership in Energy & Environmental Design). According to the United States Green Building

Council's website, the purpose of LEED is to standardize the idea of a "green building," promote whole-building design practices, recognize the environmental leaders, stimulate competition, and raise awareness of the benefits of conservation (VanGeem, 2002). Certification is based on a system of credit points for different aspects of design, spatial and material, and construction practices. LEED certification is awarded at a total of 26 points and levels of recognition are given for 33 points, silver, 39 points, gold, and 52 points, platinum (VanGeem, 2002). The criteria for points include: site selection, public transportation access, reducing heat islands, renewable energy sources, reuse of existing materials, use of recycled materials such as GGBFS, and innovative interior design. The LEED system defines sustainability "as development that meets the needs of the present without compromising the ability of future generations to meet their own needs (VanGeem, 2002)."

Concrete can be used in several ways in order to increase the LEED points of a project. Portland cement concrete can be used instead of asphalt to reduce heat islands. The reduction of the heat island is based on the increased solar reflectance of the materials used for large areas. The solar reflectance is the amount of radiation reflected back from a surface compared to the amount shone on the material. Concrete generally has a solar reflectance of approximately 0.35 and "white" concrete can have a value of 0.7 to 0.8 (VanGeem, 2002). GGBFS will also increase the "whiteness" of the concrete when added in significant amounts. Asphalt, on the other hand, will generally have a reflectance of less than 0.2. Another LEED criteria for points states, "specify a minimum of 25% of building materials that contain in aggregate a minimum weighted average of 20% post-consumer recycled content material, or, a minimum weighted average of 40% post-industrial recycled content material (VanGeem, 2002)." SCMs, including FA and GGBFS, are considered post-industrial.

The use of waste materials is also important for more reasons than the construction benefits. In 2002, 30% of FA produced yearly was used in various construction-related applications with 10% used in concrete (Ostrowski, 2002). Unless some recycling occurs, these waste products end up in landfills. Over 250 million tons of FA (Mindess et. al. 2003) and over 18 million tons of GGBFS (Schriefer, 2004) are produced every year in the United States. The American Concrete Institute (ACI) and the Environmental Protection Agency (EPA) encourage recycling by supporting the Resource Conversation and Recovery Act (RCRA) and recycling in concrete. The RCRA requires agencies under federal funding to purchase products with the highest percentages of recovered materials practicable (ACI Committee 233).

The annual global production of concrete was about 5 billion tons in 1997 according to Penttala (Penttala, 1997). Penttala also mentions the greatest threats for the earth's future as: population growth, global temperature rise, polluting of the air, water and soil, and the availability of fresh water resources (Penttala, 1997). Because of the effects of the industrial revolution and the use of fossil fuels, the level of CO_2 in the air has increased by as much as 25% in 200 years (Hogan, 2004). Increasing levels of CO_2 have helped increase the amount of greenhouse gases. The greenhouse gases deplete the layer of gases that keeps harmful radiation from the earth's surface and that also prevents heat from escaping back into the atmosphere (Hogan, 2004). Sustainable development is needed to ensure natural resources and the function of future generations. Manufacturing cement involves burning raw materials and the production of CO_2. About 0.56 ton of CO_2 per ton of cement is released during cement production and about 0.35 ton of CO_2 is released in the fuel (Hogan, 2004). CO_2 production can be reduced by about 0.5 tons per ton of cementitious material if SCMs are used to replace 50% of the cement (Hogan, 2004).

The use of SCMs will also extend our current supply of cement. In a Flash Report of *The Monitor*, the Portland Cement Association (PCA) culminated reports of a cement shortage in the United States. Although concrete use is encouraged by the industry, the lack of supply could turn industries away from the material. The report sites two major reasons for the increase in demand for cement: the reduction in the quantity of imported cement and the demand from the United States economy for construction materials (Sullivan, 2004). The use of waste products, such as GGBFS and FA, would increase the supply of cement.

Studies have also shown that the increase in construction speed has decreased the effectiveness of concrete structures. More often mixtures contain early strength admixtures and greater concentrations of highly reactive portland cement (Mehta, 2002). Although these increases allow for increased speed of construction, they also create higher thermal and drying shrinkage needing more preventative attention and costing more money in repair (Mehta, 2002). Materials such as FA and GGBFS have lower heat of hydration, preventing shrinkage cracking, increasing durability and reducing permeability. These properties are appealing in concrete because they prevent premature repair and possible failure.

2.7 Fresh Concrete Properties

The effects of GGBFS and FA on fresh concrete properties are discussed in the following sections. Slump, time to set, heat of hydration, and air content are examined in Sections 2.7.1, 2.7.2, 2.7.3, and 2.7.4, respectively.

2.7.1 Slump

Slump is a fresh concrete property that quantitatively represents the workability of the concrete. This is important because the hardened properties are not achievable if the concrete cannot be accurately placed. Generally, a higher water-to-cementitious material (w/cm) ratio will result in greater slumps because of the increase in water content. Rounded aggregates also increase slump because the aggregates are more readily able to slide past each other than angular or crushed aggregates. Water-reducing admixtures also increase slump without changing the w/cm or the quantity of any constituent material.

While GGBFS and FA are not typically used to specifically target slump, their effects on slump should be noted in order to prepare for site conditions that require a particular slump. The Federal Highway Administration (FHWA) and the United States Department of Transportation (USDOT) suggest that concrete containing GGBFS has longer-lasting workability and less slump loss than a similar mixture containing only portland cement (Blast Furnace Slag - User Guideline-Portland Cement Concrete). The USDOT and the FHWA agree that workability increases with increases in GGBFS or FA and suggest that the cause is an increase in paste volume from the lower relative density of both (Ground Granulated Blast-Furnace Slag-Materials Group). FA particles have a spherical shape and are relatively the same size as cement particles with out pulverization, unlike GGBFS; therefore it has an increasing effect on the slump (ACAA 1995). The spherical particles slide past each other more readily than angular cement and GGBFS particles, and create more workability.

2.7.2 Time to Set

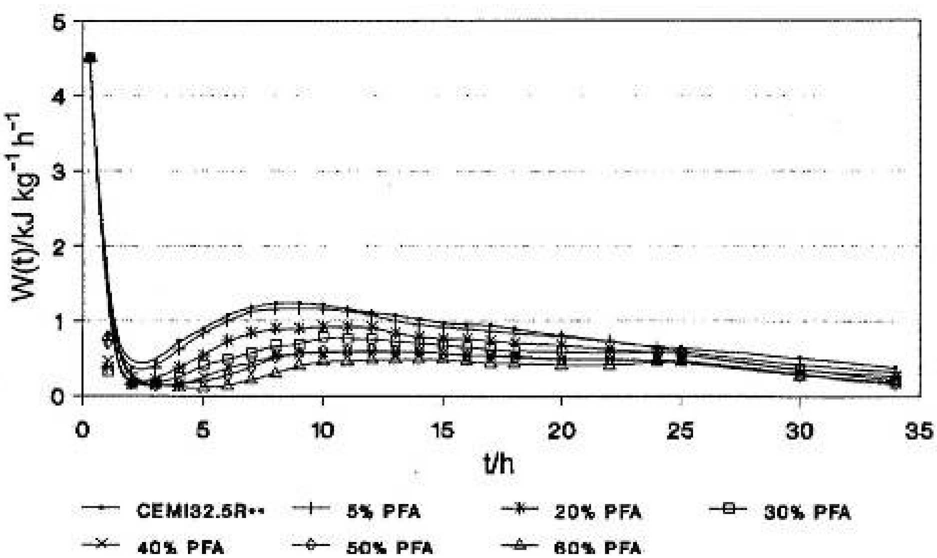
Generally, the addition of SCMs reduces strength gain because the materials do not react as quickly as cement and effectively increase the water-to-cement ratio during the early hydration stages (Babu, 1994). The FHWA and the USDOT suggest that because of the delay in set times that occur with the addition of FA the need for a set retarder (often used during construction in the summer) may be eliminated or reduced in some climates (ACAA 1995). GGBFS also has a slower hydration reaction than cement, but the reaction of GGBFS is dependent on the sodium and potassium alkali and calcium hydroxide available in the paste. This is why GGBFS is usually "activated" with portland cement, alkali salts, or lime to increase the reaction rate (ACI Committee 233). Research conducted by Luther et al. (1994) showed that the time to set was increased by 1 hour (at 70ºF) for replacements of 35 to 40% slag and that an increase in slag resulted in an increase in time to set (ACI Committee 233). A concrete mixture of 65% GGBFS and 35% cement was shown to have almost twice the initial and final set as a comparable 100% cement mixture (Khatri, 1995). The time to set is more fully explained in the following section.

2.7.3 Heat of Hydration

SCMs, such as FA and GGBFS, have a slow rate of hydration, similar to the secondary cement compound C_2S. An increase in C_2S in portland cement creates

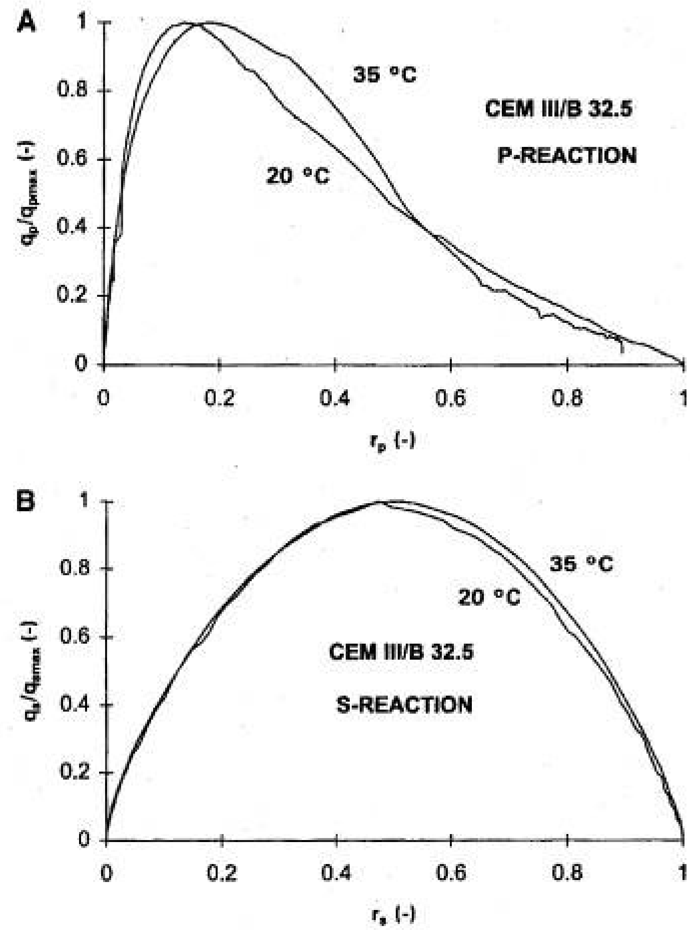
Type IV or low heat of hydration cement. In this respect, FA and GGBFS lower the heat of hydration (Mindess et. al. 2003). Nocuń-Wczelik's work with calorimetry on mixtures containing FA contents ranging from 5% to 60% determined that increases in FA resulted in a slower rate of heat evolution. At 5% FA replacement relatively little change in the heat evolution was noticed, but at replacements greater than 30%, FA resulted in an elongated induction period and lower peak in heat as seen in Figure 2.1 (Nocuń-Wczelik). The induction period is the low heat producing time between the first contact with water and the rapid acceleration of hydration, or the initial set (Nocuń-Wczelik).

Figure 2.1 Calorimetric curves of cement CEM I, 32.5 R samples mixed with PFA (Nocuń-Wczelik)**



Schutter described the hydration of slag-cement concrete as a two fold reaction of the portland cement and the slag that can be superimposed onto one heat curve and estimate the slag-cement heat curve. An adiabatic hydration test, where heat is not lost or gained from the system (Agnes, 2000), measured the heat production rate as a function of time in mixtures with GGBFS replacements of 65%-95%. The portland cement reaction curves peak quickly and then slowly taper down while the slag reaction curves are more symmetric and gain heat towards the peak at the same rate as the heat tapers down as shown in Figure 2.2 (Schutter, 1999).

Figure 2.2 (A) Standardized P-curves for CEM III/B 32.5. (B) Standardized S-curves for CEM III/B 32.5. (Schutter, 1999)

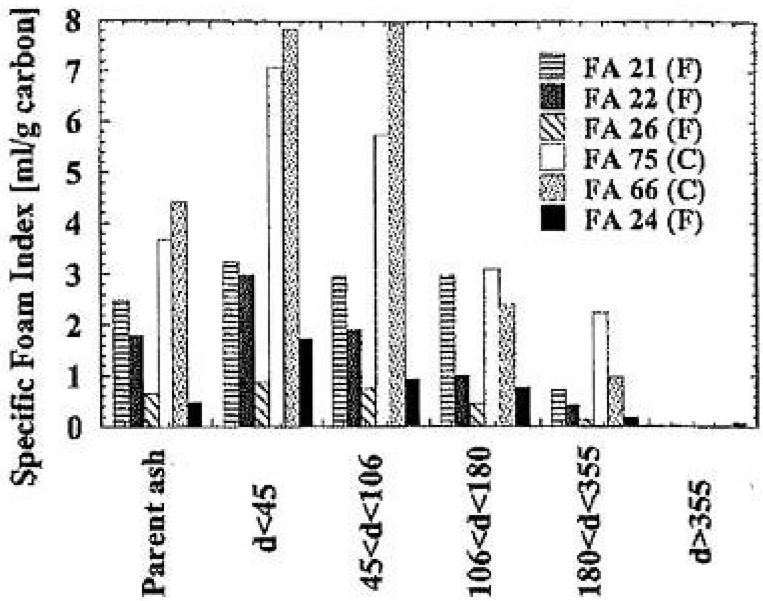


The reaction curves show that portland cement mixtures gain heat more rapidly than GGBFS. The heat gain curves also show slag cement heat gain begins later than the portland cement, explaining the slower heat of hydration and the increase in set times for mixtures containing GGBFS (Schutter, 1999).

2.7.4 Air Content

Class C and Class F FA may contain up to 5 percent per AASHTO M 295-00 (Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete) and 6 percent per ASTM C618 of unburned carbon remaining from the burning process of coal energy (ACAA 1995). The remaining unburned carbon will have detrimental effects on air entrainment and require larger doses of air entraining admixtures (AEA) (Mindess et. al. 2003). The residual unburned carbon in FA absorbs AEA so that less air is entrained into the concrete. The organic contribution (unburned carbon) to the FA is responsible for at least half, usually more, of the surface area of the FA particles. Loss-on-ignition tests (LOI - difference in weight of a sample before and after it was heated to burn off carbon) were performed in research by Kulatos et al. and compared to the Foam Index (measure of how well an AEA works to maintain bubbles) of the FA/cement/water mixtures. Figure 2.3 (Kulatos et al., 2004), below, shows that more milliliters of AEA were required per gram of unburned carbon for the two Class C FA mixtures. Kulatos et al. determined that Class C FA would absorb greater amounts of AEA per LOI of unburned carbon than Class F FA. This was attributed to the location of the unburned carbon surface area on the outside of the Class C FA particles, while the Class F FA particles have smaller holes deeper in the particle where AEA can not easily reach and be absorbed (Külatos et al. 2004). The FHWA and the USDOT suggest careful monitoring of the air content in order to observe the fluctuations (ACAA 1995). GGBFS does not have the same absorbing effect on AEA as the unburned carbon portion of FA.

Figure 2.3 Specific Foam Index for parent ashes and fractions prepared from these ashes. (Külatos et al. 2004)



Workability and air content are directly correlated. Addition of 3-4% entrained air will increase the slump about 1½ to 2 inches (35 to 50 mm). The increase in slump is due to the tiny bubbles created with AEA acting as low-friction fine aggregate. Bubbles from AEA make the mixture behave as if it had too much sand and allows the larger more angular particles slip past each other (Mindess et al. 2003).

2.8 Hardened Concrete Properties

The following sections describe the hardened concrete properties of mixtures made with GGBFS, FA, and ternary mixtures.

2.8.1 Compressive Strength

As mentioned in Section 2.3, FA contains amorphous or glassy silica and as mentioned in Section 2.2 GGBFS is a glassy granule of calcium aluminosilicate.

These SCM react with calcium hydroxide (CH) formed from the hydration of calcium silicates in a secondary reaction during the hydration process (Mindess et. al. 2003). The secondary reaction leads to the use of CH in creating more CSH (calcium silica hydrate) which is the main source of strength in concrete (refer to the principal pozzolanic equation in Section 2.4). The use of the cement products by GGBFS or FA in the secondary reaction produces greater long term strength if enough cement was hydrated to produce an adequate amount of CH (Mindess et. al. 2003).

In research conducted by Li et al, the combination of 15% GGBFS and 25% FA had similar, but slightly lower, compressive strengths to the control mixture (100% portland cement) at 28 days and then slightly higher compressive strengths at later ages. A concrete mixture containing 40% FA had much lower compressive strengths than both the control and the ternary mixture designs until 56 days. After 56 days the FA mixture had the highest compressive strength (Li, 2003).

Research by Regourd, Vanden Bosch, and Roy and Idorn (as described in the Slag Cement in Concrete and Mortar report) used calorimetric studies of the rate of heat liberation to show the two-stage effect. The results suggest that during the early hydration, the predominant reaction is with alkali hydroxide and subsequent reaction is predominantly with calcium hydroxide. This suggests that the primary reaction is from the portland cement component of the mixture while the slag cement hydration lags behind (ACI Committee 233). The portland cement produces less strength in the primary reaction when mixed with SCM while the later SCM reaction adds more CSH and creates greater strength than a cement only mixture (Mindess et al. 2003)

The USDOT and FHWA agree that FA mixtures may have lower compressive strength than a control mixture at early ages, but they usually develop higher later compressive strength when properly cured (Fly Ash-Materials Group). Cold weather seems to more adversely affect FA mixtures than 100% portland cement mixtures and it is recommended that precautions be taken in this case (Fly Ash-Materials Group). In general, GGBFS develops lower compressive strengths at 1 to 5 days but by 7 to 28 days the GGBFS mixture will have similar compressive strengths to 100% portland cement mixtures. Long-term strengths of GGBFS mixtures are above those of the control mixtures (Ground Granulated Blast-Furnace Slag-Materials Group). Fulton and Hogan and Meusel found that the greatest twenty-eight day strengths were in mixtures with as high as 65% replacements of highly reactive GGBFS (ACI Committee 233).

2.8.2 Permeability

Permeability is an important factor in the durability of concrete because it controls the entry of moisture that may contain aggressive chemicals into concrete. Water in and of itself may cause damage to the concrete by freezing and thawing cycles (Mindess et. al. 2003). It is also important for structures that are to be water-tight such as settling tanks for water purification (Mindess et. al. 2003).

Permeability can be measured directly through ponding methods, pressure head methods, or indirectly by the measure of electrons passing through a specimen. The ponding methods use a slab subjected to a fixed head of water and cores are taken to determine the extent of chloride penetration of chloride ions (Mindess et al. 2003). This method is lengthy and may take from 90 days to longer than 2 years to produce adequate data (Mindess et. al. 2003). The pressure head methods are similar to the ponding methods; however, they are designed to provide results faster than the ponding tests.

In research conducted by Leng et al., chloride ion diffusion using the Nernst-Einstein equation utilizing partial conductance, the gas constant, the absolute temperature, and the concentration of the solution to determine the diffusion coefficient. Their research results showed that chloride ion diffusion coefficient increased with increases in w/cm. The chloride ion diffusion coefficient decreased when the quantity of FA or GGBFS increased. FA and GGBFS decreased the pathways for water to flow by reacting with CH to create more C-S-H (as described in Section 2.8.2). The chloride ion diffusion coefficient decreased by 10% at 0.34 w/cm, 35% at 0.30 w/cm, and 41% at 0.26 w/cm when the concrete was made with GGBFS instead of with FA (Leng, 2000). According to the USDOT and FHWA, GGBFS transforms large pores into smaller pores and therefore decreases the permeability of the concrete (Ground Granulated Blast-Furnace Slag-Materials Group).

The rapid chloride ion penetrability test (RCPT) monitors the amount of electrical current passed through the top two inches of a 4" x 8" concrete cylinder. This trimmed sample is saturated with water and placed between chambers that hold a positively charged chemical solution, sodium hydroxide (NaOH), and a negatively charged chemical solution, sodium chloride (NaCl). The sample is subjected to a constant voltage of 60±0.1 V and the current between the two chambers, or through the sample, is recorded. The current passed, in coulombs, was related to ponding tests. An empirical relationship between accepted methods and the RCPT resulted in a table, shown in Table 2.2, to represent the permeability of the concrete vs. the flow of electrons through the sample. (ASTM C1202 Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration, AASHTO T 277-96 Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration) The RCPT was designed to give permeability results in 6 hours, much less time than either of the more direct methods. The information given by the RCPT should be examined closely because of variables inherent in the process.

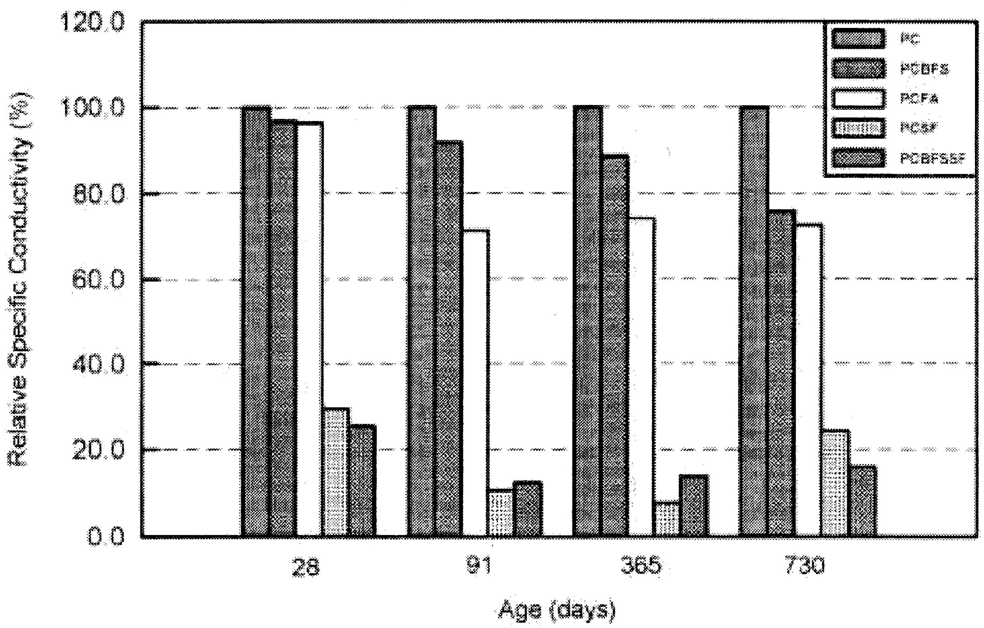
Table 2.2 Chloride Ion Penetrability (ASTM C 1202-97 Table 1)

Charge Passed (coulombs)	Chloride Ion Penetrability
>4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very Low
<100	Negligible

However, there are concerns regarding the validity of the test results. Because the test measures charge passed through a sample, several aspects should be evaluated carefully. A rapid gain of flow can signal heating of the sample which will increase flow greater than represented by the permeability of the sample (Mindess et. al. 2003). The composition of the pore solution can also affect the RCPT results.

Replacement of 60 to 70% portland cement with GGBFS reduces the OH^- concentration, increases the Na^+ concentration, and decreases the K^+ concentration in the pore solution of the concrete. Because FA sources are variable, replacements of portland cement with FA may increase or decrease Na^+ and K^+ concentrations and usually decrease Ca^{2+} and OH^- concentrations in the pore solution. This change in chemical composition from the replacement of cement with SCM may aid in the transfer of electrons between the sodium chloride and the sodium hydroxide solutions, or it may hinder the flow (Shi, 1998). The research compiled by Shi, Stegemann, and Caldwell shows the effect of SCM on relative specific conductivity, the normalized conductivity of hardened concrete made with SCM relative to the conductivity of hardened concrete made with 100% portland cement as shown in Figure 2.4 (Shi, 1998). The results of the research were that 50% GGBFS replacement reduced the conductivity by 3.25% at 28 days, about 9% at 90 days, and 24% at 730 days. FA replacements at 60% reduced the conductivity 3.8% at 28 days and 28.7% at 90 days.

Figure 2.4 Effect of SCM on relative specific electrical conductivity of pore solution in concrete (Shi 1998).



The conductivity is attributed to the pore structure and pore solution characteristics while the transport of chloride ions in the ponding and pressure tests is attributed to the pore structure. The recommendations from the research conclude that the passed charge in the RCPT is not correct to use to determine the rapid chloride permeability of concrete with SCM (Shi, 1998).

2.8.3 Durability

Freeze/thaw durability of concrete containing FA is difficult to determine because of the detrimental interaction with air entraining agents. Section 2.7.4 describes the properties of FA that reduce the effectiveness of AEA. The addition of FA requires monitoring of air content and possibly an increase in the dosage of air entraining admixtures in order to maintain freeze/thaw durability (Fly Ash-Materials Group).

Another aspect of the addition of FA is the decrease in permeability (as described in Section 2.8.1 and 2.8.2) due to the pozzolanic reaction with CH creating more CSH, which will lead to less moisture penetrating the concrete and greater durability. The same process of an increase in density with an increase GGBFS replacement accounts for the increase in freeze/thaw durability of concretes with GGBFS. Air-entrained GGBFS concretes have been noted as having durability factors greater than 91% (Ground Granulated Blast-Furnace Slag-Materials Group). Research conducted by Pigeon and Regourd in 1983 included a group of cement only mixtures, a group of 2/3 cement and 1/3 GGBFS mixtures, and a group of 1/3 cement and 2/3 GGBFS mixtures. Of the mixtures made with no admixtures, the spacing factor (1/2 the average distance between air bubbles) for the 2/3 GGBFS mixture was two times that of the cement only mixture and the spacing factor for the 1/3 GGBFS mixture was one and one-half times that of the cement only mixture. This means that an increase in GGBFS led to an increase in the distance between air bubbles. The researchers also concluded through porosity measurements that the GGBFS concretes have finer pores and more uniform pastes than cement only mixtures. The freeze-thaw results of the Pigeon and Regourd research showed that the three different mixtures survived well through the Procedure B testing (Pigeon et al., 1983).

Another factor in determining the durability of concrete is scaling due to freeze/thaw processes and the exaggeration of scaling when deicing salts are used. The finishing technique used on concrete can trap bleed water just under the finished surface causing disconnect between the finished surface paste and the bulk paste of the concrete. When the hardened concrete is subsequently saturated with water between the finished surface and the bulk paste, few freeze/thaw cycles are required to produce scaling of the surface of the concrete structure. Research conducted by Taylor et al. focused on the effect of finishing relative to time-to-set of a cement only mixture, a 50% GGBFS mixture, and a 25% FA mixture. The results show that late finishing (just before initial set) was best for the cement only mixture. Early finishing (immediately after fabrication) was the best time for the 25% FA mixture. The 50% GGBFS had better results for early and mid-finishing (when bleeding appeared to stop) than for late finishing. The time to finish recommended by ASTM C 672 (Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals) is after the concrete has stopped bleeding. The recommended time to finish concrete from this research is to specify when is best to finish specific mixtures based on time-to-set and bleeding (Taylor et al., 2004).

2.8.4 Sulfate Resistance

Irassar et al. describe the mechanisms of sulfate attack as ettringite formation, gypsum formation, and salt crystallization, all of which "occupy a greater space than the original compounds causing expansion, disruption, and cracking" (Irassar et al., 1996). SCM increase sulfate resistance by calcium hydroxide reduction, permeability reduction, and C_3A dilution. The research conducted by Irassar et al. included concrete mixtures with Type I portland cement, Type I with AEA, 20% replacement with Class F FA, 40% replacement with Class F FA, 80% replacement with GGBFS, and Type V (2% C_3A) portland cement. Cylinders were cast and buried to half height with 1% sodium sulfate soil in the outdoors to simulate in-situ conditions. In the buried section of the samples, visual signs of sulfate attack occurred within two to three years on the two Type I mixtures. Samples with 20% FA showed slight cracks and swelling in the buried zone at four to five years. The concrete with 40% FA, 80% GGBFS, and Type V portland cement showed no damage in the buried zone after five years of exposure (Irassar et al., 1996).

The same pore characteristics that is beneficial (reduces movement of ions) in SCM concrete immersed in solution is detrimental (exacerbates capillary action) to the concrete in the atmosphere. Pore size changes from the SCM inducing capillary action outweigh the chemical benefits (using sulfate attack prone CH particles to make CSH) in the paste in the above ground portion. Samples with 40 to 80% replacements of SCM incurred greater damage in the volume above ground due to the capillary action (three times higher for 80% GGBFS than all of the other mixtures) carrying the sulfate solution to the dryer end and subsequently drying to leave salt crystallization (Irassar et al., 1996).

2.8.5 Alkali-Silica Resistance

Research in alkali-aggregate reactions has shown that FA and GGBFS can lower the negative effects of alkali-silica reaction (ASR) by increasing the density of the concrete paste and preventing the migration of fluids that would contribute to ASR (Mindess et. al. 2003). A greater improvement can be gained by using SCMs and air-entraining admixtures (Gillott, 1995). Nobata and Ueki suggest one of the main reasons for the increase in popularity of GGBFS is due to the advantage of controlling alkali-aggregate reaction (Nobata, 2002). The USDOT and the FHWA suggest that using GGBFS as a partial replacement of cement can reduce the available alkalies to reduce the reaction between the siliceous components of aggregates and the alkalies in the concrete (Blast Furnace Slag - User Guideline-Portland Cement Concrete).

Duchesne and Bérubé researched concrete made with three SCM as replacement for high-alkali cement as compared to concrete made with low-alkali cement. FA with three different chemical compositions (low-calcium and low-alkali, moderate-calcium and low-alkali, and high-calcium and high-alkali), two silica fumes, and one GGBFS were used to study the degradation from ASR and the corresponding pore solution composition. FA mixtures were made at 20 and 40% replacements. Silica fume mixtures had 5 and 10% replacements. The GGBFS mixture had 50% replacement of cement. Highly reactive aggregates were used in the mixtures to induce ASR. The results showed that concrete made with low-alkali cement had expansion of near 0.04% and that 40% FA (those with low alkali content) and 50%

GGBFS decreased the ASR expansion to lower than that of the low-alkali cement mixtures. Silica fume mixtures, 20% FA replacement mixtures, and the high-alkali FA mixtures had greater ASR than the control mixture made with low-alkali portland cement (Duchesne et al., 2001).

2.8.6 Shrinkage

Plastic shrinkage is caused when the water on top of a concrete structure evaporates more quickly than bleed water is able to reach the surface (Mindess et. al. 2003). The reasons for plastic shrinkage include heat, wind, and lack of protection from the elements. The result of plastic shrinkage is cracking due to the tensile forces in the top-most layer of the concrete. The cracks allow more moisture to penetrate into the concrete than a properly finished structure (Mindess et. al. 2003). FA and GGBFS may reduce bleeding by providing a greater amount of fines that require more water because of the increase in surface area. Because FA has a spherical shape, it lowers friction and can offset the negative effects of the fineness (Fly Ash-Materials Group).

Drying shrinkage occurs in hardened concrete when strain is induced from the loss of water from the hardened material (Mindess et. al. 2003). The strain can cause shrinkage cracks and warping of the surface of the member (Mindess et. al. 2003). Joints are used in concrete slabs to control the location of shrinkage cracks and can be filled with material to prevent water and other substances from entering through the crack (Mindess et. al. 2003). Uneven moisture loss in the surface of the slab can cause warping at the corners (Mindess et al. 2003).

2.9 Conclusion

Ground granulated blast-furnace slag and fly ash are two industrial byproducts with supplementary cementitious properties. GGBFS is created from processing the excess molten material removed from refined iron ore. FA is gathered as waste from burning coal. These SCM can be disposed of in landfills or used in more environmentally sound ways such as concrete construction materials. The use of GGBFS and FA is increasingly accepted as environmentally conscious through programs like LEED and good building practice through research that determines the beneficial properties SCM lend to concrete.

The fresh concrete properties mentioned in Section 2.7 were slump, time to set, heat of hydration, and air content. Slump of concrete made with GGBFS increases as the replacement of cement with GGBFS increases due to more paste from the lower density in GGBFS than that of the cement it replaces. Increases in the FA replacements increase the slump more than GGBFS mixtures because of the rounded nature of the FA compared to the crushed, angular nature of cement and GGBFS. Time to set and heat of hydration are complementary properties because a lower heat of hydration often induces a longer time to set and vice versa. Replacements of 30% of GGBFS or FA resulted in increased time to set. GGBFS replacement of 65% had twice the time to set of the cement only mixture. The unburned carbon portion of FA absorbs AEA and requires more AEA to achieve the same air entrainment as a mixture made with GGBFS. The difference in the amount of AEA in FA mixtures is based on the LOI and class of FA.

SCM use the hydration process of cement and the production of CH to gain strength and create more CSH in concrete. The pozzolanic properties of GGBFS and FA effect the hardened concrete properties. Early compressive strength of concrete with low replacements of SCM is greater than with high replacements of SCM. Higher replacements require more CH from the cement hydration, but more CH is not produced with less cement in the mixture. The hydration of SCM also acts as a secondary reaction extending the time to set. The secondary reaction also allows the SCM to continue to gain strength after a comparable cement only mixture. High replacements with SCM produce greater strengths than lower replacements to the extent that enough cement is present. The secondary reaction produces more dense concrete matrix because of the continual conversion of CH to CSH. More dense concrete lowers the permeability and effectively increases durability because water has less chance at freeze/thaw damage and less ability to bring in chemicals that induce sulfate attack and ASR. The permeability and durability are also determined by the proper air entrainment discussed above.

The benefits provided through previous research justifies re-examination of the current Specifications in Arkansas based on research specifically designed to test materials used in this state. If the same benefits are determined from the current research as from previous research, Arkansas would benefit from an update to the Specifications that allow greater usage of GGBFS and FA.

Chapter 3 EXPERIMENTAL PROCEDURES AND RESEARCH PROGRAM

3.1 General

The goal of the research program is to provide evidence that the AHTD Specifications for concrete can be modified to allow greater replacement rates of GGBFS and FA and ternary mixtures. The fresh and hardened concrete properties were determined for mixtures containing GGBFS, FA, or both materials. In this chapter, each of the studies is described followed by detailed descriptions of the batching, curing, and testing methods used in the research. The chapter is prefaced by a brief summary of the scope of the project and AHTD's requirements for portland cement concrete pavement mixtures.

3.2 Scope

The research program is divided into three studies. Within each study, performance aspects of using GGBFS and/or FA were examined using fresh and hardened concrete properties. The studies are listed below:

1. Cement – Determine if GGBFS and/or FA react differently with various Type I cements. Five different concrete mixtures were batched with two different Type I cements. The mixtures examined included a control mixture containing only portland cement, a mixture containing 60% GGBFS (GR 100 and 120), a mixture containing 60% Class C FA, and finally a ternary mixture containing 20% GGBFS and 20% FA. The w/cm, total cementitious material content, and coarse aggregate content was constant for all mixtures. The quantity of sand varied some

among mixtures because of the differences in specific gravities of the GGBFS, FA, and portland cement.

2. Supplementary Cementitious Material – Determine, through more comprehensive testing, the effects of replacing portions of the portland cement with GGBFS and/or FA. A typical AHTD mixture proportion for concrete paving was used for the control mixture. The SCM replacements were 20, 40, and 60% by weight for GGBFS (GR 100 and 120) and FA. Ternary mixtures were 20/20, 20/40, 20/60, and 40/40 replacements with GGBFS (GR 100 and 120) for each SCM. One cement source was used and the w/cm, total cementitious material content, and coarse aggregate content was constant for all mixtures. The quantity of sand varied some among mixtures because of the differences in specific gravities of the GGBFS, FA, and portland cement. No chemical admixtures were used in order to attribute the differences in fresh and hardened properties to the replacement of cement with FA, GGBFS, or both.

3. Ground Granulated Blast Furnace Slag – Two grades of GGBFS (GR 100 and 120) were used in nine comparative concrete mixtures with a single cement source. The materials were held constant except for the ratio of cement to SCM and grade of GGBFS.

3.3 AHTD Specifications for Portland Cement Concrete Pavement Mixtures

Concrete designed as pavement under the AHTD specifications must comply with the following requirements. The minimum cement content is 564 lbs. per cubic yard or at least 6 sacks (335 kg of cement per cubic meter). The water-to-cementitious material content should not exceed 0.45 including the moisture of the aggregate.

Substitution of FA is made at a rate of one pound of FA for one pound of cement up to 20% of the weight of the cementitious material. GGBFS is also substituted at a rate of one pound GGBFS for one pound of cement up to 25% of the weight of the cementitious material. Neither can be used in conjunction with high strength or blended cements and they cannot be used in conjunction with each other in order to create a ternary mixture.

The concrete properties required are few. The minimum twenty-eight day compressive strength shall be 4000 psi (28.0 MPa) and the slump shall be not more than 2 in. (50 mm). The air content of the fresh concrete should be 6% ± 2%, and while the scope of this project did not allow for air entraining admixture, the air contents were lower and further research is recommended to determine dosage rates of air entraining admixture in FA/GGBFS concrete mixtures for Arkansas materials (AHTD, 2003).

3.4 AHTD Specifications for Portland Cement Concrete Structure Mixtures

The concrete designed for structures must comply with Section 802 of AHTD Specifications. Type I cement should be used unless a blended cement of portland-pozzolan cement-IP, pozzolan-modified portland cement-PM, or slag-modified portland cement-SM is approved by the engineer. Aggregates shall be subjected to AASHTO T 21-91, *Organic Impurities in Fine Aggregates for Concrete* and AASHTO T 27-93, *Sieve Analysis of Fine and Coarse Aggregates*. FA shall meet the requirements of AASHTO M 295 as Class C or Class F and mixing Class C and Class F FA is not allowed. GGBFS shall meet the requirements of AASHTO M 302 as GR 100 or GR 120. The concrete mixture design shall be proportioned to ensure a workable and durable concrete for each of the classes of structural concrete. The different classes of structural concrete, based on the purpose of the concrete, have different minimum compressive strengths with the minimum compressive strength for air entrained concrete at 4000psi. The minimum cement content ranges from 5.5 to 6.5 sacks of cement per cubic yard. The w/cm varies from 0.44 to 0.58 and the slump range is 1 in. to 4 in.

FA may be used as a partial replacement for Type I cement up to 20% by weight in all classes of concrete except class B. Class F FA can not be used in bridge deck concrete between October 15 and April 1. GGBFS may also be used as a partial replacement for Type I cement up to 25% except in high early strength and seal concrete (AHTD, 2003).

3.5 Materials

As required by AHTD Standard Specifications for Highway Construction, Division 500, Section 501.02 Materials, AASHTO M 85 and Type I/II portland cement was used in all mxtures. Different sources of cement were used to determine if the SCM reacted differently with each cement. As required by AHTD, total alkalis in the cement should not exceed 0.60% and the total alkalis in the cementitious material should not exceed 5 lbs./yd^3 (AHTD, 2003).

The requirements of fine aggregates, clean, hard, durable particles of natural sand or other inert materials were also followed. The coarse aggregate was crushed limestone. The sieve requirements for both the coarse and fine aggregates were followed. Fly ash used complied with AASHTO M 295 and was Class C. The two types of GGBFS complied with AASHTO M 302 and were GR 100 and GR 120, as per the specifications (AHTD, 2003). Table 3.1 lists the materials and the tests and standards that applied to each material. Cement, FA, and GGBFS chemical and compound composition are given in Table 3.2. The activity index is given in Table 3.3. The fine and coarse aggregate properties are shown in Table 3.4.

Table 3.1 Material Tests

Materials	Test Name and Standard	
Cements, GGBFS, and FA	Blaine Air Fineness	ASTM C 204 AASHTO T 153
	Slag Activity Index	ASTM C 989
Coarse Aggregate	Specific Gravity and Absorption	ASTM C 127 AASHTO T 85
	Sieve Analysis	ASTM C 13 AASHTO T 27
	Dry Rodded Unit Weight	ASTM C 29 AASHTO T 19
Fine Aggregate	Specific Gravity and Absorption	ASTM C 128 AASHTO T 84
	Sieve Analysis	ASTM C 136 AASHTO T 27

Table 3.2 Cement, FA, and GGBFS Properties

	Cement A	Cement B	Class C FA	GR 120 GGBFS	GR 100 GGBFS
	Ash Grove Cement	River Cement	ISG Resources	Buzzi Unicem	Holcim
	Chemical Composition (%)				
SiO_2	20.27	20.60	34.39	32.00	39.06
Al_2O_3	5.78	4.40	20.26	12.00	8.39
Fe_2O_3	2.73	3.40	6.17	0.60	0.43
CaO	64.32	63.8	25.71	42.00	36.56
MgO	1.31	3.70	5.95	9.00	12.58
SO_3	2.93	2.80	1.44	0.15	1.91
Loss on Ignition	1.18	0.9	0.04		
	Compound Composition (%)				
C_3S	56.72	61			
C_2S		13			
C_3A	10.70	5.9			
C_4AF		10.3			
Na_zO	0.22				
K_zO	0.29				
	Blaine Air Fineness				
Blaine (cm^2/g)	3670	365 m^2/kg		5270	580

Table 3.3 Slag Activity Index

	Compressive Strength Control Mix (psi) (1)		Compressive Strength 50% SCM (psi) (2)		Slag Activity Index (2)/(1)	
	7 Day	28 Day	7 Day	28 Day	7 Day	28 Day
GR 120 GGBFS	-	-	4390	6900	103	131
GR 100 GGBFS	3920	5080	3480	6520	90	128
Class C FA	-	-	-	-	97%	-

Table 3.4 Fine and Coarse Aggregate Properties

	Fine Aggregate (Arkhola, Van Buren, AR)	Coarse Aggregate (Arkhola, Springdale, AR)
Absorption (SSD)	0.48	0.38
Specific Gravity	2.604	2.678
Dry Rodded Unit Weight (lb/ft^3)	110.9	-

3.6 Cement Study

The cement study was conducted to determine whether the FA and GGBFS will react differently with two different cement sources often used in the state of Arkansas. For each cement source, five mixture designs were batched including one control, one high-volume FA replacement, one high-volume GGBFS replacement for each grade, and one ternary mixture design for GR 120 of GGBFS. The batching and testing matrix is shown in Table 3.5. All of the fresh and hardened concrete properties listed in Section 3.8.3 were tested for each mixture.

Table 3.5 Cement Study Batching and Testing Matrix

Cement	GGBFS GR	GGBFS %	FA %
A	-	0	0
A	120	60	0
A	-	0	60
A	120	20	20
A	100	60	0
B	-	0	0
B	120	60	0
B	-	0	60
B	120	20	20
B	100	60	0

3.7 Supplementary Cementitious Material and GGBFS Studies

The SCM study was conducted to supply data to AHTD on mixtures containing GGBFS, FA, and a combination of both. Fresh and hardened concrete properties of 22 mixtures were examined, including the five mixture designs, with cement A, used for the cement study. Two grades of GGBFS (GR 100 and 120) were used in the GGBFS study in order to determine if the two grades of GGBFS had similar fresh and hardened concrete properties. The GGBFS study included the mixture designs from the SCM study except for the FA mixtures. The SCM and GGBFS studies batching and testing matrix is shown in Table 3.6. All of the fresh and hardened concrete properties listed in Section 3.8.3 were tested for each mixture design. Repeatability was also incorporated into the SCM study by batching each of the mixture designs made with cement A twice and comparing the mixtures. This study ruled out errors that may have been introduced during batching.

Table 3.6 SCM and GGBFS Studies Batching and Testing Matrix

Cement	GGBFS GR	GGBFS %	FA %
A	-	0	0
A	120	20	0
A	120	40	0
A	120	60	0
A	-	0	20
A	-	0	40
A	-	0	60
A	120	20	20
A	120	20	40
A	120	20	60
A	120	40	20
A	120	40	40
A	120	60	20
A	100	20	0
A	100	40	0
A	100	60	0
A	100	20	20
A	100	20	40
A	100	20	60
A	100	40	20
A	100	40	40
A	100	60	20

3.8 Experimental Procedures

3.8.1 Mixtures and Batching

The control mixtures were developed according to AHTD's specifications for minimum quantity of cement and a maximum w/cm ratio of 0.45. The proportions of the control mixtures are listed in Table 3.7. The mixture proportions were developed using the absolute volume method. The only difference between the control mixture and the remaining mixtures is the quantity of SCM. The FA and GGBFS were substituted by weight for cement at a replacement rate of one pound of FA/GGBFS for one pound of cement. The w/cm was constant for all mixtures and the aggregate amount was based on the volumetric method. The batching process followed ASTM C 192 *Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory* (AASHTO T 126-97 *Making and curing Concrete Test Specimens in the Laboratory*).

Table 3.7 Mixture Proportion for Control Mixture with Cement A

Material	Batch Weight (lb/yd^3)
Cement	650
Coarse Aggregate	1894
Fine Aggregate	1169
Water	274

3.8.2 Curing

Immediately after batching, the specimens were placed in an environmental chamber. The environmental chamber was held constant at 73°F (23°C) and relative humidity of approximately 50% as per ASTM C 192 (AASHTO T 126-97). After 24 hours, the specimens were de-molded and immediately immersed in a lime saturated water bath located in the environmental chamber. The specimens remained in lime saturated water until testing.

3.8.3 Fresh and Hardened Concrete Tests

The fresh concrete tests were measured for all mixtures batched. The fresh concrete properties measured were slump (ASTM C 143, AASHTO T 119), unit weight (ASTM C 138, AASHTO T 121), and air content (ASTM C 231, AASHTO T 152). The hardened concrete properties measured were compressive strength (ASTM C 39, AASHTO T 22), rapid chloride ion penetrability (ASTM C 1202, AASHTO T

227), and freeze/thaw durability (ASTM C 666, Procedure A, AASHTO T 161). The fresh and hardened concrete tests are shown in Table 3.8.

Table 3.8 Fresh and Hardened Concrete Tests

Fresh Concrete Tests	Standard	Time of Test
Slump	ASTM C 143 AASHTO T 119	At batching
Unit Weight	ASTM C 138 AASHTO T 121	At batching
Air Content	ASTM C 231 AASHTO T 152	At batching
Hardened Concrete Tests		
Compressive Strength	ASTM C 39 AASHTO T 22	1, 3, 7, 28, 90 Days
Rapid Chloride Ion Penetrability	ASTM C 1202 AASHTO T 227	28, 90 Days
Durability	ASTM C 666, Procedure A AASHTO T 161	28 and Subsequent Days

3.9 Statistical Analysis

The number of samples tested per batch of concrete was taken from the ASTM standard for each test. Cement A mixtures were batched twice to determine batching consistency and therefore cement A mixtures have two sets of data. The two sets were compared to each other for repeatability and then combined to create one set of data for the cement study, the SCM study, and the GGBFS study. The cement B mixtures were not batched twice for batching consistency. A mean, or average, was calculated for the statistical analysis when more than one value was recorded for a mixture design.

The slump, unit weight, air content, and temperature were measured once for each batch. Two slumps, unit weights, air contents, and temperatures were measured for cement A mixtures and one slump, unit weight, air content, and temperature was measured for the cement B mixtures. Three compressive strength samples were tested for each batch. Six compressive strengths were recorded for each cement A mixture and three compressive strengths were recorded for each cement B mixture. Two RCIP and freeze/thaw samples were tested for each batch. Four RCIP and freeze/thaw results were recorded for cement A mixtures and two RCIP and freeze/thaw results were recorded for cement B.

The data gathered from the fresh and hardened concrete tests were used to perform a statistical analysis. SAS Version 8 was used to determine statistical difference in the data based on the batching matrix described previously in Chapter 3. When the data are described as not statistically different, the tests provided insufficient evidence that the data are different. In these studies, it means the mixtures produced the same result and are interchangeable to produce that particular property at similar quality. When the data are described as statistically different the mixtures are not interchangeable and one mixture is better to produce the desirable quality of the property than the other.

The SAS program performed an analysis of variance, or ANOVA, test. The ANOVA test used to compute and compare means for a complete set of data was Duncan's Multiple Range Test. This test ranked the data from greatest to least and grouped the values. The ANOVA test used to compute and compare means for an unbalanced or incomplete set of data was the least square means (LSMeans) test. This test did not rank or group the values; it only allowed two values to be compared to each other. The p-value, the probability that the sample would occur if the null hypothesis is true, and the mean of each mixture were compared to the other mixtures to determine a grouping. The null hypothesis is the statement that no significant difference occurs between the samples. A p-value close to zero signals that the null hypothesis is false and therefore a significant difference between the samples exists. A p-value close to one signals that the null hypothesis is true and therefore the samples are significantly similar (P-Value).

Confidence interval means that the results of the test fall within a standard deviation a certain percentage of the times that the test is performed. Alpha value and confidence interval add to 100%. The confidence interval was 95%, so that the alpha value was 5%. The alpha value was used to compare the mean values from the hardened concrete tests, or singular values from the fresh concrete tests. The p-values were determined from comparing two mixtures by the LSMeans test or the Duncan Grouping. When the calculated p-value was less than the chosen alpha value, the mean values were statistically different. The data must be normally distributed for the results of these tests to be valid. The Shapiro-Wilk test was used to determine normality. When data were not normally distributed they were ranked to induce normality and the ANOVA test was used on the ranked values.

Chapter 4 RESULTS AND DISCUSSION

4.1 General

The following is a presentation and discussion of the results from the experimental program. The studies are presented in the following order: cement study, supplementary cementitious material (SCM) study, and ground granulated blast furnace slag (GGBFS) study. The results and observations from the fresh concrete properties are presented first, followed by the hardened concrete results and observations. The mixtures are designated by cement brand, GGBFS replacement rate and grade, and FA replacement rate. For example, mixture A/20-120/0 contains cement A, 20% replacement with GR 120 GGBFS, and 0% replacement with Class C FA. The control mixtures, A/0/0 and B/0/0, contained 650 lb (295 kg) of cement, 1885 lb (855 kg) of coarse aggregate, 1155 lb (525 kg) of fine aggregate, and 295 lb (135 kg) of water. The statistics run on the different phases of the experimental program and referred to in the following discussion are described in Section 3.9 and included in Appendix D.

4.2 Cement Study

The cement study examined the interaction between the SCMs and two Type I cements. The fresh and hardened properties of mixtures containing cement A were compared to mixtures made with cement B. Five different mixtures were batched with cement A and cement B as described in Section 3.5. The control mixture design was made as described in Section 4.1.

4.2.1 Fresh Concrete Tests

The fresh concrete properties examined were slump, air content, concrete temperature, and unit weight. The values listed in Table 4.1 are the mean values of two batches for cement A and the actual values for cement B as described in Section 3.9. The not statistically different groupings were based on the statistical analysis as described in Section 3.9.

Table 4.1 Fresh Concrete Properties for Cement Study

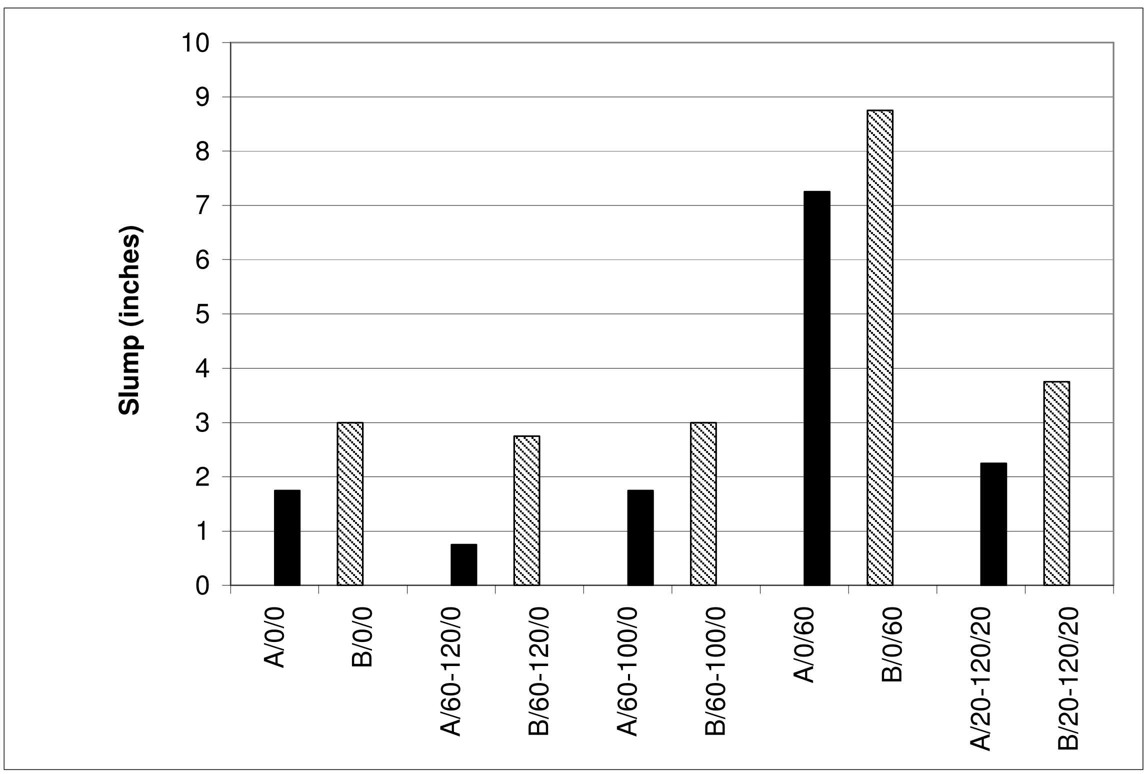
Mixture	Slump, in. (mm)	Unit Weight, lb/ft^3 (kg/m^3)	Air Content, %	Temperature, °F (°C)
A/0/0	1.75 (45)	151.5 (2426)	1.4	89.8 (32.1)
A/60-120/0	0.75 (20)	149.8 (2399)	1.6	72.5 (22.5)
A/60-100/0	1.75 (45)	148.8 (2384)	1.5	83.0 (28.3)
A/0/60	7.25 (185)	150.6 (2413)	0.6	71.7 (22.1)
A/20-120/20	2.25 (60)	150.1 (2404)	1.5	67.4 (19.6)
B/0/0	3.00 (80)	150.0 (2403)	1.7	80.0 (26.7)
B/60-120/0	2.75 (70)	148.7 (2382)	1.5	78.0 (25.6)
B/60-100/0	3.00 (80)	148.9 (2386)	1.2	82.0 (27.8)
B/0/60	8.75 (225)	148.9 (2386)	0.4	80.0 (26.7)
B/20-120/20	3.75 (95)	149.3 (2392)	1.3	80.0 (26.7)

4.2.1.1 Slump

The slump values for cement B were consistently higher than those of cement A. The statistical analysis showed that the mixtures made with cement A were significantly different than mixtures made with cement B. This difference in slump could be due to the cement brand fineness or reactivity. Even though differences in slumps existed between cement A and cement B mixtures, the values followed the trend as shown in Chart 4.1 and observed as follows:

- for cement B, the control mixture (B/0/0) had slump values similar to mixtures containing GGBFS, the addition of GGBFS had little effect on the ternary cement B mixtures,
- the addition of fly ash offset the negative effect of GGBFS on slump,
- the 60% FA mixtures resulted in more than two times higher slumps than the control mixtures for both cements,
- the 60%replacement with GR 120 GGBFS resulted in the lowest slumps for both cement A and cement B mixtures.

Chart 4.1 Slump Values for Cement Study



The 5.5 in. to 5.75 in. increase in slump over the control mixture shown by both batches with 60% FA replacements was consistent with literature. Fly ash particles are small and spherical which helps lubricate the mixture. The ternary

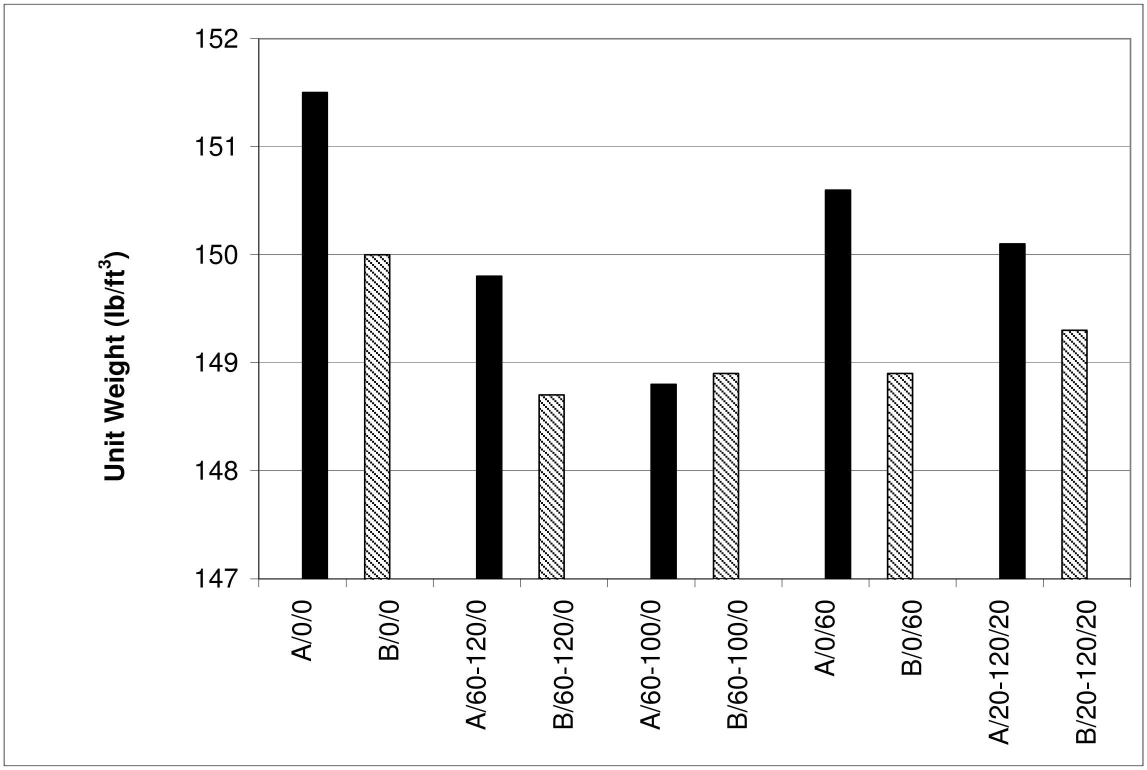
mixtures had less lubrication because of the smaller amount of FA replacement (20% vs. 60%). The fineness of GGBFS was not a big contributor to the slump in the results shown above. Typically, finer materials, such as GGBFS, reduce workability because of the increased surface area per unit volume created by the smaller particles, which absorbs more water than coarser particles such as cement.

4.2.1.2 Unit Weight

The unit weight of the cement A and cement B mixtures followed similar trends even though cement A produced higher unit weights than cement B. The control mixtures, which had only portland cement, had the highest unit weight. This trend was because cement has a higher specific gravity than GR 100 GGBFS, GR 120 GGBFS, and Class C FA. For the ternary mixtures, 40% of the cement was replaced with materials having lower specific gravity than cement, which results in a lower unit weight. The 60% replacement mixtures followed the same trend. The trends observed from the data and Chart 4.2 were as follows:

- the control mixtures had the highest unit weights,
- the ternary mixtures had the second highest unit weights, and
- the 60% replacements (except A/0/60) had the lowest unit weights.

Chart 4.2 Unit Weight Values for Cement Study

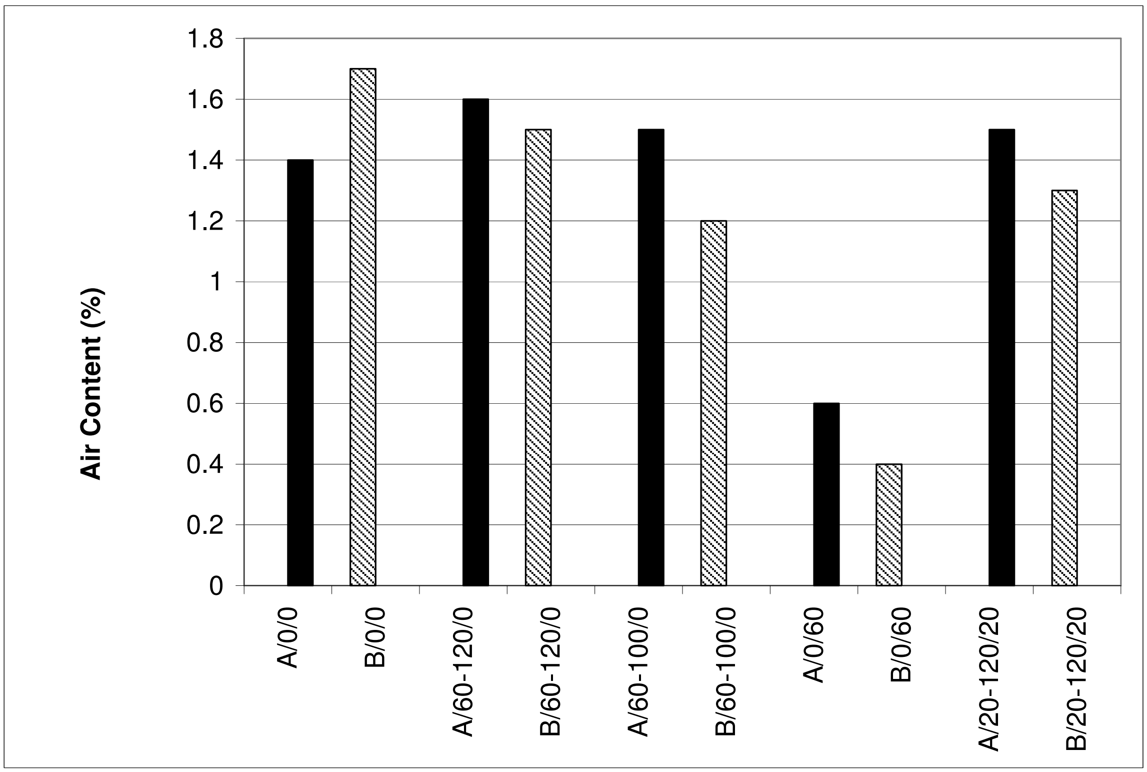


4.2.1.3 Air Content

The air contents of the ten mixtures were consistent with the exception of the FA batches. The air contents ranged from 0.4 to 1.7% with 8 out of 10 mixtures having air contents between 1.2 to 1.7%. The addition of FA lowered the air content by more than half when compared to the control mixtures. The improved workability, without the addition of air entraining agents, has allowed the particles to pack more closely (Mindess et al. 2003). Because no air entraining agents were used, the air content was only due to entrapped air. A non-air entrained mixture typically entraps 0.5% to 3.0% air (Mindess et al. 2003). The control mixtures and the mixtures with GGBFS were able to retain more entrapped air than the FA mixtures. The trends from Chart 4.3 and the data were observed as follows:

- the cement A mixtures (except for the control mixture) had higher air content than the cement B mixtures,
- the 60% FA mixtures had the lowest air content, and
- the air contents for 8 out of 10 mixtures were typical of non-air entrained concrete mixtures.

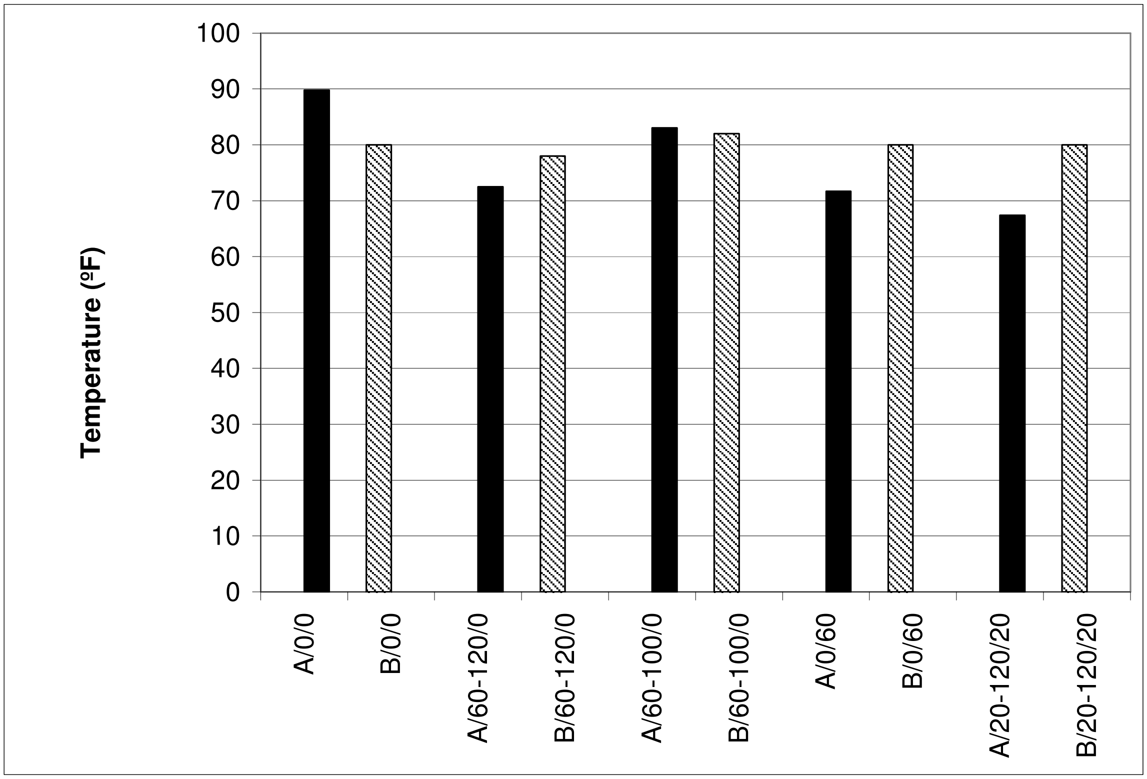
Chart 4.3 Air Content Values for Cement Study



4.2.1.4 Concrete Temperature

The fresh concrete temperature was used for quality control purposes. The temperature was a result of the temperature of the materials before mixing and the ambient temperature during mixing instead of from the hydration processes. The fresh concrete temperature ranged from 67.4 to 89.8 °F (19.6 to 32.1 °C) as shown in Chart 4.4.

Chart 4.4 Temperature Values for Cement Study



4.2.2 Hardened Concrete Tests

The hardened concrete tests performed for the cement study were compressive strength, rapid chloride ion penetrability test (RCPT), and freeze/thaw durability. The compressive strength values listed in Table 4.2 are the mean values of six samples for cement A mixtures and the mean of three samples for cement B mixtures as described in Section 3.9. The RCPT and durability factor values listed in Table 4.3 are the mean values of four samples for RCPT and freeze/thaw durability for cement A mixtures. For cement B two samples were tested for RCPT and freeze/thaw durability as described in Section 3.9. The not statistically different groupings were based on the statistical analysis as described in Section 3.9

4.2.2.1 Compressive Strength

Table 4.2 Compressive Strength (psi) for Cement Study

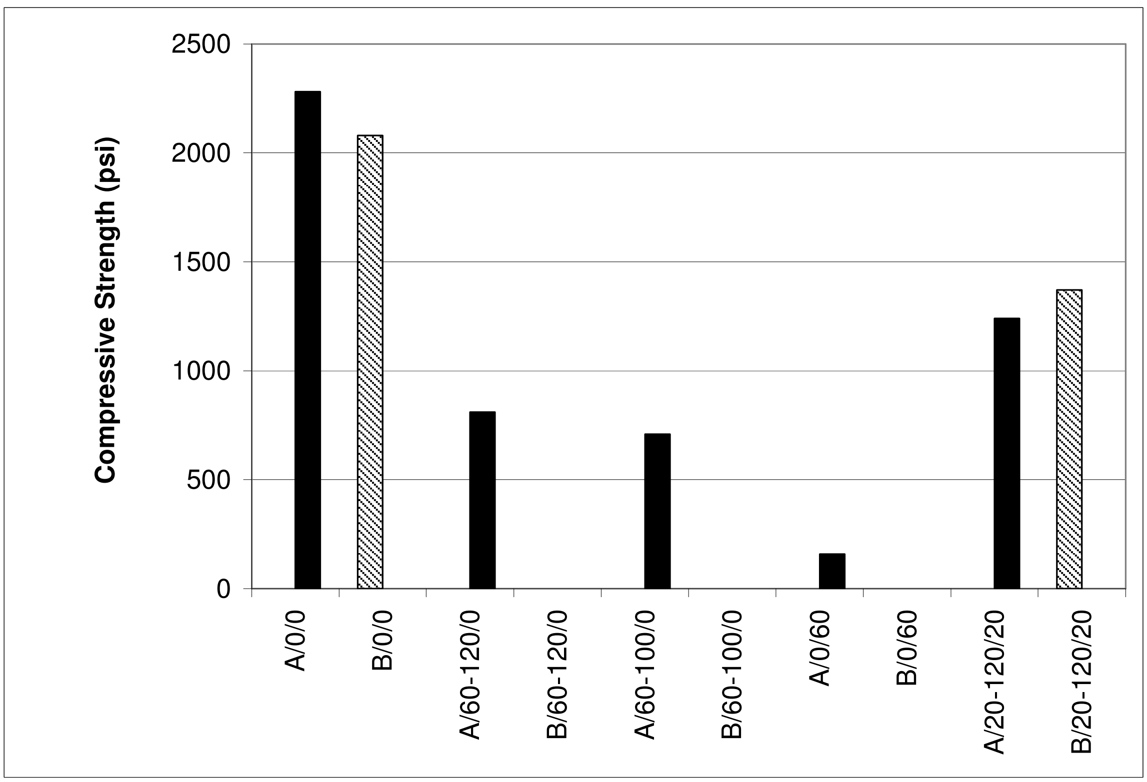
Mixture Design	1 Day	3 Days	7 Days	28 Days	90 Days
A/0/0	2280	5290	6520	7840	8250
A/60-120/0	810	3130	5150	6910	7920
A/60-100/0	710	2320	4590	7270	8090
A/0/60	160	1010	4250	7610	9480
A/20-120/20	1240	4230	6510	8600	10020
B/0/0	2080	3960	4980	6340	7850
B/60-120/0	0	2910	4630	6400	6950
B/60-100/0	0	1820	4330	5830	7870
B/0/60	0	1770	3710	6010	7780
B/20-120/20	1370	4120	5640	7290	8330

The control mixtures, A/0/0 and B/0/0, had the highest one-day compressive strength. The literature suggested that the 100% portland cement mixtures would gain strength more rapidly than the SCM. This was due to the SCM participating in the secondary reaction in concrete, as described in Section 2.6.1, and the cement participating in the primary reaction. The ternary mixtures, A/20-120/20 and B/20-120/20, had the second highest one day compressive strength, but were still 710 to 1040 psi (34 to 46%) less than the control mixtures. The 60% replacements of each SCM for cement A were strong enough to test at one day, even though the strengths measured were very low. The 60% replacements of each SCM for cement B were not strong enough to test at one day, which may indicate that cement A mixtures reacted differently with the SCMs and reduced setting times. The zero values resulted because the concrete was not strong enough to be de-molded. The trends from the data and seen in Chart 4.5 from the one day data were observed to be as follows:

- the control mixtures had the highest strength,

- the ternary mixtures had the second highest strength,
- at high replacement rates, GGBFS mixtures produced higher strengths (at one day) with GR 120 performing better than GR 100,
- the cement A mixtures achieved higher one day strengths than cement B mixtures (except for the ternary mixture), and
- the 60% replacements of FA for cement B mixtures significantly delayed time to setting.

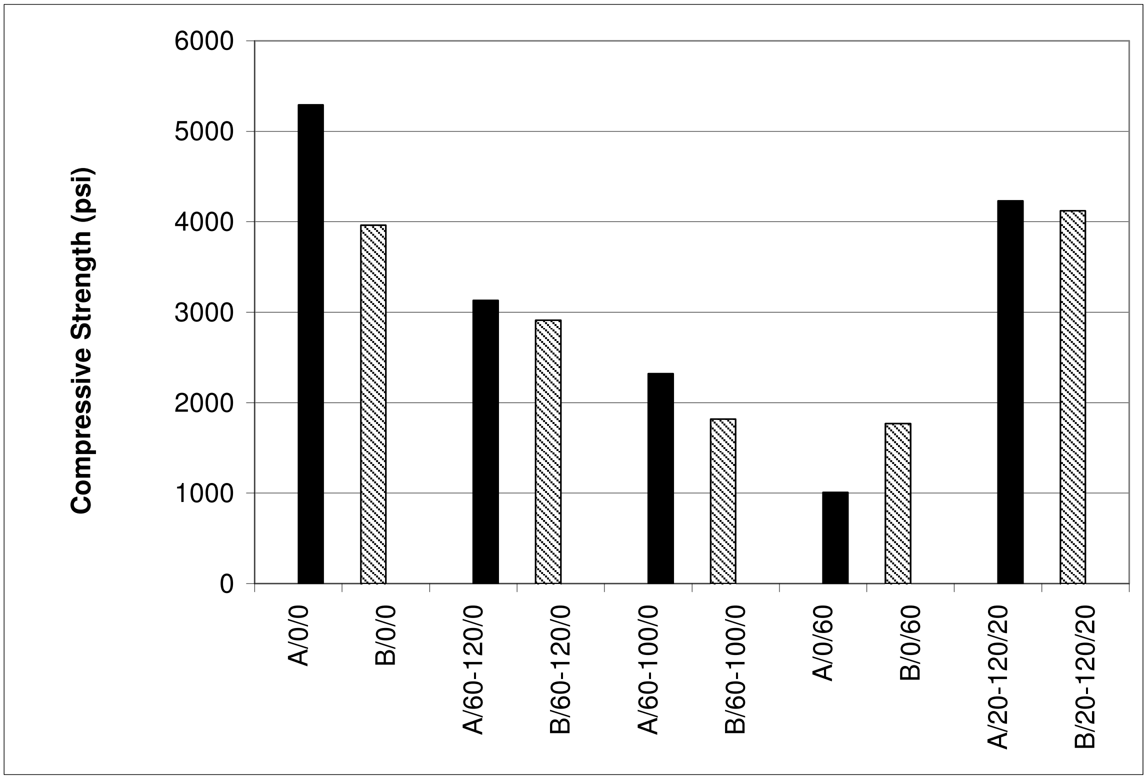
Chart 4.5 One Day Compressive Strength Values for Cement Study



Statistical analysis on the three-day compressive strengths showed that for each replacement rate the cement A and cement B mixtures had not statistically different compressive strengths (i.e. the cements were interchangeable for strength gain at 3 days). The control mixtures (A/0/0 and B/0/0) also had not statistically different compressive strengths to the ternary mixtures (A/20-120/20 and B/20-120/20) with a difference of 20% and 4% respectively. At one day the ternary mixtures were statistically different than the control mixtures and at 3 days they were similar, which suggests that the ternary mixtures gained strength more rapidly with time. The 60% SCM replacements had 26 to 81% less strength than the control mixtures. The trends observed from the statistics and Chart 4.6 were as follows:

- the control mixtures and the ternary mixtures produced higher strength than the 60% replacements,
- the ternary mixtures produced comparable compressive strength to the control mixtures,
- for mixtures containing 60% SCMs, the GR 120 GGBFS had the greatest strength followed by the GR 100 GGBFS and then the FA,
- the cement A and cement B mixtures produced comparable compressive strength for mixtures containing SCMs, but the control mixtures were significantly different, and
- the 60% SCM cement B mixtures were similar to the cement A mixtures by three-day tests.

Chart 4.6 Three Day Compressive Strength Values for Cement Study



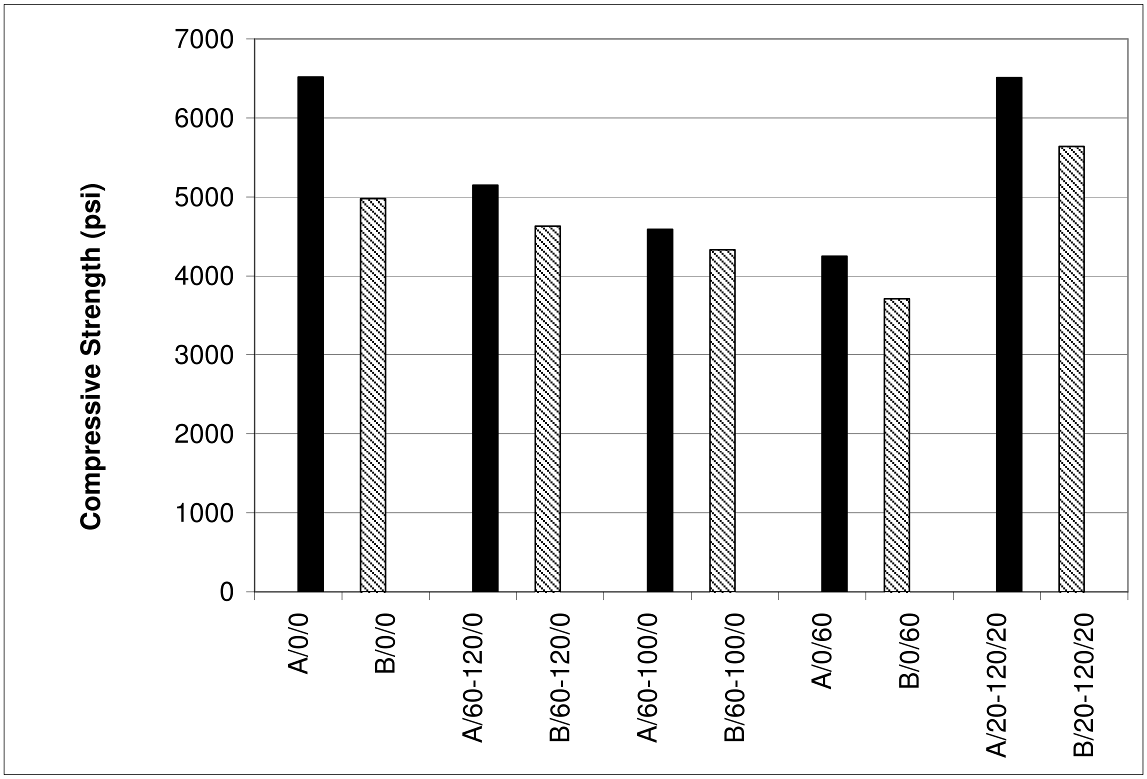
Compressive strength tests on the seventh day showed the cement A control mixture (A/0/0) had the greatest strength at 6520 psi. The cement A ternary mixture (A/20-120/20) had 0.1% less strength than the control mixture. The third greatest seven-day compressive strength was the cement B ternary mixture (B/20-120/20) that had 14% less compressive strength than the A/0/0 mixture. The cement B control mixture (B/0/0) and mixture A/60-120/0 were not statistically different. They had 23 and 21% less compressive strength than the A/0/0 mixture. The B/60-120/0, A/60-100/0, B/60-100/0, A/0/60, and B/0/60 mixtures had a range of seven-day compressive strengths of 4630 to 3710 psi. At this stage of the hydration process, it is once again obvious that the two cement sources were different in their level of strength gain, but had similar trends in compressive strength concerning the replacement rates.

The trends at seven-day compressive strength tests from the data and Chart 4.7 were as follows:

- cement A control mixture and the ternary mixtures (both cements) had the greatest compressive strengths,
- the order of greatest to least strength for 60% replacements of both cements was: GR 120 GGBFS, GR 100 GGBFS, then FA, and
- cement A strengths were not statistically different to the cement B strengths.

These trends were consistent with the literature (Section 2.2 and Section 2.3) that showed FA mixtures gained strength slower than GGBFS and 100% portland cement mixtures. GR 120 GGBFS had greater strength gain than the GR 100 GGBFS due to the increase in reactivity. The similar trends also show that the replacements of cement with the SCMs were similarly compatible with different cement sources.

Chart 4.7 Seven Day Compressive Strength Values for Cement Study

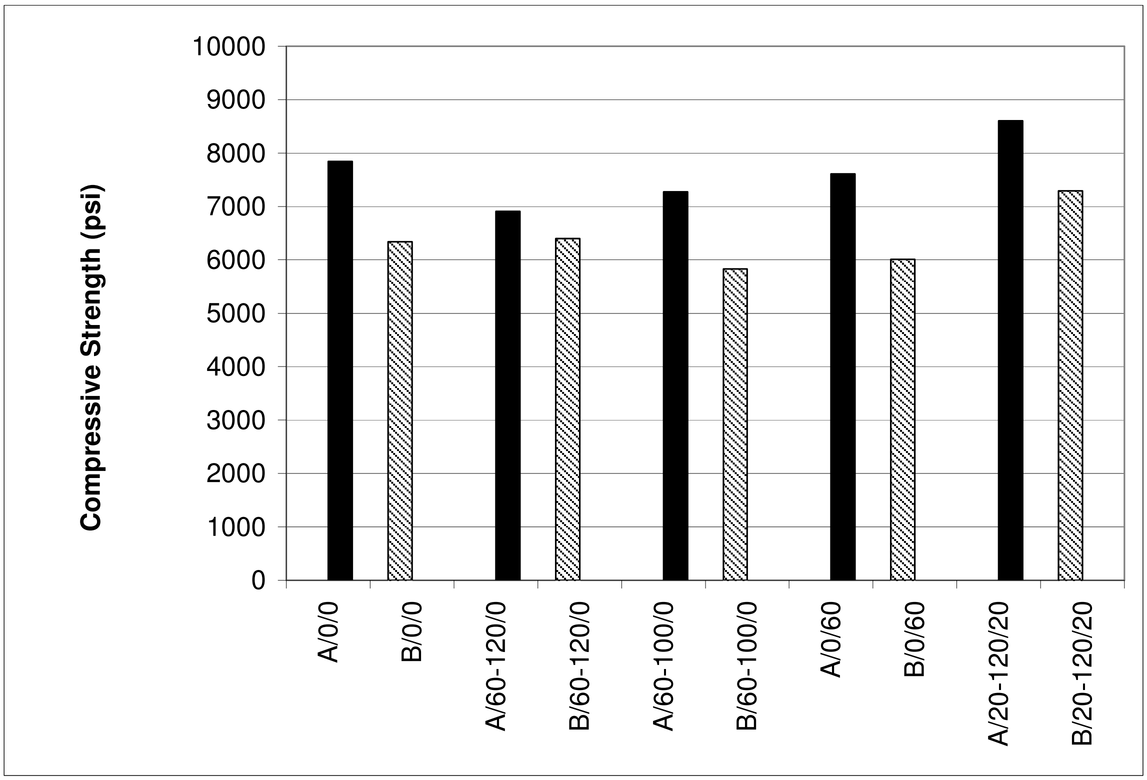


Twenty-eight day compressive strength results showed that the ternary mixtures gained more strength than the corresponding control mixture. The cement A ternary mixture, A/20-120/20, had the greatest twenty-eight day compressive strength at 8600 psi. The cement B ternary mixture, B/20-120/20, had the greatest twenty-eight day compressive strength of the cement B mixtures with 7290 psi but was 15% less than the A/20-120/0 mixture. The trends in the data and Chart 4.8 were observed as follows:

- the ternary mixtures had the highest strength for each type of cement,
- the cement A mixtures had higher strengths when compared to like cement B mixtures,

- for cement A mixtures containing 60% SCM the order of greatest to least strength was: FA, GR 100 GGBFS, then GR 120 GGBFS, and
- for cement B mixtures containing 60% SCM the order of greatest to least strength was: GR 120 GGBFS, FA, then GR 100 GGBFS.

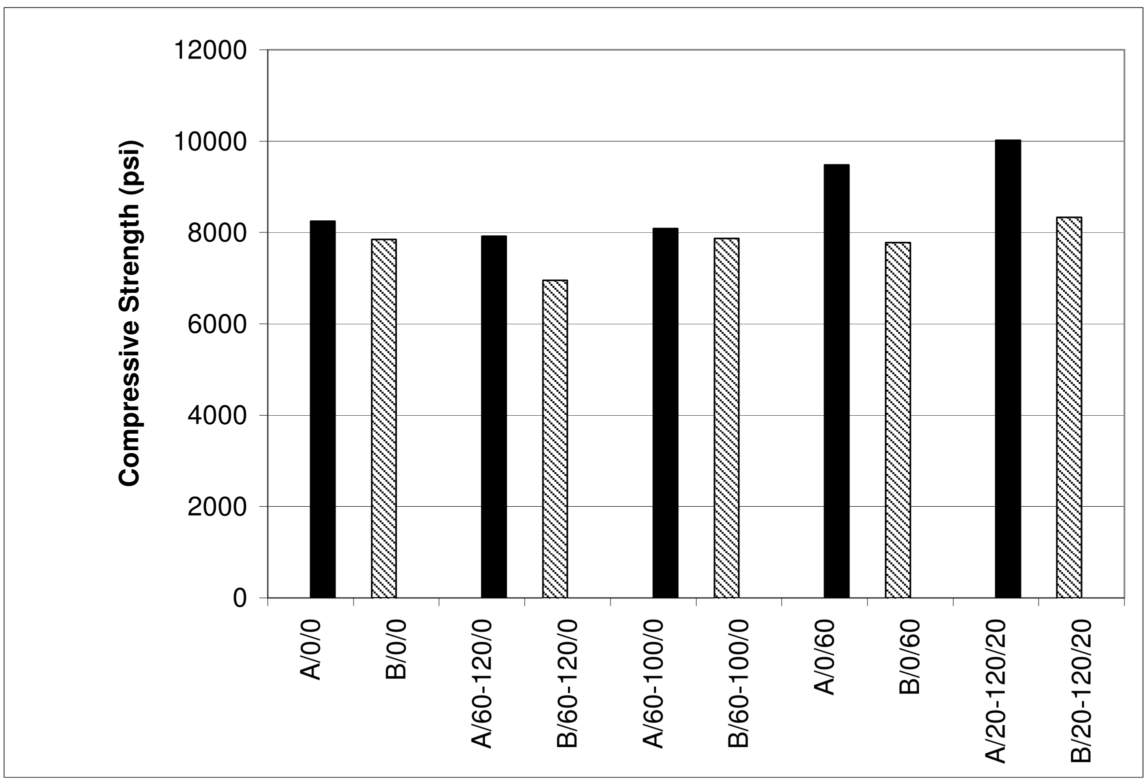
Chart 4.8 Twenty-eight Day Compressive Strength Values for Cement Study



The ternary mixture for cement A (A/20-120/20) had the greatest ninety-day strength with 10020 psi. The second highest compressive strength was A/0/60 with 9480 psi which was 5% less than the ternary mixture. The ternary mixture for cement B (B/20-120/20) had the highest ninety-day strength for cement B mixtures with 8330 psi. The B/20-120/20 mixture had 17% less compressive strength than the A/20-120/20 mixture. Cement A reacted better with the SCMs than cement B and produced higher strength at 90 days. The trends observed from the data and Chart 4.9 were as follows:

- the ternary mixtures had the highest strength for both types of cement,
- the order of greatest to least strength for 60% replacements of cement A was: FA, GR 100 GGBFS, then GR 120 GGBFS, and
- the order of greatest to least strength for 60% replacements of cement B was: GR 100 GGBFS, FA, then GR 120 GGBFS.

Chart 4.9 Ninety Day Compressive Strength Values for Cement Study



The cement study suggested that the two sources of cement did not create the same compressive strengths with the same replacement mixtures. They, however, had similar trends in mixtures with similar replacements of cement. The replacements of

SCM produced similar decreases in compressive strength in early tests and similar increases in compressive strength in ninety-day tests.

4.2.2.2 Rapid Chloride Ion Penetrability

The Rapid Chloride Ion Penetrability Test (RCPT) as described in Section 2.6.2 measured the permeability of the hardened concrete mixtures. The results from the test are shown in Table 4.3. Also shown in Table 4.3 is the permeability classification from ASTM C1202 based on the number of coulombs passed.

Table 4.3 RCIP and Freeze/Thaw Results for Cement Study

Mixture Design	RCPT 28 Days, coulomb	Chloride Ion Penetrability	RCPT 90 Days, coulomb	Chloride Ion Penetrability	Freeze/ Thaw Durability, DF
A/0/0	4265	High	3611	Moderate	2.32
A/60-120/0	937	Very Low	565	Very Low	23.08
A/60-100/0	480	Very Low	398	Very Low	0.6
A/0/60	2411	Moderate	1030	Low	18.99
A/20-120/20	1238	Low	735	Very Low	42.52
B/0/0	1568	Low	1442	Low	3.15
B/60-120/0	821	Very Low	669	Very Low	7.19
B/60-100/0	533	Very Low	341	Very Low	14.84
B/0/60	1236	Low	1436	Low	8.99
B/20-120/20	1473	Low	644	Very Low	4.53

At 28 days there was a noticeable difference in the permeability results of the two control mixtures. Results in Chart 4.10 and the statistical analysis show that the twenty-eight day permeability of the cement A control mixture was significantly greater than the cement B control mixture. The permeability of the cement B control mixture was less than the cement A control mixture. The A/0/0 mixture had higher compressive strength, higher unit weight, and lower air content, all of which suggests that it had formed a more dense structure than the B/0/0 mixture. Several factors that could override the theoretical basis for the accuracy of the RCPT were the relative resistances of the two cement sources and the microscopic saturation of the samples. Two trends were noticed between 28 day data and 90 day data. Mixture A/0/0 passed 4265 coulombs and had high permeability while mixture B/0/0 passed 1568 coulombs and had low permeability. Another trend in the data was that the 60% GR 100 GGBFS mixtures passed the least coulombs.

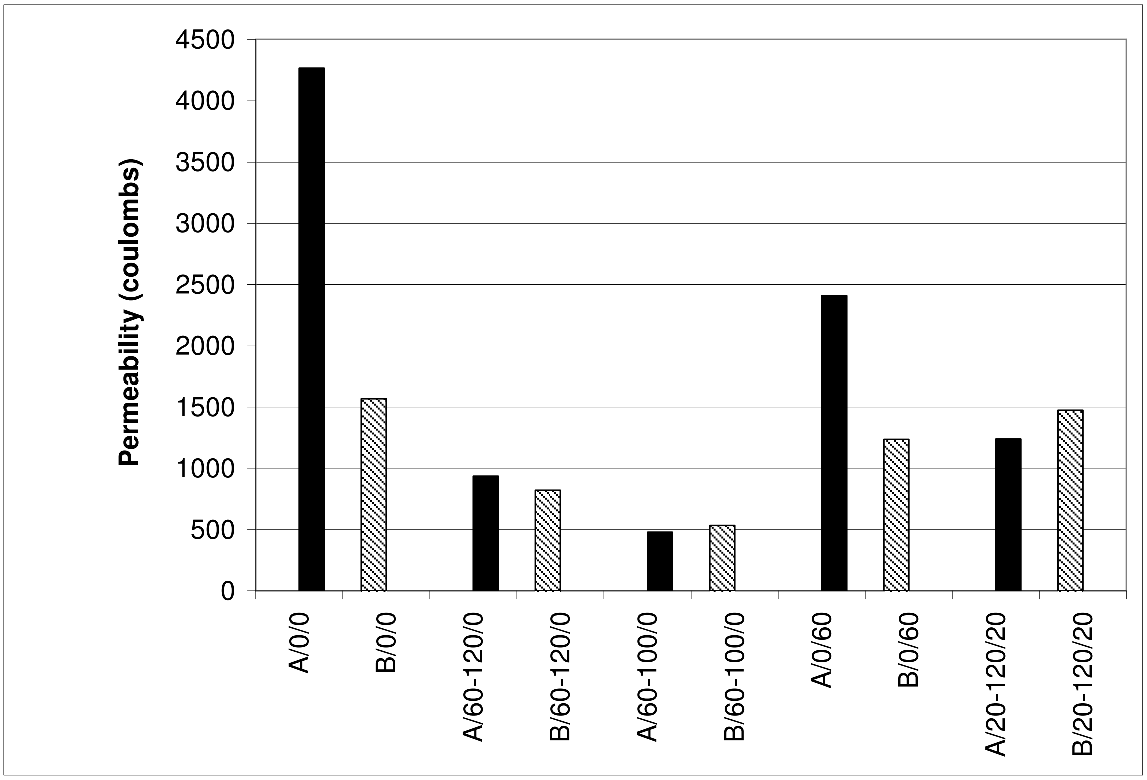
The addition of 60% GGBFS lowered the permeability of both the cement A and cement B control mixtures at 28 days by 48 to 89% when compared to their respective control mixtures. The mixtures with 60% GGBFS also saw reductions in permeability from the mixtures with 60% replacement of FA by 34 to 80%. Shi et al also found that GGBFS reduces permeability from a control mixture more than FA (Shi et al, 2003). The 60% GR 100 GGBFS mixtures also saw reductions in permeability of comparable replacements of GR 120 GGBFS by 35 to 48%. This could be because of the difference in reactivity between the SCMs. Even though the GR 120 GGBFS should produce better results than the GR 100, the different processing procedures, storage, source, and many other factors could lend better productivity to the GR 100 GGBFS. The manufacturers of the GR 100 GGBFS could also try to market their product as a GR 100/GR 120 GGBFS.

The trends observed from Chart 4.10 were as follows:

- the ternary mixtures , B/0/0, and A/0/60 low permeability,
- when compared to the control mixtures, the addition of GR 120 GGBFS reduced permeability, and

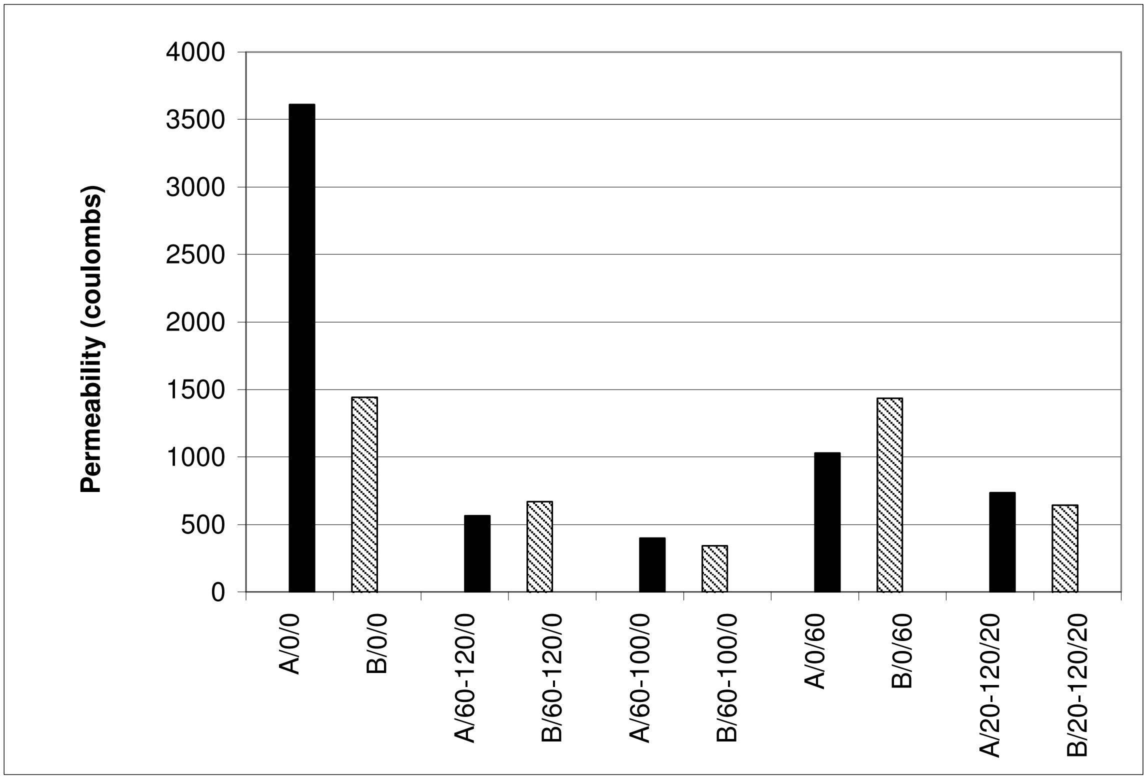
- mixtures containing GR 100 GGBFS passed fewer coulombs than like mixtures containing GR 120 GGBFS.

Chart 4.10 Twenty-eight Day Permeability Values for Cement Study



The ninety-day test results were lower than the twenty-eight day test results for all of the mixtures. The ninety-day permeability of cement A's control mixture was 2.5 times larger than the cement B control mixture. This trend was also observed at 28 days. Other cement A mixtures had 12 to 28% less permeability from the cement B mixtures. All mixtures containing GGBFS had not statistically different ninety-day permeability and were all also classified as having very low permeability by the ASTM 1202. The control and 60% FA mixtures had greater permeability, the ternary mixture had mid-range permeability, and the GGBFS mixtures had the lowest permeability, as shown in Chart 4.11.

Chart 4.11 Ninety Day Permeability Values for Cement Study

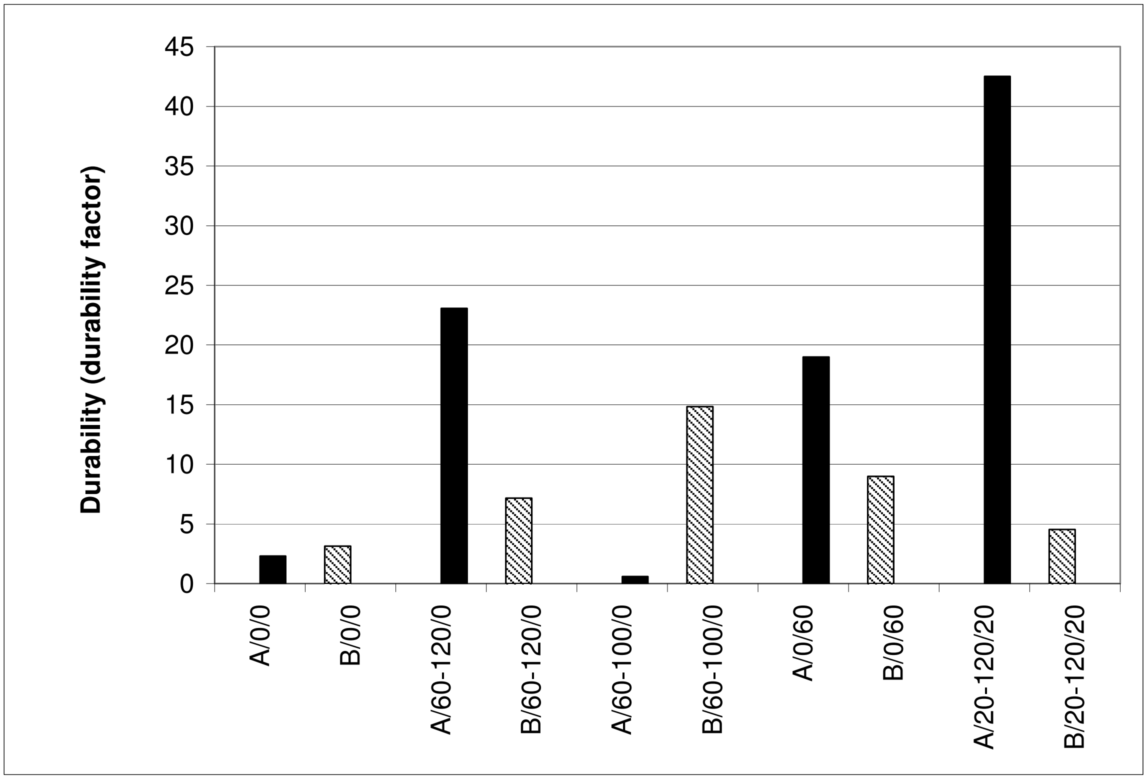


4.2.2.3 Freeze/Thaw Durability

The resonance frequency was monitored for each sample at each test and recorded as shown in Appendix A. The durability factor was determined from the last frequency recorded from each sample or near 300 cycles as per ASTM 666 (AASHTO T 161). Pictures of the freeze/thaw samples at end of testing or failure are shown in Appendix B. The results in Table 4.3 include the calculated durability factors of the concrete mixtures used in the cement study. The control mixtures, the 60% replacements of GR 120 GGBFS, the 60% replacements of GR 100 GGBFS, and the 60% replacements of FA for cement A and cement B were not statistically different for the comparable mixtures. Most researchers agree that a durability factor of 60 is adequate for freeze/thaw durability. The mixtures tested were not expected to reach a durability factor of 60 because they had no air entrainment. As described in Chapter 3, chemical admixtures were not added to the mixtures to observe the SCM's effects on the fresh and hardened properties without interference from chemical admixtures. The approximately 40 point difference between the ternary mixtures suggests that the testing of one of the groups of samples was not accurate.

The durability factors of the control mixtures were significantly similar to each other and were the lowest. The 60% replacements of GR 100 GGBFS were significantly similar and had the next smallest durability factor. The 60% replacements of FA were significantly similar and had the next higher durability factor. The 60% replacements of GR 120 GGBFS were marginally not statistically different, where the p-values in the LSMeans test were above but still very close to alpha of 0.05. The ternary mixtures were statistically different. The data and Chart 4.12 did not show a trend between the two sources of cement other than cement A mixtures had greater durability factors for three out of five mixtures.

Chart 4.12 Freeze/Thaw Durability Values for Cement Study



4.3 Supplementary Cementitious Material Study

The SCM study was designed to analyze the fresh and hardened properties of concrete mixtures with differing amounts of GGBFS, FA, or combinations of both materials. One source of Type I cement, a w/cm of 0.45, and no chemical admixtures were used in this study in order to determine the properties directly related to the change in SCMs. Twenty-two mixture designs were batched with cement A and correspond to the mixture designs in Section 3.6. The control mixture was made to the proportions described in Section 4.1.

4.3.1 Fresh Concrete Tests

The fresh concrete properties examined were slump, air content, concrete temperature, and unit weight. The values listed in Table 4.4 are the mean values of two batches as described in Section 3.9. The not statistically different groupings were based on the statistical analysis as described in Section 3.9.

Table 4.4 Fresh Concrete Properties for SCM Study

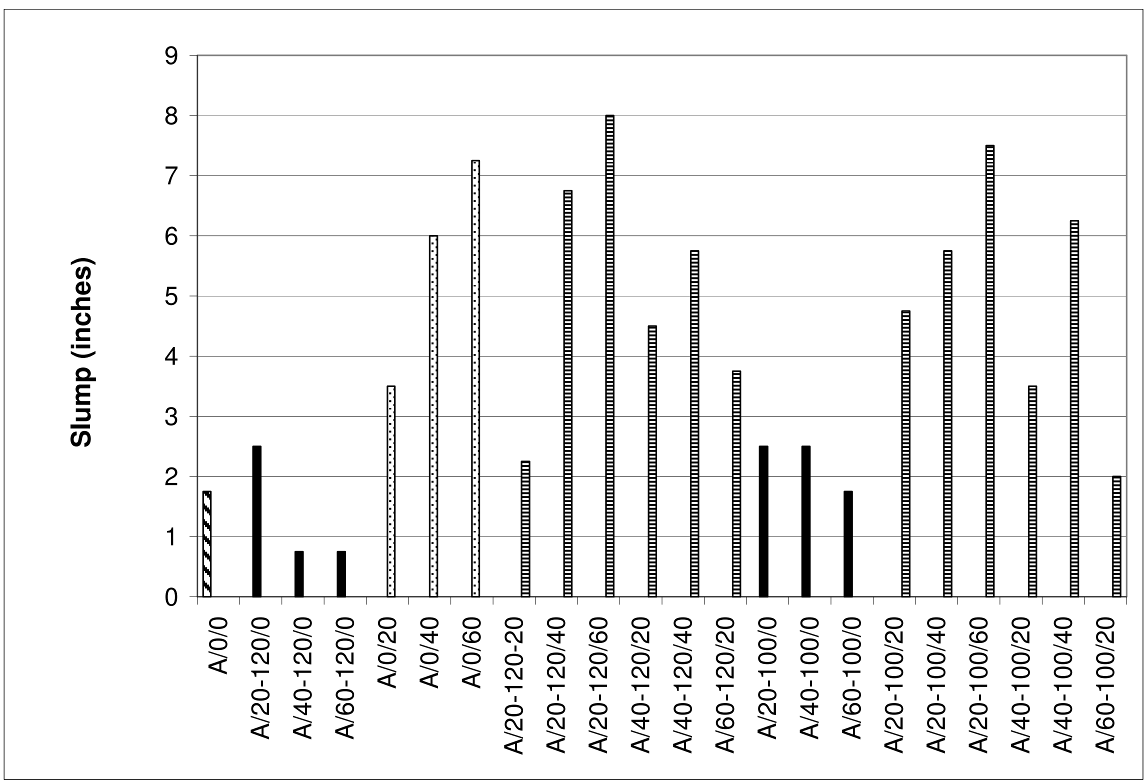
Mixture	Slump, in. (mm)	Unit Weight, lb/ft^3 (kg/m^3)	Air Content, %	Temperature, °F (°C)
A/0/0	1.75 (45)	151.5 (2426)	1.4	89.8 (32.1)
A/20-120/0	2.50 (65)	149.6 (2397)	1.5	81.8 (27.6)
A/40-120/0	0.75 (20)	150.5 (2410)	1.5	68.5 (20.3)
A/60-120/0	0.75 (20)	149.8 (2399)	1.6	72.5 (22.5)
A/0/20	3.50 (90)	150.3 (2408)	1.0	75.6 (24.3)
A/0/40	6.00 (150)	151.1 (2421)	0.9	74.0 (23.4)
A/0/60	7.25 (185)	150.6 (2413)	0.6	71.7 (22.1)
A/20-120/20	2.25 (60)	150.1 (2404)	1.5	67.4 (19.6)
A/20-120/40	6.75 (70)	150.8 (2416)	1.1	61.1 (16.2)
A/20-120/60	8.00 (205)	149.8 (2399)	0.5	61.0 (16.1)
A/40-120/20	4.50 (115)	149.1 (2388)	1.5	69.6 (20.9)
A/40-120/40	5.75 (205)	149.7 (2398)	1.1	81.5 (27.5)
A/60-120/20	3.75 (95)	149.2 (2390)	1.3	69.4 (20.8)
A/20-100/0	2.50 (65)	151.5 (2428)	1.6	82.4 (28.0)
A/40-100/0	2.50 (65)	149.5 (2395)	1.3	80.4 (26.9)
A/60-100/0	1.75 (45)	148.8 (2384)	1.5	83.0 (28.3)
A/20-100/20	4.75 (120)	150.5 (2412)	1.3	85.2 (29.6)
A/20-100/40	5.75 (145)	150.0 (2403)	0.8	77.0 (25.0)
A/20-100/60	7.50 (190)	150.1 (2405)	0.5	79.0 (26.1)
A/40-100/20	3.50 (90)	148.8 (2384)	1.2	84.0 (28.9)
A/40-100/40	6.25 (160)	149.5 (2395)	0.8	84.8 (29.3)
A/60-100/20	2.00 (50)	149.7 (2399)	1.4	76.5 (24.7)

4.3.1.1 Slump

The slump values recorded for the SCM study are listed in Table 4.4. The control mixture had one of the lowest slumps which was 1.75 in. The highest slumps were recorded in mixtures A/20-120/60, A/20-100/60, A/0/60, A/20-120/40, and A/40-100/40 with slumps ranging from 8 in. (190 mm) to 6.25 in. (158.75 mm), The mixtures with the lowest slumps were A/20-100/0, A/20-120/0, A/40-100/0, A/20-120/20, A/60-100/20, A/60-100/0, A/0/0, A/40-120/0, and A/60-120/0. These mixtures were not statistically different with slumps ranging from 2.5 in. (63. 5 mm) to 0.75 in. (19.05 mm), respectively. The trends observed from the data analysis and Chart 4.13 were as follows:

- the mixtures with high replacements of FA and low replacements of GGBFS had the greatest slumps,
- the mixtures with high replacements of GGBFS and low replacements of FA had the lowest slumps, and
- the mixtures with mid-range replacements of GGBFS or FA had mid-ranged slump values.

Chart 4.13 Slump Values for SCM Study



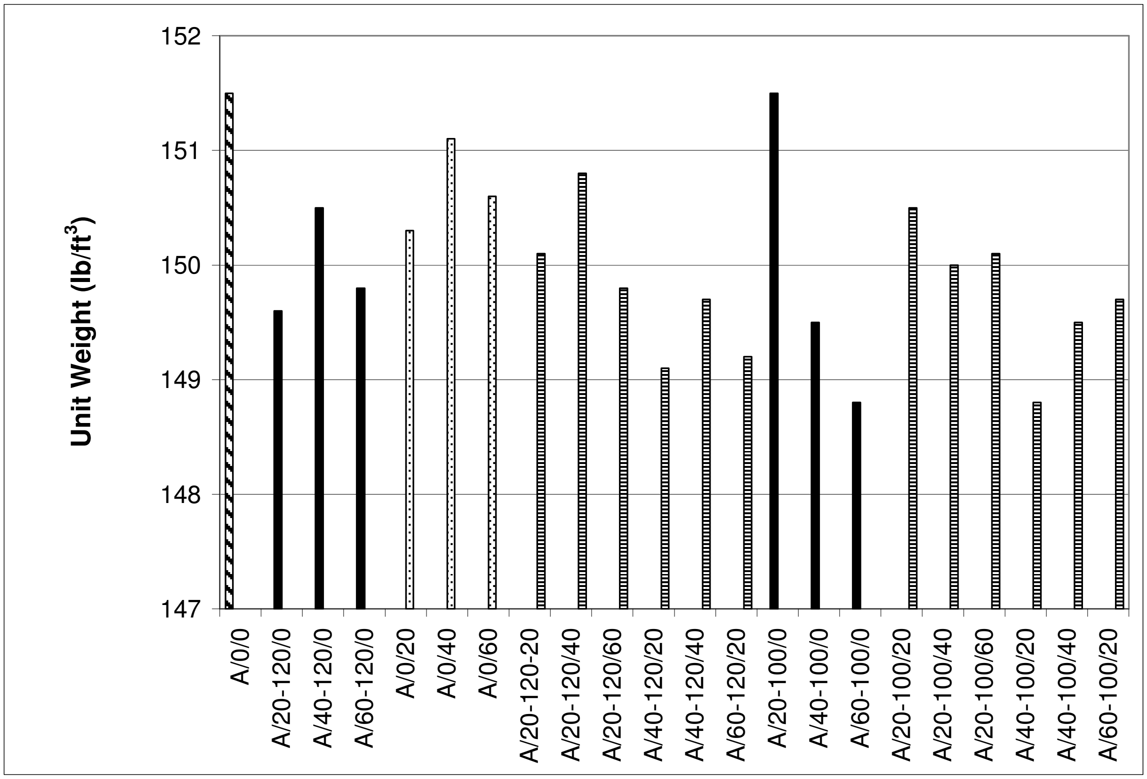
Trends from this study were consistent with the previous research that suggests that the addition of FA increases workability through the small, spherical particles

(Mindess et al. 2003). The literature also showed that the GGBFS would likely decrease slump from the control mixture because of the increase in surface area created by the finely crushed angular particles created when slag is ground to increase reactivity (Mindess et al. 2003). This study shows that the high replacements of FA will produce greater slump than comparable GGBFS mixtures. There was also not a large difference in slump at the 20% replacement level.

4.3.1.2 Unit Weight

The unit weight values are listed in Table 4.4 and shown in Chart 4.14. The unit weights ranged from 148.8 to 151.5 lb/ft^3. The unit weights did not follow a specific trend. The 20% replacement of GR 100 GGBFS had the highest unit weight and the 40% replacement of GR 100 GGBFS had a low unit weight while the opposite was found of the 20% and 40% replacements of GR120 GGBFS. Overall, the unit weights did not vary more than 2% from greatest to least.

Chart 4.14 Unit Weight Values for SCM Study



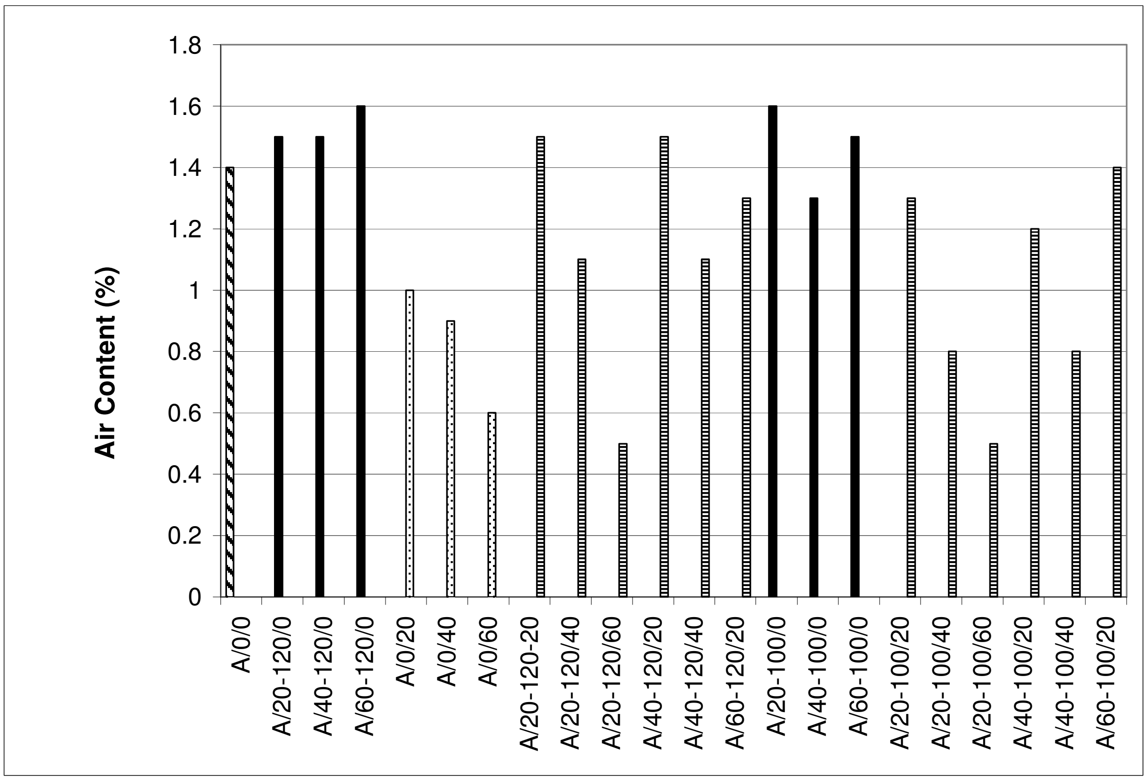
4.3.1.3 Air Content

The air content values recorded for the SCM study are listed in Table 4.4. The air contents of these mixtures ranged from 0.5 to 1.6% with the majority of the mixtures having an air content between 1.0 and 1.5%. These mixtures did not contain an air-entraining admixture (AEA). This study was conducted without the use of AEA in order to reduce the likelihood of the AEA having an adverse reaction on the fresh and hardened properties as noted in Section 3.7.1 . Therefore, the air content in the concrete was the result of entrapped air and not entrained air. Mixtures without AEA normally entrap 0.5 to 3.0% air (Mindess et al 2003).

The trends observed in the data and Chart 4.15 were as follows:

- an increase in GGBFS content resulted in similar or higher air content, and
- an increase in FA reduced the air content.

Chart 4.15 Air Content Values for SCM Study

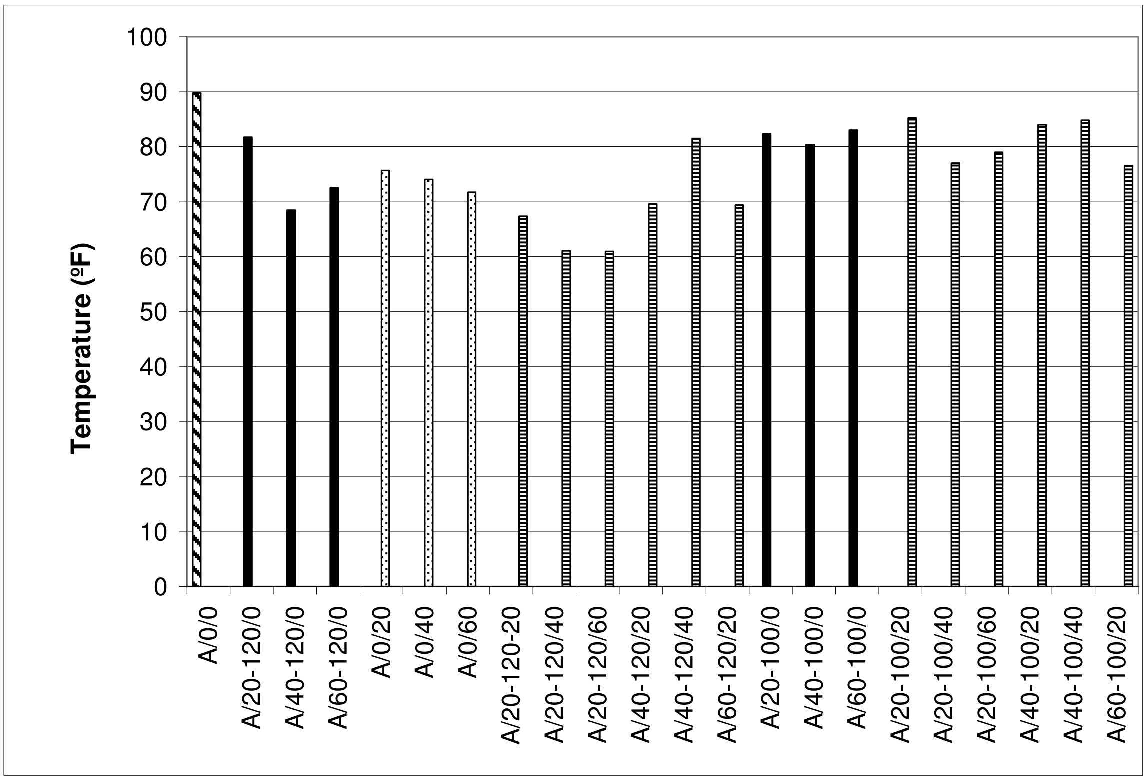


Reduction in air content with increases in FA content correlates with the increased workability observed in the FA mixtures. As discussed in the literature review section, both events could be directly related to the spherical shape of the FA particles. The smooth, round particles would allow entrapped air to easily escape; unlike the crushed and jagged particles of the cement and GGBFS that would entrap more air.

4.3.1.4 Concrete Temperature

The concrete temperature values recorded are listed in Table 4.4 and shown in Chart 4.16. As described in Section 4.2.1.3, the concrete temperature was only recorded as a quality control value. The temperatures ranged from 61.0°F (16.1°C) to 89.8°F (32.1°C).

Chart 4.16 Temperature Values for SCM Study



4.3.2 Hardened Concrete Property Tests

The hardened concrete tests performed for the SCM study were compressive strength, rapid chloride ion penetrability test (RCPT), and freeze/thaw durability. The values listed in Table 4.5 are the mean values of six samples for compressive strength of cement A samples as described in Section 3.9. The values listed in Table 4.6 are the mean values of four samples each for RCPT and freeze/thaw durability for cement

A samples as described in Section 3.9. The grouping was based on the statistical analysis as described in Section 3.9.

4.3.2.1 Compressive Strength

Table 4.5 Compressive Strength (psi) for SCM Study

Mixture Design	1 Day	3 Days	7 Days	28 Days	90 Days
A/0/0	2280	5290	6520	7840	8250
A/20-120/0	2050	4260	5730	7120	8380
A/40-120/0	1320	3920	5830	7660	8890
A/60-120/0	810	3130	5150	6910	7920
A/0/20	1230	4120	6340	7910	9030
A/0/40	900	3650	6110	8090	9270
A/0/60	160	1010	4250	7610	9480
A/20-120/20	1240	4230	6510	8600	10020
A/20-120/40	250	2070	4680	7890	10110
A/20-120/60	0	90	1160	4500	7480
A/40-120/20	1980	2740	4660	7150	8730
A/40-120/40	0	0	3310	5770	7490
A/60-120/20	0	1890	3790	6730	7630
A/20-100/0	1840	4020	5720	6370	8630
A/40-100/0	1240	3510	7270	8430	9150
A/60-100/0	710	2320	4590	7270	8090
A/20-100/20	1160	3740	6050	9030	10170
A/20-100/40	320	2110	3860	7030	9800
A/20-100/60	0	0	830	2840	6350
A/40-100/20	560	-	4240	8350	9910
A/40-100/40	0	890	1840	5000	7610
A/60-100/20	0	1200	3180	7350	8480

Compression test results for the SCM study are listed in Table 4.5. Some of the one day and three day results were recorded as zero because these mixtures had not achieved enough strength to be demolded or tested. These mixture designs produced very weak early strength concrete mainly due to the high percentage (80%) replacements of cement with the SCMs. As noted in Section 2.6.1, the 80%

replacement of cement with GGBFS and FA reduced the early age strength of the concrete (Mindess et al. 2003).

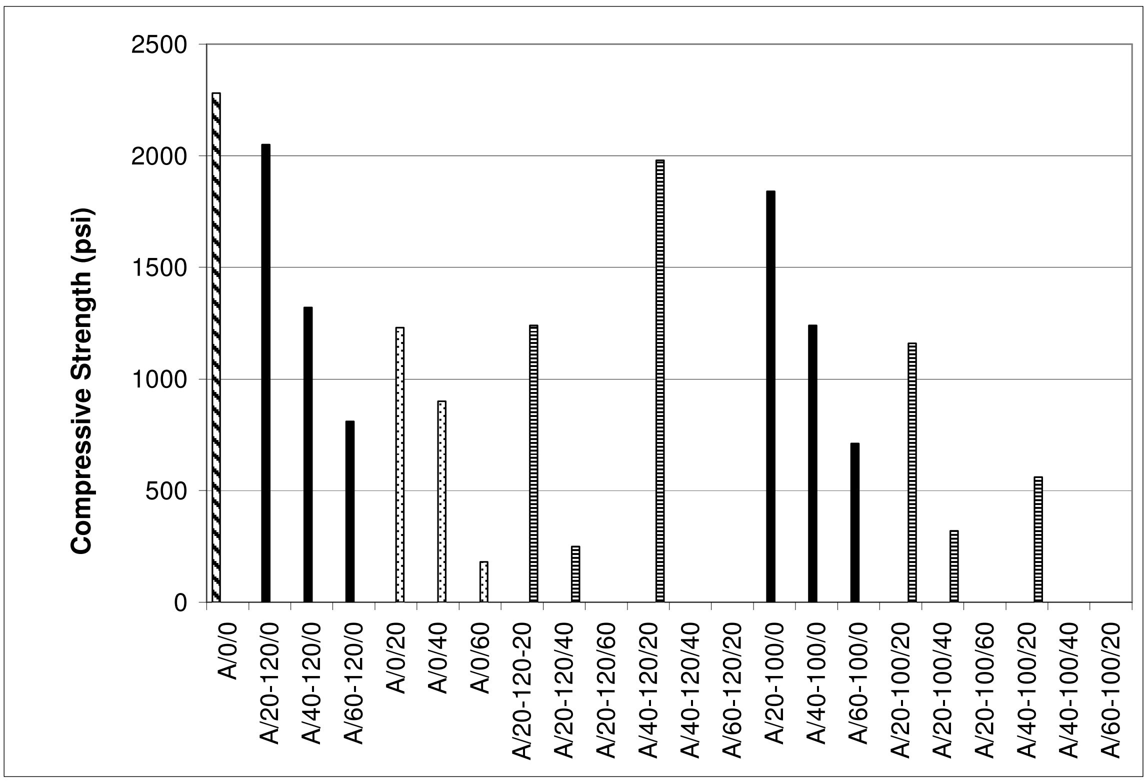
The one day control mixture (A/0/0) strengths were significantly higher than the mixtures with cement replacement. This trend follows the literature mentioned in Section 2.6.1. The second greatest strengths were mixtures A/20-120/0, A/40-120/20, and A/20-100/0 with a maximum difference of 440 psi from the control mixture. Small replacements (20%) of GGBFS had greater one-day strengths than the 20% FA mixtures and mixtures with greater than 20% SCM. At 1 day, the compressive strengths of mixtures with 40% GGBFS were not statistically different from the 20% FA mixtures. This shows that, for early age strength, a 40% replacement of GGBFS has a similar reduction in strength as 20% replacement of FA. The next to lowest mixtures were A/0/60, A/20-120/40, A/20-100/40, A/40-100/20, A/60-100/0, A/60-120/0, and A/0/40 with strengths ranging from 160 to 900 psi. These mixtures contained 60% SCM. The mixtures with the lowest one day strength of zero were A/60-120/20, A/20-120/60, A/20-100/60, A/40-120/40, A/40-100/40, and A/60-100/20. Theses mixtures contained 80% SCM and resulted in the least strength gain. The one-day compressive strength trends were observed as follows:

- the 100% cement mixture had the highest strength,
- the 20% GGBFS mixtures had higher strength than the 20% FA,
- the 20% FA, 40% FA, and 40% GGBFS mixtures had mid-range compressive strengths,
- 60% replacement of both SCM had lower strengths than the 20 to 40% replacements,

- the 80% replacements of cement had the lowest strength, and
- each 20% increase in replacement of either GGBFS or FA resulted in lower compressive strength (except the A/40-120/20 mixture).

The trend described was consistent with the literature for replacements of cement as discussed in Section 2.6.1.

Chart 4.17 One Day Compressive Strength Values for SCM Study

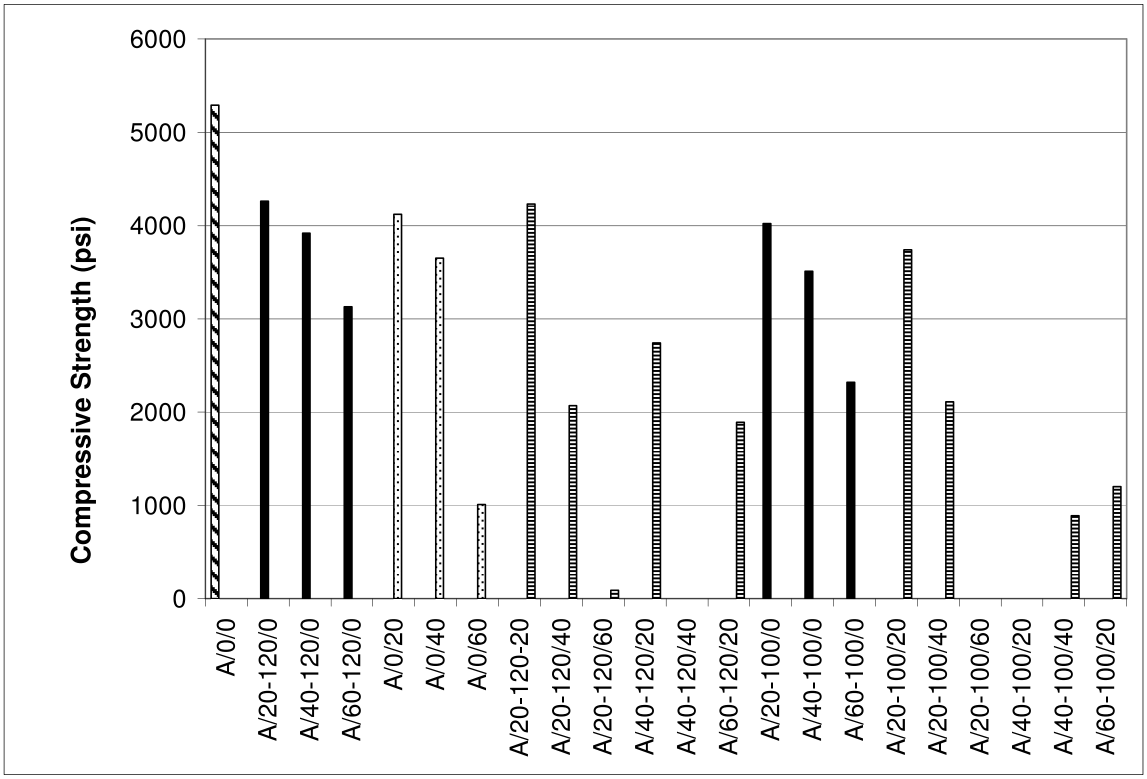


Three-day compressive strength values are listed in Table 4.5 except for the A/40-100/20 mixture. The six compressive strengths were not recorded for A/40-11/20. The highest three-day compressive strength was the control mixture (A/0/0) with a compressive strength of 5290 psi. The second highest three-day compressive strengths were recorded for A/20-120/0, A/0/20, A/20-120/20, and A/20-100/0 with compressive strengths ranging from 4260 to 4020 psi respectively. The next grouping of compressive strengths included A/40-120/0, with a compressive strength of 3920 psi, and A/20-100/20, with a compressive strength of 3740 psi. The smaller replacements of cement with SCM also had up to 80% of the three-day strength of the control mixture (100% portland cement). The exception to this trend was the ternary mixture A/20-120/20. This mixture has 40% total replacement but was statistically grouped within the 20% replacement mixtures and not with the next lower strength grouping of 40% replacements. The not statistically different grouping of the second lowest compressive strength included A/0/60 and A/40-100/40. The lowest three-day compressive strengths were recorded for mixtures A/40-120/40, A/20-120/60, and A/20-100/60. Two of which were not strong enough to be removed from the molds and the other had less than 100 psi. The trends in the three-day compressive strength test from the data and Chart 4.18 were observed to be as follows:

- the 100% cement mixture had the highest strength,
- the 20% replacements of SCM and the 20% GR 120 GGFBS/20% FA ternary mixtures had greater strengths than the other 40% replacements,
- each 20% increase in replacement of GGBFS or FA resulted in lower strength.

The trend for the three day compressive strength test was consistent with the literature as described in Section 2.6.1 except that the 20% GR 120 GGFBS/20% FA mixture had similar strength to the 20% replacements, not the 40% replacements.

Chart 4.18 Three Day Compressive Strength Values for SCM Study

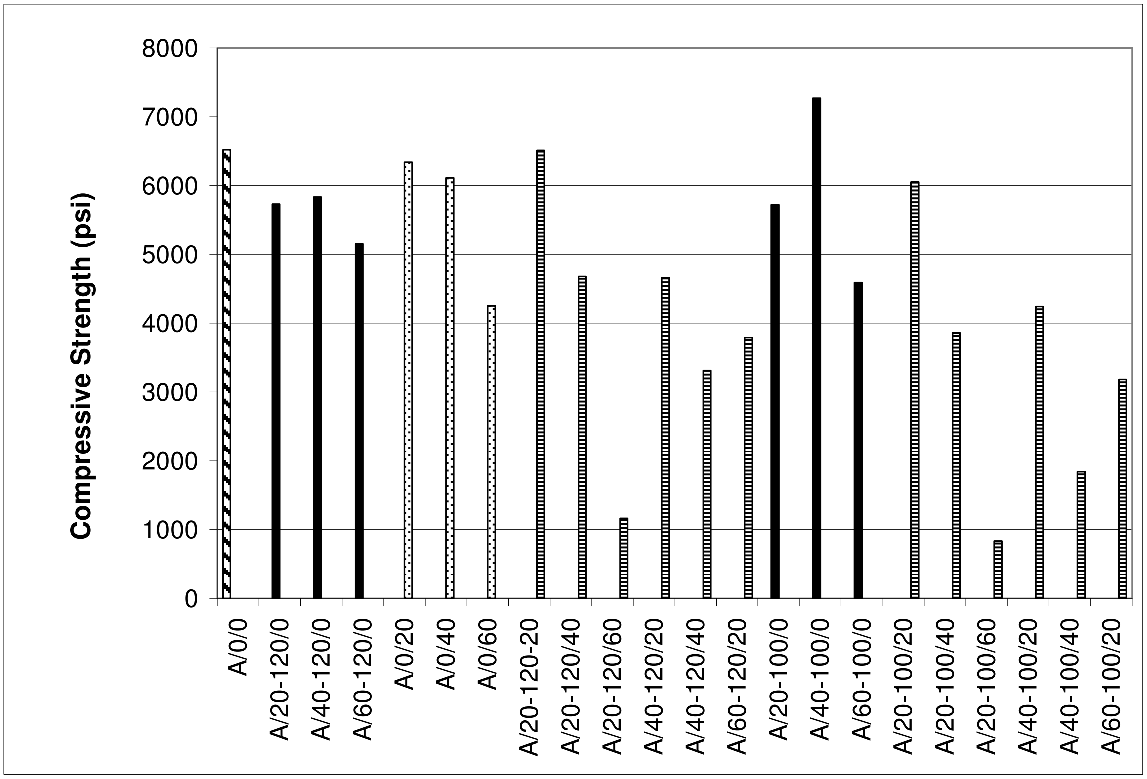


The statistically greatest compressive strength for one-day and three-day compressive strength was the 100% cement control mixture, but the seven-day compressive strength of mixture A/40-100/0 was the highest. The A/40-100/0 mixture was statistically different to the second highest compressive strength mixture, the control (A/0/0). The second grouping of not statistically different mixtures included A/0/0, A/20-120/20, A/0/20, and A/20-100/20 with compressive strengths of 6520 to 6050 psi respectively. The next group of mixtures with not statistically different compressive strengths included A/20-120/0, A/20-100/0, A/0/40, and A/60-120/0. The mixtures with the least seven-day compressive strengths were A/20-100/60, A/20-120/60, A/40-120/40. The trends in the seven-day compressive strength test were observed to be as follows from the data and Chart 4.19:

- the 100% cement mixture no longer had the highest strength,
- the 20/20 ternary mixtures and the 20% FA mixture had greater strength than the control mixture,
- mixtures containing 60% SCM (ternary mixtures and FA only or GGBFS only mixtures) ranged from 3860 to 5120 psi compared to 6520 psi for the control mixture,
- mixtures containing 40 % SCM (ternary mixtures and FA only or GGBFS only mixtures) ranged from 5830 to 7270 psi compared to 6520 psi for the control mixture,
- ternary mixtures containing 80% SCM had the lowest compressive strength, and
- the lowest compressive strength (mixture A/20-100/60) was 11% of the highest compressive strength.

At seven days of age mixtures SCM were achieving compressive strengths that were approaching, if not surpassing, the strength of the control mixture.

Chart 4.19 Seven Day Compressive Strength Values for SCM Study



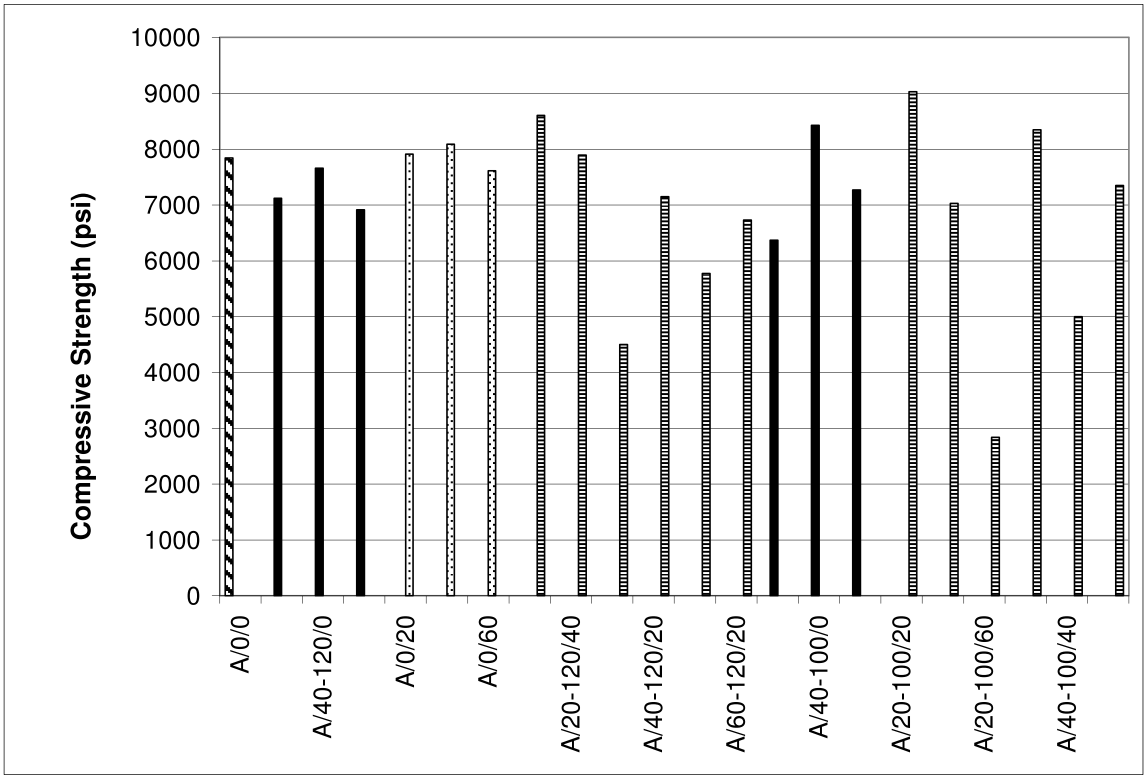
Mixtures with the greatest twenty-eight day compressive strength were A/20-100/20, A/20-120/20, A/40-100/0, and A/40-100/20, with values ranging from 9030 to 8350 psi. The grouping with the second highest twenty-eight day compressive strength included A/0/40, A/0/20, A/ 20-120/40, and A/0/0 with values ranging from 8090 to 7840 psi . The third group of mixtures included A/60-120/0, A/60-120/20, and A/40-120/40 with compressive strengths of 6910 to 5770 psi. The final group included A/40-100/40, A/20-120/60, and A/20-100/60 with compressive strengths of 5000 to 2840 psi. The trends in the data and Chart 4.20 were observed as follows:

- the 20% GGBFS and 20% FA ternary mixtures (for both grades of GGBFS) had the highest strength,

- about half of the mixtures made with GR 100 GGBFS had greater strength than like mixtures with GR 120 GGBFS,
- seven mixtures (including two 60% SCM mixtures) achieved higher twenty-eight day strengths than the control mixture,
- the data did not follow as distinct of a pattern for 20%, 40%, and 60% replacements of cement or for GGBFS vs. FA replacements as the seven day results,
- the 80% replacement mixtures had the lowest compressive strengths, (except for the A/60-100/20 mixture) and
- mixture A/20-100/60 had the lowest twenty-eight day strength, which was 44% of the control mixture.

The twenty-eight day compressive strength results show that a less definite range separated the 100% cement, GGBFS, FA, and ternary mixtures after early age strength tests. The trend of the replacement mixtures having greater later strength than the 100% cement mixture followed the literature as described in Section 2.6.1.

Chart 4.20 Twenty-eight Day Compressive Strength Values for SCM Study



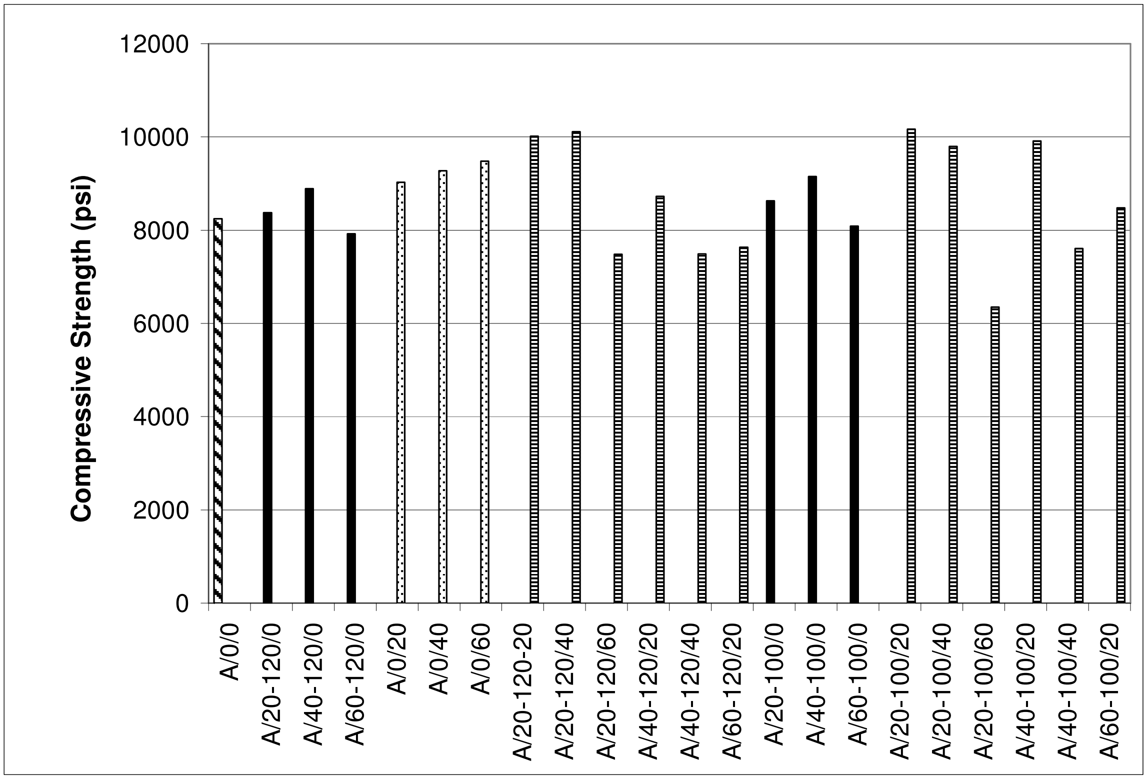
Mixture designs with the highest ninety-day compressive strengths were A/20-100/20, A/20-120/40, A/ 20-120/20, A/40-100/20, and A/20-100/40 with strengths ranging from 10170 to 9800 psi. The second highest strengths were mixtures A/0/60, A/0/40, and A/40-100/0 with ninety-day compressive strengths of 9480 to 9150 psi. The third group included A/60-120/20, A/40-100/40, A/40-120/40, and A/20-120/60 with strengths of 7630 to 7480 psi. The final group included mixture A/20-100/60 with 6350 psi. The trends observed in the ninety-day compressive strength data and Chart 4.21 were as follows:

- the control mixture, which had the highest one day strength, was in the bottom third at ninety days,

- the ternary mixtures with 20% GGBFS and 20 or 40% FA were in the top ¼ of the strengths measured,
- the 20% FA mixture had greater strength than the 20% GGBFS mixtures,
- 88% mixtures made with GR 120 GGBFS or with GR 100 GGBFS had higher strength when made with GR 100 GGBFS, and
- the 80% replacements with 40 and 60% replacements of FA had the lowest compressive strengths.

This trend was also consistent with the literature discussed in Section 2.6.1. The mixtures with SCM were observed to have higher strength than the control mixture in replacements up to 80%. The very high replacements (80%) with SCM possibly had less late age strength because of the lack of calcium hydroxide produced in the first reaction of the cement and water because of less cement in the mixture (as described in Section 2.7.3).

Chart 4.21 Ninety Day Compressive Strength Values for SCM Study



4.3.2.2 Rapid Chloride Ion Penetrability

The permeability of the hardened concrete mixtures was measured by the Rapid Chloride Ion Penetrability Test (RCPT) as described in Section 2.6.2. The results from the test are shown in Table 4.6. Also shown in Table 4.6 is the permeability classification based on the number of coulombs passed.

Table 4.6 Hardened Concrete Property Tests for SCM Study

Mixture	RCPT 28 Days, coulombs	Chloride Ion Penetrability	RCPT 90 Days, coulombs	Chloride Ion Penetrability	Freeze/ Thaw Durability, DF
A/0/0	4265	High	3611	Moderate	2
A/20-120/0	2442	Moderate	1433	Low	24
A/40-120/0	1719	Low	630	Very Low	23
A/60-120/0	937	Very Low	565	Very Low	23
A/0/20	4142	High	1477	Low	8
A/0/40	2079	Moderate	991	Very Low	10
A/0/60	2411	Moderate	1030	Low	19
A/20-120/20	1238	Low	735	Very Low	43
A/20-120/40	1639	Low	817	Very Low	16
A/20-120/60	3104	Moderate	495	Very Low	9
A/40-120/20	540	Very Low	642	Very Low	14
A/40-120/40	331	Very Low	420	Very Low	19
A/60-120/20	507	Very Low	357	Very Low	1
A/20-100/0	1957	Low	701	Very Low	10
A/40-100/0	1035	Low	625	Very Low	6
A/60-100/0	480	Very Low	398	Very Low	1
A/20-100/20	1235	Low	866	Very Low	1
A/20-100/40	3352	Moderate	867	Very Low	6
A/20-100/60	6124	High	1162	Low	2
A/40-100/20	824	Very Low	328	Very Low	23
A/40-100/40	1128	Low	337	Very Low	27
A/60-100/20	265	Very Low	342	Very Low	6

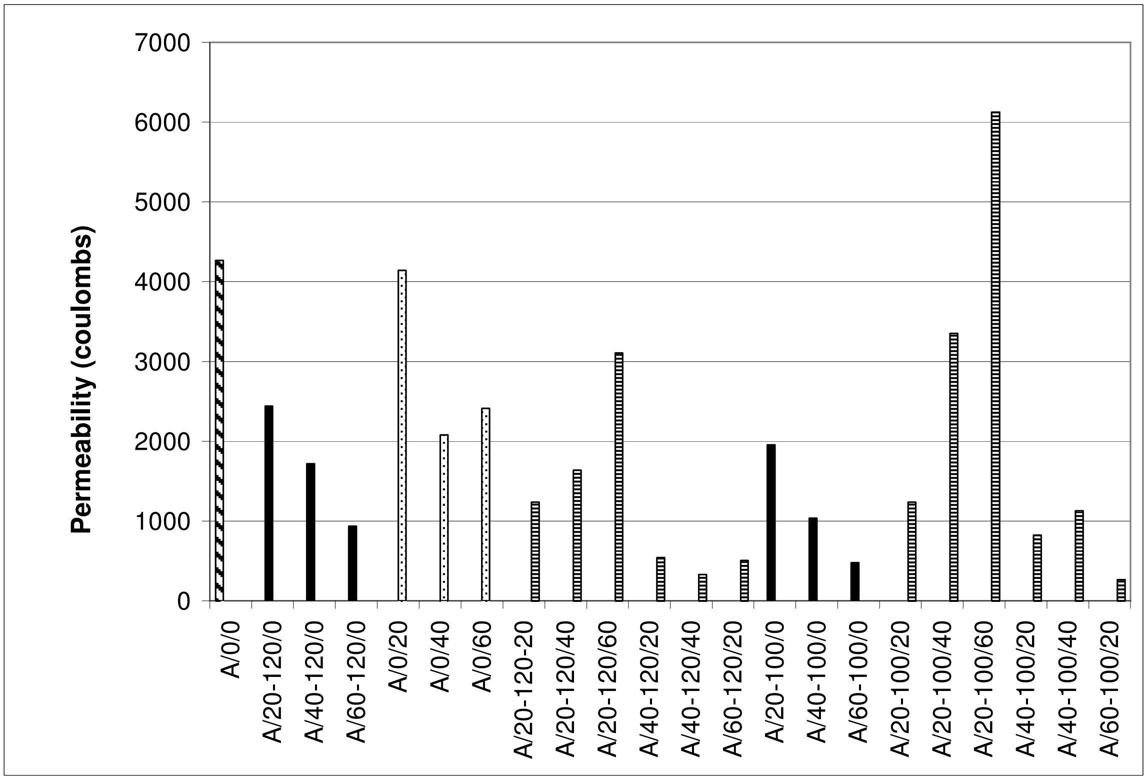
The group of mixtures with the highest twenty-eight day chloride ion penetrability included A/20-100/60, A/0/0, A/0/20, and A/20-100/40 with 6124 to 3352 coulombs passed. The next highest permeability mixtures included A/20-120/60 and A/20-120/0 with 3104 and 2442 coulombs. This range of mixtures decreased the permeability of the control mixture by 27% to 43%. The mixtures with the next to lowest chloride ion penetrability were A/40-100/40, A/40-100/0, A/40-120/20, A/60-120/0, and A/40-100/20 with coulombs passed of 1128 to 824. These mixtures lowered the permeability of the control mixture by 74% to 81%. The mixtures with the lowest twenty-eight day chloride ion penetrability were A/40-120/20, A/40-120/40, and A/60-100/20 with coulombs passed of 507 to 265. These mixtures lowered the permeability of the control by 88% to 94%.

The 20%, 40%, and 60% replacements of GR 120 GGBFS decreased the permeability 43%, 60%, and 78% from the control mixture. 20% FA decreased the permeability 3% from the control mixture and the 40% and 60% replacements of FA reduced the permeability by approximately 50% when compared to the control mixture. The 20%, 40%, and 60% replacements of GR 100 GGBFS decreased the permeability 54%, 76%, and 89% from the control mixture. The ternary mixtures with 20% of GGBFS (either grade) showed an increase in permeability for each additional 20% of FA replacement. The ternary mixtures with 20% FA show a decrease in permeability for each additional 20% of either grade GGBFS. The trends observed from the twenty-eight day RCPT and Chart 4.22 were as follows:

- the 100% cement mixture had the second highest permeability,
- the mixtures that passed more coulombs, and therefore were considered as having higher permeability, had 0 to 20% replacements of both GR 100 and GR 120 GGBFS and a range of replacements of FA,
- each 20% increase in replacement of GGBFS lowered the permeability,
- each 20% increase in replacement of FA to ternary mixtures increased permeability,
- the mixtures with low permeability had 40 to 60% replacements of both grades of GGBFS and a range of FA replacement, and

- higher replacements of GGBFS had a lowering effect on permeability unlike higher replacements of FA at twenty-eight days.

Chart 4.22 Twenty-eight Day Permeability Values for SCM Study

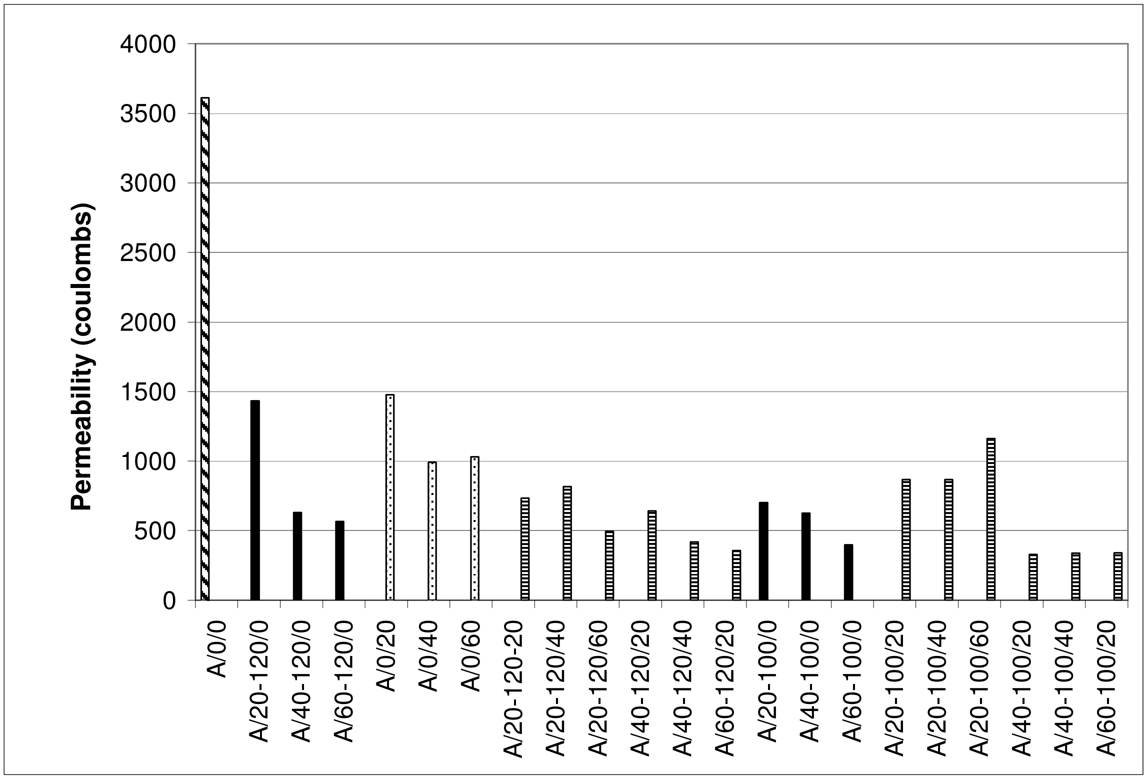


Mixture A/0/0 had the highest ninety-day chloride ion penetrability. The control mixture passed 3611 coulombs. Mixtures A/0/20, A/20-120/0, A/20-100/60, and A/0/60, with coulombs passed ranging from 1477 to 1030, decreased the permeability of the control mixture by 59% to 71%. The third group of mixtures included A/0/40, A/20-100/0, A/20-100/40, A/20-100/20, and A/20-120/20 with coulombs passed of 991 to 735. This group reduced the permeability of the control mixture by 73% to 80%. The fourth group included A/40-120/20, A/40-100/0, A/60-120/0, A/20-120/60, and A/60-100/0 with coulombs passed of 642 to 398. These mixtures reduced the permeability of the control mixture by 82% to 89%. The mixtures with the lowest permeability were A/40-120/40, A/60-120/20, A/60-100/20, A/40-100/40, and A/40-100/20 with coulombs passed of 369 to 328. This group of mixtures lowered the permeability of the control mixture by 90% to 91%.

Adding 20% SCM (GR100 GGBFS, GR 120 GGBFS, or FA) reduced the permeability approximately 60 to 70% from the control mixture. An additional 20% of FA or GGBFS (to make 40 % FA, 40% GGBFS or 20/20 ternary mixtures) reduced the permeability by 72 to 82% from the control mixture. Replacements with 60 to 80% SCM lowered the permeability up to 90% form the control mixture at 90 days. Therefore, the greatest improvement (60%) was observed within the first 20% SCM mixtures and an additional 10 to 20% reduction was observed with up to 40% SCM mixtures. SCM replacements greater than 40% only reduced the permeability at 90 days by a maximum of 10% more than the 40% mixtures, which does not represent a great benefit. The ninety-day permeability trends were observed to be as follows from the data and Chart 4.23:

- the 100% cement mixture had moderate permeability,
- the mixtures with the highest ninety-day permeability had 0 to 20% replacements of GGBFS and 40% to 60% replacements of FA,
- the mixtures with the lowest ninety-day permeability had 40% to 60% replacements of GGBFS and 20% to 40% replacements of FA, and
- the ninety-day permeability trends were not as clearly defined between the different combinations of replacements as the twenty-eight day permeability trends.

Chart 4.23 Ninety Day Permeability Values for SCM Study



Overall trends were observed as follows:

- the control mixture dropped one level of permeability (high to moderate) from twenty-eight day tests to ninety-day tests,
- 27% of the mixtures did not change permeability level from 28 to 90 days because they were classified as very low permeability at 28 days,
- 50% of the mixtures lowered one level of permeability from 28 to 90 days,
- 23% of the mixtures lowered two levels of permeability from 28 to 90 days,
- each 20% addition of GGBFS replacement lowered the 28 and ninety-day permeability one level,

- the replacement of 20% FA did not lower the twenty-eight day permeability but lowered the ninety-day permeability by one level,
- the replacement of 40 and 60% FA lowered the 28 and ninety-day permeability by one level,
- the ternary mixtures decreased the twenty-eight day permeability by at least 1 level, with the exception of the A/20-100/60 mixture, and
- the ternary mixtures decreased the ninety-day permeability by two levels (to very low), with the exception of the A/20-100/60 mixture.

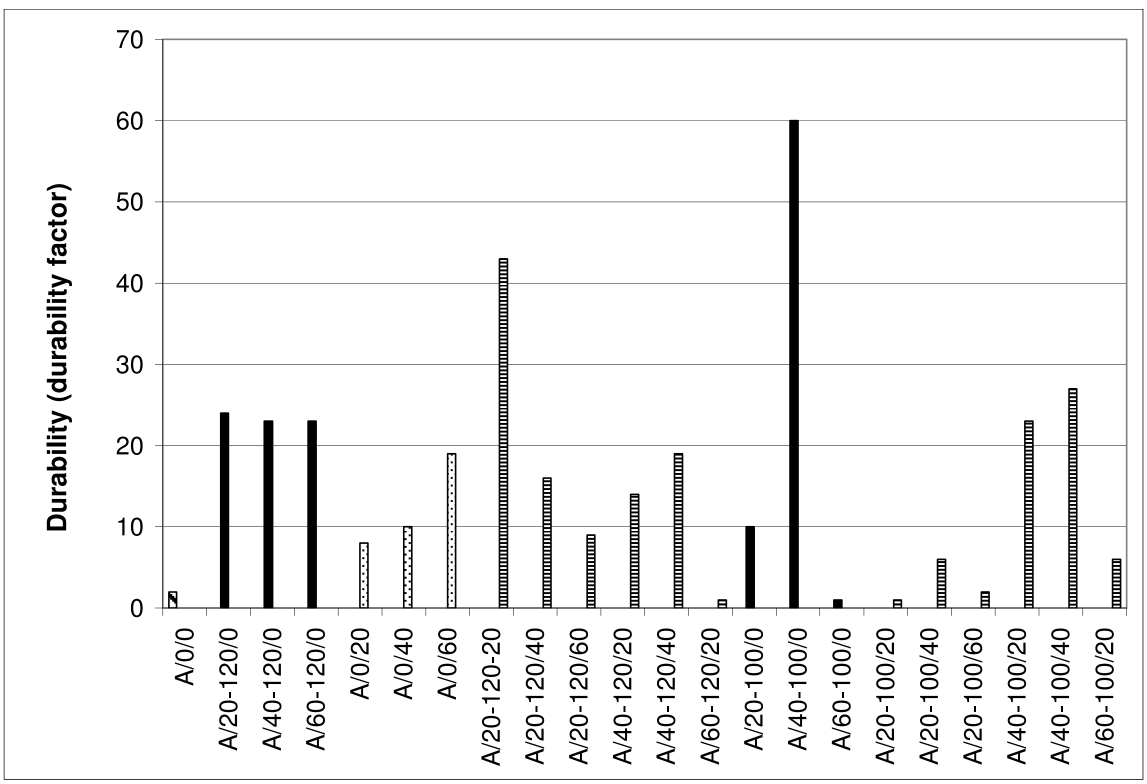
4.3.2.3 Freeze/Thaw Durability

The resonance frequency was monitored for each sample at each test and recorded as shown in Appendix A. The durability factor was determined from the last frequency recorded from each sample as per ASTM 666 (AASHTO T 161). Pictures of the freeze/thaw samples at end of testing or failure are shown in Appendix B. The mixtures with the lowest durability factors, representing the mixtures with the lowest durability, were A/60-120/20, A/60-100/0, A/20-100/20, A/0/0, A/20-100/60, A/40-100/0, A/20-100/40, and A/60-100/20. These mixtures had durability factors of 1 to 6. The mixtures with the highest durability factors were A/40-100/20, A/40-120/0, A/60-120/0, A/20-120/0, A/40-100/40, and A/20-120/20 with durability factors of 23 to 43. The addition of GGBFS increased the durability factor from the control mixture twelve fold. The 20% FA replacement increased the durability of the control mixture by a factor of 4. The 40% FA replacement increased the durability of the control mixture by a factor of 5. And the 60% FA replacement increased the durability of the control mixture by a factor of 9.5. The ternary mixture of 20% replacement of GR

120 GGBFS and 20% replacement of FA had the highest durability factor of 43. The trends observed from the data and Chart 4.24 were as follows:

- the durability factors of the GR 100 GGBFS mixtures were less than GR 120 GGBFS mixtures for all but two like mixtures,
- the durability factors of the GR 120 GGBFS mixtures were similar to each other,
- each 20% increase in FA replacement increased the durability factor in FA only mixtures, and
- 20% increase in FA decreased the durability factor in ternary mixtures.

Chart 4.24 Freeze/Thaw Durability Values for SCM Study



4.4 Ground Granulated Blast Furnace Slag Study

The purpose of the GGBFS study was to determine if differences in GR 100 and GR 120 GGBFS affects concrete performance. The two grades came from different locally available sources and may have different properties because of the raw material source, refinement process, and quality control standards. The fresh and hardened properties of mixtures made with GR 100 GGBFS were compared to the mixtures made with GR 120 GGBFS. Nine mixtures were batched with each grade of GGBFS as discussed in Section 3.6. The control mixture design was made as described in Section 4.1.

4.4.1 Fresh Concrete Tests

The fresh concrete tests performed for the GGBFS study were slump, air content, concrete temperature, and unit weight. The values listed in Table 4.7 are the mean values of two batches for each grade of GGBFS as described in Section 3.9. The grouping was based on the statistical analysis as described in Section 3.9.

Table 4.7 Fresh Concrete Tests for Ground Granulated Blast Furnace Slag Study

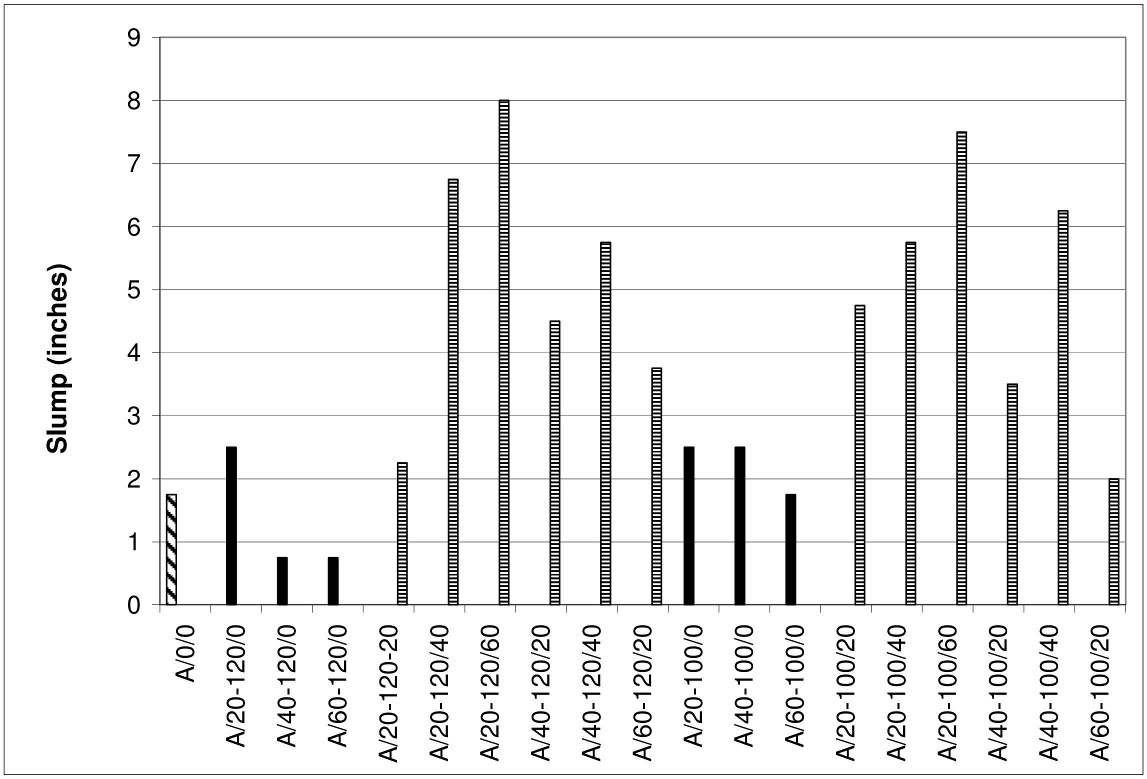
Mixture	Slump, in. (mm)	Unit Weight, lb/ft^3 (kg/m^3)	Air Content, %	Temperature, °F (°C)
A/0/0	1.75 (45)	151.5 (2426)	1.4	89.8 (32.1)
A/20-120/0	2.50 (65)	149.6 (2397)	1.5	81.8 (27.6)
A/40-120/0	0.75 (20)	150.5 (2410)	1.5	68.5 (20.3)
A/60-120/0	0.75 (20)	149.8 (2399)	1.6	72.5 (22.5)
A/20-120/20	2.25 (60)	150.1 (2404)	1.5	67.4 (19.6)
A/20-120/40	6.75 (70)	150.8 (2416)	1.1	61.1 (16.2)
A/20-120/60	8.00 (205)	149.8 (2399)	0.5	61.0 (16.1)
A/40-120/20	4.50 (115)	149.1 (2388)	1.5	69.6 (20.9)
A/40-120/40	5.75 (205)	149.7 (2398)	1.1	81.5 (27.5)
A/60-120/20	3.75 (95)	149.2 (2390)	1.3	69.4 (20.8)
A/20-100/0	2.50 (65)	151.5 (2428)	1.6	82.4 (28.0)
A/40-100/0	2.50 (65)	149.5 (2395)	1.3	80.4 (26.9)
A/60-100/0	1.75 (45)	148.8 (2384)	1.5	83.0 (28.3)
A/20-100/20	4.75 (120)	150.5 (2412)	1.3	85.2 (29.6)
A/20-100/40	5.75 (145)	150.0 (2403)	0.8	77.0 (25.0)
A/20-100/60	7.50 (190)	150.1 (2405)	0.5	79.0 (26.1)
A/40-100/20	3.50 (90)	148.8 (2384)	1.2	84.0 (28.9)
A/40-100/40	6.25 (160)	149.5 (2395)	0.8	84.8 (29.3)
A/60-100/20	2.00 (50)	149.7 (2399)	1.4	76.5 (24.7)

4.4.1.1 Slump

Slump values for the ground granulated blast furnace slag study are listed in Table 4.7. The slumps ranged from 0.75 to 8.0 inches (20 to 205 mm). The trends in the slump were observed as follows from the data and Chart 4.25:

- four out of the 9 mixtures had greater slumps with GR 120 GGBFS,
- one out of the 9 mixtures had the same slump, and
- four out of the 9 mixtures had greater slumps with GR 100 GGBFS.

Chart 4.25 Slump Values for GGBFS Study



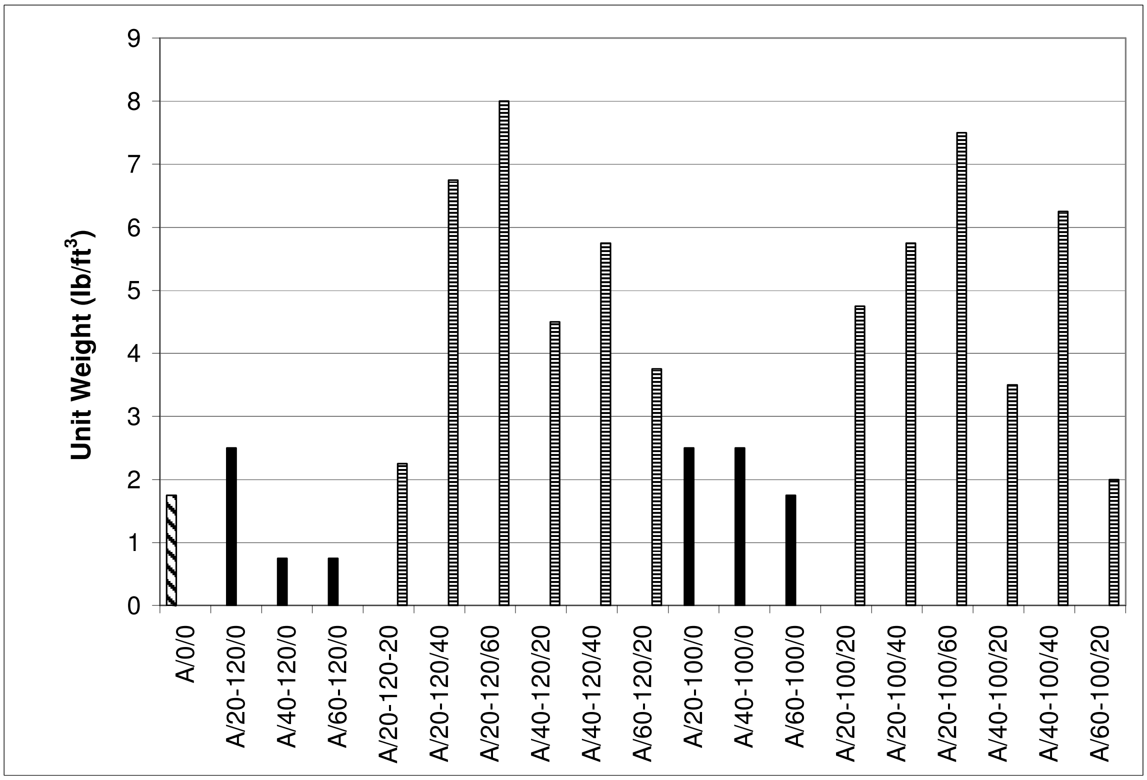
4.4.1.2 Unit Weight

Unit weight values for the ground granulated blast furnace slag study are listed in Table 4.7. The unit weights for the GGBFS study ranged from 148.8 to 151.5 lb/ft^3 (2384 to 2426 kg/m^3). All of the mixtures were not statistically different whether they were made with GR 100 or GR120 GGBFS, except the 20 % replacement with GGBFS. This means that if unit weight was part of the design criteria for mixtures with GGBFS the grade of GGBFS used would not be a factor. The following trends were observed from the data and Chart 4.26:

- the control mixture, A/0/0, had higher unit weight than the other mixtures,

- the unit weights were consistent between the mixtures made with GR 100 GGBFS and the mixtures made with GR 120 GGBFS.

Chart 4.26 Unit Weight Values for GGBFS Study



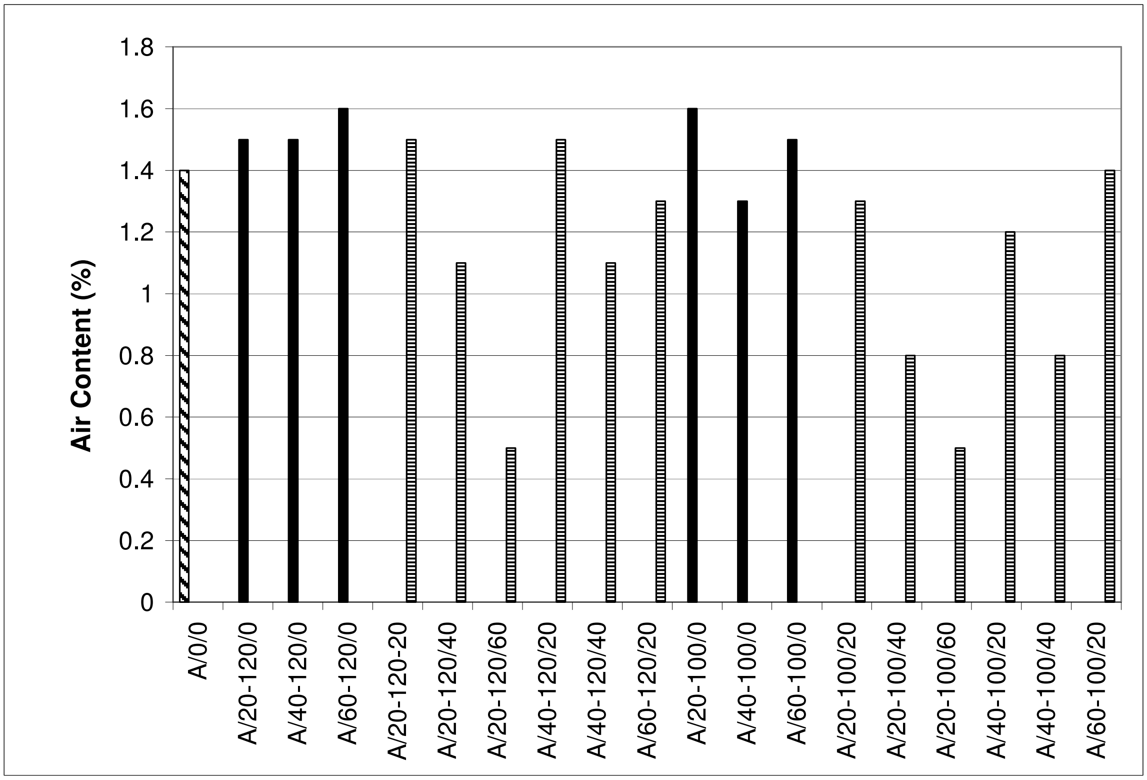
4.4.1.3 Air Content

Air content for the ground granulated blast furnace slag study are listed in Table 4.7. The air contents ranged from 0.5 to 1.6% with the majority of samples having a 1.1 to 1.6 % air content. As described in Section 3.7.1, the air content in the concrete was the result of entrapped air and not entrained air. Mixtures without AEA normally entrap 1.0 to 2.0% air. The trends observed from the data and Chart 4.27 were as follows:

- 67% of the air contents were not statistically different when made with different grades of GGBFS, and

- the other mixtures had higher air content when made with GR 120 GGBFS.

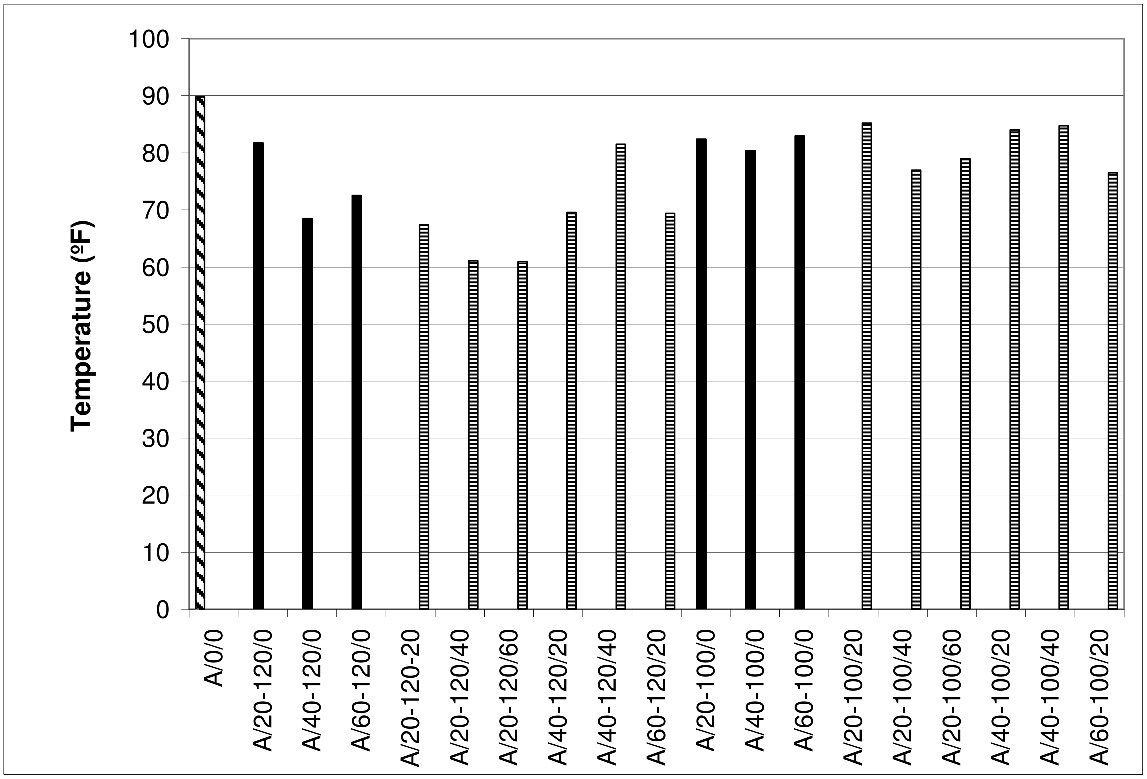
Chart 4.27 Air Content Values for GGBFS Study



4.4.1.4 Concrete Temperature

As mentioned in the other studies, the concrete temperature listed in Table 4.7 was only taken as a quality control measure. The fresh concrete temperature ranged from 60.95 to 89.8ºF (16.1 to 32.1ºC) as shown in the data and Chart 4.28.

Chart 4.28 Temperature Values for GGBFS Study



4.4.2 Hardened Concrete Tests

The hardened concrete tests performed during the ground granulated blast furnace slag study were compressive strength, rapid chloride ion penetrability test (RCPT), and freeze/thaw durability. The values listed in Table 4.8 are the mean values of six compressive strength samples as described in Section 3.9. The values listed in Table 4.9 are the mean values of four samples each for RCPT and freeze/thaw durability, two from each trial batch as described in Section 3.9. The grouping was based on the statistical analysis as described in Section 3.9.

4.4.2.1 Compressive Strength

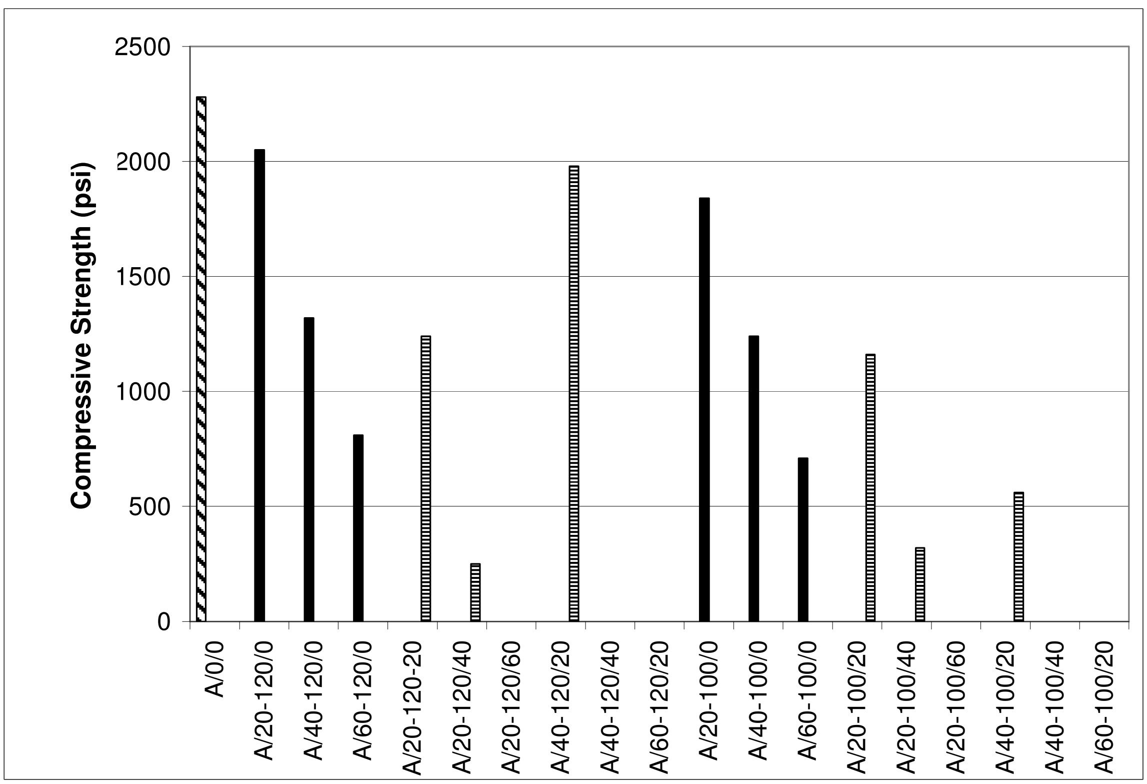
Table 4.8 Compressive Strength (psi) for GGBFS Study

Mixture Design	1 Day	3 Days	7 Days	28 Days	90 Days
A/0/0	2280	5290	6520	7840	8250
A/20-120/0	2050	4260	5730	7120	8380
A/40-120/0	1320	3920	5830	7660	8890
A/60-120/0	810	3130	5150	6910	7920
A/20-120/20	1240	4230	6510	8600	10020
A/20-120/40	250	2070	4680	7890	10110
A/20-120/60	0	90	1160	4500	7480
A/40-120/20	1980	2740	4660	7150	8730
A/40-120/40	0	0	3310	5770	7490
A/60-120/20	0	1890	3790	6730	7630
A/20-100/0	1840	4020	5720	6370	8630
A/40-100/0	1240	3510	7270	8430	9150
A/60-100/0	710	2320	4590	7270	8090
A/20-100/20	1160	3740	6050	9030	10170
A/20-100/40	320	2110	3860	7030	9800
A/20-100/60	0	0	830	2840	6350
A/40-100/20	560	-	4240	8350	9910
A/40-100/40	0	890	1840	5000	7610
A/60-100/20	0	1200	3180	7350	8480

Results of the compression test for the ground granulated blast furnace slag study are listed in Table 4.8. The mixtures that had not statistically different one day compressive strengths whether they were made with GR 100 GGBFS or GR 120 GGBFS were A/20/0, A/40/0, A20/20, A/20/60, A/40/40, and A/60/20. The mixture made with 60% GGBFS had a 12% decrease in compressive strength when made with GR 100 GGBFS. The ternary mixture made with 40% GGBFS and 20% FA had a 71% decrease in one day compressive strength when made with GR 100 GGBFS. The only mixture that had statistically greater compressive strength when made with GR 100 GGBFS was A/20-100/40. The GR 120 mixture (A/20-120/40) decreased the compressive strength by 22%. The trends in the one day compressive strength data and Chart 4.29 were observed as follows:

- each 20% increase in replacement (amount of FA held constant) resulted in lower strength,
- 67% of the mixtures had not statistically different compressive strengths with either GR 100 or GR 120 GGBFS,
- 22% had greater compressive strengths with GR 120 GGBFS, and
- 11% had greater compressive strengths with GR 100 GGBFS.

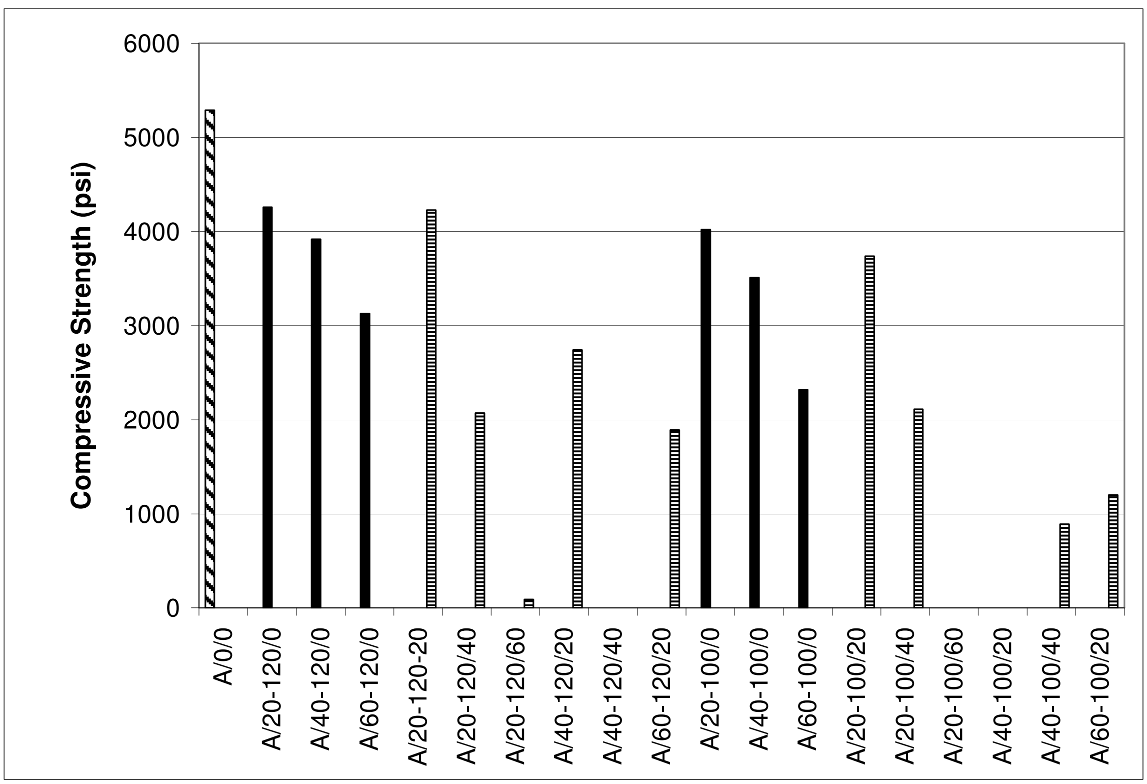
Chart 4.29 One Day Compressive Strength Values for GGBFS Study



At three days of age, mixtures that had not statistically different compressive strengths were A/20/0, A/20/40, A/20/60, A/40/40, and A/60/20. The A/40/0, A/60/0, and A/20/20 mixtures had an average of 14% less three-day compressive strength when made with GR 100 GGBFS. The A/40-100/20 mixture did not have three-day compressive strength data recorded and therefore could not be compared to the A/40-120/20 mixture. The trends observed in the GGBFS three day compressive strength data and Chart 4.30 were as follows:

- 56% of the mixtures had not statistically different compressive strengths with either GR 100 or GR 120 GGBFS,
- 33% had greater compressive strengths with GR 120 GGBFS, and
- 11% had greater compressive strengths with GR 100 GGBFS.

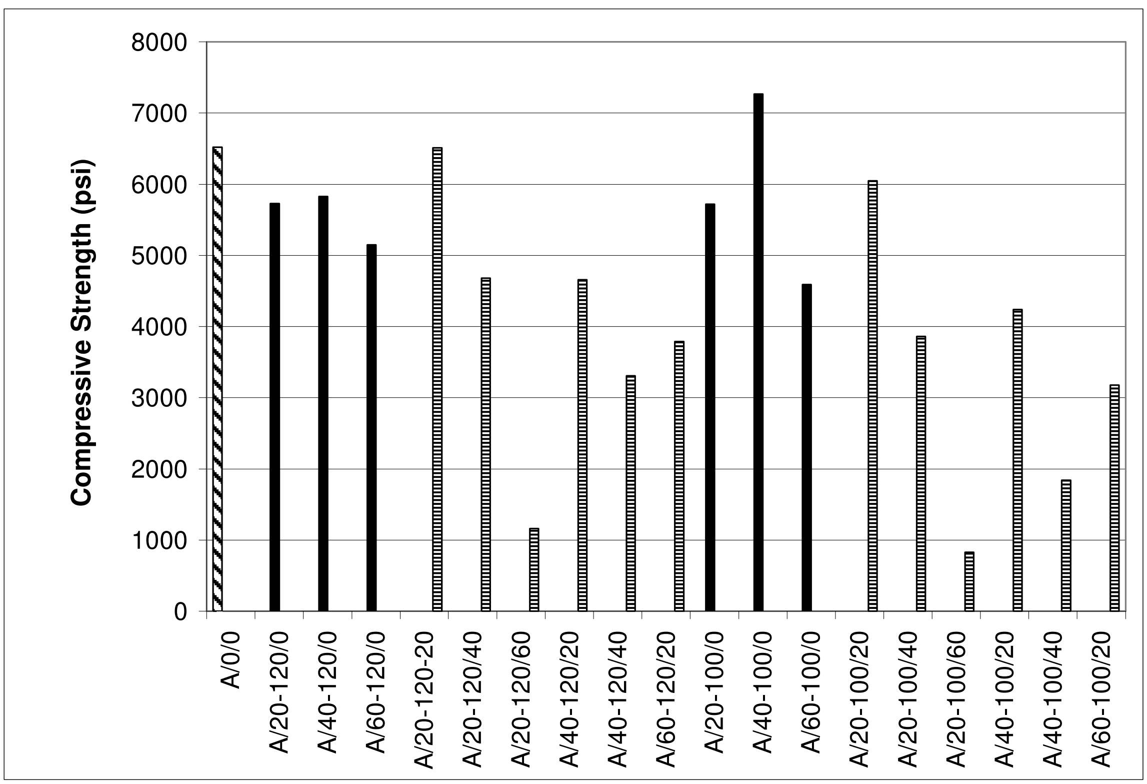
Chart 4.30 Three Day Compressive Strength Values GGBFS Study



At seven days of age, the A/20/0, A/20/60, A/40/40, and A/60/20 mixtures had not statistically different compressive strengths between the GR 100 and GR 120 GGBFS mixtures. The A/60/0, A/20/20, A/20/40, and A/40/20 mixtures saw a 11%, 7%, 2%, and 9% decrease in compressive strength with GR 100 GGBFS. The A/40/0 mixture had a 20% decrease in strength when made with GR 120 GGBFS. The 7day compressive strength trends were observed to be as follows from the data and Chart 4.31:

- the 40% GR 100 mixture had the highest strength and higher strength than the like GR 120 mixture,
- 44% of the mixtures had not statistically different compressive strengths with either GR 100 or GR 120 GGBFS,
- 44% had greater compressive strengths with GR 120 GGBFS, and
- 12% had greater compressive strengths with GR 100 GGBFS.

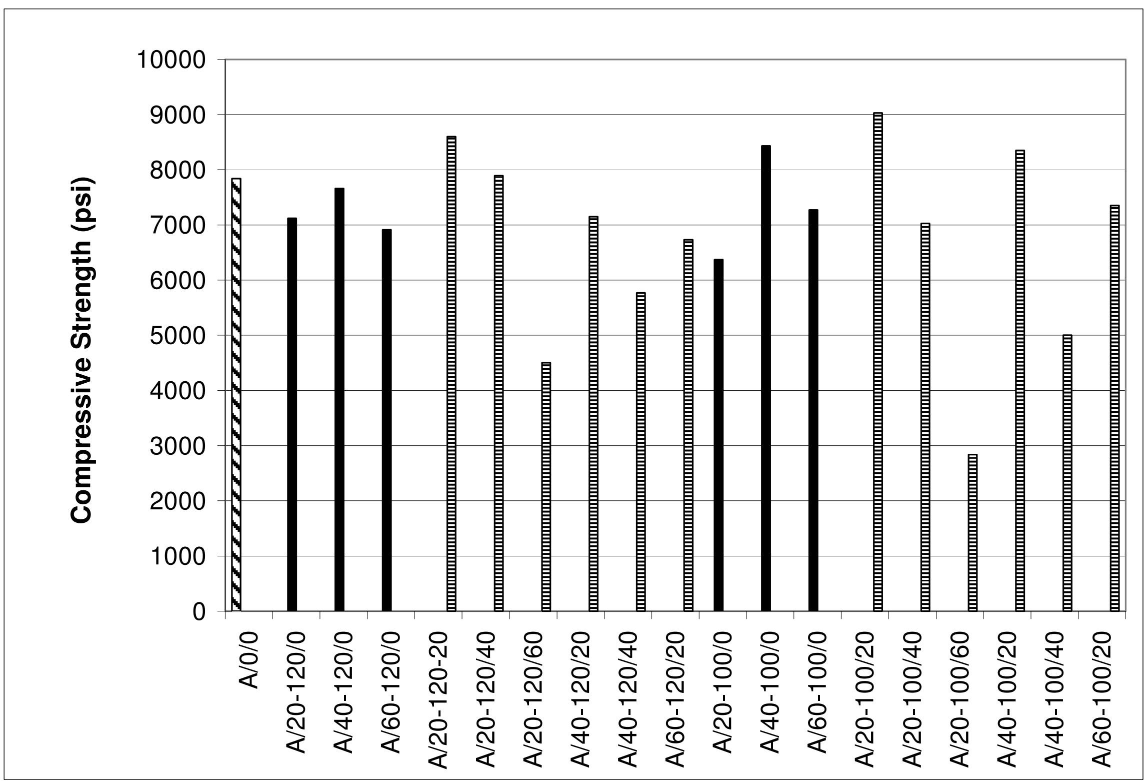
Chart 4.31 Seven Day Compressive Strength Values for GGBFS Study



The mixtures that had not statistically different twenty-eight day strengths whether they were made with GR 100 or GR 120 GGBFS were A/20/0, A/20/20, A/20/60, and A/40/40. Four of the remaining five mixtures had greater twenty-eight day compressive strength when made with GR 100 GGBFS. These mixtures were A/40/0, A/60/0, A/20/20, A/40/20, and A/60/20. The trends in twenty-eight day compressive strength data and Chart4.32 were observed to be as follows:

- 44% of the mixtures had not statistically different compressive strengths with either GR 100 or GR 120 GGBFS,
- 44% had greater compressive strengths with GR 100 GGBFS, and
- 12% had greater compressive strengths with GR 120 GGBFS.

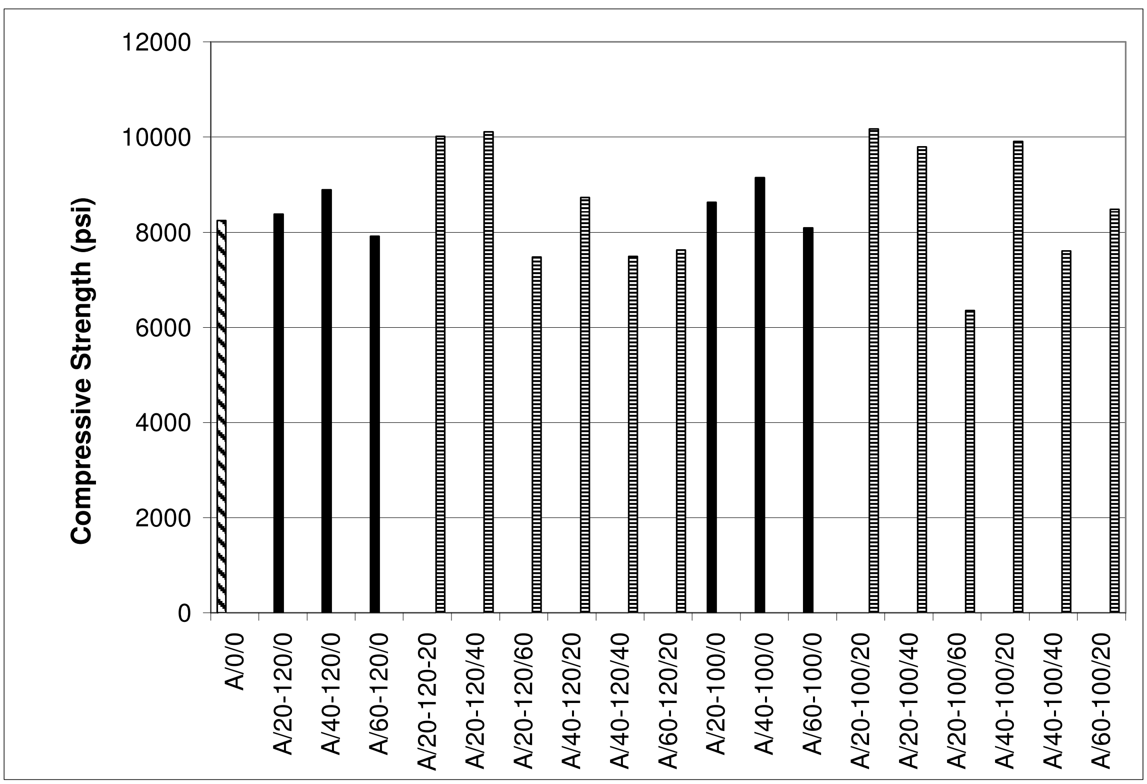
Chart 4.32 Twenty-eight Day Compressive Strength Values for GGBFS Study



Not statistically different mixtures in ninety-day compressive strength between GR 100 GGBFS and GR 120 GGBFS were: A/20/0, A/40/0, A/60/0, A/20/20, A/20/40, and A/40/40. The A/40/20 and A/60/20 mixtures were decreased by 11% when made with GR 120 GGBFS. The A/20/60 mixture had a 15% decrease in ninety-day compressive strength when made with GR 100 GGBFS. The 90 day compressive strength trends observed were as follows from the data and Chart 4.33:

- 67% of the mixtures had not statistically different compressive strengths with either GR 100 or GR 120 GGBFS,
- 22% had greater compressive strengths with GR 100 GGBFS, and
- 11% had greater compressive strengths with GR 120 GGBFS.

Chart 4.33 Ninety Day Compressive Strength Values for GGBFS Study



Overall, half of the like mixtures were not statistically different when compared to each other for compressive strength. Two thirds were similar at one day and two thirds were similar at ninety days. At 1, 3, and 7 days, one third of the like mixtures had higher compressive strength when made with GR 120 GGBFS. At 28 and 90 days one third of the like mixtures had higher compressive strength when made with GR 100 GGBFS. The GR 100 GGBFS reactivity index was 87% of the GR 120 GGBFS reactivity index at 7 days, but by 28 days the GR 100 GGBFS reactivity index was 98% the GR 120 GGBFS reactivity index. The convergence of the two SCMs reactivity indexes would account for the shift in more mixtures with greater compressive strengths from GR 120 at 1, 3, and 7 days to GR 100 at 28 and 90 days.

4.4.2.2 Rapid Chloride Ion Penetrability

The permeability of the hardened concrete mixtures was measured by RCPT as described in Section 2.6.2. The results from the test are shown in Table 4.9. Also shown in Table 4.9 is the permeability classification based on the number of coulombs passed.

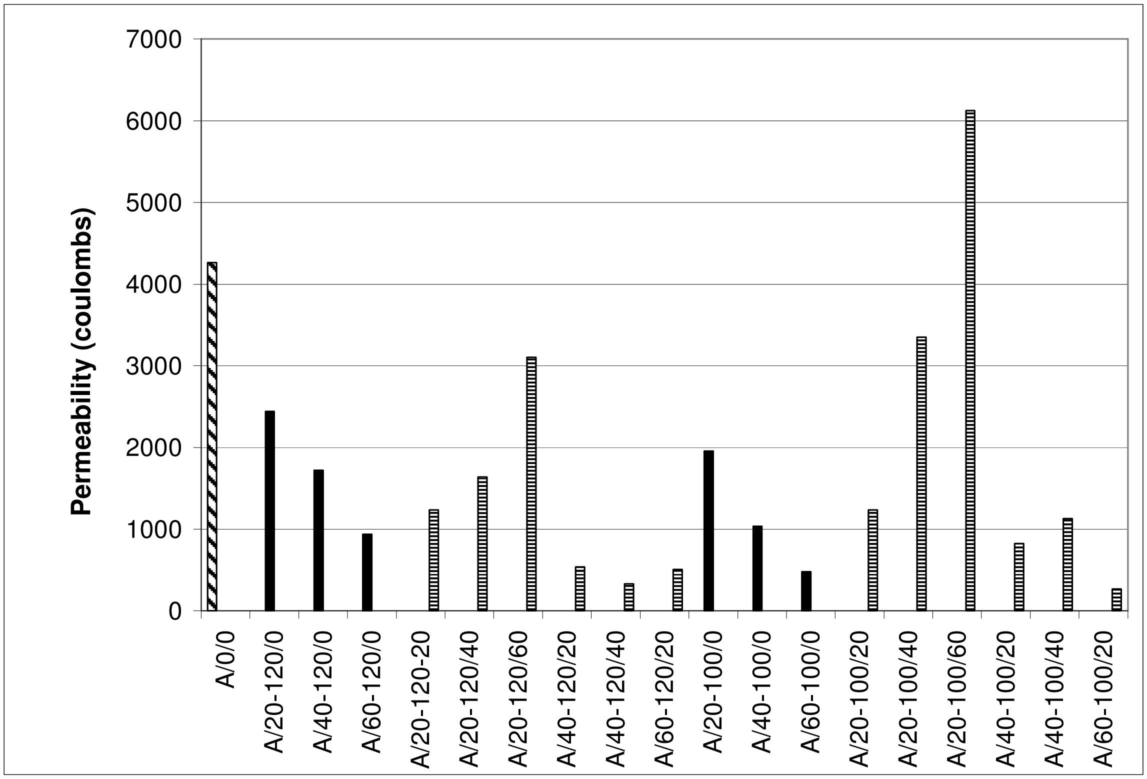
Table 4.9 Hardened Concrete Property Tests for GGBFS Study

Mixture	RCPT 28 Days, coulombs	Chloride Ion Penetrability	RCPT 90 Days, coulombs	Chloride Ion Penetrability	Freeze/Thaw Durability, DF
A/0/0	4265	High	3611	Moderate	2
A/20-120/0	2442	Moderate	1433	Low	24
A/40-120/0	1719	Low	630	Very Low	23
A/60-120/0	937	Very Low	565	Very Low	23
A/20-120/20	1238	Low	735	Very Low	43
A/20-120/40	1639	Low	817	Very Low	16
A/20-120/60	3104	Moderate	495	Very Low	9
A/40-120/20	540	Very Low	642	Very Low	14
A/40-120/40	331	Very Low	420	Ver`y Low	19
A/60-120/20	507	Very Low	357	Very Low	1
A/20-100/0	1957	Low	701	Very Low	10
A/40-100/0	1035	Low	625	Very Low	6
A/60-100/0	480	Very Low	398	Very Low	1
A/20-100/20	1235	Low	866	Very Low	1
A/20-100/40	3352	Moderate	867	Very Low	6
A/20-100/60	6124	High	1162	Low	2
A/40-100/20	824	Very Low	328	Very Low	23
A/40-100/40	1128	Low	337	Very Low	27
A/60-100/20	265	Very Low	342	Very Low	6

The mixtures with not statistically different twenty-eight day permeability whether made with GR 100 or GR 120 GGBFS were A/20/0, A20/20, A/40/20, and A60/20. The mixtures that had lower permeability when made with GR 100 GGBFS were A/40/0 and A/60/0. When these mixtures were made with GR 100 GGBFS the permeability decreased by 40% and 49% respectively. The mixtures that had lower permeability when made with GR 120 GGBFS were A/20/40, A/20/60, and A/40/40. When these mixtures were made with GR 120 GGBFS the permeability decreased by 51%, 49%, and 70% respectively. The twenty-eight day permeability trends from the data and Chart 4.34 were observed to be as follows:

- when combined with FA, GR 100 GGBFS mixtures had higher permeability than like GR 120 mixtures,
- 44% of the mixtures had not statistically different permeability with either GR 100 or GR 120 GGBFS,
- 22% had lower permeability with GR 100 GGBFS, and
- 34% had lower permeability with GR 120 GGBFS.

Chart 4.34 Twenty-eight Day Permeability Values for GGBFS Study

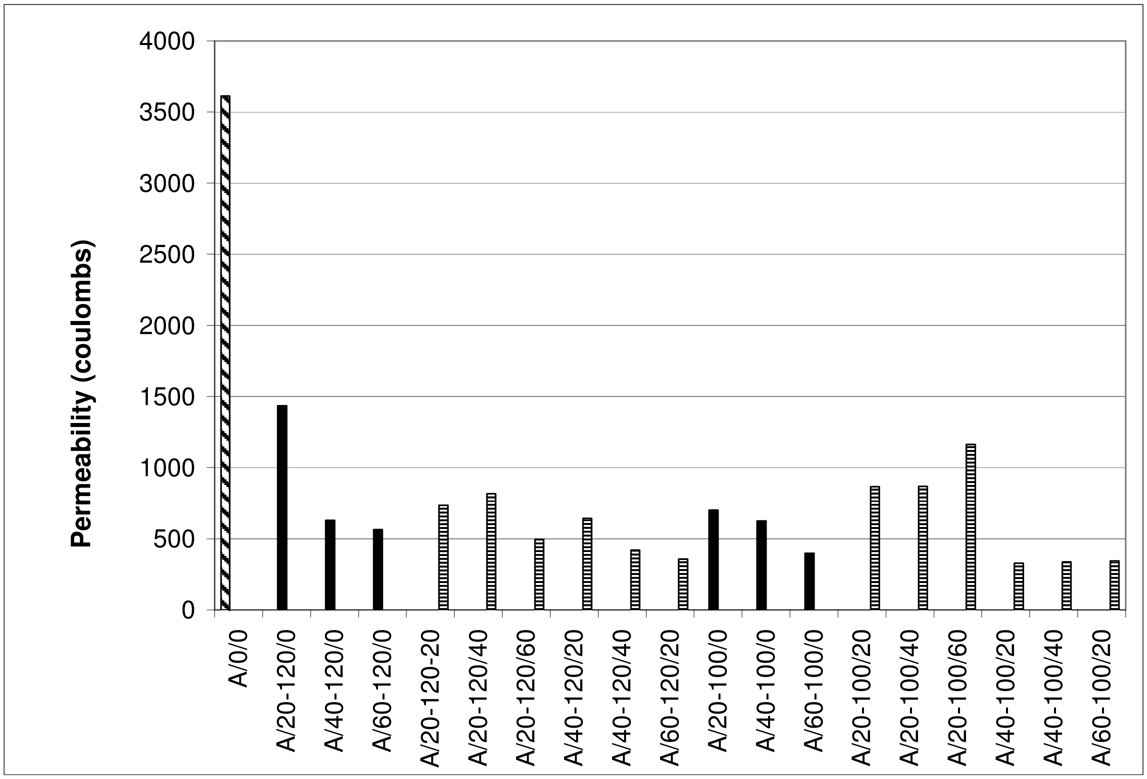


Not statistically different mixtures for ninety-day permeability were A/40/0, A/60/0, A/20/20, A20/40, and A/60/20. One of the nine mixtures in the GGBFS study, A/20/60, had a 57% decrease in permeability when made with GR 120 GGBFS. Three mixtures, A/20/0, A/40/20, and A/40/40, had a decrease of 51%, 50%, and 20% when made with GR 100 GGBFS. The trends in the ninety-day permeability data and Chart 4.35 were observed to be as follows:

- at ninety days the difference between ternary GR 100 and GR 120 mixtures was not as pronounced as twenty-eight day results,
- 56% of the mixtures had not statistically different permeability with either GR 100 or GR 120 GGBFS,
- 33% had lower permeability with GR 100 GGBFS, and

- 11% had lower permeability with GR 120 GGBFS.

Chart 4.35 Ninety Day Permeability Values for GGBFS Study



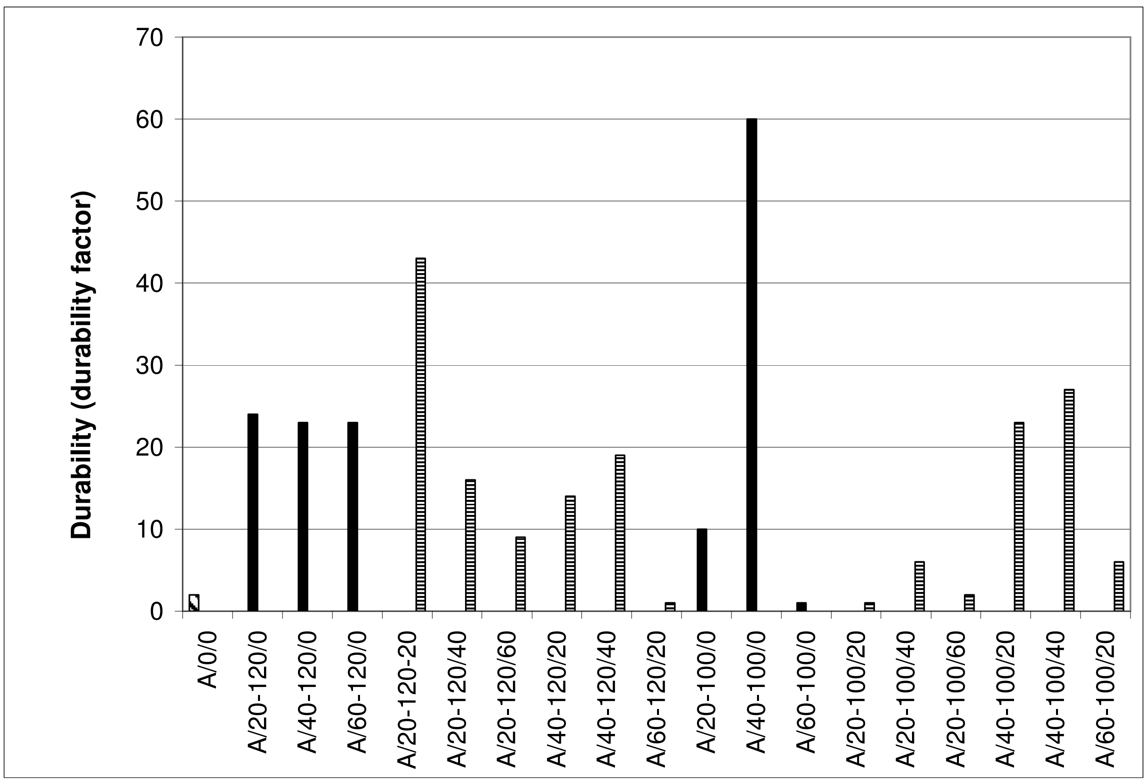
4.4.2.3 Freeze/Thaw Durability

The resonance frequency was monitored for each sample at each test and recorded as shown in Appendix A. The durability factor was determined from the last frequency recorded from each sample as per ASTM 666 (AASHTO T 161). Pictures of the freeze/thaw samples at end of testing or failure are shown in Appendix B. Three of the nine mixtures had not statistically different durability factors for freeze/thaw durability. The mixtures were A/20/0, A/20/60, and A/40/40. The mixtures with greater durability when made with GR 120 GGBFS were A/40/0, A/60/0, A/20/20, and A/20/20. The mixtures that had greater durability with GR 100

GGBFS were A/40/20 and A/60/20. The trends observed from the data and Chart 4.36 were as follows:

- the durability factors of the GR 100 GGBFS mixtures less consistent than GR 120 mixtures, and
- the durability factors of the GR 120 GGBFS mixtures were similar to each other.

Chart 4.36 Freeze/Thaw Durability Values for GGBFS Study



Chapter 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 General

The research program described in Sections 3.5 and 3.6 was designed to examine the fresh and hardened properties of concrete mixtures containing GGBFS and FA. The replacement rates encompass the range defined conservatively by a replacement below that allowed by AHTD (20%) and liberally by greater replacement rates (80%) than recommended in previous studies. The following sections present the conclusions and recommendations from the cement, SCM, and GGBFS studies with the fresh concrete properties followed by the hardened concrete properties.

5.2 Cement Study

Section 3.5 described the cement study portion of the research program. Section 4.2 presented the results from the study. The purpose of the study was to determine if the SCM produced similar properties when combined with different locally available Type I cement sources.

5.2.1 Fresh Concrete Properties

Slumps were statistically different between the two cement sources. The slump values for cement B were greater than the slump values for cement A. The two cements did show a similar trend in slump with higher FA replacement rates producing greater slump and higher GGBFS contents decreasing the slump.

Unit weights of mixtures made with cement A were higher than the unit weights of mixtures made with cement B. Unit weight was tested as a quality control method to check the amounts of materials in the concrete.

This study did not include adding air entraining admixtures; therefore the air content was due only to entrapped air. The air contents were observed to be within 1 to 2%, which is typical of mixtures containing only entrapped air. Literature suggests mixtures with SCMs require more attention and testing with air-entraining admixtures to achieve higher air contents. The literature also suggests that the unburned carbon in FA will have a detrimental effect on the air content and that observations in the air content should be monitored for fluctuation.

5.2.2 Hardened Concrete Properties

Even though cement A mixtures generally had higher strength than like cement B mixtures; they followed the same trend and therefore react similarly to the addition of SCMs. For all ages, only 8 of the 25 mixtures were not statistically different, meaning that cement A and cement B produce different compressive strengths in 68% of the mixtures. Even though there were differences, both mixtures (cement A and cement B) benefited from the addition of SCM. Mixtures from both cement sources met the AHTD twenty-eight day strength requirement of 4,000 psi.

At all ages, cement A mixtures generally produced higher compressive strengths than cement B mixtures but similar trends were observed between the two sources. Cement A reacted differently with SCMs than cement B to lower permeability from the control mixture for 28 and 90 days. The freeze/thaw results were not as consistent between cement A and cement B mixtures, however, the addition of SCM generally improved the durability when compared to the control mixtures.

5.3 Supplementary Cementitious Material Study

Section 3.6 described the SCM study portion of the research program. Section 4.3 presented the results from the study. The SCM study analyzed the fresh and hardened properties of concrete mixtures with differing amounts of GGBFS, FA, or combinations of both materials.

5.3.1 Fresh Concrete Properties

Slump increased as FA content increased, and decreased as GGBFS content increased. These two trends were also observed in the ternary mixtures. The slump data were taken at a variety of mixing temperatures but the trends in slump were not dependent on the temperature. Mixtures containing more than 20% GGBFS had a reduced slump from the control mixture. Reduction in slump observed in the GGBFS mixtures can be offset by the addition of a high range water reducer.

5.3.2 Hardened Concrete Properties

One of the main concerns with the use of SCM is the reduction of strength associated with replacing cement. The compressive strength results for the SCM study repeated the trend noted from the literature in Section 2.8.1 that cement only mixtures had higher early strength than mixtures containing SCM. The study also showed that some mixtures with cement replacements obtained higher later strength than the cement only mixture. The statistical analysis, described in Section 3.9, determined the differences and similarities between the compressive strengths.

At one day, the cement only mixture had statistically higher compressive strength than mixtures containing SCM. The control mixture also had the greatest three-day compressive strength. Three of the 20% replacement mixtures and the 20%

GGBFS/ 20% FA mixture were not statistically different and had the second highest strengths. Mixtures with greater than 40% replacements (of either SCM) had the lowest strengths.

AHTD specifications require at least 3000 psi (21.0 MPa) compressive strength at seven days to open a roadway to traffic. At seven days, 19 of 22 mixtures in the SCM study had over 3000 psi compressive strength. Even the 60% replacement of GGBFS, FA, and ternary mixtures with 60% total replacement met the seven day compressive strength requirement. The control mixture did not have a statistically greater strength than the 20% GGBFS/20% FA and 20% FA mixtures; meaning that the three mixtures are interchangeable at seven-days. The mixtures with a seven day compressive strength less than 3000 psi were the ternary mixtures with 40 or 60% FA replacements combined with GGBFS replacements to total 80% SCM. Such high replacements of cement generally have very low early strength as described in Section 2.6.1.

The twenty-eight day compressive strength is widely used as the design strength of concrete mixtures. As described in Section 3.2 and Section 3.3, the AHTD specifications for concrete pavement require 4000 psi (28.0 MPa) as the minimum twenty-eight day compressive strength. Twenty-one of the 22 mixtures in the SCM study resulted in greater than 4000 psi strength at 28 days. Three ternary mixtures and a 40% GGBFS mixture had statistically higher 28 day compressive strength than the control mixture containing only portland cement. The lone mixture with the 28 day compressive strength less than 4000 psi was the 20% Gr. 100 and 60% FA mixture. The literature review suggests that GGBFS and FA replacement mixtures could gain more strength than cement only mixtures in later strength tests as described in Section 2.6.1.

Eight mixtures made with 40 or 60% SCM replacements had statistically higher ninety-day compressive strength than the control mixture. The 8 mixtures had a compressive strength that was at least 1000 psi greater than the control mixture. The 80% replacement ternary mixtures had the lowest 90 day strength with 5 out of 6 mixtures having less than 8000 psi compared to 8250 psi for the control mixture. These results show that SCM mixtures, containing up to 60% SCM, have greater or comparable later strength when compared to cement only mixtures as described in the literature in Section 2.6.1.

Three mixtures, including the control mixture, are classified as having high permeability at 28 days based on the RCPT results. FA only mixtures, 20% GGBFS only mixtures, and ternary mixtures with 20% GGBFS and 60% FA had high or moderate permeability. For permeability at 28 days, GGBFS was a better mixture design component than FA because an increase in GGBFS decreased permeability while an increase in FA increased permeability. But at 90 days of age, the FA mixtures would also be classified as having low permeability. All mixtures experienced a reduction in permeability from 28 to 90 days.

The freeze/thaw durability is greatly dependent on the air content, especially entrained air as described in Section 2.5.4. Mixtures with air contents of approximately 7 to 9% have the highest durability factors from freeze/thaw tests (Mindess et al. 2003). Without AEA, the mixtures in this study did not meet the AHTD specifications. Due to the addition of FA and GGBFS, seventeen of the 21

SCM mixtures had greater durability than the control mixture. However, none of the mixtures had a DF over 60, the value recognized as having acceptable freeze/thaw resistance.

5.4 Ground Granulated Blast Furnace Slag Study

The ground granulated blast furnace slag study was described in Section 3.6. The results from the study were presented in Section 4.4. The purpose of the GGBFS study was to determine if the proposed replacement rates of Gr. 120 GGBFS would be acceptable for Gr. 100 GGBFS.

5.4.1 Fresh Concrete Properties

Mixtures containing only GGBFS (no FA) had comparable slump to the control mixture within 1". The ternary mixtures had statistically higher slump than the control mixture in 10 of the 12 ternary mixtures. The slump results for the GGBFS were not consistent. Four of 9 mixture designs had greater slump when made with GR 120 GGBFS, and 4 of 9 mixture designs had greater slump when made with GR 100 GGBFS.

5.4.2 Hardened Concrete Properties

The early strength tests on 1, 3, and 7 days show a trend of greater compressive strength in mixtures made with GR 120 GGBFS when compared to like GR 100 mixtures. The one day compressive strength tests showed that 6 of the 9 designs were not statistically different, 2 of 9 had greater strength with GR 120 GGBFS, and 1 of 9 had greater strength with GR 100 GGBFS. With the exception of the A/40-120/20 mixture, the mixtures showed similar trends in strength. Three day compressive strength results showed 5 of 9 mixtures with not statistically different strength, 3 of 9 had greater strength with GR 120 GGBFS and 1 of 9 had greater strength with GR 100 GGBFS. At 7 days of age, the compressive strengths for 4 of 9 mixtures were not statistically different strength, another 4 mixtures had greater strength with GR 120 GGBFS, and 1 mixture had greater strength with GR 100 GGBFS.

The results from the twenty-eight day compressive strengths showed that 4 of 9 mixtures were not statistically different strength, 4 of 9 had greater strength when made with GR 100 GGBFS, and 1 of 9 had greater strength when made with GR 120 GGBFS. This trend was opposite of the seven-day results and contrary to the trend from 1 to seven-day results. The twenty-eight day strength is used in the industry to determine the grade of GGBFS, as described in Section 2.2. The GR 120 GGBFS should have greater strength than the GR 100 GGBFS based on the method used to grade the material. The GR 100 GGBFS used in this study could fall just short of the requirements for GR 120 for the seven-day strength requirements, as suggested by the seven-day results. The GGBFS has to meet both 7 and twenty-eight day requirements according to the ASTM C989 to be considered GR 100 or GR 120.

The 90 day compressive strengths results show that the mixtures with different grades of GGBFS became more similar. Six of 9 mixtures were not statistically different, the highest number of similar results in the GGBFS study. The strengths were greater for GR 100 GGBFS in 2 of 9 mixtures and greater for GR 120 GGBFS in 1 of 9 mixture designs.

The similarity in permeability between the GR 100 and GR 120 mixtures also increased from 28 to 90 days. At 28 days, 4 of 9 mixture designs were not statistically different, 2 had lower permeability with GR 100 GGBFS, and 3 had lower permeability with GR 120 GGBFS. At 90 days, 5 of 9 mixture designs were not statistically different, 3 had lower permeability with GR 100 GGBFS, and 1 had lower permeability with GR 120 GGBFS. All mixtures were statistically different in durability factor between GR 100 GGBFS and GR 120 GGBFS mixtures, but the similarly poor freeze/thaw performance was due to the lack of AEA.

5.5 Recommendations

The purpose of the cement study was to determine if the SCMs produced similar properties when combined with different locally available Type I cement sources. The results of the fresh and hardened concrete tests for the cement study showed that some of the properties were not statistically different while some were. The properties that were not similar between the two cements showed similar trends. The two different portland cement sources did not produce extremely varying results. The recommendations from the cement study results are as follows:

- the differences in properties between cement A and cement B can be attributed to the differences in cement source, not varying reactions to the SCMs,
- cement source did not cause extreme variance in the fresh and hardened concrete properties, and
- GR 100 GGBFS, GR 120 GGBFS, and FA can be used in mixtures with different cement sources available in Arkansas.

The purpose of the SCM study was to analyze the fresh and hardened properties of concrete mixtures with differing amounts of GGBFS, FA, or combinations of both materials. The results of the fresh and hardened concrete tests for the GGBFS study showed that SCM replacements can improve the properties of concrete mixtures. Because the GGBFS study resulted in viable mixture design properties from concrete with at least 40% SCM replacements, the recommendations are as follows:

- add AEA to the mixtures for the air contents to be within AHTD specifications while observing for lower strengths and slump increases typical of adding AEA,
- compressive strengths at one day suggest that up to 40% SCM (as FA and GGBFS only or ternary mixtures) can be used with a strength of at or above 900 psi for joint construction within two days of pour,
- compressive strengths at three days suggest that up to 40 % SCM (as FA and GGBFS only or ternary mixtures) can be used with a strength of at or above 3510 psi (nearly AHTD 28 day design criteria) for form removal,
- 90 day permeability results suggest that the greatest benefit is at 20% SCM, but that additional 20% SCM lowers permeability slightly,
- freeze/thaw results show that SCMs improve the freeze/thaw durability of concrete mixtures over the control mixtures even without AEA, and therefore,
- it is recommended that up to 40% maximum replacements with SCM (GR 100 and GR 120 GGBFS, FA, and ternary mixtures) be allowed for concrete pavement design in Arkansas.

The purpose of the GGBFS study was to determine if the proposed replacement rates produced the same properties using GR 100 and GR 120 GGBFS. Either grade (GR 100 or GR 120) GGBFS could be used in concrete mixtures without widely varying fresh concrete properties. At three days the difference in strength, between GR 100 and GR 120 mixtures, is not so great that one, and not the other, would have sufficient strength for cutting joints without tearing and raveling (AHTD requirement for joint sawing). GR 120 GGBFS produced greater strength because the seven day reactivity index of the GR 100 is 87% of the GR 120. In this study, the reactivity index of the GR 100 GGBFS converged on that of the GR 120 GGBFS (87% to 98%) so that the mixtures produced more similar compressive strength results at later age. Mixtures with both grades met the AHTD twenty-eight day compressive strength requirement of 4000 psi. Both grades also produced mixtures with permeability values lower than the control mixture and similar freeze/thaw durability greater than the control mixture. The GGBFS Study recommendations are as follows:

- GR 100 and GR 120 produced similar and acceptable fresh and hardened concrete properties,
- recommended replacements rates for GR 100 and GR 120 are interchangeable, and
- GR 100 and GR 120 GGBFS should be allowed.

BIBILIOGRAPHY

ACI Committee 233. Slag Cement in Concrete and Mortar. Farmington Hills: American Concrete Institute, 2003.

Agnes, Michael, and David Guralnik. *Webster's New World College Dictionary*. 4th ed. Foster City: IDG Books Worldwide, Inc., 2000.

American Coal Ash Association (ACAA). Fly Ash Facts for Highway Engineers. Springfield: National Technical Information Service, 1995.

Arkansas Highway and Transportation Department. Standard Specifications for Highway Construction. Little Rock: Arkansas Highway and Transportation Department, 2003.

Babu, K. Ganesh, and G. Siva Nageswara Rao. "Early Strength Behaviour of Fly Ash Concretes." Cement and Concrete Research. Vol. 24. No. 2 (1994): 277-284.

"Blast Furnace Slag-Material Description." Blast Furnace Slag-Material Description. Turner-Fairbanks Highway Research Center. 21 Dec. 2004 <http://www.tfhrc.gov/hnr20/recycle/waste/bfs1.htm>.

"Blast Furnace Slag – User Guideline – Portland Cement Concrete." Blast Furnace Slag – User Guideline – Portland Cement Concrete. Turner-Fairbanks Highway Research Center. 21 Dec. 2004 <http://www.tfhrc.gov/hnr20/recycle/waste/bfs3.htm>.

"Coal Fly Ash-Material Description ." Coal Fly Ash-Material Description. Turner-Fairbanks Highway Research Center. 21 Dec. 2004 <http://www.tfhrc.gov/hnr20/recycle/waste/cfa51.htm>.

"Coal Fly Ash-User Guideline." Coal Fly Ash-User Guideline. Turner-Fairbanks Highway Research Center. 21 Dec. 2004 <http://www.tfhrc.gov/hnr20/recycle/waste/cfa53.htm>.

Duchesne, Josée, and Marc-André Bérubé. "Long-term Effectiveness of Supplementary Cementing Materials Against Alkali-Silica Reaction." Cement and Concrete Research. Vol. 31. No. 7 (2001): 1057-1063.

"Fly Ash-Materials Group." Fly Ash-Materials Group. United States Department of Transportation; Federal Highway Administration. 23 Dec. 2004 <http://www.fhwa.dot.gov/infrastructure/materialsgrp/flyash.htm>.

Gillott, J. E. “Review of Expansive Alkali-Aggregate Reactions in Concrete.” Journal of Materials in Civil Engineering. Nov. 1995: 278-282.

“Ground Granulated Blast-Furnace Slag-Materials Group.” Ground Granulated Blast-Furnace Slag-Materials Group. United States Department of Transportation; Federal Highway Administration. 21 Dec. 2004 <http://www.fhwa.dot.gov/infrastructure/materialsgrp/ggbfs.htm>.

Hogan, Frank, Jerry Meusel, and Lou Spellman. “Breathing Easier with Blast Furnace Slag.” Cement Americas. December 23, 2004. <http://cementamericas.com/mag/cement_breathing_easier_blast/index.html> July 2001.

Irassar, E. F., and A. Di Maio, and O. R. Batic. “Sulfate Attack on Concrete with Mineral Admixtures.” Cement and Concrete Research. Vol. 26. No. 1. (1996): 113-123.

Khatri, R. P., V. Sirivivatnanon,, and W. Gross. “Effect of Different Supplementary Cementitious Materials on Mechanical Properties of High Performance Concrete.” Cement and Concrete Research. Vol. 25. No. 1 (1995): 209-220.

Külaots, Indrek, Robert H. Hurt, and Eric M. Suuberg. “Size Distribution of Unburned Carbon in Coal Fly Ash and its Implications.” Fuel. Vol. 83. No. 2 (2004): 223-230.

“Leadership in Energy & Environmental Design.” Leadership in Energy & Environmental Design. United States Green Building Council. 21 Dec. 2004 <http://www.usgbc.org/LEED/LEED_main.asp>.

Leng, Faguang, Naiqain Feng, and Xinying Lu. “An Experimental Study on the Properties of Resistance to Diffusion of Chloride Ions of Fly Ash and Blast Furnace Slag Concrete.” Cement and Concrete Research. Vol. 30. (2000): 989-992.

Li, Gengying, and Xiaohua Zhao. “Properties of Concrete Incorporating Fly Ash and Ground Granulated Blast-Furnace Slag.” Cement and Concrete Composites. Vol. 25. No. 3 (2003): 293-299.

Luther, M. D., W. J. Mikols, A. J. De Maio, and J. I. Whitlinger 1994, “Scaling Resistance of Ground Granulated Blast Furnace Slag (GGBFS) Concretes,” *Durability of Concrete*, Proceedings of the Third International Conference, SP-145, V. M. Malhotra, ed., American Concrete Institute, Farmington Hills, Mich., pp.47-64.

Mehta, P. Kumar. “Greening of the Concrete Industry for Sustainable Development.” Concrete International. Vol. 24. No.7 July (2002): 23-28.

Mindess, Sidney, J. Francis Young, and David Darwin. Concrete. 2nd ed. Upper Saddle River: Pearson Education, Inc., 2003.

Nobata, Kenji, and Yasutomo Ueki. “Basic Property and the Method of Effective Use on Portland Blast-Furnace Slag Cement and Ground Granulated Blast Furnace Slag.” Nippon Steel technical report. No. 86. (2002): 44-47.

Nocuń-Wczelik, W. “Heat Evolution in Hydrated Cementitious Systems Admixtured with Fly Ash.” Journal of Thermal Analysis and Calorimetry. Vol. 65 (2001): 613-619.

Ostrowski, Christopher. “Fly Ash, Slag put ‘Green’ Concrete on the Map.” Intermountain Contractor. Vol. 58. No. 7 20 July (2002): 48.

Penttala, Vesa. “Concrete and Sustainable Development.” ACI Materials Journal. Vol. 94. No. 5 Sept.-Oct. (1997): 409-416.

Pigeon, Michel, and Micheline Regourd. “Freezing and Thawing Durability of Three Cements with Various Granulated Blast Furnace Slag Contents.” American Concrete Institute SP 79-52. Vol. 2. (1983):.979-998.

“P-Value.” iSix Sigma Dictionary. 7 July 2003. iSix Sigma. 27 July 2005 <http://www.isixsigma.com/dictionary/P-Value-301.htm>.

Schriefer, John. “Reaping the Value from Dust and Slag.” New Steel. 21 Dec. 2004. <http://www.newsteel.com/features/Ns9702f3.htm> Feb. (1997).

Schutter, G. De. “Hydration and Temperature Development of Concrete Made with Blast-Furnace Slag Cement.” Cement and Concrete Research. Vol. 29. No. 1 (1999): 143-149.

Shi, Caijun, Julia A. Stegemann, and Robert J. Caldwell. “Effect of Supplementary Cementing Materials on the Specific Conductivity of Pore Solution and its Implications on the Rapid Chloride Permeability Test (AASHTO T277 and ASTM C 1202) Results.” ACI Materials Journal. Vol. 95. No. 4 July-Aug. (1998) 389-394.

Sullivan, Ed, and Dave Czechowski. “Cement Shortage Assessment.” The Monitor: Flash Report. Portland Cement Association. 13 May (2004).

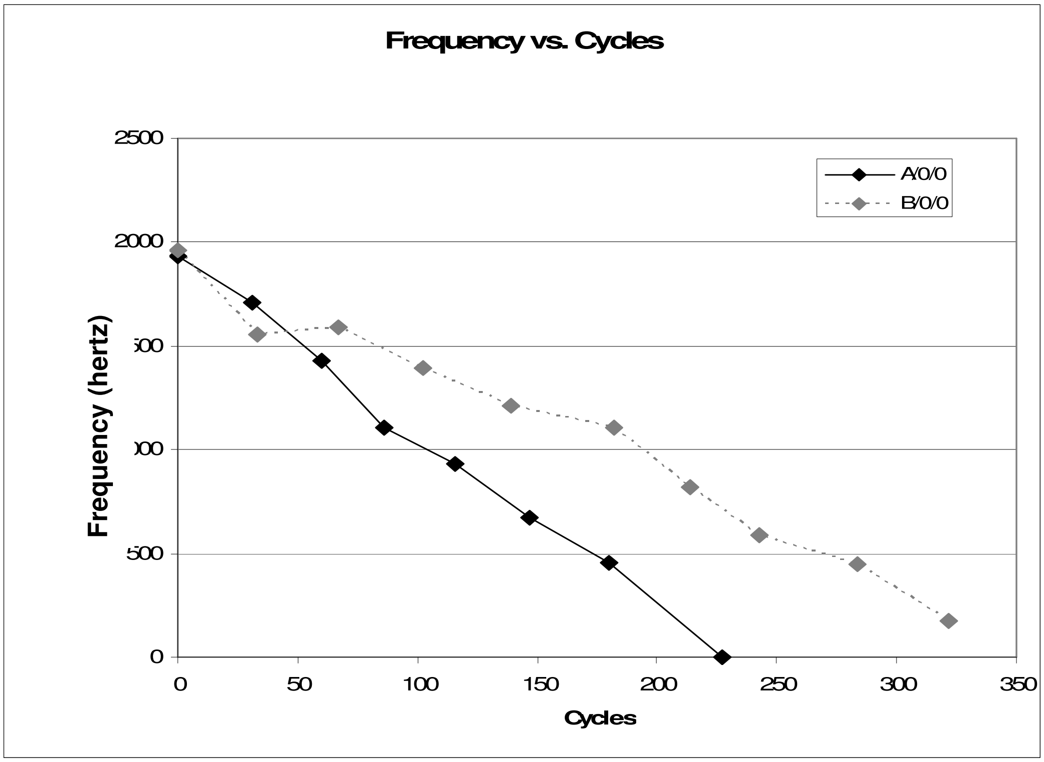
Taylor, Peter C., Willy Morrison, and Victoria A. Jennings. “Effect of Finishing Practices on Performance of Concrete Containing Slag and Fly Ash as

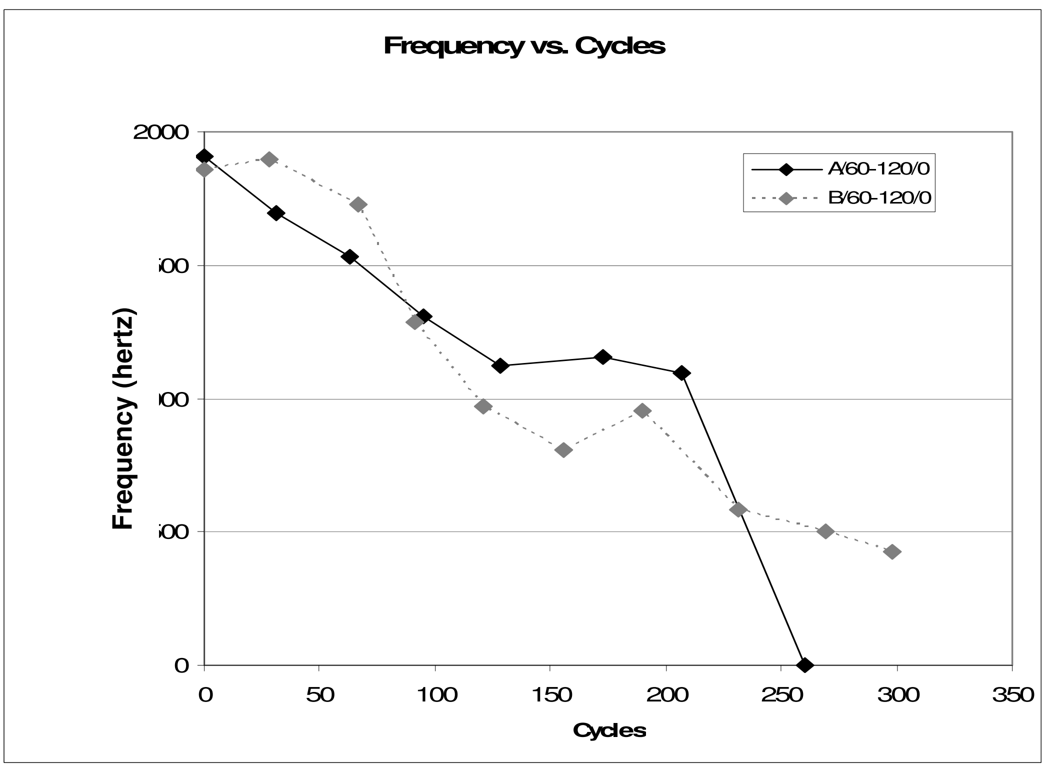
Measured by ASTM C 672 Resistance to Deicer Scaling Tests." Cement, Concrete, and Aggregates. Vol. 26. No. 2 Dec.(2004): 155-159.

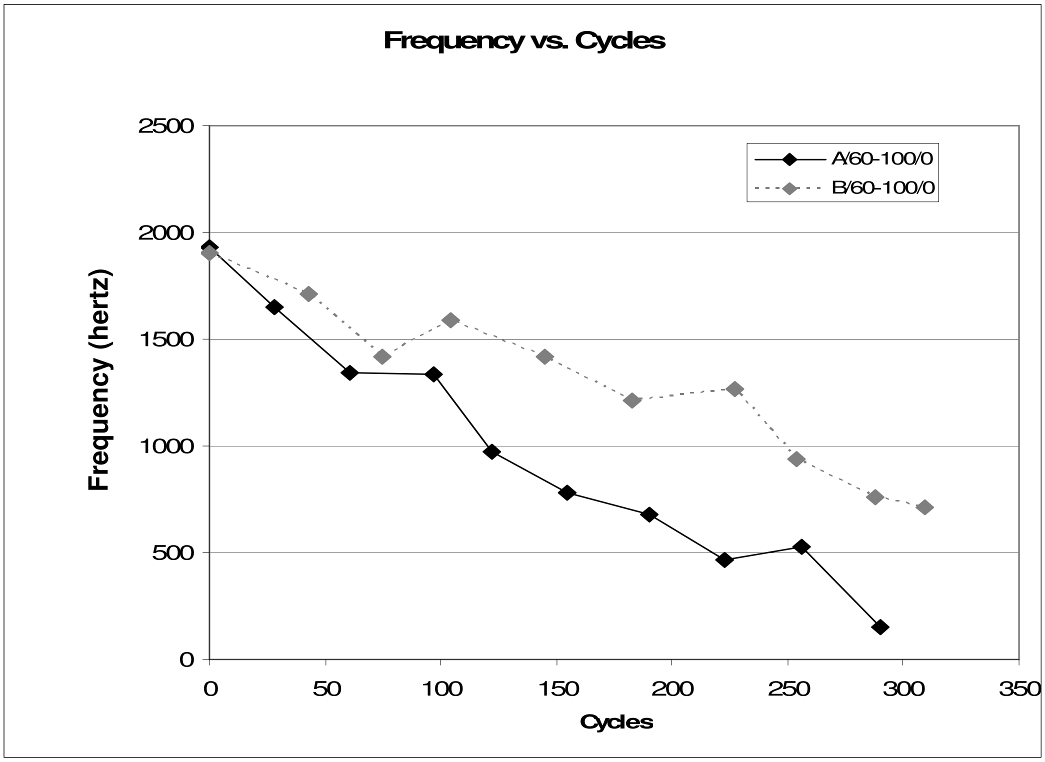
VanGeem, Martha, and Medgar Marceau. "Using concrete to maximize LEED points." Concrete International. November (2002): 69-73.

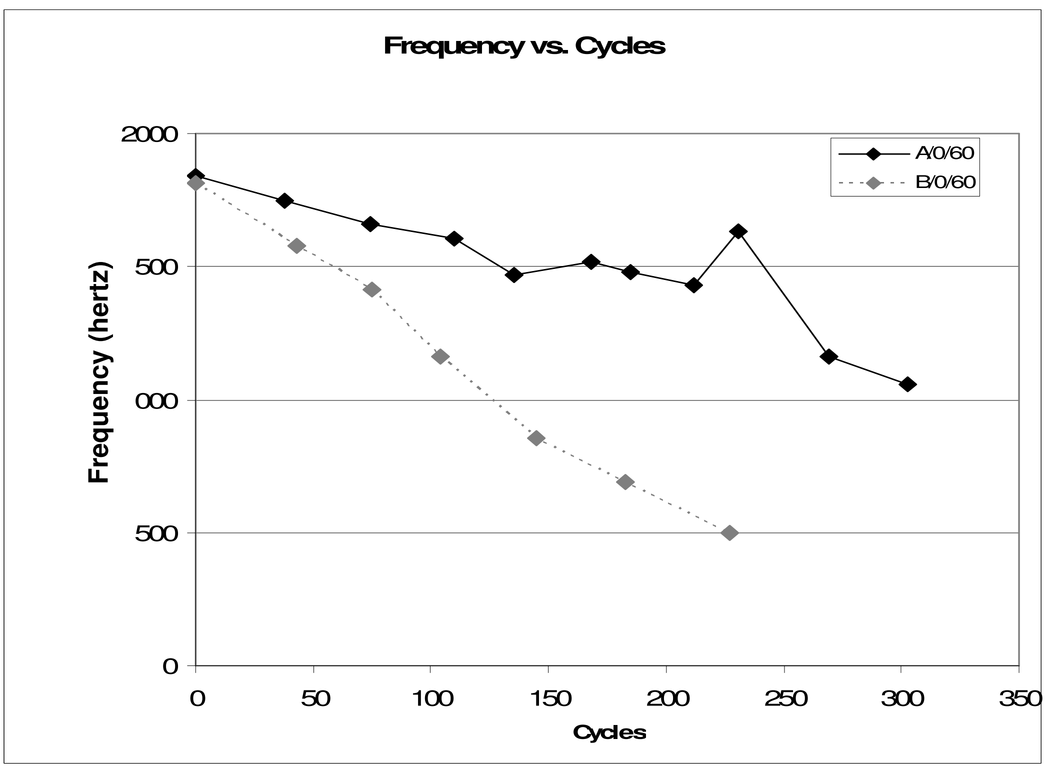
APPENDIX A: FREQUENCY VS CYCLES GRAPHS

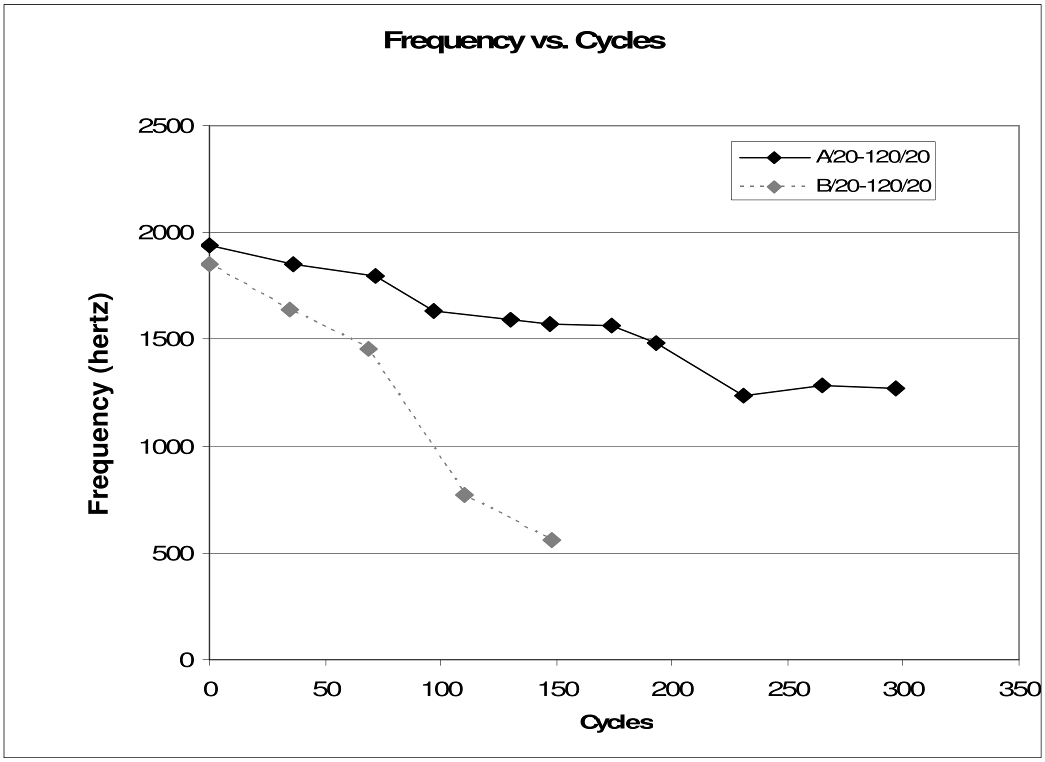
A.1 Cement A and Cement B Batches for Cement Study



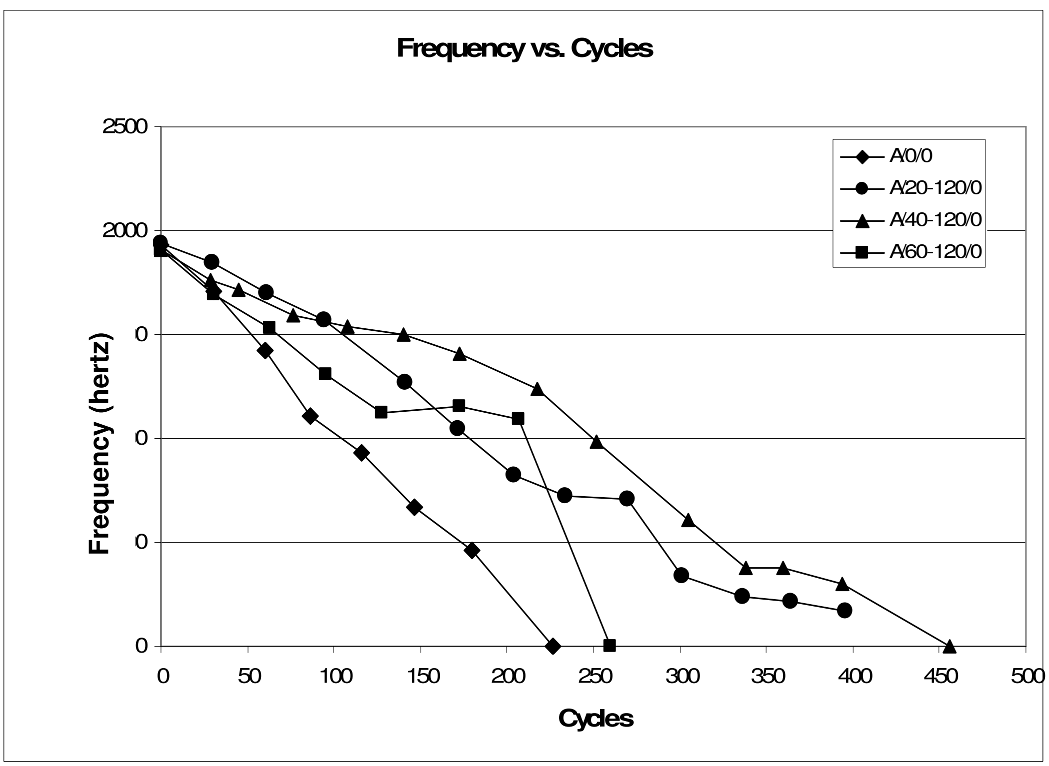


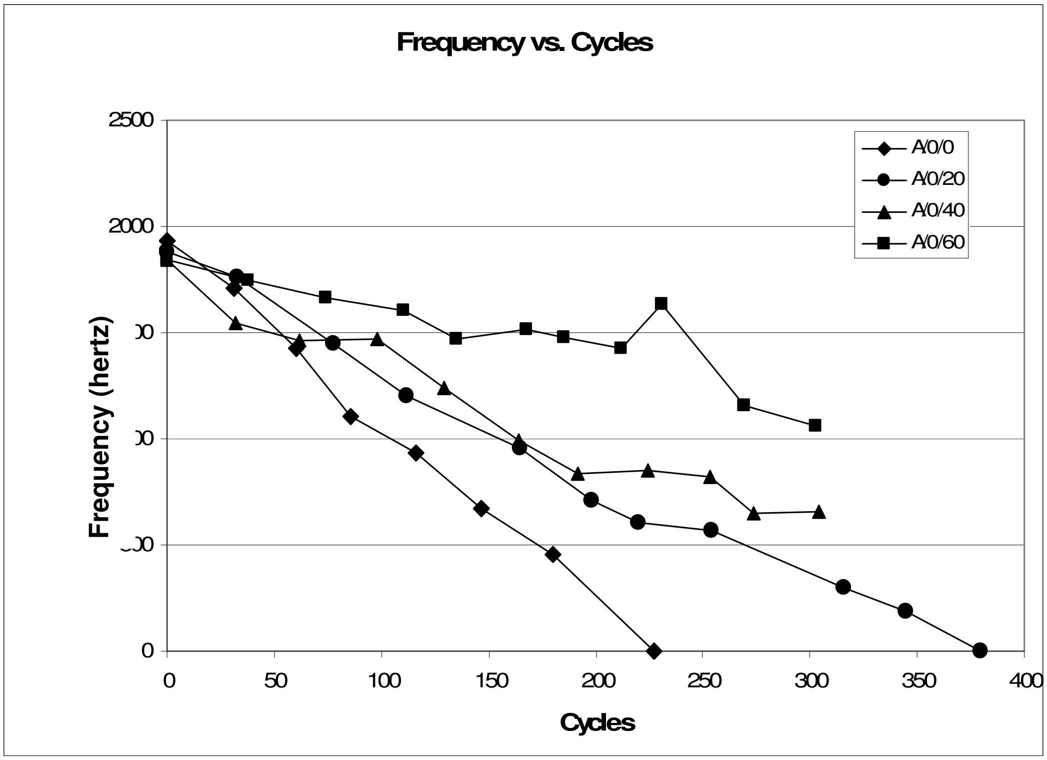

Frequency vs. Cycles
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
350
Cycles
Frequency (hertz)
A/60-100/0
B/60-100/0

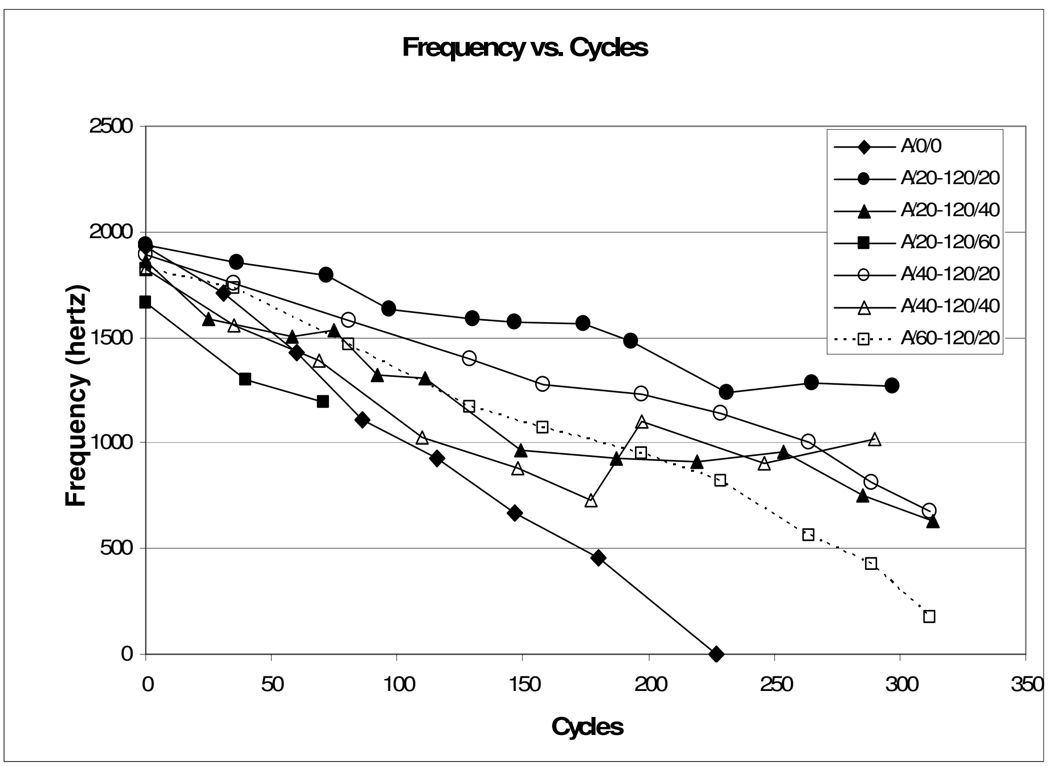

Frequency vs. Cycles
2000
500
000
500
0
0
50
100
150
200
250
300
350
Cycles
Frequency (hertz)
A/0/60
B/0/60

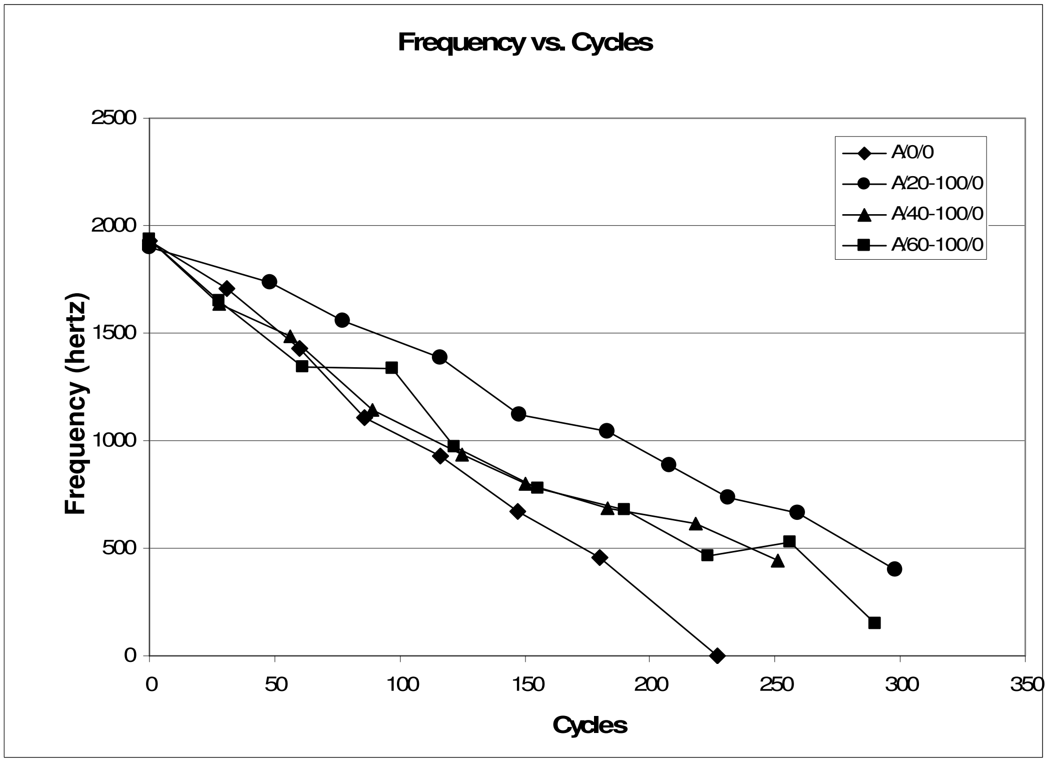


A.2 Cement A Batches with GGBFS and FA for SCM Study

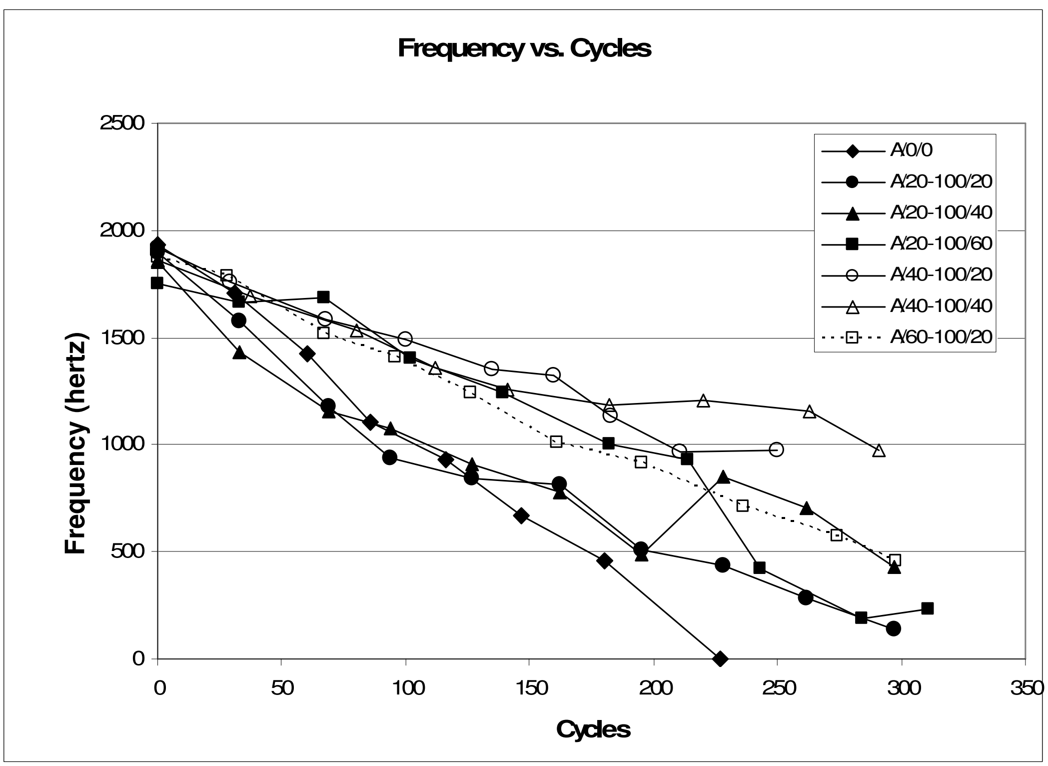



Frequency vs. Cycles
Frequency (hertz)
Cycles
A/0/0
A/0/20
A/0/40
A/0/60
2500
2000
0
0
50
100
150
200
250
300
350
400


Frequency vs. Cycles
Frequency (hertz)
Cycles
A/0/0
A/20-120/20
A/20-120/40
A/20-120/60
A/40-120/20
A/40-120/40
A/60-120/20
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
350

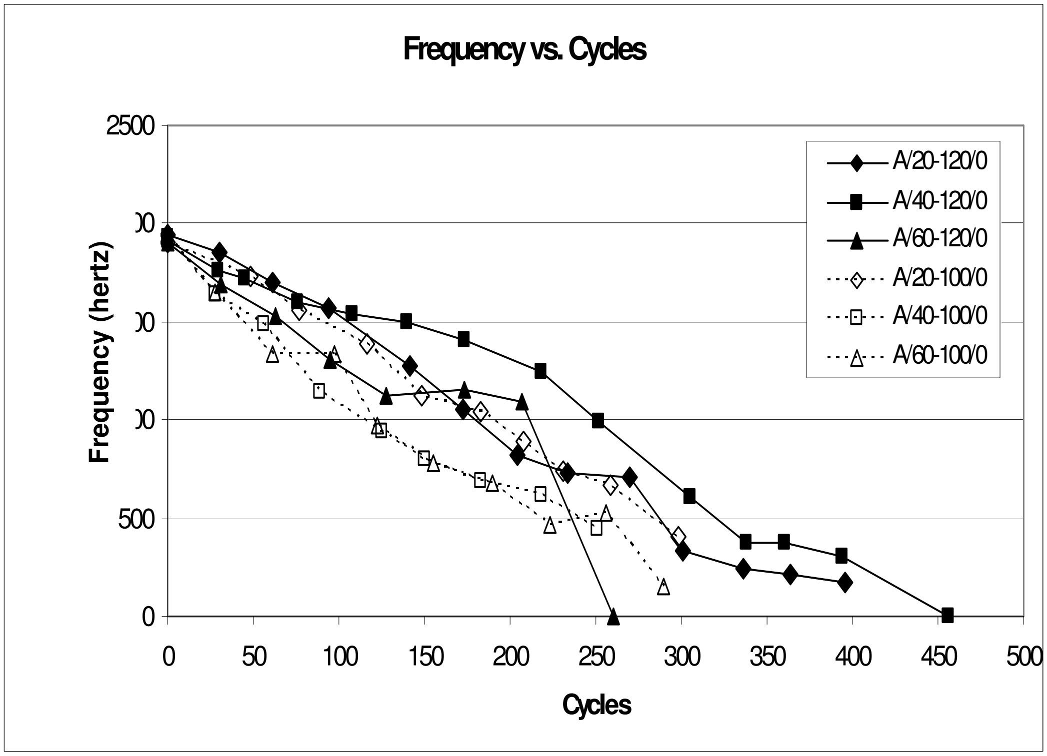


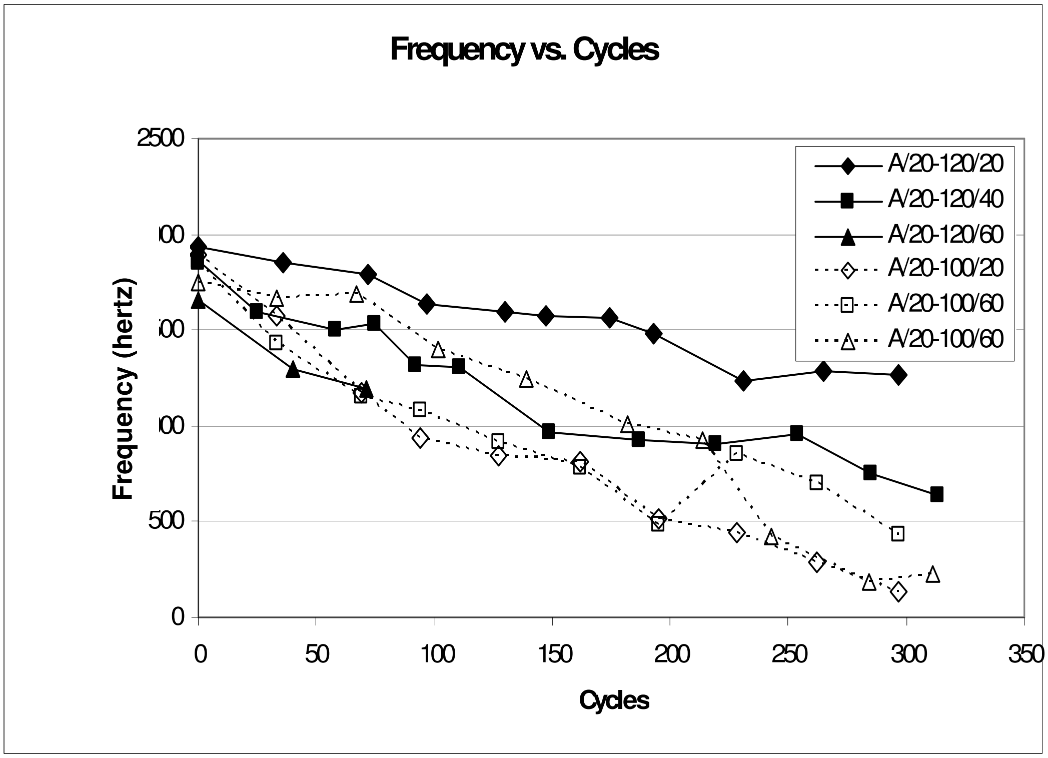
Frequency vs. Cycles
Frequency (hertz)
Cycles
A/0/0
A/20-100/0
A/40-100/0
A/60-100/0

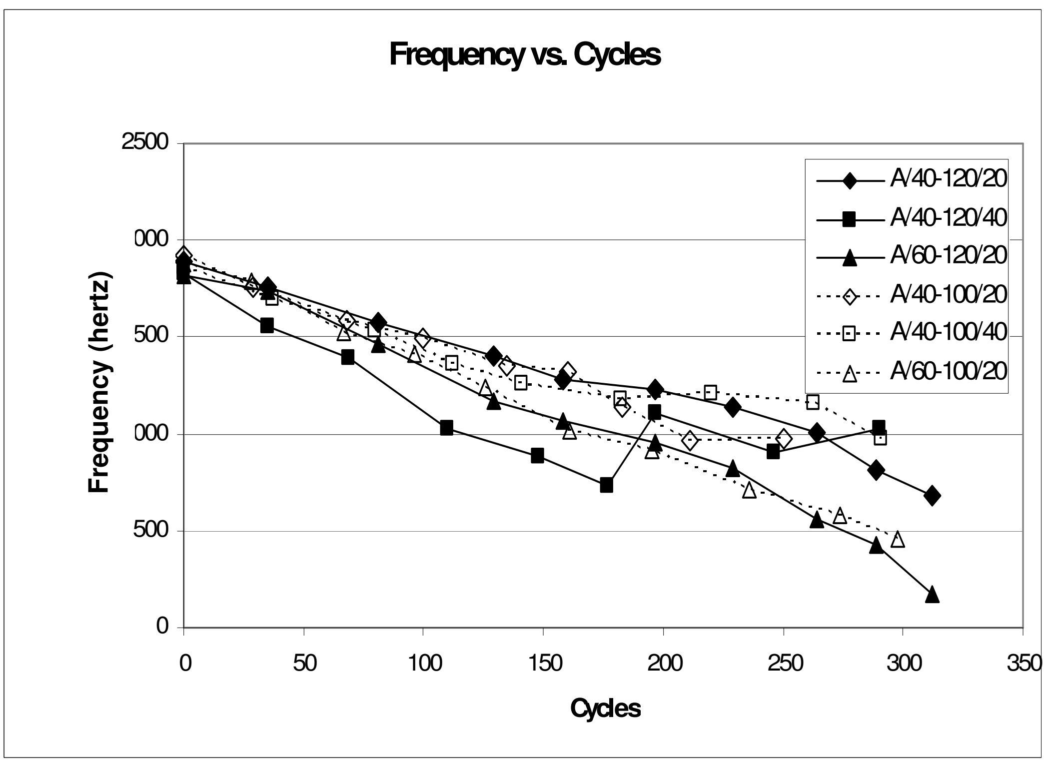


Frequency vs. Cycles
Frequency (hertz)
Cycles
A/0/0
A/20-100/20
A/20-100/40
A/20-100/60
A/40-100/20
A/40-100/40
A/60-100/20

A.3 Cement A Batches with GR 120 and GR 100 GGBFS for GGBFS Study




Frequency vs. Cycles
Frequency (hertz)
Cycles
A/20-120/20
A/20-120/40
A/20-120/60
A/20-100/20
A/20-100/60
A/20-100/60


Frequency vs. Cycles
Frequency (hertz)
Cycles
A/40-120/20
A/40-120/40
A/60-120/20
A/40-100/20
A/40-100/40
A/60-100/20

APPENDIX B: FREEZE/THAW SAMPLES AT FAILURE OR END OF TEST

Figure B.1 A/0/0

Figure B.2 A/0/0

Figure B.3 A/20-120/0

Figure B.4 A/40-120/0

Figure B.5 A/40-120/0

Figure B.6 A/40-120/0

Figure B.7 A/60-120/0

Figure B.8 A/60-120/0

Figure B.9 A/0/20

Figure B.10 A/0/20

Figure B.11 A/0/40

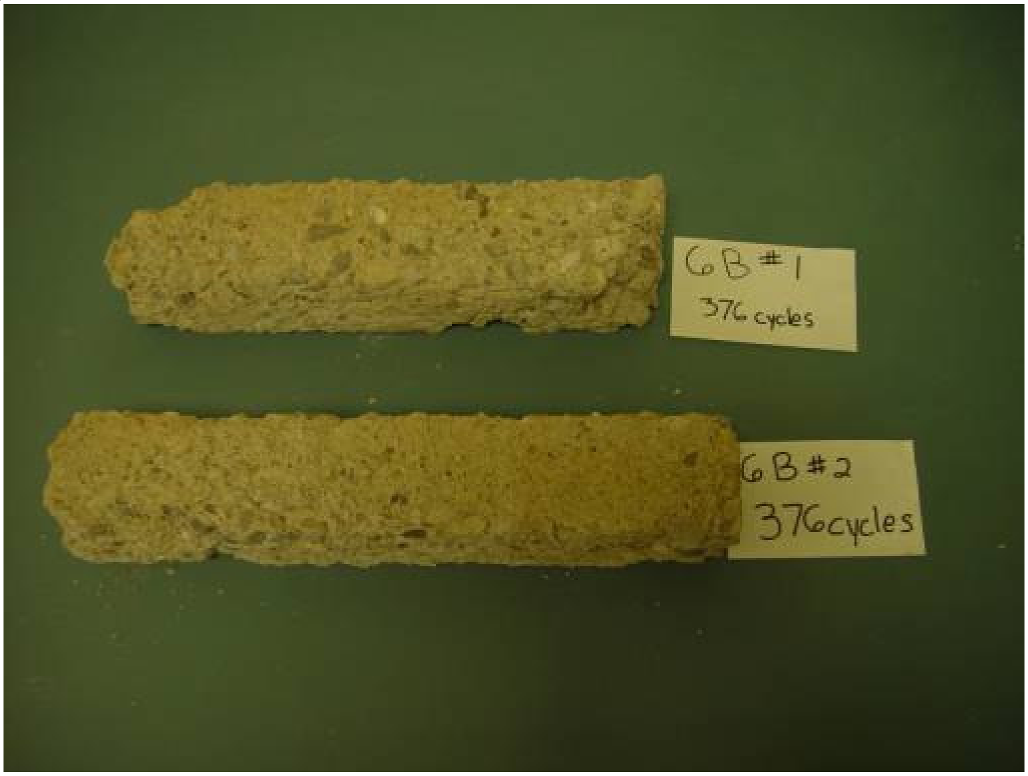


Figure B.12 A/0/60

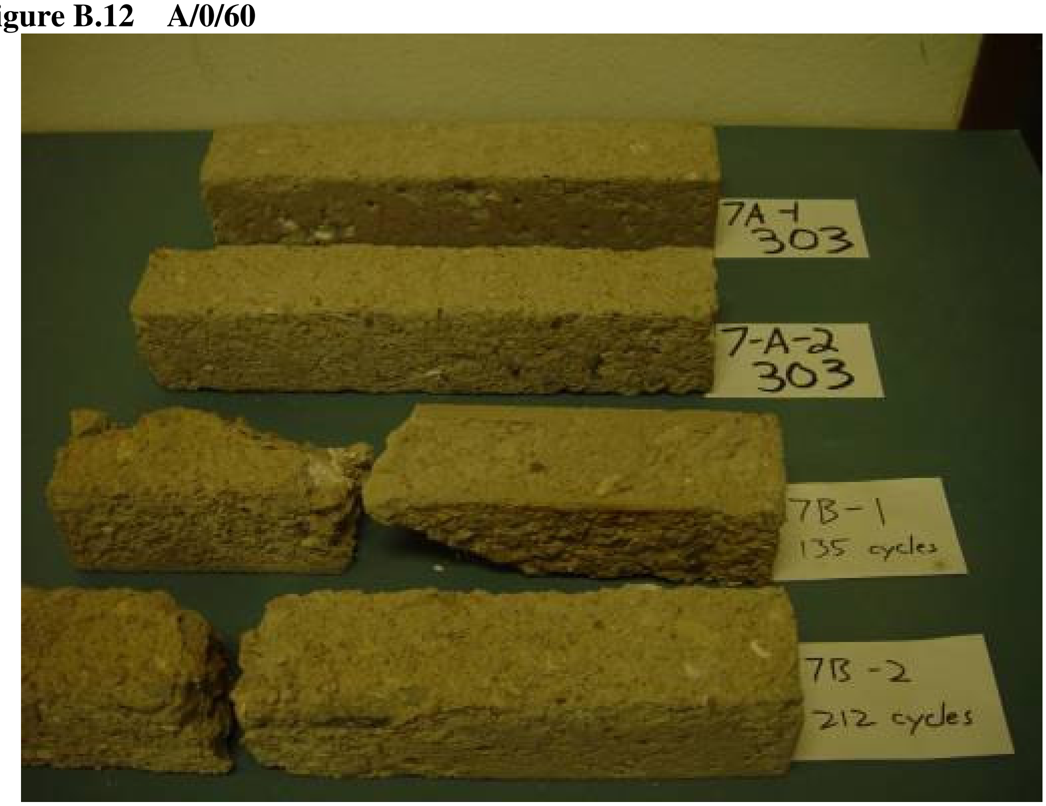


Figure B.13 A/20-120/20

Figure B.14 A/20-120/40

Figure B.15 A/20-120/60

Figure B.16 A/40-120/20

Figure B.17 A/40-120/40

Figure B.18 A/60-120/20

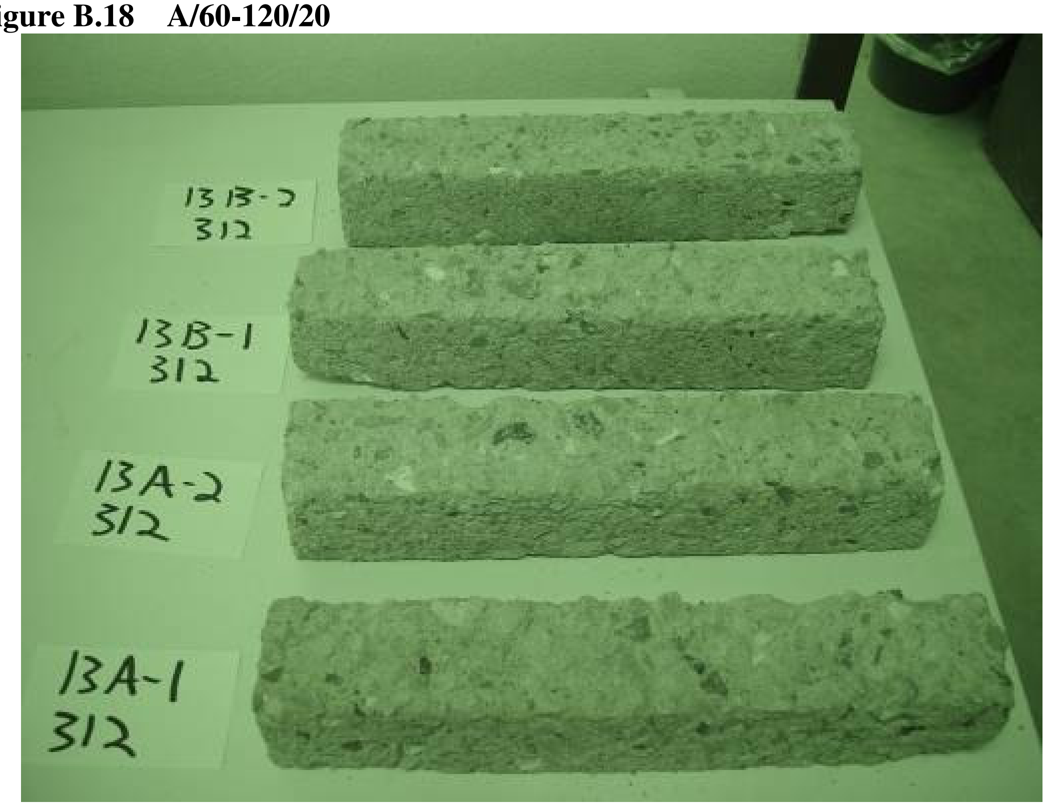


Figure B.19 A/20-100/0

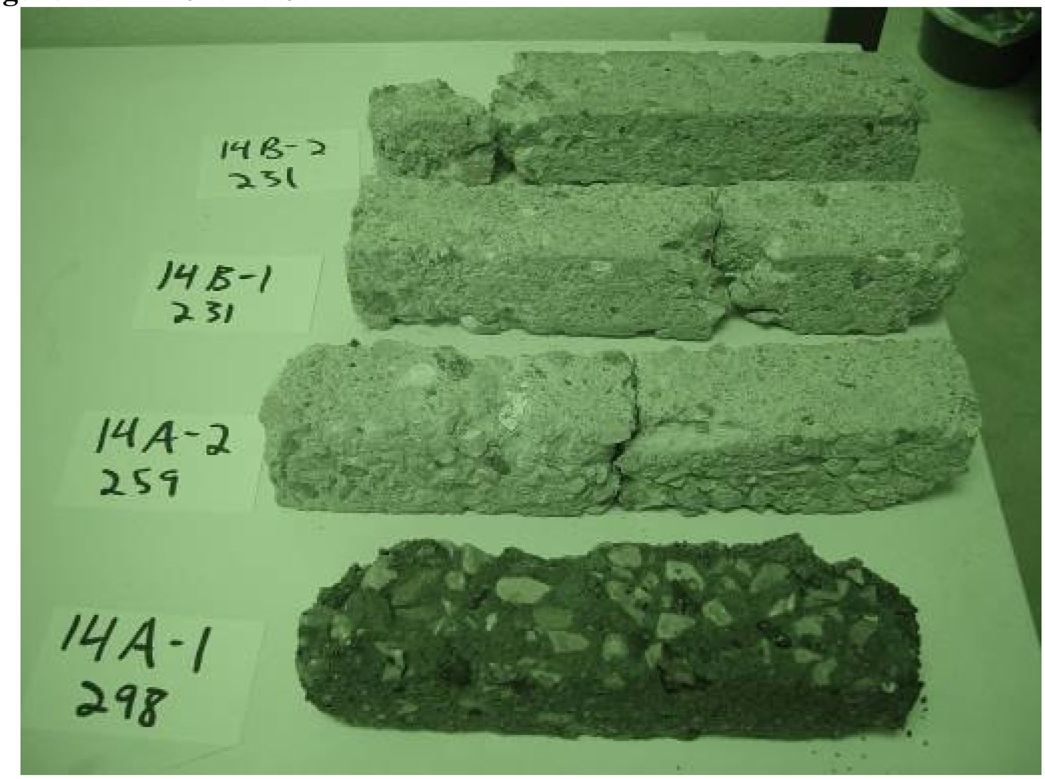


Figure B.20 A/40-100/0

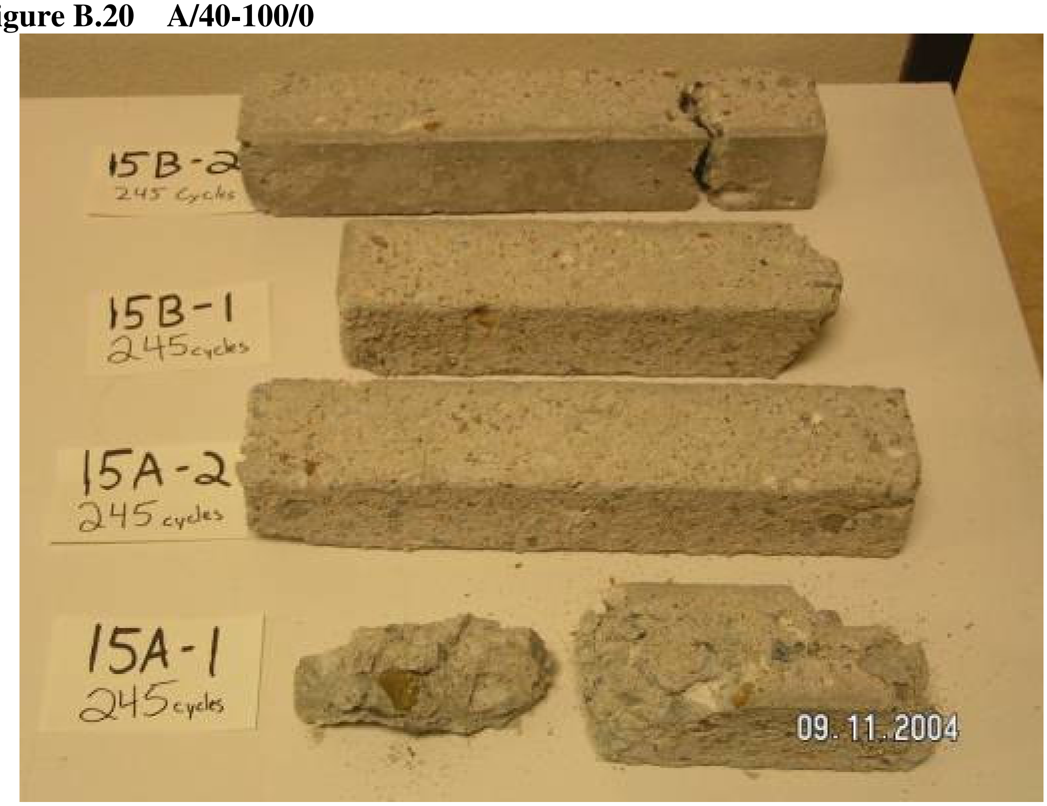


Figure B.21 A/60-100/0

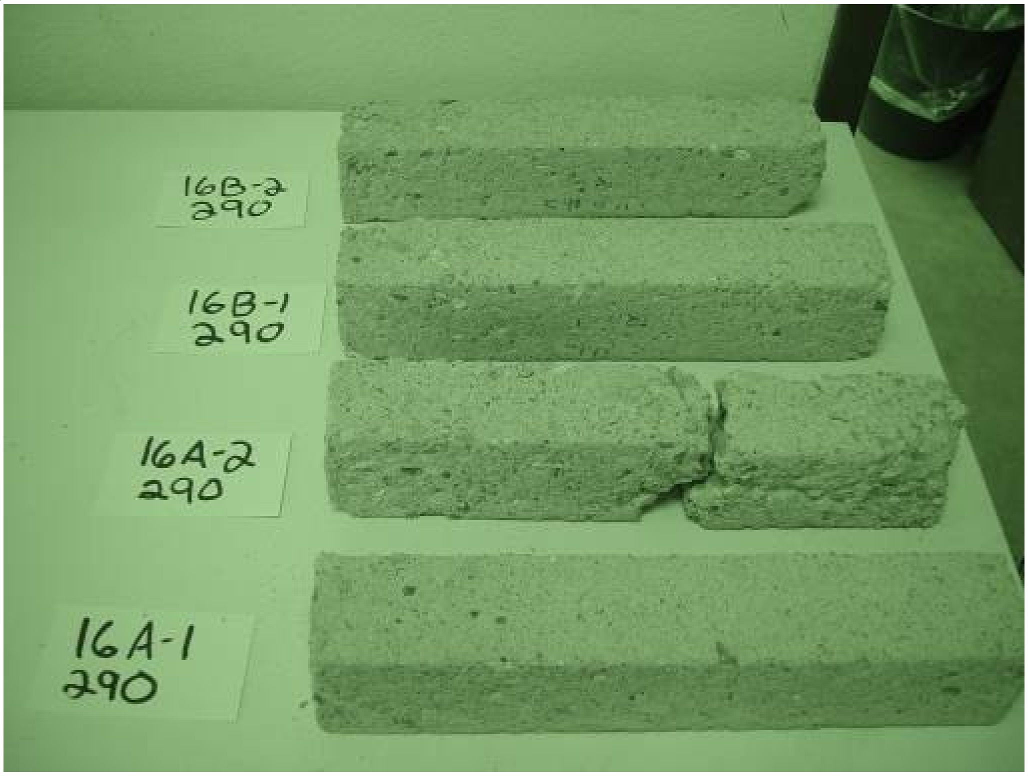


Figure B.22 A/20-100/20

Figure B.23   A/20-100/40

Figure B.24   A/40-100/20

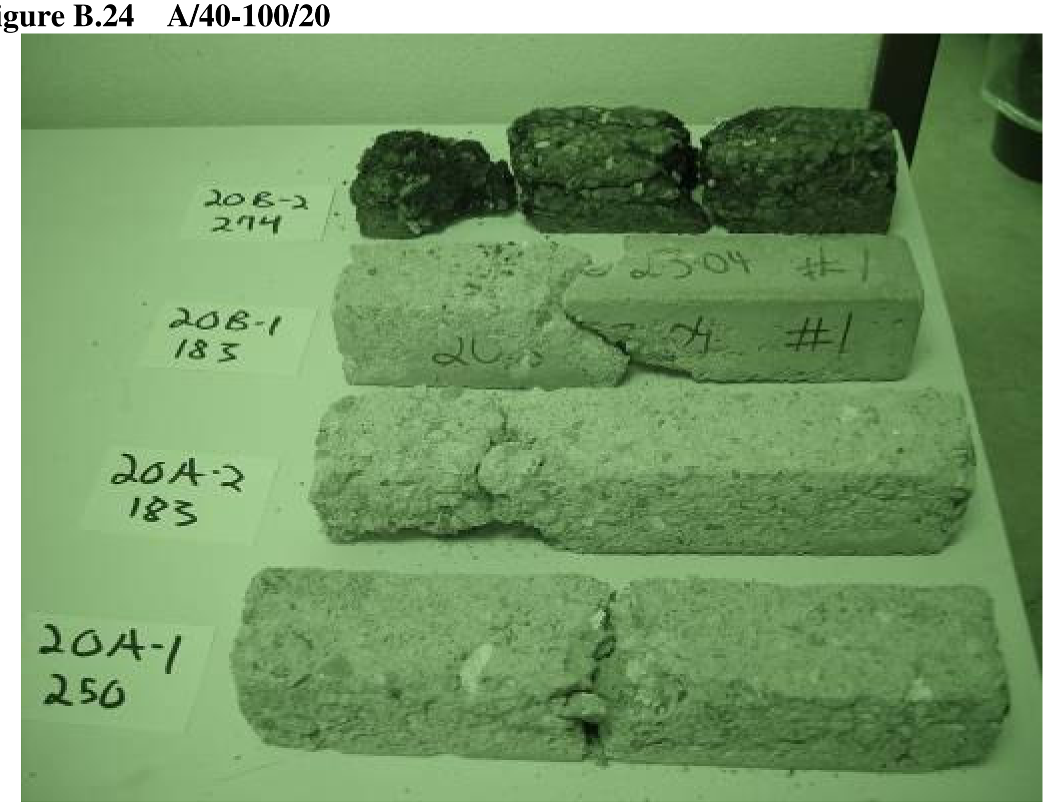


Figure B.25 A/40-100/40

Figure B.26 A/60-100/20

Figure B.27 B/0/0

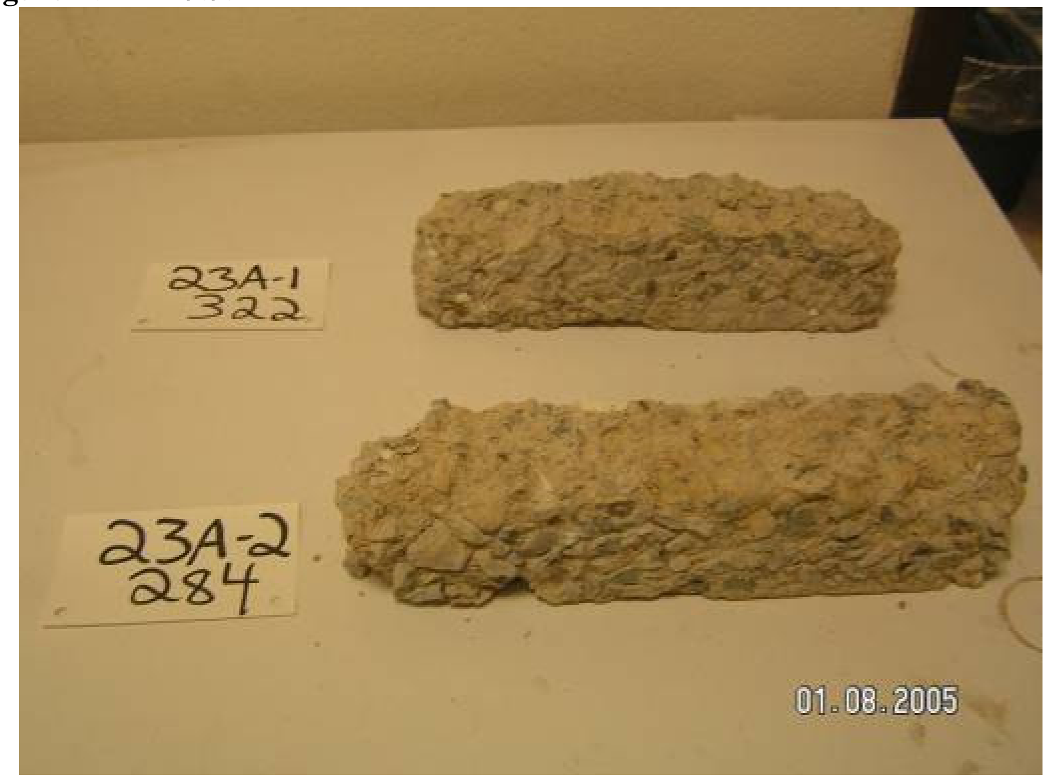


Figure B.28 B/60-120/0

Figure B.29 B/0/60

Figure B.30 B/20-120/20

Figure B.31 B/60-100/0

APPENDIX C: FRESH CONCRETE PROPERTY DATA

Table C.1 Slump (inches)

Mixture Design	Batch	Slump	Batch	Slump
A/0/0	A	1.75	B	1.5
A/20-120/0	C	2.25	D	2.5
A/40-120/0	A	0.75	B	0.75
A/60-120/0	A	0.75	B	0.75
A/0/20	A	2.75	B	4
A/0/40	A	6.5	B	5.5
A/0/60	A	7	B	7.5
A/20-120/20	A	2.25	B	2
A/20-120/40	A	6.5	B	6.75
A/20-120/60	C	7.75	D	8.25
A/40-120/20	A	4	B	5
A/40-120/40	C	3.25	D	8
A/60-120/20	A	4	B	3.25
A/20-100/0	A	2.5	B	2.5
A/40-100/0	A	2.5	B	2.25
A/60-100/0	A	1.75	B	1.75
A/20-100/20	A	4.25	B	5
A/20-100/40	A	5.25	B	6
A/20-100/60	A	7.25	B	7.5
A/40-100/20	A	4.25	B	2.75
A/40-100/40	A	7	B	5.5
A/60-100/20	A	2.5	B	1.25
B/0/0	A	3	-	-
B/60-120/0	A	2.75	-	-
B/0/60	A	8.75	-	-
B/20-120/20	A	3.75	-	-
B/60-100/0	A	3	-	-

Table C.2 Unit Weight (lb.ft^3)

Mixture Design	Batch	Unit Weight	Batch	Unit Weight
A/0/0	A	151.1	B	151.8
A/20-120/0	C	149.7	D	149.6
A/40-120/0	A	150.7	B	150.2
A/60-120/0	A	149.8	B	149.8
A/0/20	A	150.1	B	150.6
A/0/40	A	151.1	B	151.1
A/0/60	A	150.9	B	150.3
A/20-120/20	A	150.3	B	149.8
A/20-120/40	A	150.8	B	150.8
A/20-120/60	C	150.5	D	149.1
A/40-120/20	A	149.0	B	149.2
A/40-120/40	C	150.3	D	149.0
A/60-120/20	A	149.0	B	149.4
A/20-100/0	A	152.4	B	150.7
A/40-100/0	A	149.8	B	149.3
A/60-100/0	A	149.0	B	148.6
A/20-100/20	A	150.1	B	151.0
A/20-100/40	A	149.8	B	150.2
A/20-100/60	A	150.0	B	150.2
A/40-100/20	A	148.9	B	148.8
A/40-100/40	A	149.5	B	149.5
A/60-100/20	A	149.6	B	149.9
B/0/0	A	150.0	-	-
B/60-120/0	A	148.7	-	-
B/0/60	A	148.9	-	-
B/20-120/20	A	149.3	-	-
B/60-100/0	A	148.9	-	-

Table C.3 Air Content (%)

Mixture Design	Batch	Air Content	Batch	Air Content
A/0/0	A	1.4	B	1.3
A/20-120/0	C	1.5	D	1.5
A/40-120/0	A	1.4	B	1.6
A/60-120/0	A	1.5	B	1.7
A/0/20	A	1.0	B	1.0
A/0/40	A	0.7	B	1.1
A/0/60	A	0.6	B	0.5
A/20-120/20	A	1.4	B	1.5
A/20-120/40	A	1.2	B	0.9
A/20-120/60	C	0.5	D	0.5
A/40-120/20	A	1.5	B	1.5
A/40-120/40	C	1.2	D	1.0
A/60-120/20	A	1.2	B	1.3
A/20-100/0	A	1.6	B	1.5
A/40-100/0	A	1.2	B	1.3
A/60-100/0	A	1.4	B	1.5
A/20-100/20	A	1.3	B	1.2
A/20-100/40	A	0.7	B	0.9
A/20-100/60	A	0.4	B	0.5
A/40-100/20	A	0.9	B	1.4
A/40-100/40	A	0.7	B	0.9
A/60-100/20	A	1.2	B	1.5
B/0/0	A	1.7	-	-
B/60-120/0	A	1.5	-	-
B/0/60	A	0.4	-	-
B/20-120/20	A	1.3	-	-
B/60-100/0	A	1.2	-	-

Table C.4 Temperature (°F)

Mixture Design	Batch	Temperature	Batch	Temperature
A/0/0	A	88.7	B	90.9
A/20-120/0	C	82.5	D	81.0
A/40-120/0	A	69.7	B	67.3
A/60-120/0	A	73.5	B	71.5
A/0/20	A	76.5	B	74.8
A/0/40	A	74.0	B	74.1
A/0/60	A	75.2	B	68.2
A/20-120/20	A	70.0	B	64.7
A/20-120/40	A	65.1	B	57.1
A/20-120/60	C	64.8	D	57.1
A/40-120/20	A	70.2	B	69.0
A/40-120/40	C	81.0	D	82.0
A/60-120/20	A	71.4	B	67.4
A/20-100/0	A	82.0	B	82.9
A/40-100/0	A	80.8	B	80.1
A/60-100/0	A	82.4	B	83.6
A/20-100/20	A	83.5	B	86.9
A/20-100/40	A	77.1	B	76.9
A/20-100/60	A	79.3	B	78.6
A/40-100/20	A	84.0	B	84.0
A/40-100/40	A	84.5	B	85.0
A/60-100/20	A	78.0	B	75.0
B/0/0	A	80.0	-	-
B/60-120/0	A	78.0	-	-
B/0/60	A	80.0	-	-
B/20-120/20	A	80.0	-	-
B/60-100/0	A	82.0	-	-

APPENDIX D: HARDENED CONCRETE PROPERTY DATA

Table D.1 One Day Compressive Strength (psi)

Mixture Design	A	A	A	B	B	B
A/0/0	2250	2142	2255	2286	2400	2344
A/20-120/0	2282	2242	2099	1949	1845	1877
A/40-120/0	1555	1567	1481	1066	1099	1174
A/60-120/0	832	844	866	765	819	744
A/0/20	1272	1214	1370	1263	1105	1157
A/0/40	913	904	956	902	914	821
A/0/60	144	156	136	178	187	174
A/20-120/20	1347	1395	1372	1168	1127	1051
A/20-120/40	253	253	232	246	274	229
A/20-120/60	0	0	0	0	0	0
A/40-120/20	2040	2003	2087	1907	1969	1896
A/40-120/40	0	0	0	0	0	0
A/60-120/20	0	0	0	0	0	0
A/20-100/0	1935	1984	2187	1604	1713	1629
A/40-100/0	1250	1244	1296	1167	1207	1275
A/60-100/0	744	688	727	736	677	703
A/20-100/20	1292	1222	1160	1124	1055	1128
A/20-100/40	320	282	318	328	317	346
A/20-100/60	0	0	0	0	0	0
A/40-100/20	573	519	575	547	544	575
A/40-100/40	0	0	0	0	0	0
A/60-100/20	0	0	0	0	0	0
B/0/0	2163	2088	2005	-	-	-
B/60-120/0	0	0	0	-	-	-
B/0/60	1740	1870	1709	-	-	-
B/20-120/20	1393	1433	1283	-	-	-
B/60-100/0	0	0	0	-	-	-

Table D.2 Three Day Compressive Strength (psi)

Mixture Design	A	A	A	B	B	B
A/0/0	5123	5018	4660	5757	5612	5568
A/20-120/0	3352	4583	4583	4415	4118	4530
A/40-120/0	4070	4191	4260	3458	3718	3816
A/60-120/0	3046	2885	3288	3389	3045	3108
A/0/20	3996	4044	3766	4035	4452	4441
A/0/40	3389	3532	3587	3798	3755	3836
A/0/60	925	897	857	1081	1078	1222
A/20-120/20	4120	4245	4226	4347	4233	4210
A/20-120/40	2073	2088	2119	2007	2058	2084
A/20-120/60	92	92	96	92	97	92
A/40-120/20	2371	2683	2549	2942	2968	2920
A/40-120/40	0	0	0	0	0	0
A/60-120/20	1773	1802	1775	2059	2011	1943
A/20-100/0	4419	4374	4154	3836	3637	3676
A/40-100/0	3519	3536	3372	3513	3599	3514
A/60-100/0	2357	2338	2244	2329	2240	2440
A/20-100/20	3810	3551	3890	3646	3863	3686
A/20-100/40	2033	2034	1935	2253	2183	2223
A/20-100/60	0	0	0	0	0	0
A/40-100/20	-	-	-	-	-	-
A/40-100/40	873	832	804	949	914	957
A/60-100/20	1245	1227	1132	1223	1166	1185
B/0/0	3801	4335	3759	-	-	-
B/60-120/0	2794	2759	3189	-	-	-
B/0/60	1740	1870	1709	-	-	-
B/20-120/20	4200	4237	3927	-	-	-
B/60-100/0	1923	1884	1666	-	-	-

Table D.3 Seven Day Compressive Strength (psi)

Mixture Design	A	A	A	B	B	B
A/0/0	6087	6063	6350	6995	6745	6886
A/20-120/0	-	-	-	5672	5696	5834
A/40-120/0	5734	6004	6236	6094	5255	5634
A/60-120/0	5099	5091	5340	5461	5026	4869
A/0/20	6308	6175	6015	6324	6864	6368
A/0/40	6030	6122	5613	6419	6162	6329
A/0/60	4491	4576	4227	4008	4149	4062
A/20-120/20	6253	6248	6749	6540	6603	6685
A/20-120/40	4821	4814	4703	4528	4598	4619
A/20-120/60	1150	1058	1100	1200	1292	1155
A/40-120/20	4997	4918	4775	4626	4377	4269
A/40-120/40	3634	3671	3786	2940	2866	2936
A/60-120/20	3664	3603	3774	3748	3938	4010
A/20-100/0	6001	5524	5975	5454	5677	5699
A/40-100/0	7127	7444	7291	7407	7241	7131
A/60-100/0	4396	4600	4338	4877	4629	4697
A/20-100/20	6076	5975	5807	6377	6082	6005
A/20-100/40	3591	3766	3736	4021	4043	3986
A/20-100/60	762	802	832	791	864	938
A/40-100/20	4452	3918	3934	4387	4370	4355
A/40-100/40	1675	1716	1694	1943	1982	2016
A/60-100/20	3286	2958	3002	3311	3202	3300
B/0/0	5072	4844	5033	-	-	-
B/60-120/0	4455	4680	4755	-	-	-
B/0/60	3562	3769	3786	-	-	-
B/20-120/20	5632	5372	5917	-	-	-
B/60-100/0	4393	4227	4364	-	-	-

Table D.4 Twenty-eight Day Compressive Strength (ºF)

Mixture Design	A	A	A	B	B	B
A/0/0	7377	7092	7950	8303	7982	8352
A/20-120/0	7009	7043	6926	7168	7296	7251
A/40-120/0	7803	7663	8345	7572	7284	7291
A/60-120/0	6880	6942	6782	6953	7209	6677
A/0/20	7751	7762	8009	8113	7915	7910
A/0/40	8260	7757	7870	8142	8032	8490
A/0/60	7783	7766	7389	7401	7536	7762
A/20-120/20	8519	8757	7911	8750	9076	8581
A/20-120/40	8403	7908	7942	7657	7854	7566
A/20-120/60	4655	4612	4575	4317	4349	4506
A/40-120/20	7129	6969	7366	7144	7307	6969
A/40-120/40	6451	6308	6053	5476	5044	5279
A/60-120/20	6259	6799	6895	6853	6587	7004
A/20-100/0	7431	8059	7250	5696	4400	5373
A/40-100/0	8656	8404	8350	8220	8403	8540
A/60-100/0	7518	7680	7047	7240	6965	7150
A/20-100/20	8553	9390	9237	8754	8800	9451
A/20-100/40	6778	7174	6628	6988	7289	7337
A/20-100/60	2907	2882	2947	2718	2817	2748
A/40-100/20	8372	8075	8146	8524	8309	8689
A/40-100/40	4648	4788	4904	5622	4859	5195
A/60-100/20	7174	7797	7172	7155	7607	7169
B/0/0	6216	6223	6597	-	-	-
B/60-120/0	6599	5928	6681	-	-	-
B/0/60	5815	6182	6026	-	-	-
B/20-120/20	7442	7186	7235	-	-	-
B/60-100/0	5680	5856	5946	-	-	-

Table D.5 Ninety Day Compressive Strength (ºF)

Mixture Design	A	A	A	B	B	B
A/0/0	7857	8526	7935	8524	8676	7992
A/20-120/0	8613	8617	8356	8671	7881	8157
A/40-120/0	8985	8999	9078	8635	8755	8899
A/60-120/0	8098	8062	7737	7679	7978	7972
A/0/20	8620	9120	8984	9096	9139	9200
A/0/40	9381	9248	8918	9782	8964	9323
A/0/60	9518	9691	9554	9245	9358	9502
A/20-120/20	10299	9402	9492	10445	10029	10468
A/20-120/40	10108	10258	10248	9860	9814	10359
A/20-120/60	7543	7530	7873	7270	6970	7682
A/40-120/20	8902	8829	8392	8564	8769	8917
A/40-120/40	8093	7896	7900	6840	7309	6925
A/60-120/20	7616	7631	7405	7275	7895	7958
A/20-100/0	8146	9095	9260	8679	8614	7960
A/40-100/0	8887	8789	8777	9431	9465	9576
A/60-100/0	7758	7533	7986	8613	8062	8561
A/20-100/20	9664	10480	10180	10071	10589	10020
A/20-100/40	9685	9301	9634	10246	10137	9777
A/20-100/60	6527	6586	6491	6260	6039	6185
A/40-100/20	10039	9214	9646	10210	10605	9739
A/40-100/40	7433	7494	7764	7479	7619	7874
A/60-100/20	8622	8190	8480	8808	8336	8421
B/0/0	8053	7392	8114	-	-	-
B/60-120/0	6669	7500	6688	-	-	-
B/0/60	7889	7737	7718	-	-	-
B/20-120/20	8189	8719	8088	-	-	-
B/60-100/0	7720	7967	7922	-	-	-

Table D.6 Twenty-eight Day Permeability (adjusted coulombs)

Mixture Design				
A/0/0	6131	5021	2958	2951
A/20-120/0	2634	2258	2459	2415
A/40-120/0	1860	1727	1696	1591
A/60-120/0	857	1027	1032	831
A/0/20	4132	3790	4505	0
A/0/40	1985	2540	1713	0
A/0/60	1111	2555	3568	0
A/20-120/20	1251	1473	1586	641
A/20-120/40	1795	2138	1589	1034
A/20-120/60	3144	3281	2887	0
A/40-120/20	59	1021	0	0
A/40-120/40	419	433	221	250
A/60-120/20	422	504	595	0
A/20-100/0	1807	1636	2297	2088
A/40-100/0	1069	1025	1014	1034
A/60-100/0	489	475	0	477
A/20-100/20	1100	0	1420	185
A/20-100/40	3270	3146	0	3642
A/20-100/60	6387	5744	6240	0
A/40-100/20	0	848	807	818
A/40-100/40	1101	0	1022	1260
A/60-100/20	272	229	297	260
B/0/0	1670	1465	-	-
B/60-120/0	832	810	-	-
B/0/60	1193	1280	-	-
B/20-120/20	1253	1693	-	-
B/60-100/0	555	511	-	-

Table D.7 Ninety Day Permeability (adjusted coulombs)

Mixture Design				
A/0/0	3783	3439	0	0
A/20-120/0	1816	1416	1078	1423
A/40-120/0	889	221	782	0
A/60-120/0	690	686	218	667
A/0/20	1535	1458	1439	0
A/0/40	991	915	1027	1032
A/0/60	1097	1055	1220	749
A/20-120/20	729	722	753	0
A/20-120/40	800	789	941	737
A/20-120/60	589	410	488	0
A/40-120/20	588	563	773	0
A/40-120/40	345	412	332	388
A/60-120/20	0	362	334	376
A/20-100/0	0	826	1048	929
A/40-100/0	652	605	591	654
A/60-100/0	449	376	375	393
A/20-100/20	845	991	897	731
A/20-100/40	770	974	967	757
A/20-100/60	1161	1088	1053	1345
A/40-100/20	341	313	317	340
A/40-100/40	346	288	359	354
A/60-100/20	346	298	340	382
B/0/0	1754	1129	-	-
B/60-120/0	725	613	-	-
B/0/60	1447	1425	-	-
B/20-120/20	539	750	-	-
B/60-100/0	244	439	-	-

Table D.8 Freeze/Thaw Durability

Mixture Design	N at 0 cycles (Hz)	N1 at c cycles (Hz)	Cycles	Durability Factor
A/0/0	1963	455	180	3.22
	1916	476	180	3.70
	1925	327	180	1.73
	1925	165	258	0.63
A/20-120/0	1895	527	298	7.68
	1881	677	298	12.87
	1893	1040	298	29.98
	1860	1265	298	45.95
A/40-120/0	1891	1068	252	26.79
	1932	852	252	16.34
	1941	818	252	14.92
	1881	1210	252	34.76
A/60-120/0	1995	1012	207	17.76
	1863	1232	207	30.17
	1950	1073	207	20.89
	1811	1057	207	23.51
A/0/20	1882	393	254	3.69
	1852	667	254	10.98
	1903	606	254	8.59
	1894	590	254	8.22
A/0/40	1834	1277	62	10.02
	1817	996	62	6.21
	1903	695	304	13.52
	1829	625	304	11.83
A/0/60	1874	1099	303	34.74
	1870	1017	303	29.87
	1856	1236	74	10.94
	1775	142	185	0.39
A/20-120/20	1899	1300	297	46.40
	1975	1235	297	38.71
	1918	1176	297	37.22
	1965	1365	297	47.77
A/20-120/40	1865	655	313	12.87
	1890	991	313	28.68
	1831	631	313	12.39
	1888	614	313	11.03

Mixture Design	N at 0 cycles (Hz)	N1 at c cycles (Hz)	Cycles	Durability Factor
A/20-120/60	1640	1191	71	12.48
	1647	1362	40	9.12
	1705	1326	40	8.06
	1652	1164	40	6.62
A/40-120/20	1891	779	312	17.65
	1900	892	312	22.92
	1892	543	312	8.57
	1885	493	312	7.11
A/40-120/40	1764	680	289	14.32
	1747	968	289	29.58
	1789	637	289	12.21
	-	-	-	-
A/60-120/20	1953	191	312	0.99
	1793	173	312	0.97
	1754	172	312	1.00
	1791	166	312	0.89
A/20-100/0	1911	402	298	4.40
	1863	653	231	9.46
	1928	890	208	14.77
	1911	786	231	13.03
A/40-100/0	1876	684	218	9.66
	1933	470	251	4.95
	1974	501	251	5.39
	1959	363	251	2.87
A/60-100/0	1947	153	290	0.60
	1911	151	290	0.60
	1975	161	290	0.64
	1904	145	290	0.56
A/20-100/20	1958	139	297	0.50
	1853	136	297	0.53
	-	-	-	-
	1870	137	297	0.53
A/20-100/40	1864	652	297	12.11
	1835	342	297	3.44
	1880	352	297	3.47
	1841	376	297	4.13

Mixture Design	**N at 0 cycles (Hz)**	**N1 at c cycles (Hz)**	**Cycles**	**Durability Factor**
A/20-100/60	-	-	-	-
	-	-	-	-
	1707	211	311	1.58
	1796	248	311	1.98
A/40-100/20	1864	980	211	19.44
	1932	1358	183	30.14
	1925	1259	160	22.81
	1951	976	250	20.85
A/40-100/40	1846	837	291	19.94
	1841	1102	291	34.76
	1898	987	291	26.23
	-	-	-	-
A/60-100/20	1936	588	303	9.32
	1946	562	303	8.42
	1893	447	298	5.54
	1838	230	298	1.56
B/0/0	2015	176	322	0.82
	1900	494	243	5.48
B/60-120/0	1856	689	298	13.69
	1863	156	298	0.70
B/0/60	1809	500	227	5.78
	1815	912	145	12.20
B/20-120/20	1857	611	148	5.34
	1851	508	148	3.72
B/60-100/0	1891	570	309	9.36
	1914	850	309	20.31

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Ground Granulated Blast Furnace Slag and Fly Ash in Concrete Mixtures		5. Report Date March 2006 6. Performing Organization Code	
7. Authors Natalie Peterson Becknell and Micah Hale		8. Performing Organization Report No. AHTD TRC 0405	
9. Performing Organization Name and Address University of Arkansas 4190 Bell Engineering Center Fayetteville, AR 72701		10. Work Unit No. (TRAIS) 11. Contract or Grant No.	
12. Sponsoring Agency Name and Address Arkansas Highway and Transportation Department P. O. Box 2261 Little Rock, AR 72203		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code	
15. Supplementary Notes Supported by a grant from the Arkansas Highway and Transportation Department			
16. Abstract Currently, the Arkansas State Highway and Transportation Department limits cementitious materials in concrete mixtures to portland cement, ground granulated blast-furnace slag (GGBFS), and fly ash. GGBFS is limited to cement replacement rate of 25% by weight and fly ash is limited to a cement replacement rate of 20% by weight. A body of knowledge on concrete mixtures containing both GGBFS and fly ash needs to be developed before the use of both materials is allowed in state projects. The experimental program focuses on the fresh and hardened concrete properties of a range of replacement rates for GGBFS, fly ash, and ternary mixtures without chemical admixtures. The research shows that: different cement sources, up to 40% GGBFS, up to 40% fly ash, up to 20% of each for ternary mixtures, and both grade 100 and grade 120 GGBFS can be used in concrete mixtures in Arkansas.			
17. Key Words Slag cement, fly ash, ternary concrete mixtures	18. Distribution Statement NO RESTRICTIONS. THIS DOCUMENT IS AVAILABLE FROM THE NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD, VA. 22161		
19. Security Classif. (of this report) UNCLASSIFIED	20. Security Class. (of this page) UNCLASSIFIED	21. No. of Pages	22. Price N/A

Abstract

Currently, the Arkansas State Highway and Transportation Department limits cementitious materials in concrete mixtures to portland cement, ground granulated blast-furnace slag (GGBFS), and fly ash. GGBFS is limited to cement replacement rate of 25% by weight and fly ash is limited to a cement replacement rate of 20% by weight. A body of knowledge on concrete mixtures containing both GGBFS and fly ash needs to be developed before the use of both materials is allowed in state projects. The experimental program focuses on the fresh and hardened concrete properties of a range of replacement rates for GGBFS, fly ash, and ternary mixtures without chemical admixtures. The research shows that: different cement sources, up to 40% GGBFS, up to 40% fly ash, up to 20% of each for ternary mixtures, and both grade 100 and grade 120 GGBFS can be used in concrete mixtures in Arkansas.

Table of Contents

List of Tables

List of Figures

List of Charts

Chapter 1 INTRODUCTION

1.1 General

Currently, the Arkansas State Highway and Transportation Department (AHTD, 2003) limits cementitious materials in concrete mixtures to portland cement, ground granulated blast furnace slag (GGBFS), and fly ash (FA). In the AHTD's Standard Specifications for Highway Construction 2003 (Specifications) (AHTD, 2003) GGBFS is limited to a cement replacement rate of 25% by weight and FA is limited to a cement replacement rate of 20% by weight, as described in Section 3.2 and Section 3.3. The Specifications also do not allow the use of ternary mixture designs (mixture designs where more than one supplementary cementitious material is combined with cement). Previous research has shown that GGBFS and FA can have beneficial effects on the fresh and hardened concrete properties at replacements of 40% and beyond and the benefits are also present in ternary mixtures (ACI Committee 233). Before changes can be made to AHTD's Specifications, the effects of GGBFS, FA, or both materials on concrete mixtures incorporating native Arkansas materials should be examined.

1.2 Objectives

The purpose of this research was to examine the fresh and hardened properties of concrete mixtures containing GGBFS, FA, and a combination of both materials. Due to different grades of GGBFS and sources of Type I cement available in the state of Arkansas, the following variables were investigated:

1. Source of Type I cement,
2. GGBFS and FA replacements of cement by weight, and

3. Grade of GGBFS.

The information collected through the study allowed the investigators to draw conclusions on the allowances of GGBFS and FA in concrete mixtures in the state of Arkansas. These conclusions were used to form recommendations to AHTD in the matter of updating the Specifications to include the new findings from this study. The change in specifications could benefit the construction industry and AHTD. The construction industry would benefit by having more options in mixture design. AHTD would benefit by promoting better economy and materials for construction projects; and the public would benefit from longer lasting concrete structures which would reduce the amount of tax dollars needed for repair.

1.3 Scope

Mixture designs with varying quantities of GGBFS, FA, and ternary mixtures were examined in the research programs. The mixture designs were created to range from the current replacement rates allowed to replacement rates greater than recommended in the literature from previous research. Type I cement from two different sources, two grades of GGBFS, and Class C FA were used in the study. The materials are common in Arkansas, and they were chosen to accurately represent typical mixture designs. The same coarse and fine aggregates were used throughout the project and were also chosen to represent typical concrete in Arkansas. The water-to-cementitious materials ratio (w/cm) was held constant for all mixtures tested. No admixtures such as air entraining and water reducing admixtures were employed in the mixtures so that changes in the concrete properties would be properly attributed to the experimental variables. The project was limited to the effects of varying replacements of GGBFS, FA, or both on the fresh and hardened properties of concrete.

Chapter 2 LITERATURE REVIEW

2.1 General

Environmental concerns and the current stress on the cement producing industry have fueled the interest in alternative mixture design strategies. One strategy that fulfills both environmental concerns and cement shortage is the replacement of part of the cement with waste materials. Ground granulated blast-furnace slag and fly ash are the two materials allowed in the state of Arkansas. These materials are industrial by-products and, when not used as a construction material, are discarded as waste in large amounts. Other studies have shown the benefits and drawbacks of using either material or both together in portland cement concrete mixtures. The following sections describe those studies, their results, and the impact of the research.

2.2 Ground-Granulated Blast-Furnace Slag

GGBFS used in concrete is created from pulverizing waste products created during the refining of iron ore. The by-products from other metallurgical processes, such as refining iron to steel or producing nickel, are iron-rich and not suitable for concrete (Mindess et. al. 2003). Lime-based inorganic fluxes are used in iron ore refining to remove the impurities to create useable iron (Mindess et. al. 2003). The ore, fluxes, and energy source-coke are heated in a blast furnace until the molten iron is extruded. The waste product, blast furnace slag, is screened from the iron. Typically blast furnace slag consists of about 20 percent by mass of iron production (Blast Furnace Slag-Material Description).

Several different structures of blast furnace slag (BFS) can be formed depending on the cooling process used between the removal of the slag from the furnace and storage. Most of the BFS produced in the United States is in the form of air-cooled blast furnace slag (Blast Furnace Slag-Material Description). The air-cooling process is less expensive because it does not use water to cool and heat to dry the pellets created by the water. The air-cooled products are usually crystalline without cementitious properties when ground and the larger sizes require a more arduous grinding process (ACI Committee 233). The air-cooled pellets are used as aggregates because of their hardness (Blast Furnace Slag-Material Description). However, the amount of BFS being used in a cementitious form is growing because of the advances in pelletizing which reduce costs from quenching processes.

The preferred cooling process which produces the highest quality cementitious material is pelletizing (Blast Furnace Slag-Material Description). During the pelletizing process, the molten slag is quickly cooled by water and a glassy granule of calcium aluminosilicate is formed without crystallization. Water is administered to the hot blast furnace slag with spray jets while the slag is dropped into a collecting bin. Before pelletizing, quenching was the preferred water method. Quenching involves immersing the hot blast furnace slag into a bath of water. Quenching requires a large amount of water for the bath and also requires more energy for a more strenuous drying process (ACI Committee 233). After cooling, the BFS is ground to less than 4mm and then is further ground to a size that is similar to cement size 10-15 μm (Mindess et. al. 2003). When crushed or milled very finely, GGBFS has cementitious properties because of its silica and calcium content (Mindess et. al. 2003).

The slag created in iron refining is rich in lime, silica, and alumina which allow it to be suitable for use in concrete as a SCM (Mindess et. al. 2003). The grade of GGBFS is based on the reactivity of the GGBFS. The reactivity is measured by comparing seven and twenty-eight day compressive strength of mortar cubes made from 100% portland cement to mortar cubes containing 50% GGBFS and 50% cement. The slag activity index is calculated by dividing the compressive strength of the GGBFS/cement mortar cubes by the compressive strength of the cement only mortar cubes. The resulting number is multiplied by 100 resulting in a "grade" (ASTM C989, AASHTO) of GGBFS.

$$activity-index = \frac{7(or28)day}{7(or28)day}\frac{compressive}{compressive}\frac{strength}{strength}\frac{slag/cement-cubes}{cement-only-cubes}\times 100$$

Three grades of GGBFS are used to identify the cementitious nature of the slag: GR 80, GR 100, and GR 120. Table 1 shows the test requirements for ASTM C989 (Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars).

Table 2.1 Physical Requirements (ASTM C989)

Slag activity index, min %	Average of last five consecutive samples	Any individual sample
7-day index		
GR 80	---	---
GR 100	75	70
GR 120	95	90
28-Day Index		
GR 80	75	70
GR 100	95	90
GR 120	115	110

2.3 Fly Ash

Fly ash (FA) is a by-product of burning coal. Fly ash is collected from the flue gases (Coal Fly Ash-Material Description). The source of coal used to produce FA is divided into two classes; Class C and Class F. Class F is normally produced from anthracite or bituminous coal with pozzolanic properties and Class C is produced from subbituminous coal and lignite with pozzolanic and cementitious properties (ASTM C618 Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete). Class F FA is generally found east of the Mississippi River and Class C FA is generally found on the western side of the Mississippi River in the United States. Some coal sources from the western states are not suitable for FA used in concrete and their use should be heavily monitored (Mindess et. al. 2003). Typically, three types of coal-fired plants are used in producing electricity: dry-bottom boilers, wet-bottom boilers, and cyclone furnaces. A dry-bottom boiler is best for collecting FA because about 80% of the FA will leave with the separation of the flue gas and is easily collected. A wet-bottom boiler will trap about 50% FA within the furnace and a cyclone furnace only allows 20-30% to leave with the flue gas (Coal Fly Ash-Material Description). Care must be taken to avoid chemicals, such as scrubber products, from removing sulfur dioxide from gases that escape from the energy process (Mindess et. al. 2003). FA must conform to the standards in ASTM C618.

Class F FA that is good for concrete mixtures has 70-90% glass. The high glass content signifies the useful nature of Class F FA in concrete as described in Section 2.4. Some Class C FA contains free lime (CaO) and anhydrite ($CaSO_4$). Class C FA may also contain C_3A (the most reactive cementitious compound) which can cause high water demand, early stiffening, or rapid setting all of which are undesirable in concrete. The compound C_3A forms ettringite when enough sulfate is available and monosulfoaluminate when not enough sulfate is present during hydration. When the monosulfoaluminate comes into contact with sulfate ions, ettringite is formed again and is referred to as sulfate attack (Mindess et. al. 2003).

2.4 Pozzolanic Reaction

The SCMs, GGBFS and FA, contain amorphous or glassy silica which reacts with calcium hydroxide (CH) formed from the hydration of calcium silicates (C_2S and C_3S). This is a secondary reaction during the hydration process (further discussed in Section 2.7.3) and often will allow benefits such as lower heat of hydration and a denser, and less permeable, concrete (Mindess et. al. 2003). This secondary reaction can also hinder the early strength gain of the concrete if used to excess. Two hydration reaction equations and the principal pozzolanic reaction equations are as follows (Mindess et. al. 2003):

$$2C_3S + 11H \rightarrow C_3S_2H_8 + 3CH$$

$$2C_2S + 11H \rightarrow C_3S_2H_8 + 2CH$$

$$CH + S + H \rightarrow CSH \quad .$$

One of the products of cement hydration and the SCM reaction, CSH (calcium silicate hydrate), is 50% of the volume of concrete paste. Another product, CH (calcium hydroxide), is about 25% of the volume of concrete paste. The CSH is the product that binds cement particles together and gives concrete strength. CH crystals grow in the void space left by the hydration process (Mindess et. al. 2003).

2.5 Common Use of Ground Granulated Blast-Furnace Slag and Fly Ash

Combinations of cement-FA, cement-GGBFS, and cement-FA-GGBFS have been used in concrete successfully in various areas around the world (ACI Committee

233). GGBFS was used as a separate product to combine with portland cement in the late 1970's in the United States even though intergrinding slag and portland cement clinker was done thirty years earlier. The United States Department of Transportation and the Federal Highway Administration suggest that substitutions for cement by weight with GGBFS be limited to 50% when not exposed to deicing salts and 25% when exposed to deicing salts. They also state that while replacements of up to 70% have been used successfully for specific projects, a more optimum replacement rate is approximately 50% (Ground Granulated Blast-Furnace Slag-Materials Group). Research suggests that 25% is optimum for scaling resistance but that concrete with up to 50% GGBFS has comparable scaling resistance to 100% portland cement concrete (ACI Committee 233). Fly ash has been used in portland cement concrete for over 60 years in the United States (Coal Fly Ash-Material Description). A 1992 survey indicated that 44 states out of 50 in the United States used FA with portland cement in concrete but is generally avoided in bridge decks (Coal Fly Ash-User Guideline). FA is generally avoided because of variable composition, negative impact on early strength for stripping forms, and negative impact on air content (Fly Ash-Materials Group).

2.6 "Green" Concrete

An increasingly popular trend in construction is the ability to produce "Green" projects. The force behind the green movement is to design and build structures that are more environmentally friendly and conservative. Buildings can be certified as a Leadership in Energy and Environmental Design (LEED) building (Leadership in Energy & Environmental Design). According to the United States Green Building

Council's website, the purpose of LEED is to standardize the idea of a "green building," promote whole-building design practices, recognize the environmental leaders, stimulate competition, and raise awareness of the benefits of conservation (VanGeem, 2002). Certification is based on a system of credit points for different aspects of design, spatial and material, and construction practices. LEED certification is awarded at a total of 26 points and levels of recognition are given for 33 points, silver, 39 points, gold, and 52 points, platinum (VanGeem, 2002). The criteria for points include: site selection, public transportation access, reducing heat islands, renewable energy sources, reuse of existing materials, use of recycled materials such as GGBFS, and innovative interior design. The LEED system defines sustainability "as development that meets the needs of the present without compromising the ability of future generations to meet their own needs (VanGeem, 2002)."

Concrete can be used in several ways in order to increase the LEED points of a project. Portland cement concrete can be used instead of asphalt to reduce heat islands. The reduction of the heat island is based on the increased solar reflectance of the materials used for large areas. The solar reflectance is the amount of radiation reflected back from a surface compared to the amount shone on the material. Concrete generally has a solar reflectance of approximately 0.35 and "white" concrete can have a value of 0.7 to 0.8 (VanGeem, 2002). GGBFS will also increase the "whiteness" of the concrete when added in significant amounts. Asphalt, on the other hand, will generally have a reflectance of less than 0.2. Another LEED criteria for points states, "specify a minimum of 25% of building materials that contain in aggregate a minimum weighted average of 20% post-consumer recycled content material, or, a minimum weighted average of 40% post-industrial recycled content material (VanGeem, 2002)." SCMs, including FA and GGBFS, are considered post-industrial.

The use of waste materials is also important for more reasons than the construction benefits. In 2002, 30% of FA produced yearly was used in various construction-related applications with 10% used in concrete (Ostrowski, 2002). Unless some recycling occurs, these waste products end up in landfills. Over 250 million tons of FA (Mindess et. al. 2003) and over 18 million tons of GGBFS (Schriefer, 2004) are produced every year in the United States. The American Concrete Institute (ACI) and the Environmental Protection Agency (EPA) encourage recycling by supporting the Resource Conversation and Recovery Act (RCRA) and recycling in concrete. The RCRA requires agencies under federal funding to purchase products with the highest percentages of recovered materials practicable (ACI Committee 233).

The annual global production of concrete was about 5 billion tons in 1997 according to Penttala (Penttala, 1997). Penttala also mentions the greatest threats for the earth's future as: population growth, global temperature rise, polluting of the air, water and soil, and the availability of fresh water resources (Penttala, 1997). Because of the effects of the industrial revolution and the use of fossil fuels, the level of CO_2 in the air has increased by as much as 25% in 200 years (Hogan, 2004). Increasing levels of CO_2 have helped increase the amount of greenhouse gases. The greenhouse gases deplete the layer of gases that keeps harmful radiation from the earth's surface and that also prevents heat from escaping back into the atmosphere (Hogan, 2004). Sustainable development is needed to ensure natural resources and the function of future generations. Manufacturing cement involves burning raw materials and the production of CO_2. About 0.56 ton of CO_2 per ton of cement is released during cement production and about 0.35 ton of CO_2 is released in the fuel (Hogan, 2004). CO_2 production can be reduced by about 0.5 tons per ton of cementitious material if SCMs are used to replace 50% of the cement (Hogan, 2004).

The use of SCMs will also extend our current supply of cement. In a Flash Report of *The Monitor*, the Portland Cement Association (PCA) culminated reports of a cement shortage in the United States. Although concrete use is encouraged by the industry, the lack of supply could turn industries away from the material. The report sites two major reasons for the increase in demand for cement: the reduction in the quantity of imported cement and the demand from the United States economy for construction materials (Sullivan, 2004). The use of waste products, such as GGBFS and FA, would increase the supply of cement.

Studies have also shown that the increase in construction speed has decreased the effectiveness of concrete structures. More often mixtures contain early strength admixtures and greater concentrations of highly reactive portland cement (Mehta, 2002). Although these increases allow for increased speed of construction, they also create higher thermal and drying shrinkage needing more preventative attention and costing more money in repair (Mehta, 2002). Materials such as FA and GGBFS have lower heat of hydration, preventing shrinkage cracking, increasing durability and reducing permeability. These properties are appealing in concrete because they prevent premature repair and possible failure.

2.7 Fresh Concrete Properties

The effects of GGBFS and FA on fresh concrete properties are discussed in the following sections. Slump, time to set, heat of hydration, and air content are examined in Sections 2.7.1, 2.7.2, 2.7.3, and 2.7.4, respectively.

2.7.1 Slump

Slump is a fresh concrete property that quantitatively represents the workability of the concrete. This is important because the hardened properties are not achievable if the concrete cannot be accurately placed. Generally, a higher water-to-cementitious material (w/cm) ratio will result in greater slumps because of the increase in water content. Rounded aggregates also increase slump because the aggregates are more readily able to slide past each other than angular or crushed aggregates. Water-reducing admixtures also increase slump without changing the w/cm or the quantity of any constituent material.

While GGBFS and FA are not typically used to specifically target slump, their effects on slump should be noted in order to prepare for site conditions that require a particular slump. The Federal Highway Administration (FHWA) and the United States Department of Transportation (USDOT) suggest that concrete containing GGBFS has longer-lasting workability and less slump loss than a similar mixture containing only portland cement (Blast Furnace Slag - User Guideline-Portland Cement Concrete). The USDOT and the FHWA agree that workability increases with increases in GGBFS or FA and suggest that the cause is an increase in paste volume from the lower relative density of both (Ground Granulated Blast-Furnace Slag-Materials Group). FA particles have a spherical shape and are relatively the same size as cement particles with out pulverization, unlike GGBFS; therefore it has an increasing effect on the slump (ACAA 1995). The spherical particles slide past each other more readily than angular cement and GGBFS particles, and create more workability.

2.7.2 Time to Set

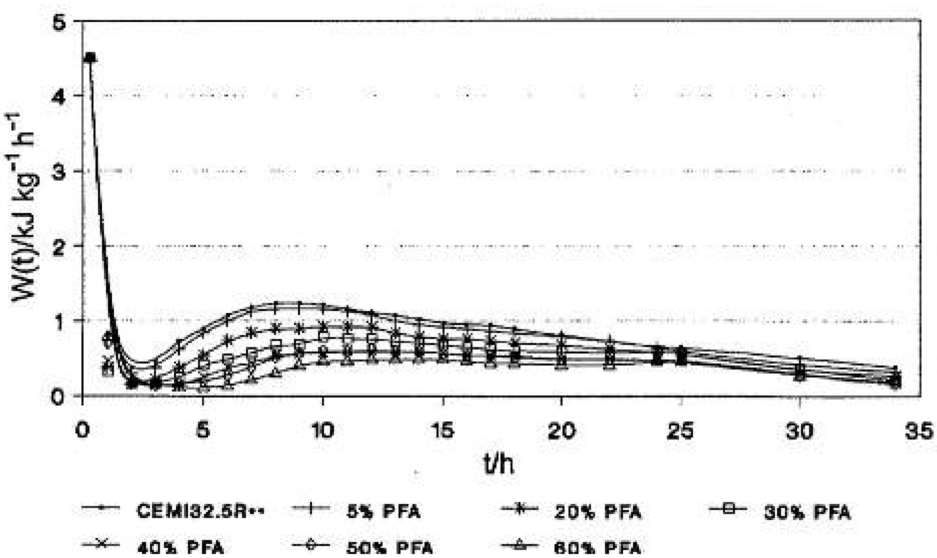
Generally, the addition of SCMs reduces strength gain because the materials do not react as quickly as cement and effectively increase the water-to-cement ratio during the early hydration stages (Babu, 1994). The FHWA and the USDOT suggest that because of the delay in set times that occur with the addition of FA the need for a set retarder (often used during construction in the summer) may be eliminated or reduced in some climates (ACAA 1995). GGBFS also has a slower hydration reaction than cement, but the reaction of GGBFS is dependent on the sodium and potassium alkali and calcium hydroxide available in the paste. This is why GGBFS is usually "activated" with portland cement, alkali salts, or lime to increase the reaction rate (ACI Committee 233). Research conducted by Luther et al. (1994) showed that the time to set was increased by 1 hour (at 70ºF) for replacements of 35 to 40% slag and that an increase in slag resulted in an increase in time to set (ACI Committee 233). A concrete mixture of 65% GGBFS and 35% cement was shown to have almost twice the initial and final set as a comparable 100% cement mixture (Khatri, 1995). The time to set is more fully explained in the following section.

2.7.3 Heat of Hydration

SCMs, such as FA and GGBFS, have a slow rate of hydration, similar to the secondary cement compound C_2S. An increase in C_2S in portland cement creates

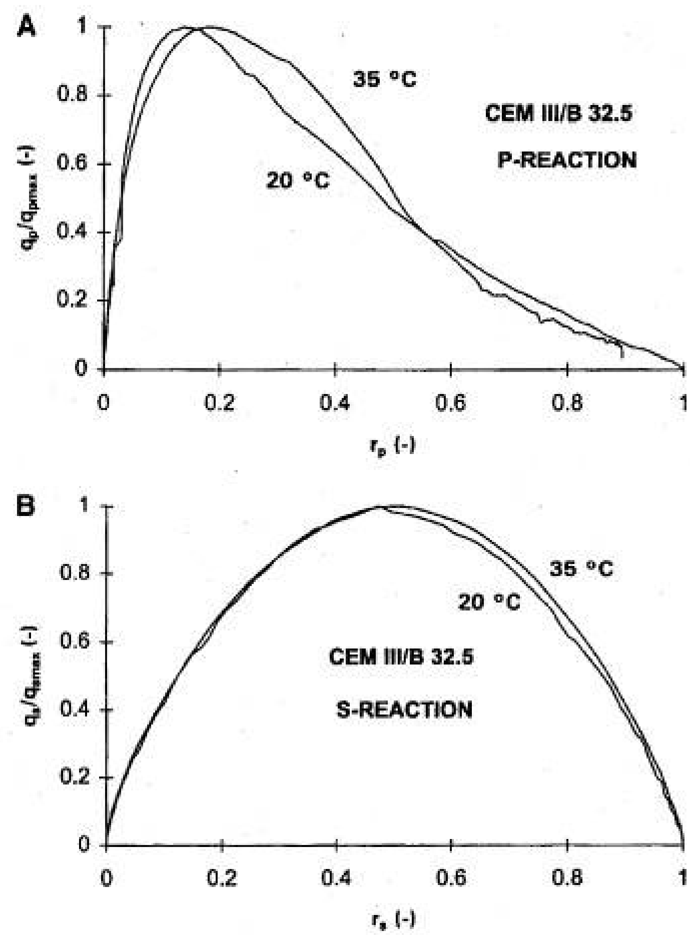
Type IV or low heat of hydration cement. In this respect, FA and GGBFS lower the heat of hydration (Mindess et. al. 2003). Nocuń-Wczelik's work with calorimetry on mixtures containing FA contents ranging from 5% to 60% determined that increases in FA resulted in a slower rate of heat evolution. At 5% FA replacement relatively little change in the heat evolution was noticed, but at replacements greater than 30%, FA resulted in an elongated induction period and lower peak in heat as seen in Figure 2.1 (Nocuń-Wczelik). The induction period is the low heat producing time between the first contact with water and the rapid acceleration of hydration, or the initial set (Nocuń-Wczelik).

Figure 2.1 Calorimetric curves of cement CEM I, 32.5 R samples mixed with PFA (Nocuń-Wczelik)**



Schutter described the hydration of slag-cement concrete as a two fold reaction of the portland cement and the slag that can be superimposed onto one heat curve and estimate the slag-cement heat curve. An adiabatic hydration test, where heat is not lost or gained from the system (Agnes, 2000), measured the heat production rate as a function of time in mixtures with GGBFS replacements of 65%-95%. The portland cement reaction curves peak quickly and then slowly taper down while the slag reaction curves are more symmetric and gain heat towards the peak at the same rate as the heat tapers down as shown in Figure 2.2 (Schutter, 1999).

Figure 2.2 (A) Standardized P-curves for CEM III/B 32.5. (B) Standardized S-curves for CEM III/B 32.5. (Schutter, 1999)

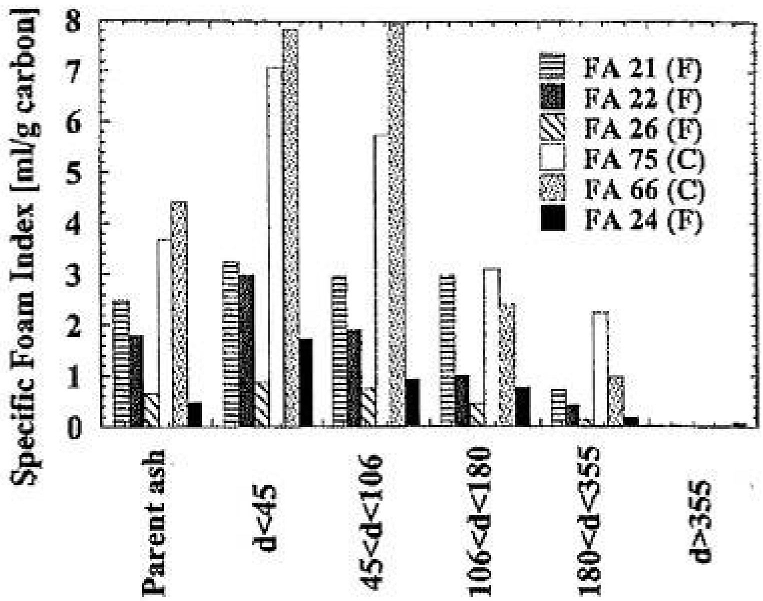


The reaction curves show that portland cement mixtures gain heat more rapidly than GGBFS. The heat gain curves also show slag cement heat gain begins later than the portland cement, explaining the slower heat of hydration and the increase in set times for mixtures containing GGBFS (Schutter, 1999).

2.7.4 Air Content

Class C and Class F FA may contain up to 5 percent per AASHTO M 295-00 (Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete) and 6 percent per ASTM C618 of unburned carbon remaining from the burning process of coal energy (ACAA 1995). The remaining unburned carbon will have detrimental effects on air entrainment and require larger doses of air entraining admixtures (AEA) (Mindess et. al. 2003). The residual unburned carbon in FA absorbs AEA so that less air is entrained into the concrete. The organic contribution (unburned carbon) to the FA is responsible for at least half, usually more, of the surface area of the FA particles. Loss-on-ignition tests (LOI - difference in weight of a sample before and after it was heated to burn off carbon) were performed in research by Kulatos et al. and compared to the Foam Index (measure of how well an AEA works to maintain bubbles) of the FA/cement/water mixtures. Figure 2.3 (Kulatos et al., 2004), below, shows that more milliliters of AEA were required per gram of unburned carbon for the two Class C FA mixtures. Kulatos et al. determined that Class C FA would absorb greater amounts of AEA per LOI of unburned carbon than Class F FA. This was attributed to the location of the unburned carbon surface area on the outside of the Class C FA particles, while the Class F FA particles have smaller holes deeper in the particle where AEA can not easily reach and be absorbed (Külatos et al. 2004). The FHWA and the USDOT suggest careful monitoring of the air content in order to observe the fluctuations (ACAA 1995). GGBFS does not have the same absorbing effect on AEA as the unburned carbon portion of FA.

Figure 2.3 Specific Foam Index for parent ashes and fractions prepared from these ashes. (Külatos et al. 2004)



Workability and air content are directly correlated. Addition of 3-4% entrained air will increase the slump about 1½ to 2 inches (35 to 50 mm). The increase in slump is due to the tiny bubbles created with AEA acting as low-friction fine aggregate. Bubbles from AEA make the mixture behave as if it had too much sand and allows the larger more angular particles slip past each other (Mindess et al. 2003).

2.8 Hardened Concrete Properties

The following sections describe the hardened concrete properties of mixtures made with GGBFS, FA, and ternary mixtures.

2.8.1 Compressive Strength

As mentioned in Section 2.3, FA contains amorphous or glassy silica and as mentioned in Section 2.2 GGBFS is a glassy granule of calcium aluminosilicate.

These SCM react with calcium hydroxide (CH) formed from the hydration of calcium silicates in a secondary reaction during the hydration process (Mindess et. al. 2003). The secondary reaction leads to the use of CH in creating more CSH (calcium silica hydrate) which is the main source of strength in concrete (refer to the principal pozzolanic equation in Section 2.4). The use of the cement products by GGBFS or FA in the secondary reaction produces greater long term strength if enough cement was hydrated to produce an adequate amount of CH (Mindess et. al. 2003).

In research conducted by Li et al, the combination of 15% GGBFS and 25% FA had similar, but slightly lower, compressive strengths to the control mixture (100% portland cement) at 28 days and then slightly higher compressive strengths at later ages. A concrete mixture containing 40% FA had much lower compressive strengths than both the control and the ternary mixture designs until 56 days. After 56 days the FA mixture had the highest compressive strength (Li, 2003).

Research by Regourd, Vanden Bosch, and Roy and Idorn (as described in the Slag Cement in Concrete and Mortar report) used calorimetric studies of the rate of heat liberation to show the two-stage effect. The results suggest that during the early hydration, the predominant reaction is with alkali hydroxide and subsequent reaction is predominantly with calcium hydroxide. This suggests that the primary reaction is from the portland cement component of the mixture while the slag cement hydration lags behind (ACI Committee 233). The portland cement produces less strength in the primary reaction when mixed with SCM while the later SCM reaction adds more CSH and creates greater strength than a cement only mixture (Mindess et al. 2003)

The USDOT and FHWA agree that FA mixtures may have lower compressive strength than a control mixture at early ages, but they usually develop higher later compressive strength when properly cured (Fly Ash-Materials Group). Cold weather seems to more adversely affect FA mixtures than 100% portland cement mixtures and it is recommended that precautions be taken in this case (Fly Ash-Materials Group). In general, GGBFS develops lower compressive strengths at 1 to 5 days but by 7 to 28 days the GGBFS mixture will have similar compressive strengths to 100% portland cement mixtures. Long-term strengths of GGBFS mixtures are above those of the control mixtures (Ground Granulated Blast-Furnace Slag-Materials Group). Fulton and Hogan and Meusel found that the greatest twenty-eight day strengths were in mixtures with as high as 65% replacements of highly reactive GGBFS (ACI Committee 233).

2.8.2 Permeability

Permeability is an important factor in the durability of concrete because it controls the entry of moisture that may contain aggressive chemicals into concrete. Water in and of itself may cause damage to the concrete by freezing and thawing cycles (Mindess et. al. 2003). It is also important for structures that are to be water-tight such as settling tanks for water purification (Mindess et. al. 2003).

Permeability can be measured directly through ponding methods, pressure head methods, or indirectly by the measure of electrons passing through a specimen. The ponding methods use a slab subjected to a fixed head of water and cores are taken to determine the extent of chloride penetration of chloride ions (Mindess et al. 2003). This method is lengthy and may take from 90 days to longer than 2 years to produce adequate data (Mindess et. al. 2003). The pressure head methods are similar to the ponding methods; however, they are designed to provide results faster than the ponding tests.

In research conducted by Leng et al., chloride ion diffusion using the Nernst-Einstein equation utilizing partial conductance, the gas constant, the absolute temperature, and the concentration of the solution to determine the diffusion coefficient. Their research results showed that chloride ion diffusion coefficient increased with increases in w/cm. The chloride ion diffusion coefficient decreased when the quantity of FA or GGBFS increased. FA and GGBFS decreased the pathways for water to flow by reacting with CH to create more C-S-H (as described in Section 2.8.2). The chloride ion diffusion coefficient decreased by 10% at 0.34 w/cm, 35% at 0.30 w/cm, and 41% at 0.26 w/cm when the concrete was made with GGBFS instead of with FA (Leng, 2000). According to the USDOT and FHWA, GGBFS transforms large pores into smaller pores and therefore decreases the permeability of the concrete (Ground Granulated Blast-Furnace Slag-Materials Group).

The rapid chloride ion penetrability test (RCPT) monitors the amount of electrical current passed through the top two inches of a 4" x 8" concrete cylinder. This trimmed sample is saturated with water and placed between chambers that hold a positively charged chemical solution, sodium hydroxide (NaOH), and a negatively charged chemical solution, sodium chloride (NaCl). The sample is subjected to a constant voltage of 60±0.1 V and the current between the two chambers, or through the sample, is recorded. The current passed, in coulombs, was related to ponding tests. An empirical relationship between accepted methods and the RCPT resulted in a table, shown in Table 2.2, to represent the permeability of the concrete vs. the flow of electrons through the sample. (ASTM C1202 Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration, AASHTO T 277-96 Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration) The RCPT was designed to give permeability results in 6 hours, much less time than either of the more direct methods. The information given by the RCPT should be examined closely because of variables inherent in the process.

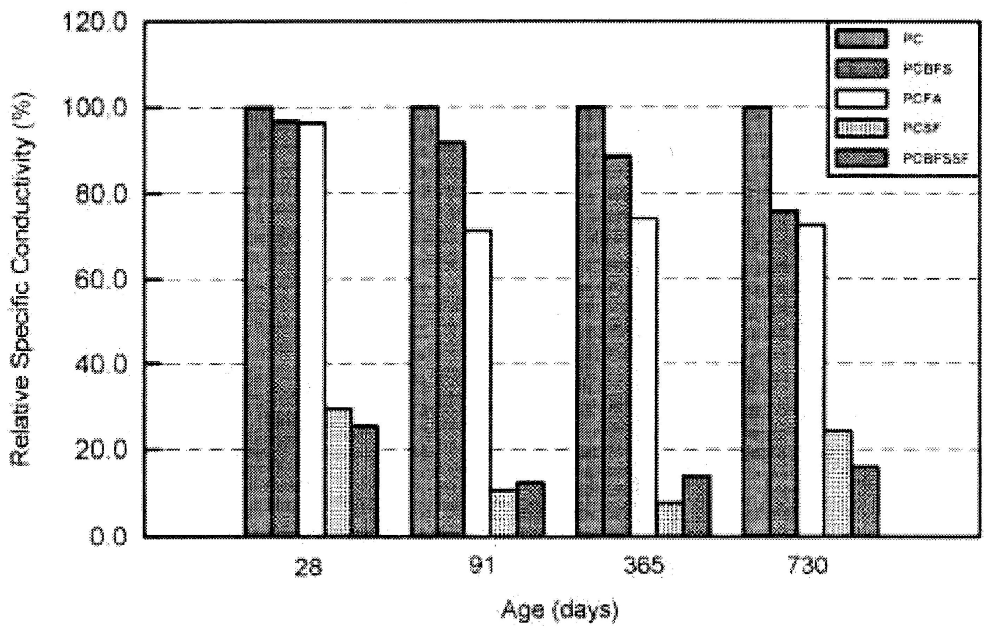
Table 2.2 Chloride Ion Penetrability (ASTM C 1202-97 Table 1)

Charge Passed (coulombs)	Chloride Ion Penetrability
>4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very Low
<100	Negligible

However, there are concerns regarding the validity of the test results. Because the test measures charge passed through a sample, several aspects should be evaluated carefully. A rapid gain of flow can signal heating of the sample which will increase flow greater than represented by the permeability of the sample (Mindess et. al. 2003). The composition of the pore solution can also affect the RCPT results.

Replacement of 60 to 70% portland cement with GGBFS reduces the OH^- concentration, increases the Na^+ concentration, and decreases the K^+ concentration in the pore solution of the concrete. Because FA sources are variable, replacements of portland cement with FA may increase or decrease Na^+ and K^+ concentrations and usually decrease Ca^{2+} and OH^- concentrations in the pore solution. This change in chemical composition from the replacement of cement with SCM may aid in the transfer of electrons between the sodium chloride and the sodium hydroxide solutions, or it may hinder the flow (Shi, 1998). The research compiled by Shi, Stegemann, and Caldwell shows the effect of SCM on relative specific conductivity, the normalized conductivity of hardened concrete made with SCM relative to the conductivity of hardened concrete made with 100% portland cement as shown in Figure 2.4 (Shi, 1998). The results of the research were that 50% GGBFS replacement reduced the conductivity by 3.25% at 28 days, about 9% at 90 days, and 24% at 730 days. FA replacements at 60% reduced the conductivity 3.8% at 28 days and 28.7% at 90 days.

Figure 2.4 Effect of SCM on relative specific electrical conductivity of pore solution in concrete (Shi 1998).



The conductivity is attributed to the pore structure and pore solution characteristics while the transport of chloride ions in the ponding and pressure tests is attributed to the pore structure. The recommendations from the research conclude that the passed charge in the RCPT is not correct to use to determine the rapid chloride permeability of concrete with SCM (Shi, 1998).

2.8.3 Durability

Freeze/thaw durability of concrete containing FA is difficult to determine because of the detrimental interaction with air entraining agents. Section 2.7.4 describes the properties of FA that reduce the effectiveness of AEA. The addition of FA requires monitoring of air content and possibly an increase in the dosage of air entraining admixtures in order to maintain freeze/thaw durability (Fly Ash-Materials Group).

Another aspect of the addition of FA is the decrease in permeability (as described in Section 2.8.1 and 2.8.2) due to the pozzolanic reaction with CH creating more CSH, which will lead to less moisture penetrating the concrete and greater durability. The same process of an increase in density with an increase GGBFS replacement accounts for the increase in freeze/thaw durability of concretes with GGBFS. Air-entrained GGBFS concretes have been noted as having durability factors greater than 91% (Ground Granulated Blast-Furnace Slag-Materials Group). Research conducted by Pigeon and Regourd in 1983 included a group of cement only mixtures, a group of 2/3 cement and 1/3 GGBFS mixtures, and a group of 1/3 cement and 2/3 GGBFS mixtures. Of the mixtures made with no admixtures, the spacing factor (1/2 the average distance between air bubbles) for the 2/3 GGBFS mixture was two times that of the cement only mixture and the spacing factor for the 1/3 GGBFS mixture was one and one-half times that of the cement only mixture. This means that an increase in GGBFS led to an increase in the distance between air bubbles. The researchers also concluded through porosity measurements that the GGBFS concretes have finer pores and more uniform pastes than cement only mixtures. The freeze-thaw results of the Pigeon and Regourd research showed that the three different mixtures survived well through the Procedure B testing (Pigeon et al., 1983).

Another factor in determining the durability of concrete is scaling due to freeze/thaw processes and the exaggeration of scaling when deicing salts are used. The finishing technique used on concrete can trap bleed water just under the finished surface causing disconnect between the finished surface paste and the bulk paste of the concrete. When the hardened concrete is subsequently saturated with water between the finished surface and the bulk paste, few freeze/thaw cycles are required to produce scaling of the surface of the concrete structure. Research conducted by Taylor et al. focused on the effect of finishing relative to time-to-set of a cement only mixture, a 50% GGBFS mixture, and a 25% FA mixture. The results show that late finishing (just before initial set) was best for the cement only mixture. Early finishing (immediately after fabrication) was the best time for the 25% FA mixture. The 50% GGBFS had better results for early and mid-finishing (when bleeding appeared to stop) than for late finishing. The time to finish recommended by ASTM C 672 (Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals) is after the concrete has stopped bleeding. The recommended time to finish concrete from this research is to specify when is best to finish specific mixtures based on time-to-set and bleeding (Taylor et al., 2004).

2.8.4 Sulfate Resistance

Irassar et al. describe the mechanisms of sulfate attack as ettringite formation, gypsum formation, and salt crystallization, all of which "occupy a greater space than the original compounds causing expansion, disruption, and cracking" (Irassar et al., 1996). SCM increase sulfate resistance by calcium hydroxide reduction, permeability reduction, and C_3A dilution. The research conducted by Irassar et al. included concrete mixtures with Type I portland cement, Type I with AEA, 20% replacement with Class F FA, 40% replacement with Class F FA, 80% replacement with GGBFS, and Type V (2% C_3A) portland cement. Cylinders were cast and buried to half height with 1% sodium sulfate soil in the outdoors to simulate in-situ conditions. In the buried section of the samples, visual signs of sulfate attack occurred within two to three years on the two Type I mixtures. Samples with 20% FA showed slight cracks and swelling in the buried zone at four to five years. The concrete with 40% FA, 80% GGBFS, and Type V portland cement showed no damage in the buried zone after five years of exposure (Irassar et al., 1996).

The same pore characteristics that is beneficial (reduces movement of ions) in SCM concrete immersed in solution is detrimental (exacerbates capillary action) to the concrete in the atmosphere. Pore size changes from the SCM inducing capillary action outweigh the chemical benefits (using sulfate attack prone CH particles to make CSH) in the paste in the above ground portion. Samples with 40 to 80% replacements of SCM incurred greater damage in the volume above ground due to the capillary action (three times higher for 80% GGBFS than all of the other mixtures) carrying the sulfate solution to the dryer end and subsequently drying to leave salt crystallization (Irassar et al., 1996).

2.8.5 Alkali-Silica Resistance

Research in alkali-aggregate reactions has shown that FA and GGBFS can lower the negative effects of alkali-silica reaction (ASR) by increasing the density of the concrete paste and preventing the migration of fluids that would contribute to ASR (Mindess et. al. 2003). A greater improvement can be gained by using SCMs and air-entraining admixtures (Gillott, 1995). Nobata and Ueki suggest one of the main reasons for the increase in popularity of GGBFS is due to the advantage of controlling alkali-aggregate reaction (Nobata, 2002). The USDOT and the FHWA suggest that using GGBFS as a partial replacement of cement can reduce the available alkalies to reduce the reaction between the siliceous components of aggregates and the alkalies in the concrete (Blast Furnace Slag - User Guideline-Portland Cement Concrete).

Duchesne and Bérubé researched concrete made with three SCM as replacement for high-alkali cement as compared to concrete made with low-alkali cement. FA with three different chemical compositions (low-calcium and low-alkali, moderate-calcium and low-alkali, and high-calcium and high-alkali), two silica fumes, and one GGBFS were used to study the degradation from ASR and the corresponding pore solution composition. FA mixtures were made at 20 and 40% replacements. Silica fume mixtures had 5 and 10% replacements. The GGBFS mixture had 50% replacement of cement. Highly reactive aggregates were used in the mixtures to induce ASR. The results showed that concrete made with low-alkali cement had expansion of near 0.04% and that 40% FA (those with low alkali content) and 50%

GGBFS decreased the ASR expansion to lower than that of the low-alkali cement mixtures. Silica fume mixtures, 20% FA replacement mixtures, and the high-alkali FA mixtures had greater ASR than the control mixture made with low-alkali portland cement (Duchesne et al., 2001).

2.8.6 Shrinkage

Plastic shrinkage is caused when the water on top of a concrete structure evaporates more quickly than bleed water is able to reach the surface (Mindess et. al. 2003). The reasons for plastic shrinkage include heat, wind, and lack of protection from the elements. The result of plastic shrinkage is cracking due to the tensile forces in the top-most layer of the concrete. The cracks allow more moisture to penetrate into the concrete than a properly finished structure (Mindess et. al. 2003). FA and GGBFS may reduce bleeding by providing a greater amount of fines that require more water because of the increase in surface area. Because FA has a spherical shape, it lowers friction and can offset the negative effects of the fineness (Fly Ash-Materials Group).

Drying shrinkage occurs in hardened concrete when strain is induced from the loss of water from the hardened material (Mindess et. al. 2003). The strain can cause shrinkage cracks and warping of the surface of the member (Mindess et. al. 2003). Joints are used in concrete slabs to control the location of shrinkage cracks and can be filled with material to prevent water and other substances from entering through the crack (Mindess et. al. 2003). Uneven moisture loss in the surface of the slab can cause warping at the corners (Mindess et al. 2003).

2.9 Conclusion

Ground granulated blast-furnace slag and fly ash are two industrial byproducts with supplementary cementitious properties. GGBFS is created from processing the excess molten material removed from refined iron ore. FA is gathered as waste from burning coal. These SCM can be disposed of in landfills or used in more environmentally sound ways such as concrete construction materials. The use of GGBFS and FA is increasingly accepted as environmentally conscious through programs like LEED and good building practice through research that determines the beneficial properties SCM lend to concrete.

The fresh concrete properties mentioned in Section 2.7 were slump, time to set, heat of hydration, and air content. Slump of concrete made with GGBFS increases as the replacement of cement with GGBFS increases due to more paste from the lower density in GGBFS than that of the cement it replaces. Increases in the FA replacements increase the slump more than GGBFS mixtures because of the rounded nature of the FA compared to the crushed, angular nature of cement and GGBFS. Time to set and heat of hydration are complementary properties because a lower heat of hydration often induces a longer time to set and vice versa. Replacements of 30% of GGBFS or FA resulted in increased time to set. GGBFS replacement of 65% had twice the time to set of the cement only mixture. The unburned carbon portion of FA absorbs AEA and requires more AEA to achieve the same air entrainment as a mixture made with GGBFS. The difference in the amount of AEA in FA mixtures is based on the LOI and class of FA.

SCM use the hydration process of cement and the production of CH to gain strength and create more CSH in concrete. The pozzolanic properties of GGBFS and FA effect the hardened concrete properties. Early compressive strength of concrete with low replacements of SCM is greater than with high replacements of SCM. Higher replacements require more CH from the cement hydration, but more CH is not produced with less cement in the mixture. The hydration of SCM also acts as a secondary reaction extending the time to set. The secondary reaction also allows the SCM to continue to gain strength after a comparable cement only mixture. High replacements with SCM produce greater strengths than lower replacements to the extent that enough cement is present. The secondary reaction produces more dense concrete matrix because of the continual conversion of CH to CSH. More dense concrete lowers the permeability and effectively increases durability because water has less chance at freeze/thaw damage and less ability to bring in chemicals that induce sulfate attack and ASR. The permeability and durability are also determined by the proper air entrainment discussed above.

The benefits provided through previous research justifies re-examination of the current Specifications in Arkansas based on research specifically designed to test materials used in this state. If the same benefits are determined from the current research as from previous research, Arkansas would benefit from an update to the Specifications that allow greater usage of GGBFS and FA.

Chapter 3 EXPERIMENTAL PROCEDURES AND RESEARCH PROGRAM

3.1 General

The goal of the research program is to provide evidence that the AHTD Specifications for concrete can be modified to allow greater replacement rates of GGBFS and FA and ternary mixtures. The fresh and hardened concrete properties were determined for mixtures containing GGBFS, FA, or both materials. In this chapter, each of the studies is described followed by detailed descriptions of the batching, curing, and testing methods used in the research. The chapter is prefaced by a brief summary of the scope of the project and AHTD's requirements for portland cement concrete pavement mixtures.

3.2 Scope

The research program is divided into three studies. Within each study, performance aspects of using GGBFS and/or FA were examined using fresh and hardened concrete properties. The studies are listed below:

1. Cement – Determine if GGBFS and/or FA react differently with various Type I cements. Five different concrete mixtures were batched with two different Type I cements. The mixtures examined included a control mixture containing only portland cement, a mixture containing 60% GGBFS (GR 100 and 120), a mixture containing 60% Class C FA, and finally a ternary mixture containing 20% GGBFS and 20% FA. The w/cm, total cementitious material content, and coarse aggregate content was constant for all mixtures. The quantity of sand varied some

among mixtures because of the differences in specific gravities of the GGBFS, FA, and portland cement.

2. Supplementary Cementitious Material – Determine, through more comprehensive testing, the effects of replacing portions of the portland cement with GGBFS and/or FA. A typical AHTD mixture proportion for concrete paving was used for the control mixture. The SCM replacements were 20, 40, and 60% by weight for GGBFS (GR 100 and 120) and FA. Ternary mixtures were 20/20, 20/40, 20/60, and 40/40 replacements with GGBFS (GR 100 and 120) for each SCM. One cement source was used and the w/cm, total cementitious material content, and coarse aggregate content was constant for all mixtures. The quantity of sand varied some among mixtures because of the differences in specific gravities of the GGBFS, FA, and portland cement. No chemical admixtures were used in order to attribute the differences in fresh and hardened properties to the replacement of cement with FA, GGBFS, or both.

3. Ground Granulated Blast Furnace Slag – Two grades of GGBFS (GR 100 and 120) were used in nine comparative concrete mixtures with a single cement source. The materials were held constant except for the ratio of cement to SCM and grade of GGBFS.

3.3 AHTD Specifications for Portland Cement Concrete Pavement Mixtures

Concrete designed as pavement under the AHTD specifications must comply with the following requirements. The minimum cement content is 564 lbs. per cubic yard or at least 6 sacks (335 kg of cement per cubic meter). The water-to-cementitious material content should not exceed 0.45 including the moisture of the aggregate.

Substitution of FA is made at a rate of one pound of FA for one pound of cement up to 20% of the weight of the cementitious material. GGBFS is also substituted at a rate of one pound GGBFS for one pound of cement up to 25% of the weight of the cementitious material. Neither can be used in conjunction with high strength or blended cements and they cannot be used in conjunction with each other in order to create a ternary mixture.

The concrete properties required are few. The minimum twenty-eight day compressive strength shall be 4000 psi (28.0 MPa) and the slump shall be not more than 2 in. (50 mm). The air content of the fresh concrete should be 6% ± 2%, and while the scope of this project did not allow for air entraining admixture, the air contents were lower and further research is recommended to determine dosage rates of air entraining admixture in FA/GGBFS concrete mixtures for Arkansas materials (AHTD, 2003).

3.4 AHTD Specifications for Portland Cement Concrete Structure Mixtures

The concrete designed for structures must comply with Section 802 of AHTD Specifications. Type I cement should be used unless a blended cement of portland-pozzolan cement-IP, pozzolan-modified portland cement-PM, or slag-modified portland cement-SM is approved by the engineer. Aggregates shall be subjected to AASHTO T 21-91, *Organic Impurities in Fine Aggregates for Concrete* and AASHTO T 27-93, *Sieve Analysis of Fine and Coarse Aggregates*. FA shall meet the requirements of AASHTO M 295 as Class C or Class F and mixing Class C and Class F FA is not allowed. GGBFS shall meet the requirements of AASHTO M 302 as GR 100 or GR 120. The concrete mixture design shall be proportioned to ensure a workable and durable concrete for each of the classes of structural concrete. The different classes of structural concrete, based on the purpose of the concrete, have different minimum compressive strengths with the minimum compressive strength for air entrained concrete at 4000psi. The minimum cement content ranges from 5.5 to 6.5 sacks of cement per cubic yard. The w/cm varies from 0.44 to 0.58 and the slump range is 1 in. to 4 in.

FA may be used as a partial replacement for Type I cement up to 20% by weight in all classes of concrete except class B. Class F FA can not be used in bridge deck concrete between October 15 and April 1. GGBFS may also be used as a partial replacement for Type I cement up to 25% except in high early strength and seal concrete (AHTD, 2003).

3.5 Materials

As required by AHTD Standard Specifications for Highway Construction, Division 500, Section 501.02 Materials, AASHTO M 85 and Type I/II portland cement was used in all mxtures. Different sources of cement were used to determine if the SCM reacted differently with each cement. As required by AHTD, total alkalis in the cement should not exceed 0.60% and the total alkalis in the cementitious material should not exceed 5 lbs./yd^3 (AHTD, 2003).

The requirements of fine aggregates, clean, hard, durable particles of natural sand or other inert materials were also followed. The coarse aggregate was crushed limestone. The sieve requirements for both the coarse and fine aggregates were followed. Fly ash used complied with AASHTO M 295 and was Class C. The two types of GGBFS complied with AASHTO M 302 and were GR 100 and GR 120, as per the specifications (AHTD, 2003). Table 3.1 lists the materials and the tests and standards that applied to each material. Cement, FA, and GGBFS chemical and compound composition are given in Table 3.2. The activity index is given in Table 3.3. The fine and coarse aggregate properties are shown in Table 3.4.

Table 3.1 Material Tests

Materials	Test Name and Standard	
Cements, GGBFS, and FA	Blaine Air Fineness	ASTM C 204 AASHTO T 153
	Slag Activity Index	ASTM C 989
Coarse Aggregate	Specific Gravity and Absorption	ASTM C 127 AASHTO T 85
	Sieve Analysis	ASTM C 13 AASHTO T 27
	Dry Rodded Unit Weight	ASTM C 29 AASHTO T 19
Fine Aggregate	Specific Gravity and Absorption	ASTM C 128 AASHTO T 84
	Sieve Analysis	ASTM C 136 AASHTO T 27

Table 3.2 Cement, FA, and GGBFS Properties

	Cement A	Cement B	Class C FA	GR 120 GGBFS	GR 100 GGBFS
	Ash Grove Cement	River Cement	ISG Resources	Buzzi Unicem	Holcim
	Chemical Composition (%)				
SiO_2	20.27	20.60	34.39	32.00	39.06
Al_2O_3	5.78	4.40	20.26	12.00	8.39
Fe_2O_3	2.73	3.40	6.17	0.60	0.43
CaO	64.32	63.8	25.71	42.00	36.56
MgO	1.31	3.70	5.95	9.00	12.58
SO_3	2.93	2.80	1.44	0.15	1.91
Loss on Ignition	1.18	0.9	0.04		
	Compound Composition (%)				
C_3S	56.72	61			
C_2S		13			
C_3A	10.70	5.9			
C_4AF		10.3			
Na_zO	0.22				
K_zO	0.29				
	Blaine Air Fineness				
Blaine (cm^2/g)	3670	365 m^2/kg		5270	580

Table 3.3 Slag Activity Index

	Compressive Strength Control Mix (psi) (1)		Compressive Strength 50% SCM (psi) (2)		Slag Activity Index (2)/(1)	
	7 Day	28 Day	7 Day	28 Day	7 Day	28 Day
GR 120 GGBFS	-	-	4390	6900	103	131
GR 100 GGBFS	3920	5080	3480	6520	90	128
Class C FA	-	-	-	-	97%	-

Table 3.4 Fine and Coarse Aggregate Properties

	Fine Aggregate (Arkhola, Van Buren, AR)	Coarse Aggregate (Arkhola, Springdale, AR)
Absorption (SSD)	0.48	0.38
Specific Gravity	2.604	2.678
Dry Rodded Unit Weight (lb/ft^3)	110.9	-

3.6 Cement Study

The cement study was conducted to determine whether the FA and GGBFS will react differently with two different cement sources often used in the state of Arkansas. For each cement source, five mixture designs were batched including one control, one high-volume FA replacement, one high-volume GGBFS replacement for each grade, and one ternary mixture design for GR 120 of GGBFS. The batching and testing matrix is shown in Table 3.5. All of the fresh and hardened concrete properties listed in Section 3.8.3 were tested for each mixture.

Table 3.5 Cement Study Batching and Testing Matrix

Cement	GGBFS GR	GGBFS %	FA %
A	-	0	0
A	120	60	0
A	-	0	60
A	120	20	20
A	100	60	0
B	-	0	0
B	120	60	0
B	-	0	60
B	120	20	20
B	100	60	0

3.7 Supplementary Cementitious Material and GGBFS Studies

The SCM study was conducted to supply data to AHTD on mixtures containing GGBFS, FA, and a combination of both. Fresh and hardened concrete properties of 22 mixtures were examined, including the five mixture designs, with cement A, used for the cement study. Two grades of GGBFS (GR 100 and 120) were used in the GGBFS study in order to determine if the two grades of GGBFS had similar fresh and hardened concrete properties. The GGBFS study included the mixture designs from the SCM study except for the FA mixtures. The SCM and GGBFS studies batching and testing matrix is shown in Table 3.6. All of the fresh and hardened concrete properties listed in Section 3.8.3 were tested for each mixture design. Repeatability was also incorporated into the SCM study by batching each of the mixture designs made with cement A twice and comparing the mixtures. This study ruled out errors that may have been introduced during batching.

Table 3.6 SCM and GGBFS Studies Batching and Testing Matrix

Cement	GGBFS GR	GGBFS %	FA %
A	-	0	0
A	120	20	0
A	120	40	0
A	120	60	0
A	-	0	20
A	-	0	40
A	-	0	60
A	120	20	20
A	120	20	40
A	120	20	60
A	120	40	20
A	120	40	40
A	120	60	20
A	100	20	0
A	100	40	0
A	100	60	0
A	100	20	20
A	100	20	40
A	100	20	60
A	100	40	20
A	100	40	40
A	100	60	20

3.8 Experimental Procedures

3.8.1 Mixtures and Batching

The control mixtures were developed according to AHTD's specifications for minimum quantity of cement and a maximum w/cm ratio of 0.45. The proportions of the control mixtures are listed in Table 3.7. The mixture proportions were developed using the absolute volume method. The only difference between the control mixture and the remaining mixtures is the quantity of SCM. The FA and GGBFS were substituted by weight for cement at a replacement rate of one pound of FA/GGBFS for one pound of cement. The w/cm was constant for all mixtures and the aggregate amount was based on the volumetric method. The batching process followed ASTM C 192 *Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory* (AASHTO T 126-97 *Making and curing Concrete Test Specimens in the Laboratory*).

Table 3.7 Mixture Proportion for Control Mixture with Cement A

Material	Batch Weight (lb/yd^3)
Cement	650
Coarse Aggregate	1894
Fine Aggregate	1169
Water	274

3.8.2 Curing

Immediately after batching, the specimens were placed in an environmental chamber. The environmental chamber was held constant at 73°F (23°C) and relative humidity of approximately 50% as per ASTM C 192 (AASHTO T 126-97). After 24 hours, the specimens were de-molded and immediately immersed in a lime saturated water bath located in the environmental chamber. The specimens remained in lime saturated water until testing.

3.8.3 Fresh and Hardened Concrete Tests

The fresh concrete tests were measured for all mixtures batched. The fresh concrete properties measured were slump (ASTM C 143, AASHTO T 119), unit weight (ASTM C 138, AASHTO T 121), and air content (ASTM C 231, AASHTO T 152). The hardened concrete properties measured were compressive strength (ASTM C 39, AASHTO T 22), rapid chloride ion penetrability (ASTM C 1202, AASHTO T

227), and freeze/thaw durability (ASTM C 666, Procedure A, AASHTO T 161). The fresh and hardened concrete tests are shown in Table 3.8.

Table 3.8 Fresh and Hardened Concrete Tests

Fresh Concrete Tests	**Standard**	**Time of Test**
Slump	ASTM C 143 AASHTO T 119	At batching
Unit Weight	ASTM C 138 AASHTO T 121	At batching
Air Content	ASTM C 231 AASHTO T 152	At batching
Hardened Concrete Tests		
Compressive Strength	ASTM C 39 AASHTO T 22	1, 3, 7, 28, 90 Days
Rapid Chloride Ion Penetrability	ASTM C 1202 AASHTO T 227	28, 90 Days
Durability	ASTM C 666, Procedure A AASHTO T 161	28 and Subsequent Days

3.9 Statistical Analysis

The number of samples tested per batch of concrete was taken from the ASTM standard for each test. Cement A mixtures were batched twice to determine batching consistency and therefore cement A mixtures have two sets of data. The two sets were compared to each other for repeatability and then combined to create one set of data for the cement study, the SCM study, and the GGBFS study. The cement B mixtures were not batched twice for batching consistency. A mean, or average, was calculated for the statistical analysis when more than one value was recorded for a mixture design.

The slump, unit weight, air content, and temperature were measured once for each batch. Two slumps, unit weights, air contents, and temperatures were measured for cement A mixtures and one slump, unit weight, air content, and temperature was measured for the cement B mixtures. Three compressive strength samples were tested for each batch. Six compressive strengths were recorded for each cement A mixture and three compressive strengths were recorded for each cement B mixture. Two RCIP and freeze/thaw samples were tested for each batch. Four RCIP and freeze/thaw results were recorded for cement A mixtures and two RCIP and freeze/thaw results were recorded for cement B.

The data gathered from the fresh and hardened concrete tests were used to perform a statistical analysis. SAS Version 8 was used to determine statistical difference in the data based on the batching matrix described previously in Chapter 3. When the data are described as not statistically different, the tests provided insufficient evidence that the data are different. In these studies, it means the mixtures produced the same result and are interchangeable to produce that particular property at similar quality. When the data are described as statistically different the mixtures are not interchangeable and one mixture is better to produce the desirable quality of the property than the other.

The SAS program performed an analysis of variance, or ANOVA, test. The ANOVA test used to compute and compare means for a complete set of data was Duncan's Multiple Range Test. This test ranked the data from greatest to least and grouped the values. The ANOVA test used to compute and compare means for an unbalanced or incomplete set of data was the least square means (LSMeans) test. This test did not rank or group the values; it only allowed two values to be compared to each other. The p-value, the probability that the sample would occur if the null hypothesis is true, and the mean of each mixture were compared to the other mixtures to determine a grouping. The null hypothesis is the statement that no significant difference occurs between the samples. A p-value close to zero signals that the null hypothesis is false and therefore a significant difference between the samples exists. A p-value close to one signals that the null hypothesis is true and therefore the samples are significantly similar (P-Value).

Confidence interval means that the results of the test fall within a standard deviation a certain percentage of the times that the test is performed. Alpha value and confidence interval add to 100%. The confidence interval was 95%, so that the alpha value was 5%. The alpha value was used to compare the mean values from the hardened concrete tests, or singular values from the fresh concrete tests. The p-values were determined from comparing two mixtures by the LSMeans test or the Duncan Grouping. When the calculated p-value was less than the chosen alpha value, the mean values were statistically different. The data must be normally distributed for the results of these tests to be valid. The Shapiro-Wilk test was used to determine normality. When data were not normally distributed they were ranked to induce normality and the ANOVA test was used on the ranked values.

Chapter 4 RESULTS AND DISCUSSION

4.1 General

The following is a presentation and discussion of the results from the experimental program. The studies are presented in the following order: cement study, supplementary cementitious material (SCM) study, and ground granulated blast furnace slag (GGBFS) study. The results and observations from the fresh concrete properties are presented first, followed by the hardened concrete results and observations. The mixtures are designated by cement brand, GGBFS replacement rate and grade, and FA replacement rate. For example, mixture A/20-120/0 contains cement A, 20% replacement with GR 120 GGBFS, and 0% replacement with Class C FA. The control mixtures, A/0/0 and B/0/0, contained 650 lb (295 kg) of cement, 1885 lb (855 kg) of coarse aggregate, 1155 lb (525 kg) of fine aggregate, and 295 lb (135 kg) of water. The statistics run on the different phases of the experimental program and referred to in the following discussion are described in Section 3.9 and included in Appendix D.

4.2 Cement Study

The cement study examined the interaction between the SCMs and two Type I cements. The fresh and hardened properties of mixtures containing cement A were compared to mixtures made with cement B. Five different mixtures were batched with cement A and cement B as described in Section 3.5. The control mixture design was made as described in Section 4.1.

4.2.1 Fresh Concrete Tests

The fresh concrete properties examined were slump, air content, concrete temperature, and unit weight. The values listed in Table 4.1 are the mean values of two batches for cement A and the actual values for cement B as described in Section 3.9. The not statistically different groupings were based on the statistical analysis as described in Section 3.9.

Table 4.1 Fresh Concrete Properties for Cement Study

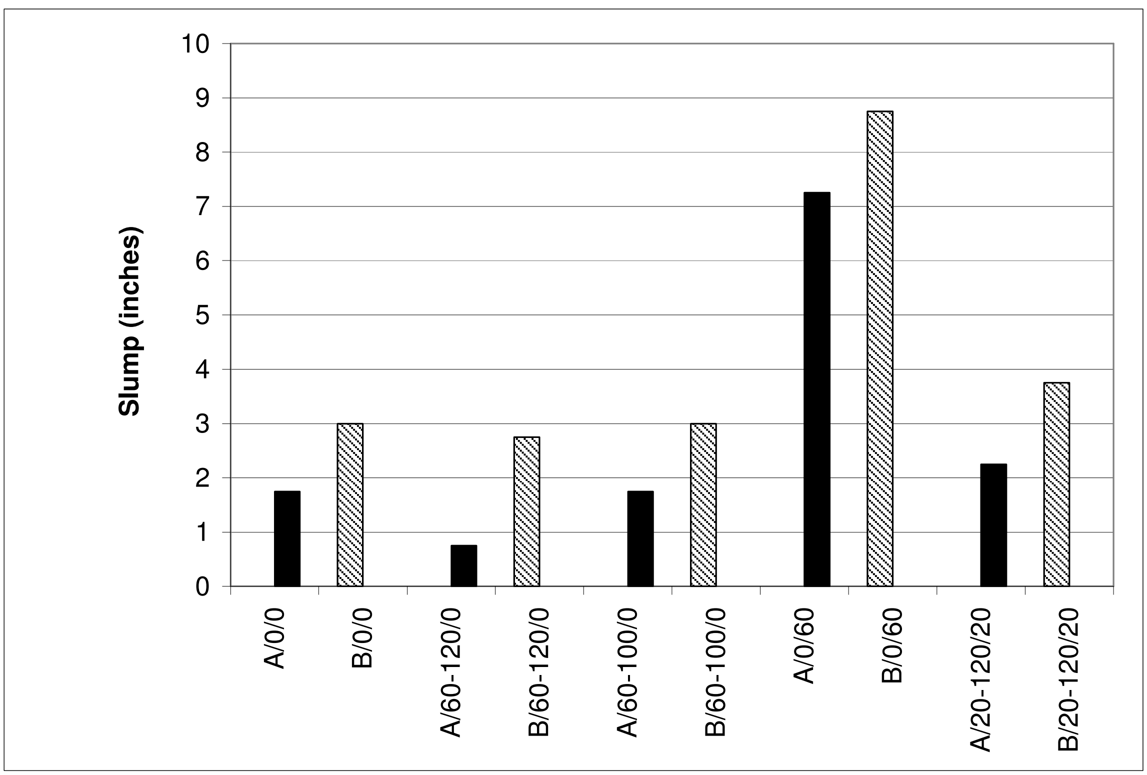
Mixture	Slump, in. (mm)	Unit Weight, lb/ft^3 (kg/m^3)	Air Content, %	Temperature, °F (°C)
A/0/0	1.75 (45)	151.5 (2426)	1.4	89.8 (32.1)
A/60-120/0	0.75 (20)	149.8 (2399)	1.6	72.5 (22.5)
A/60-100/0	1.75 (45)	148.8 (2384)	1.5	83.0 (28.3)
A/0/60	7.25 (185)	150.6 (2413)	0.6	71.7 (22.1)
A/20-120/20	2.25 (60)	150.1 (2404)	1.5	67.4 (19.6)
B/0/0	3.00 (80)	150.0 (2403)	1.7	80.0 (26.7)
B/60-120/0	2.75 (70)	148.7 (2382)	1.5	78.0 (25.6)
B/60-100/0	3.00 (80)	148.9 (2386)	1.2	82.0 (27.8)
B/0/60	8.75 (225)	148.9 (2386)	0.4	80.0 (26.7)
B/20-120/20	3.75 (95)	149.3 (2392)	1.3	80.0 (26.7)

4.2.1.1 Slump

The slump values for cement B were consistently higher than those of cement A. The statistical analysis showed that the mixtures made with cement A were significantly different than mixtures made with cement B. This difference in slump could be due to the cement brand fineness or reactivity. Even though differences in slumps existed between cement A and cement B mixtures, the values followed the trend as shown in Chart 4.1 and observed as follows:

- for cement B, the control mixture (B/0/0) had slump values similar to mixtures containing GGBFS, the addition of GGBFS had little effect on the ternary cement B mixtures,
- the addition of fly ash offset the negative effect of GGBFS on slump,
- the 60% FA mixtures resulted in more than two times higher slumps than the control mixtures for both cements,
- the 60%replacement with GR 120 GGBFS resulted in the lowest slumps for both cement A and cement B mixtures.

Chart 4.1 Slump Values for Cement Study



The 5.5 in. to 5.75 in. increase in slump over the control mixture shown by both batches with 60% FA replacements was consistent with literature. Fly ash particles are small and spherical which helps lubricate the mixture. The ternary

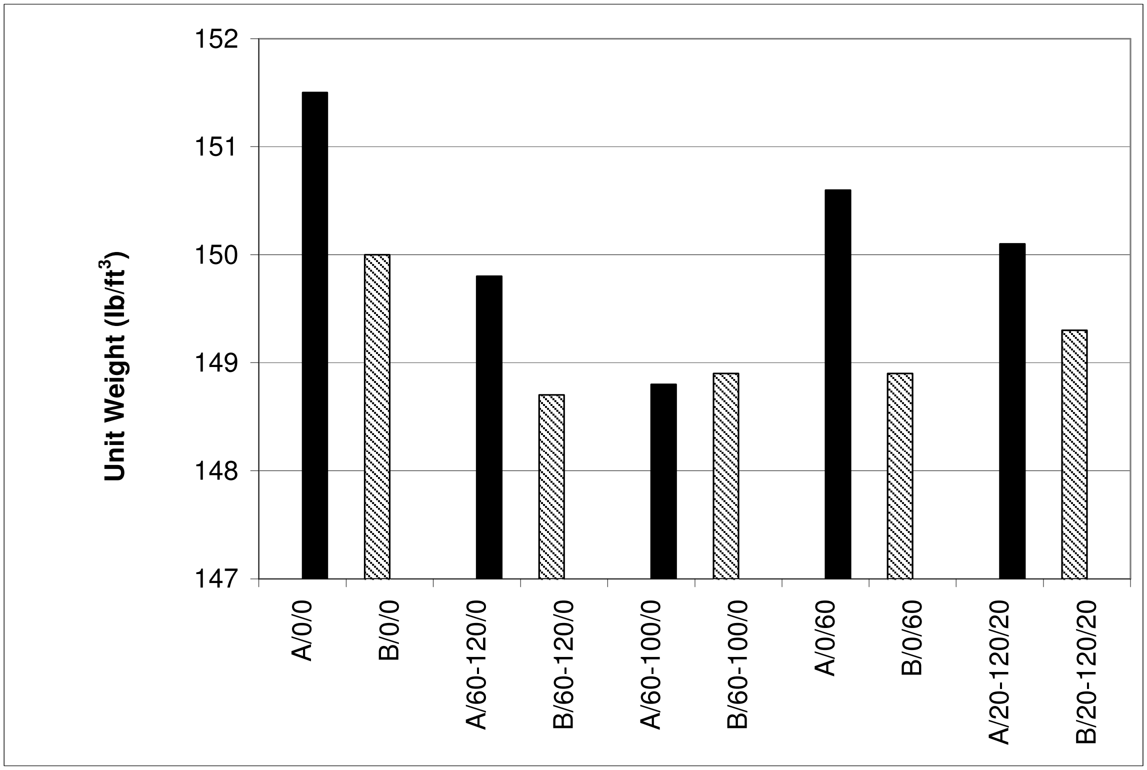
mixtures had less lubrication because of the smaller amount of FA replacement (20% vs. 60%). The fineness of GGBFS was not a big contributor to the slump in the results shown above. Typically, finer materials, such as GGBFS, reduce workability because of the increased surface area per unit volume created by the smaller particles, which absorbs more water than coarser particles such as cement.

4.2.1.2 Unit Weight

The unit weight of the cement A and cement B mixtures followed similar trends even though cement A produced higher unit weights than cement B. The control mixtures, which had only portland cement, had the highest unit weight. This trend was because cement has a higher specific gravity than GR 100 GGBFS, GR 120 GGBFS, and Class C FA. For the ternary mixtures, 40% of the cement was replaced with materials having lower specific gravity than cement, which results in a lower unit weight. The 60% replacement mixtures followed the same trend. The trends observed from the data and Chart 4.2 were as follows:

- the control mixtures had the highest unit weights,
- the ternary mixtures had the second highest unit weights, and
- the 60% replacements (except A/0/60) had the lowest unit weights.

Chart 4.2 Unit Weight Values for Cement Study

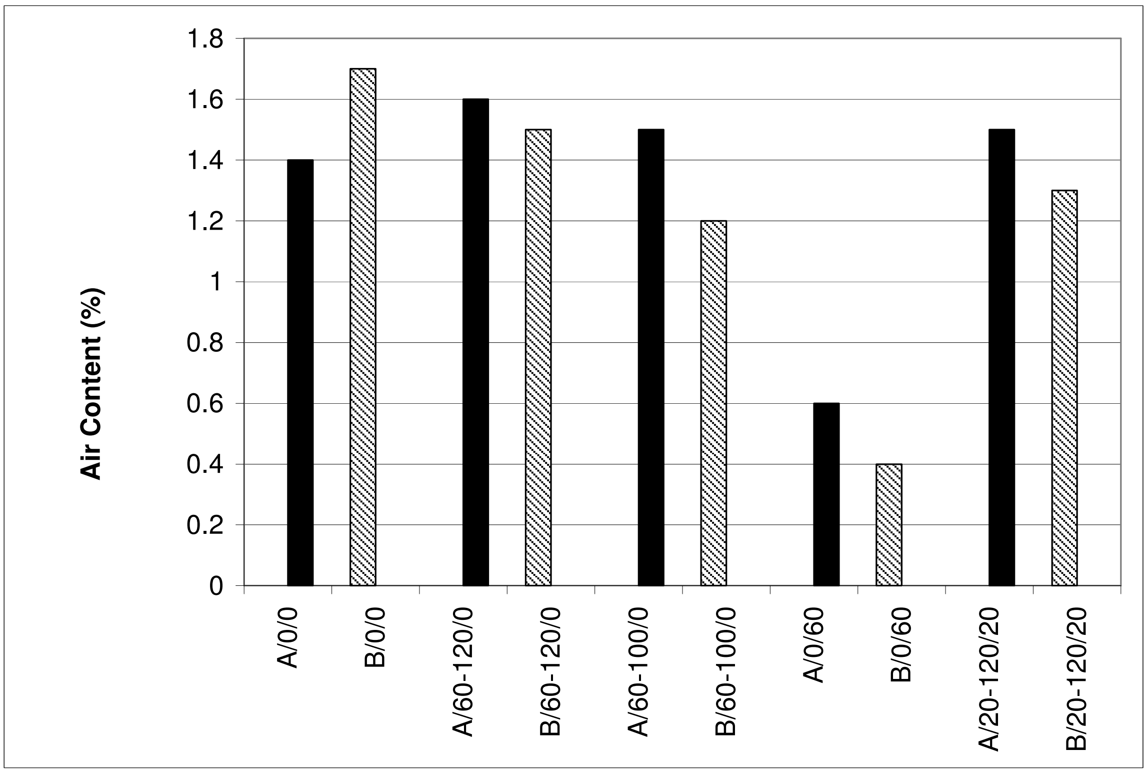


4.2.1.3 Air Content

The air contents of the ten mixtures were consistent with the exception of the FA batches. The air contents ranged from 0.4 to 1.7% with 8 out of 10 mixtures having air contents between 1.2 to 1.7%. The addition of FA lowered the air content by more than half when compared to the control mixtures. The improved workability, without the addition of air entraining agents, has allowed the particles to pack more closely (Mindess et al. 2003). Because no air entraining agents were used, the air content was only due to entrapped air. A non-air entrained mixture typically entraps 0.5% to 3.0% air (Mindess et al. 2003). The control mixtures and the mixtures with GGBFS were able to retain more entrapped air than the FA mixtures. The trends from Chart 4.3 and the data were observed as follows:

- the cement A mixtures (except for the control mixture) had higher air content than the cement B mixtures,
- the 60% FA mixtures had the lowest air content, and
- the air contents for 8 out of 10 mixtures were typical of non-air entrained concrete mixtures.

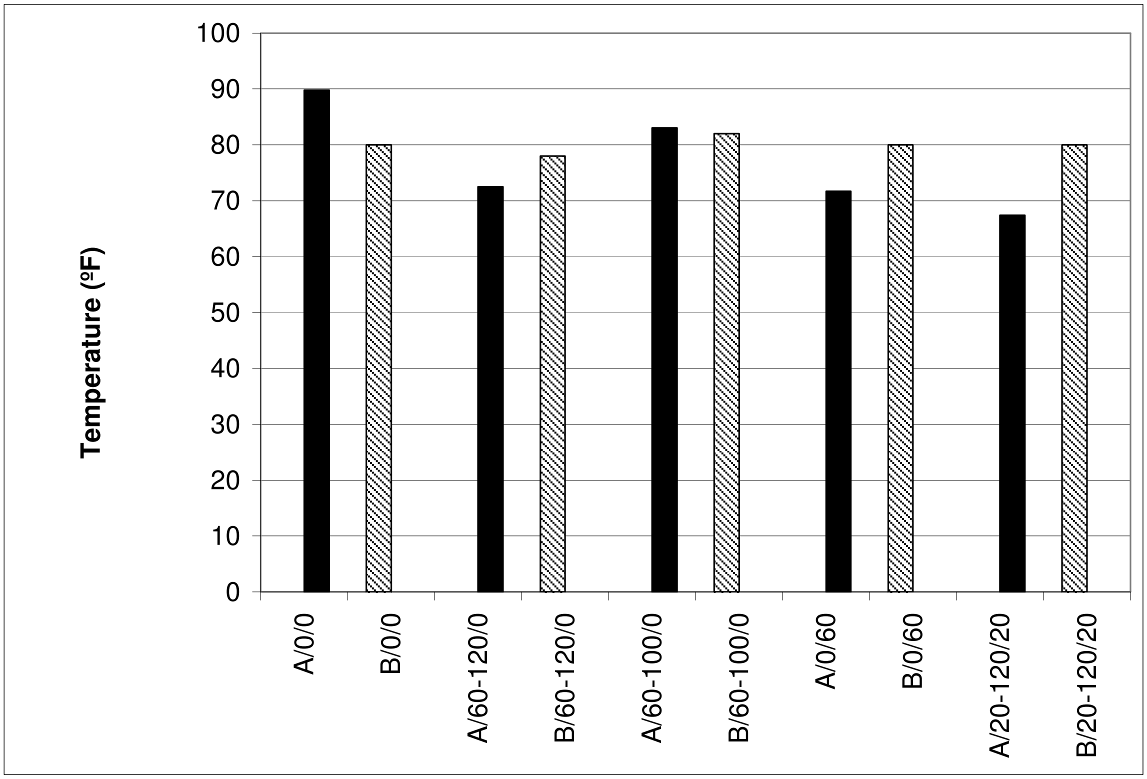
Chart 4.3 Air Content Values for Cement Study



4.2.1.4 Concrete Temperature

The fresh concrete temperature was used for quality control purposes. The temperature was a result of the temperature of the materials before mixing and the ambient temperature during mixing instead of from the hydration processes. The fresh concrete temperature ranged from 67.4 to 89.8 °F (19.6 to 32.1 °C) as shown in Chart 4.4.

Chart 4.4 Temperature Values for Cement Study



4.2.2 Hardened Concrete Tests

The hardened concrete tests performed for the cement study were compressive strength, rapid chloride ion penetrability test (RCPT), and freeze/thaw durability. The compressive strength values listed in Table 4.2 are the mean values of six samples for cement A mixtures and the mean of three samples for cement B mixtures as described in Section 3.9. The RCPT and durability factor values listed in Table 4.3 are the mean values of four samples for RCPT and freeze/thaw durability for cement A mixtures. For cement B two samples were tested for RCPT and freeze/thaw durability as described in Section 3.9. The not statistically different groupings were based on the statistical analysis as described in Section 3.9

4.2.2.1 Compressive Strength

Table 4.2 Compressive Strength (psi) for Cement Study

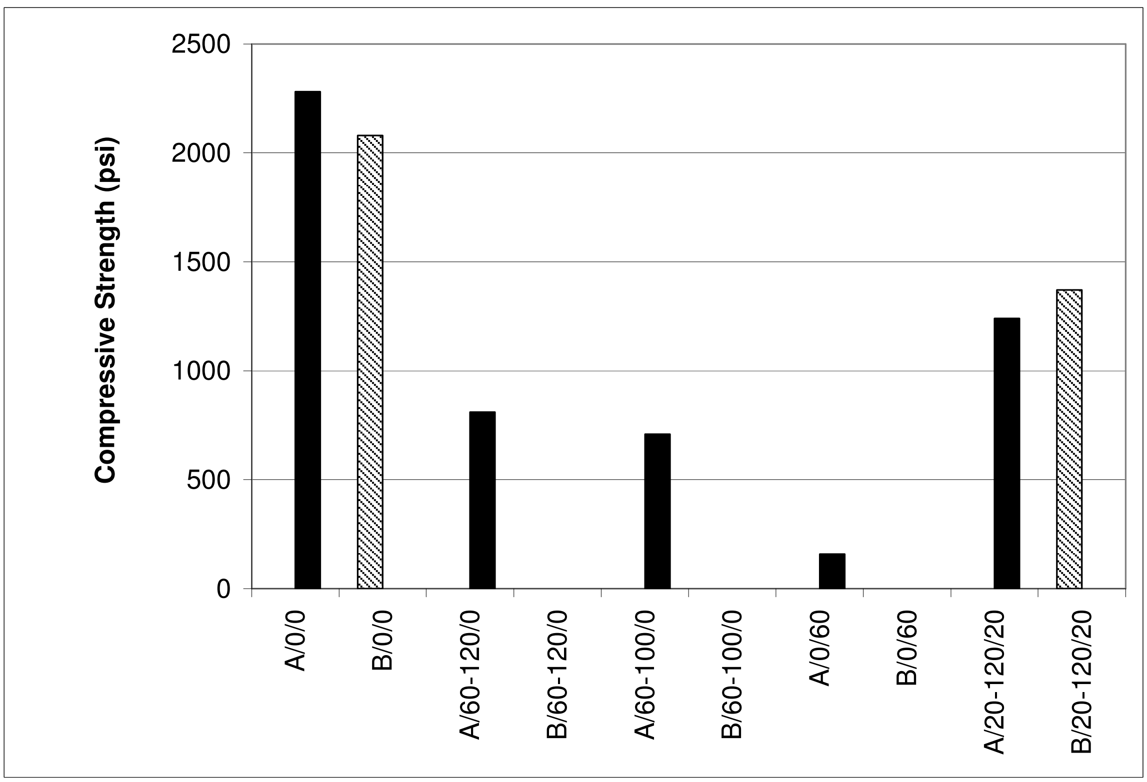
Mixture Design	1 Day	3 Days	7 Days	28 Days	90 Days
A/0/0	2280	5290	6520	7840	8250
A/60-120/0	810	3130	5150	6910	7920
A/60-100/0	710	2320	4590	7270	8090
A/0/60	160	1010	4250	7610	9480
A/20-120/20	1240	4230	6510	8600	10020
B/0/0	2080	3960	4980	6340	7850
B/60-120/0	0	2910	4630	6400	6950
B/60-100/0	0	1820	4330	5830	7870
B/0/60	0	1770	3710	6010	7780
B/20-120/20	1370	4120	5640	7290	8330

The control mixtures, A/0/0 and B/0/0, had the highest one-day compressive strength. The literature suggested that the 100% portland cement mixtures would gain strength more rapidly than the SCM. This was due to the SCM participating in the secondary reaction in concrete, as described in Section 2.6.1, and the cement participating in the primary reaction. The ternary mixtures, A/20-120/20 and B/20-120/20, had the second highest one day compressive strength, but were still 710 to 1040 psi (34 to 46%) less than the control mixtures. The 60% replacements of each SCM for cement A were strong enough to test at one day, even though the strengths measured were very low. The 60% replacements of each SCM for cement B were not strong enough to test at one day, which may indicate that cement A mixtures reacted differently with the SCMs and reduced setting times. The zero values resulted because the concrete was not strong enough to be de-molded. The trends from the data and seen in Chart 4.5 from the one day data were observed to be as follows:

- the control mixtures had the highest strength,

- the ternary mixtures had the second highest strength,
- at high replacement rates, GGBFS mixtures produced higher strengths (at one day) with GR 120 performing better than GR 100,
- the cement A mixtures achieved higher one day strengths than cement B mixtures (except for the ternary mixture), and
- the 60% replacements of FA for cement B mixtures significantly delayed time to setting.

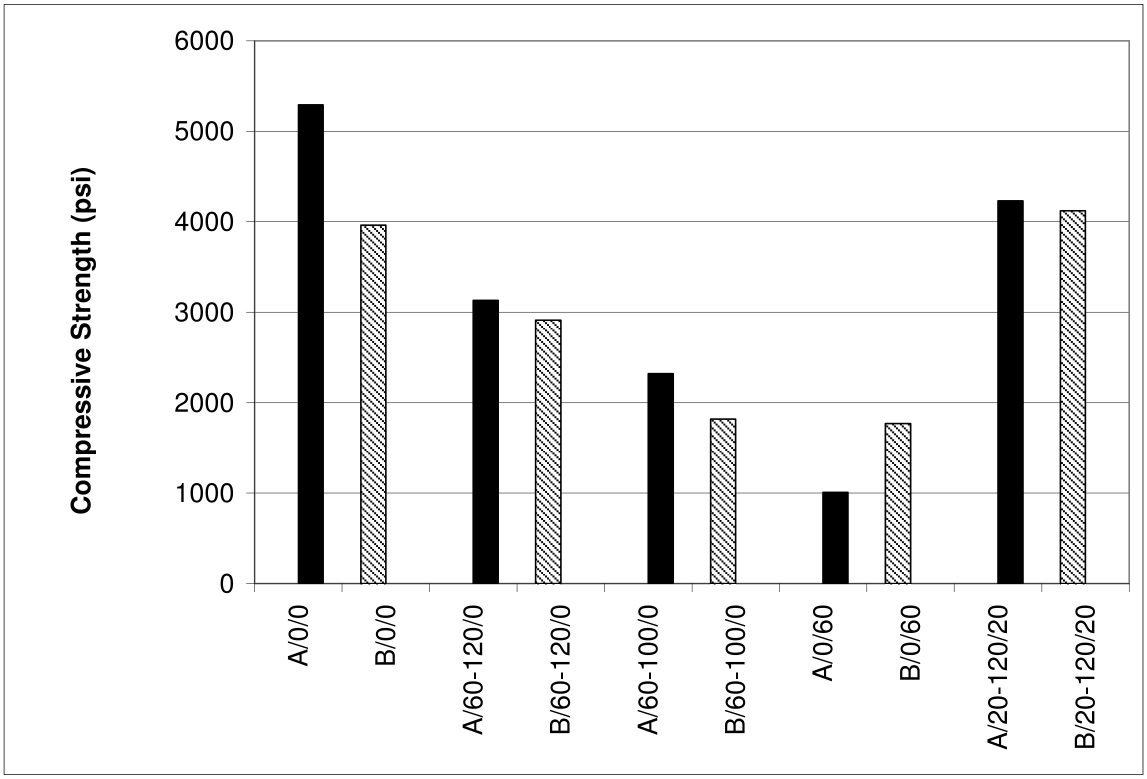
Chart 4.5 One Day Compressive Strength Values for Cement Study



Statistical analysis on the three-day compressive strengths showed that for each replacement rate the cement A and cement B mixtures had not statistically different compressive strengths (i.e. the cements were interchangeable for strength gain at 3 days). The control mixtures (A/0/0 and B/0/0) also had not statistically different compressive strengths to the ternary mixtures (A/20-120/20 and B/20-120/20) with a difference of 20% and 4% respectively. At one day the ternary mixtures were statistically different than the control mixtures and at 3 days they were similar, which suggests that the ternary mixtures gained strength more rapidly with time. The 60% SCM replacements had 26 to 81% less strength than the control mixtures. The trends observed from the statistics and Chart 4.6 were as follows:

- the control mixtures and the ternary mixtures produced higher strength than the 60% replacements,
- the ternary mixtures produced comparable compressive strength to the control mixtures,
- for mixtures containing 60% SCMs, the GR 120 GGBFS had the greatest strength followed by the GR 100 GGBFS and then the FA,
- the cement A and cement B mixtures produced comparable compressive strength for mixtures containing SCMs, but the control mixtures were significantly different, and
- the 60% SCM cement B mixtures were similar to the cement A mixtures by three-day tests.

Chart 4.6 Three Day Compressive Strength Values for Cement Study



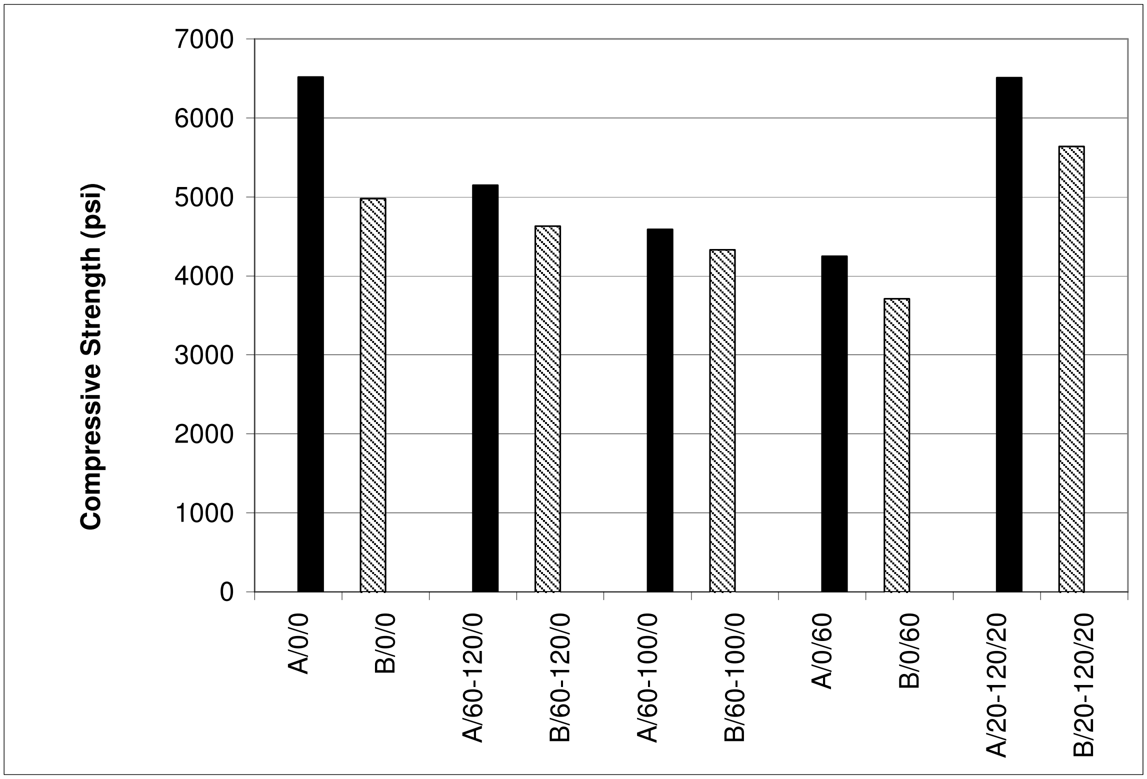
Compressive strength tests on the seventh day showed the cement A control mixture (A/0/0) had the greatest strength at 6520 psi. The cement A ternary mixture (A/20-120/20) had 0.1% less strength than the control mixture. The third greatest seven-day compressive strength was the cement B ternary mixture (B/20-120/20) that had 14% less compressive strength than the A/0/0 mixture. The cement B control mixture (B/0/0) and mixture A/60-120/0 were not statistically different. They had 23 and 21% less compressive strength than the A/0/0 mixture. The B/60-120/0, A/60-100/0, B/60-100/0, A/0/60, and B/0/60 mixtures had a range of seven-day compressive strengths of 4630 to 3710 psi. At this stage of the hydration process, it is once again obvious that the two cement sources were different in their level of strength gain, but had similar trends in compressive strength concerning the replacement rates.

The trends at seven-day compressive strength tests from the data and Chart 4.7 were as follows:

- cement A control mixture and the ternary mixtures (both cements) had the greatest compressive strengths,
- the order of greatest to least strength for 60% replacements of both cements was: GR 120 GGBFS, GR 100 GGBFS, then FA, and
- cement A strengths were not statistically different to the cement B strengths.

These trends were consistent with the literature (Section 2.2 and Section 2.3) that showed FA mixtures gained strength slower than GGBFS and 100% portland cement mixtures. GR 120 GGBFS had greater strength gain than the GR 100 GGBFS due to the increase in reactivity. The similar trends also show that the replacements of cement with the SCMs were similarly compatible with different cement sources.

Chart 4.7 Seven Day Compressive Strength Values for Cement Study

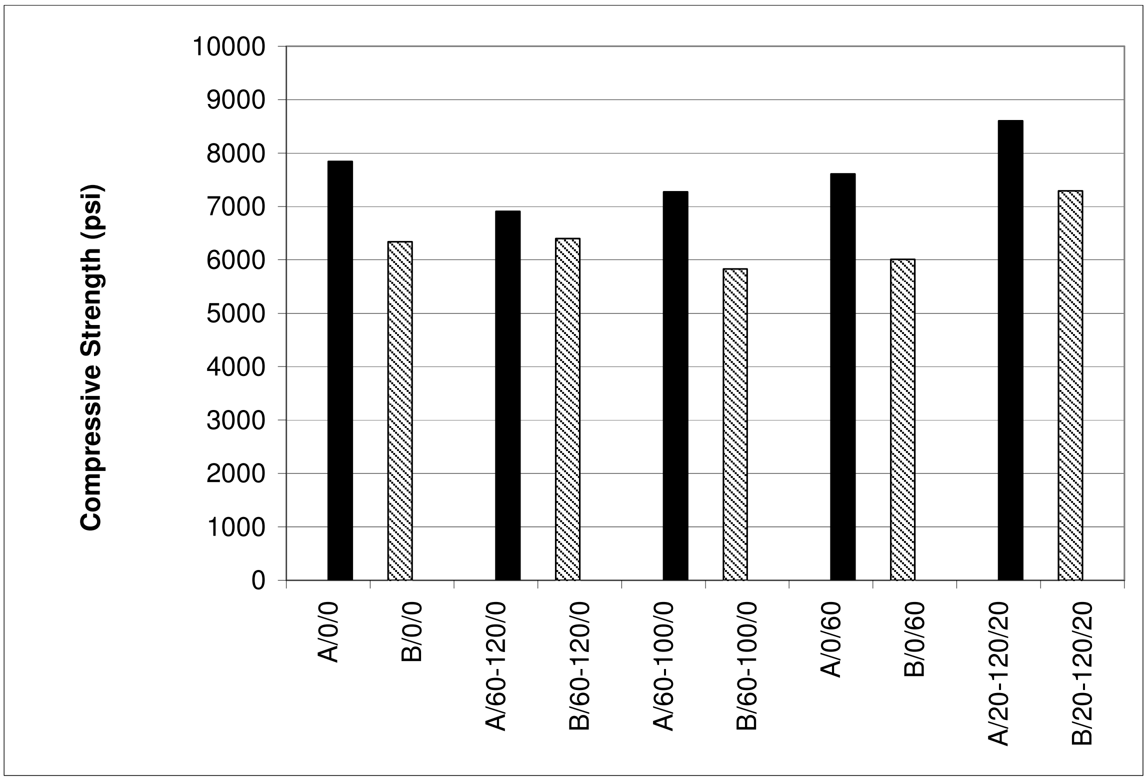


Twenty-eight day compressive strength results showed that the ternary mixtures gained more strength than the corresponding control mixture. The cement A ternary mixture, A/20-120/20, had the greatest twenty-eight day compressive strength at 8600 psi. The cement B ternary mixture, B/20-120/20, had the greatest twenty-eight day compressive strength of the cement B mixtures with 7290 psi but was 15% less than the A/20-120/0 mixture. The trends in the data and Chart 4.8 were observed as follows:

- the ternary mixtures had the highest strength for each type of cement,
- the cement A mixtures had higher strengths when compared to like cement B mixtures,

- for cement A mixtures containing 60% SCM the order of greatest to least strength was: FA, GR 100 GGBFS, then GR 120 GGBFS, and
- for cement B mixtures containing 60% SCM the order of greatest to least strength was: GR 120 GGBFS, FA, then GR 100 GGBFS.

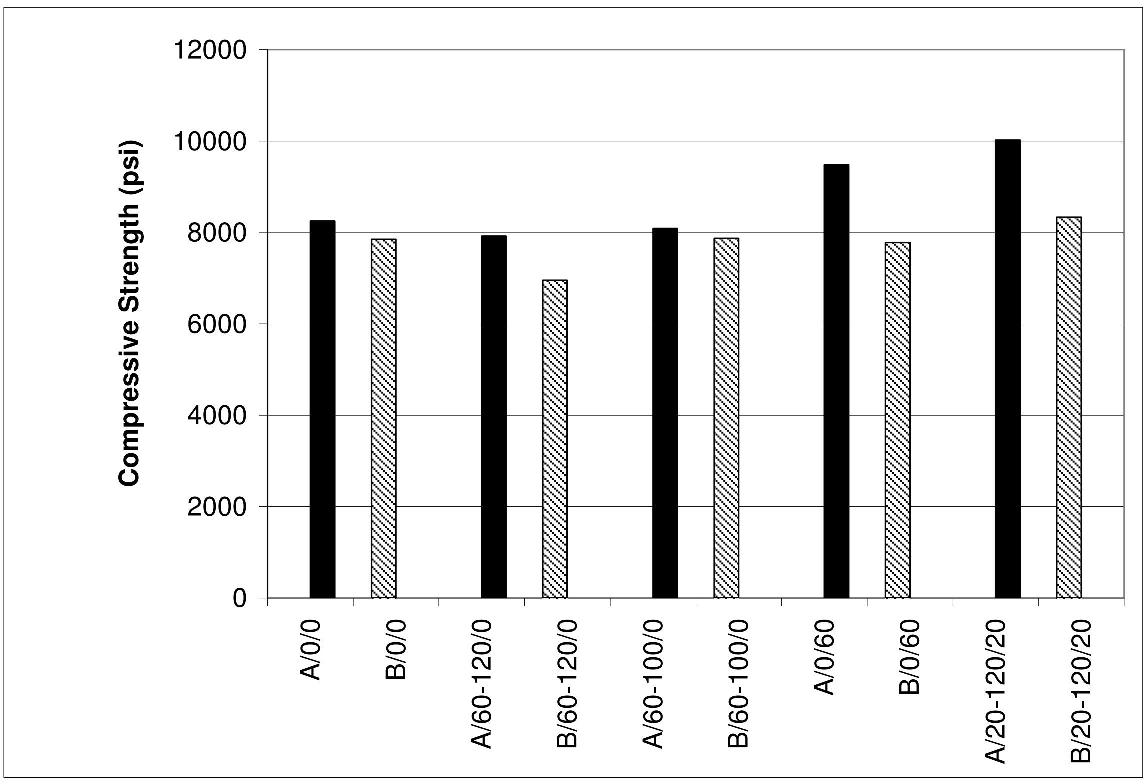
Chart 4.8 Twenty-eight Day Compressive Strength Values for Cement Study



The ternary mixture for cement A (A/20-120/20) had the greatest ninety-day strength with 10020 psi. The second highest compressive strength was A/0/60 with 9480 psi which was 5% less than the ternary mixture. The ternary mixture for cement B (B/20-120/20) had the highest ninety-day strength for cement B mixtures with 8330 psi. The B/20-120/20 mixture had 17% less compressive strength than the A/20-120/20 mixture. Cement A reacted better with the SCMs than cement B and produced higher strength at 90 days. The trends observed from the data and Chart 4.9 were as follows:

- the ternary mixtures had the highest strength for both types of cement,
- the order of greatest to least strength for 60% replacements of cement A was: FA, GR 100 GGBFS, then GR 120 GGBFS, and
- the order of greatest to least strength for 60% replacements of cement B was: GR 100 GGBFS, FA, then GR 120 GGBFS.

Chart 4.9 Ninety Day Compressive Strength Values for Cement Study



The cement study suggested that the two sources of cement did not create the same compressive strengths with the same replacement mixtures. They, however, had similar trends in mixtures with similar replacements of cement. The replacements of

SCM produced similar decreases in compressive strength in early tests and similar increases in compressive strength in ninety-day tests.

4.2.2.2 Rapid Chloride Ion Penetrability

The Rapid Chloride Ion Penetrability Test (RCPT) as described in Section 2.6.2 measured the permeability of the hardened concrete mixtures. The results from the test are shown in Table 4.3. Also shown in Table 4.3 is the permeability classification from ASTM C1202 based on the number of coulombs passed.

Table 4.3 RCIP and Freeze/Thaw Results for Cement Study

Mixture Design	RCPT 28 Days, coulomb	Chloride Ion Penetrability	RCPT 90 Days, coulomb	Chloride Ion Penetrability	Freeze/ Thaw Durability, DF
A/0/0	4265	High	3611	Moderate	2.32
A/60-120/0	937	Very Low	565	Very Low	23.08
A/60-100/0	480	Very Low	398	Very Low	0.6
A/0/60	2411	Moderate	1030	Low	18.99
A/20-120/20	1238	Low	735	Very Low	42.52
B/0/0	1568	Low	1442	Low	3.15
B/60-120/0	821	Very Low	669	Very Low	7.19
B/60-100/0	533	Very Low	341	Very Low	14.84
B/0/60	1236	Low	1436	Low	8.99
B/20-120/20	1473	Low	644	Very Low	4.53

At 28 days there was a noticeable difference in the permeability results of the two control mixtures. Results in Chart 4.10 and the statistical analysis show that the twenty-eight day permeability of the cement A control mixture was significantly greater than the cement B control mixture. The permeability of the cement B control mixture was less than the cement A control mixture. The A/0/0 mixture had higher compressive strength, higher unit weight, and lower air content, all of which suggests that it had formed a more dense structure than the B/0/0 mixture. Several factors that could override the theoretical basis for the accuracy of the RCPT were the relative resistances of the two cement sources and the microscopic saturation of the samples. Two trends were noticed between 28 day data and 90 day data. Mixture A/0/0 passed 4265 coulombs and had high permeability while mixture B/0/0 passed 1568 coulombs and had low permeability. Another trend in the data was that the 60% GR 100 GGBFS mixtures passed the least coulombs.

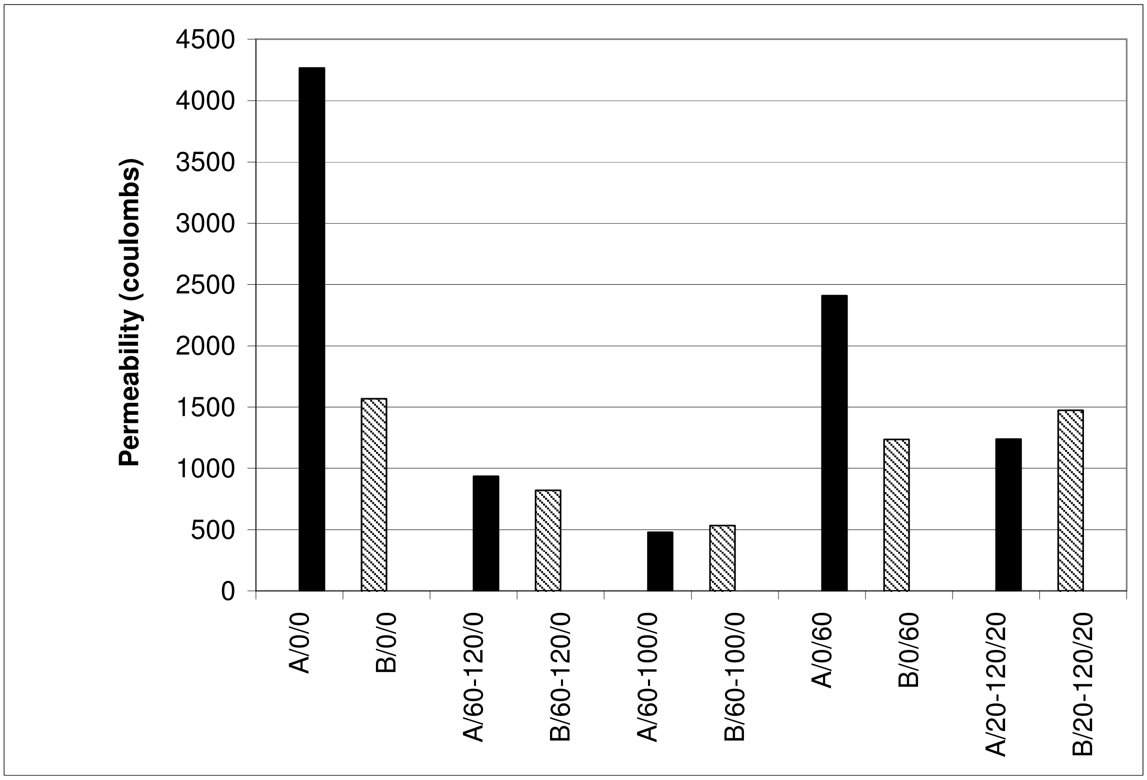
The addition of 60% GGBFS lowered the permeability of both the cement A and cement B control mixtures at 28 days by 48 to 89% when compared to their respective control mixtures. The mixtures with 60% GGBFS also saw reductions in permeability from the mixtures with 60% replacement of FA by 34 to 80%. Shi et al also found that GGBFS reduces permeability from a control mixture more than FA (Shi et al, 2003). The 60% GR 100 GGBFS mixtures also saw reductions in permeability of comparable replacements of GR 120 GGBFS by 35 to 48%. This could be because of the difference in reactivity between the SCMs. Even though the GR 120 GGBFS should produce better results than the GR 100, the different processing procedures, storage, source, and many other factors could lend better productivity to the GR 100 GGBFS. The manufacturers of the GR 100 GGBFS could also try to market their product as a GR 100/GR 120 GGBFS.

The trends observed from Chart 4.10 were as follows:

- the ternary mixtures , B/0/0, and A/0/60 low permeability,
- when compared to the control mixtures, the addition of GR 120 GGBFS reduced permeability, and

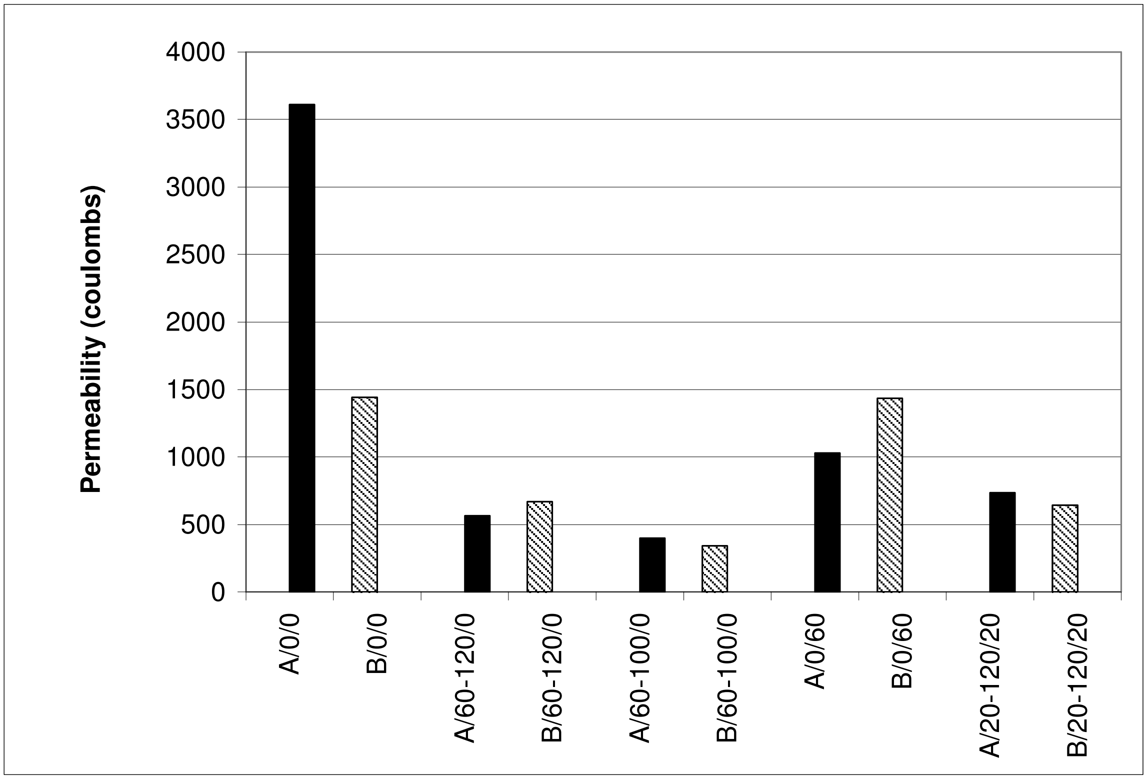
- mixtures containing GR 100 GGBFS passed fewer coulombs than like mixtures containing GR 120 GGBFS.

Chart 4.10 Twenty-eight Day Permeability Values for Cement Study



The ninety-day test results were lower than the twenty-eight day test results for all of the mixtures. The ninety-day permeability of cement A's control mixture was 2.5 times larger than the cement B control mixture. This trend was also observed at 28 days. Other cement A mixtures had 12 to 28% less permeability from the cement B mixtures. All mixtures containing GGBFS had not statistically different ninety-day permeability and were all also classified as having very low permeability by the ASTM 1202. The control and 60% FA mixtures had greater permeability, the ternary mixture had mid-range permeability, and the GGBFS mixtures had the lowest permeability, as shown in Chart 4.11.

Chart 4.11 Ninety Day Permeability Values for Cement Study

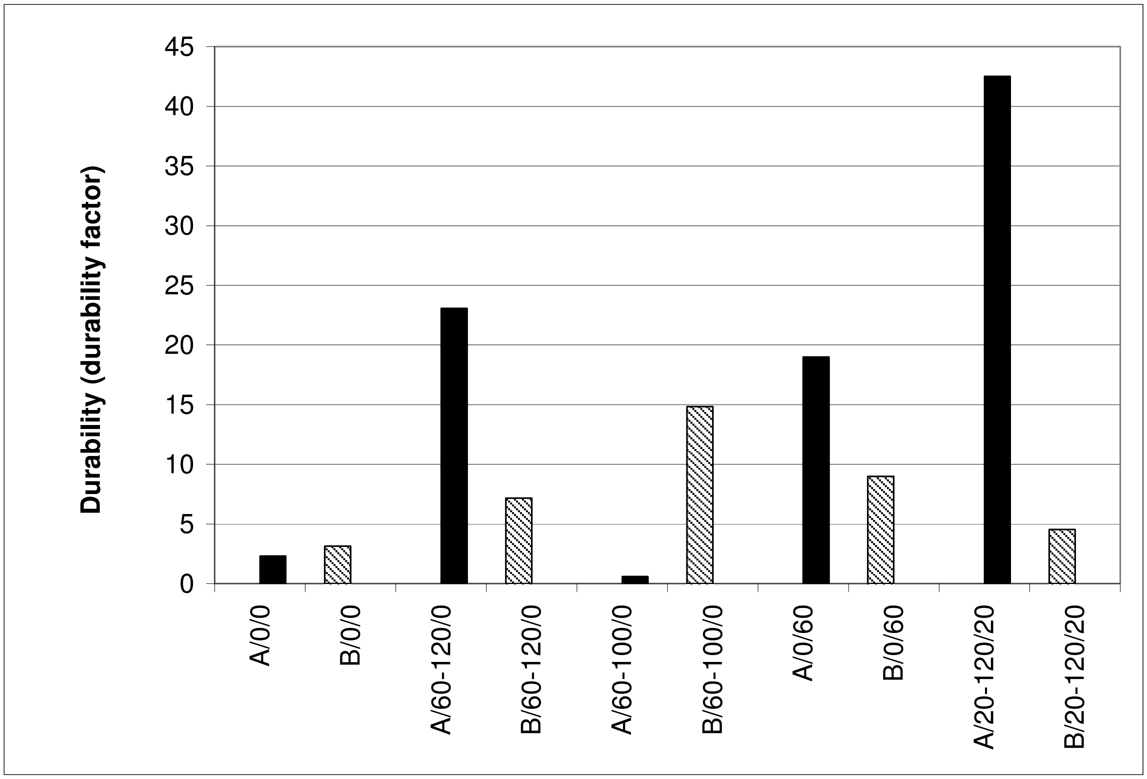


4.2.2.3 Freeze/Thaw Durability

The resonance frequency was monitored for each sample at each test and recorded as shown in Appendix A. The durability factor was determined from the last frequency recorded from each sample or near 300 cycles as per ASTM 666 (AASHTO T 161). Pictures of the freeze/thaw samples at end of testing or failure are shown in Appendix B. The results in Table 4.3 include the calculated durability factors of the concrete mixtures used in the cement study. The control mixtures, the 60% replacements of GR 120 GGBFS, the 60% replacements of GR 100 GGBFS, and the 60% replacements of FA for cement A and cement B were not statistically different for the comparable mixtures. Most researchers agree that a durability factor of 60 is adequate for freeze/thaw durability. The mixtures tested were not expected to reach a durability factor of 60 because they had no air entrainment. As described in Chapter 3, chemical admixtures were not added to the mixtures to observe the SCM's effects on the fresh and hardened properties without interference from chemical admixtures. The approximately 40 point difference between the ternary mixtures suggests that the testing of one of the groups of samples was not accurate.

The durability factors of the control mixtures were significantly similar to each other and were the lowest. The 60% replacements of GR 100 GGBFS were significantly similar and had the next smallest durability factor. The 60% replacements of FA were significantly similar and had the next higher durability factor. The 60% replacements of GR 120 GGBFS were marginally not statistically different, where the p-values in the LSMeans test were above but still very close to alpha of 0.05. The ternary mixtures were statistically different. The data and Chart 4.12 did not show a trend between the two sources of cement other than cement A mixtures had greater durability factors for three out of five mixtures.

Chart 4.12 Freeze/Thaw Durability Values for Cement Study



4.3 Supplementary Cementitious Material Study

The SCM study was designed to analyze the fresh and hardened properties of concrete mixtures with differing amounts of GGBFS, FA, or combinations of both materials. One source of Type I cement, a w/cm of 0.45, and no chemical admixtures were used in this study in order to determine the properties directly related to the change in SCMs. Twenty-two mixture designs were batched with cement A and correspond to the mixture designs in Section 3.6. The control mixture was made to the proportions described in Section 4.1.

4.3.1 Fresh Concrete Tests

The fresh concrete properties examined were slump, air content, concrete temperature, and unit weight. The values listed in Table 4.4 are the mean values of two batches as described in Section 3.9. The not statistically different groupings were based on the statistical analysis as described in Section 3.9.

Table 4.4 Fresh Concrete Properties for SCM Study

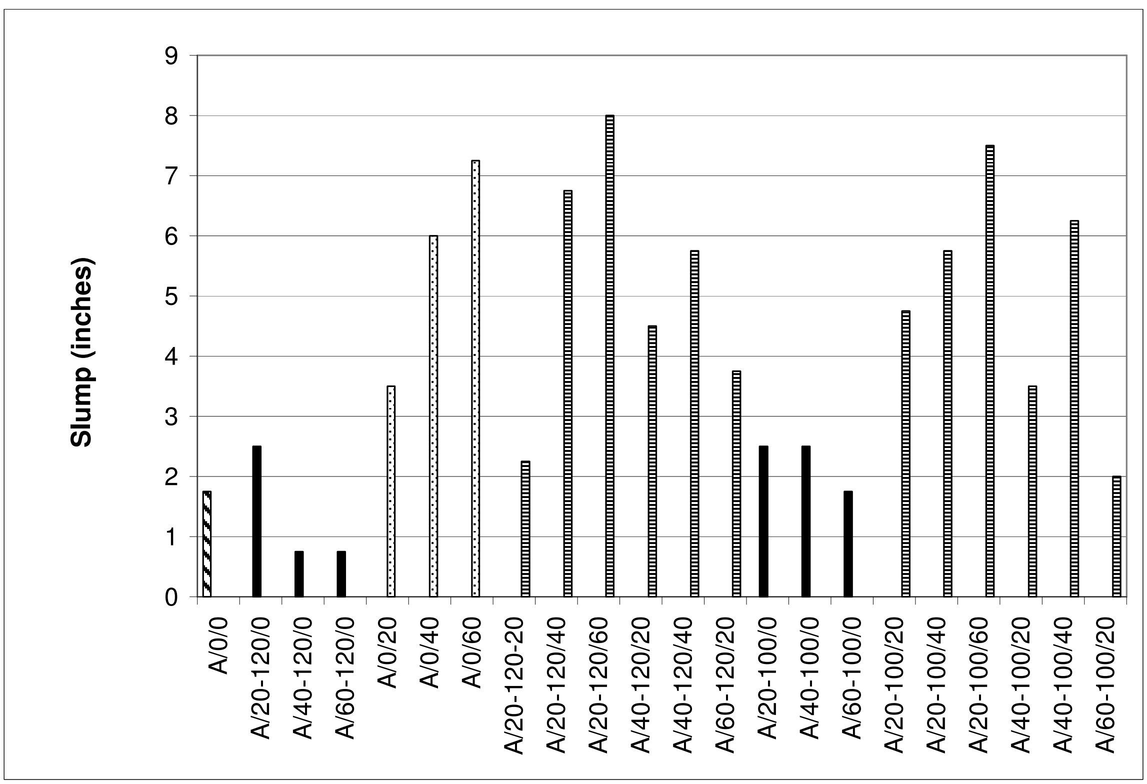
Mixture	Slump, in. (mm)	Unit Weight, lb/ft^3 (kg/m^3)	Air Content, %	Temperature, °F (°C)
A/0/0	1.75 (45)	151.5 (2426)	1.4	89.8 (32.1)
A/20-120/0	2.50 (65)	149.6 (2397)	1.5	81.8 (27.6)
A/40-120/0	0.75 (20)	150.5 (2410)	1.5	68.5 (20.3)
A/60-120/0	0.75 (20)	149.8 (2399)	1.6	72.5 (22.5)
A/0/20	3.50 (90)	150.3 (2408)	1.0	75.6 (24.3)
A/0/40	6.00 (150)	151.1 (2421)	0.9	74.0 (23.4)
A/0/60	7.25 (185)	150.6 (2413)	0.6	71.7 (22.1)
A/20-120/20	2.25 (60)	150.1 (2404)	1.5	67.4 (19.6)
A/20-120/40	6.75 (70)	150.8 (2416)	1.1	61.1 (16.2)
A/20-120/60	8.00 (205)	149.8 (2399)	0.5	61.0 (16.1)
A/40-120/20	4.50 (115)	149.1 (2388)	1.5	69.6 (20.9)
A/40-120/40	5.75 (205)	149.7 (2398)	1.1	81.5 (27.5)
A/60-120/20	3.75 (95)	149.2 (2390)	1.3	69.4 (20.8)
A/20-100/0	2.50 (65)	151.5 (2428)	1.6	82.4 (28.0)
A/40-100/0	2.50 (65)	149.5 (2395)	1.3	80.4 (26.9)
A/60-100/0	1.75 (45)	148.8 (2384)	1.5	83.0 (28.3)
A/20-100/20	4.75 (120)	150.5 (2412)	1.3	85.2 (29.6)
A/20-100/40	5.75 (145)	150.0 (2403)	0.8	77.0 (25.0)
A/20-100/60	7.50 (190)	150.1 (2405)	0.5	79.0 (26.1)
A/40-100/20	3.50 (90)	148.8 (2384)	1.2	84.0 (28.9)
A/40-100/40	6.25 (160)	149.5 (2395)	0.8	84.8 (29.3)
A/60-100/20	2.00 (50)	149.7 (2399)	1.4	76.5 (24.7)

4.3.1.1 Slump

The slump values recorded for the SCM study are listed in Table 4.4. The control mixture had one of the lowest slumps which was 1.75 in. The highest slumps were recorded in mixtures A/20-120/60, A/20-100/60, A/0/60, A/20-120/40, and A/40-100/40 with slumps ranging from 8 in. (190 mm) to 6.25 in. (158.75 mm), The mixtures with the lowest slumps were A/20-100/0, A/20-120/0, A/40-100/0, A/20-120/20, A/60-100/20, A/60-100/0, A/0/0, A/40-120/0, and A/60-120/0. These mixtures were not statistically different with slumps ranging from 2.5 in. (63. 5 mm) to 0.75 in. (19.05 mm), respectively. The trends observed from the data analysis and Chart 4.13 were as follows:

- the mixtures with high replacements of FA and low replacements of GGBFS had the greatest slumps,
- the mixtures with high replacements of GGBFS and low replacements of FA had the lowest slumps, and
- the mixtures with mid-range replacements of GGBFS or FA had mid-ranged slump values.

Chart 4.13 Slump Values for SCM Study



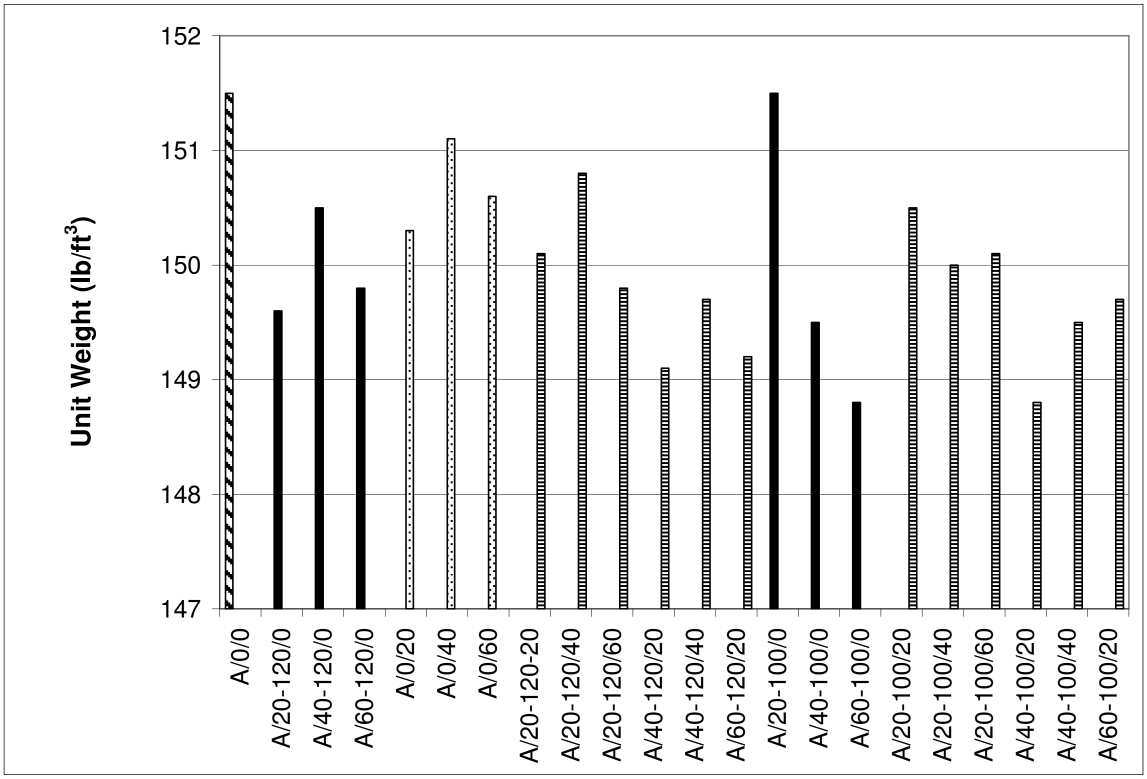
Trends from this study were consistent with the previous research that suggests that the addition of FA increases workability through the small, spherical particles

(Mindess et al. 2003). The literature also showed that the GGBFS would likely decrease slump from the control mixture because of the increase in surface area created by the finely crushed angular particles created when slag is ground to increase reactivity (Mindess et al. 2003). This study shows that the high replacements of FA will produce greater slump than comparable GGBFS mixtures. There was also not a large difference in slump at the 20% replacement level.

4.3.1.2 Unit Weight

The unit weight values are listed in Table 4.4 and shown in Chart 4.14. The unit weights ranged from 148.8 to 151.5 lb/ft^3. The unit weights did not follow a specific trend. The 20% replacement of GR 100 GGBFS had the highest unit weight and the 40% replacement of GR 100 GGBFS had a low unit weight while the opposite was found of the 20% and 40% replacements of GR120 GGBFS. Overall, the unit weights did not vary more than 2% from greatest to least.

Chart 4.14 Unit Weight Values for SCM Study



4.3.1.3 Air Content

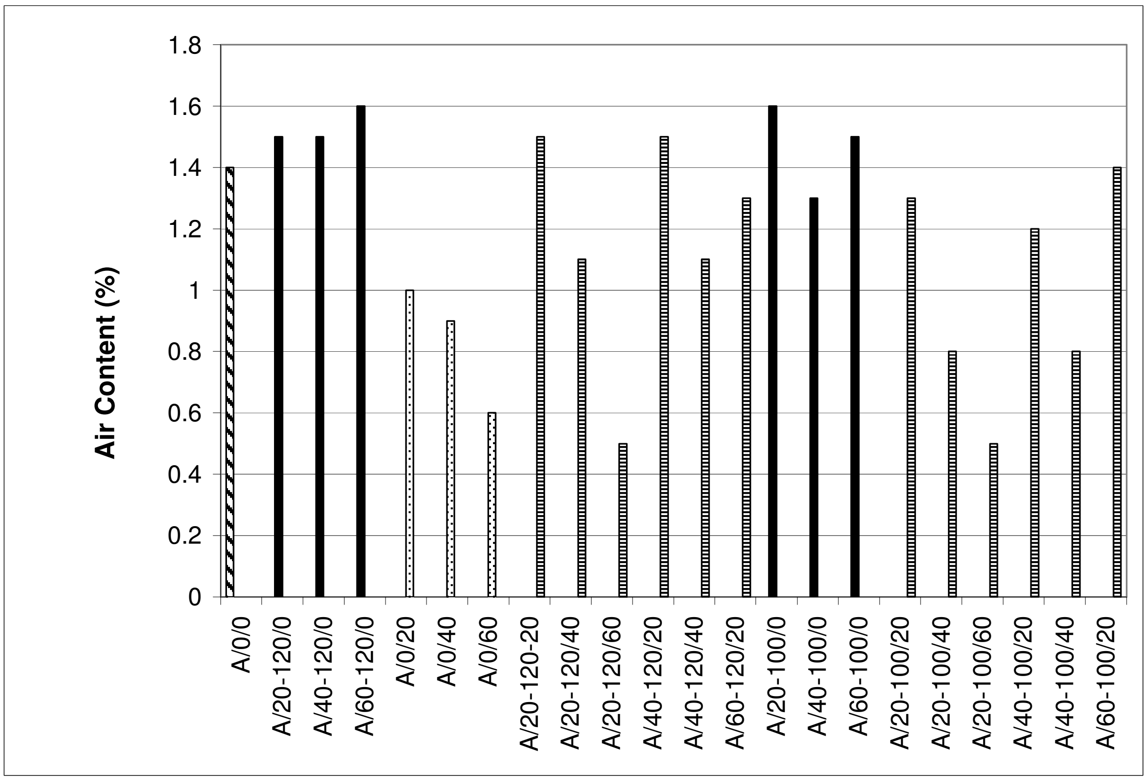
The air content values recorded for the SCM study are listed in Table 4.4. The air contents of these mixtures ranged from 0.5 to 1.6% with the majority of the mixtures having an air content between 1.0 and 1.5%. These mixtures did not contain an air-entraining admixture (AEA). This study was conducted without the use of AEA in order to reduce the likelihood of the AEA having an adverse reaction on the fresh and hardened properties as noted in Section 3.7.1 . Therefore, the air content in the concrete was the result of entrapped air and not entrained air. Mixtures without AEA normally entrap 0.5 to 3.0% air (Mindess et al 2003).

The trends observed in the data and Chart 4.15 were as follows:

- an increase in GGBFS content resulted in similar or higher air content, and

- an increase in FA reduced the air content.

Chart 4.15 Air Content Values for SCM Study

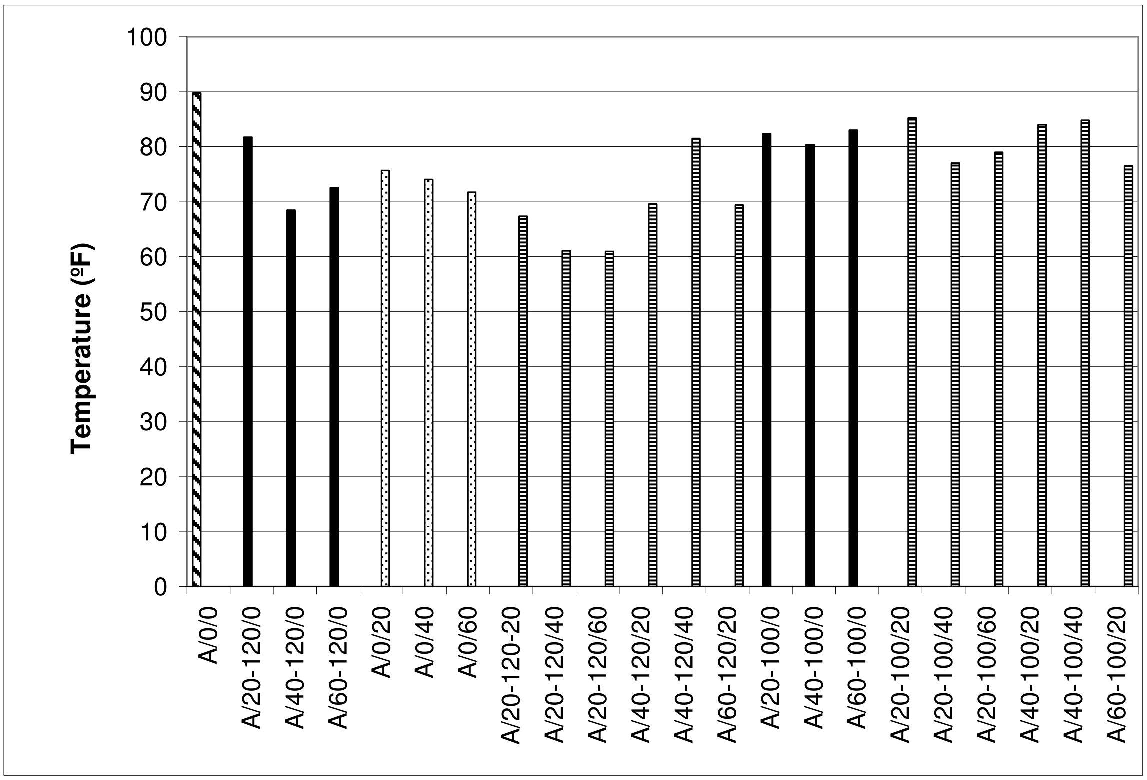


Reduction in air content with increases in FA content correlates with the increased workability observed in the FA mixtures. As discussed in the literature review section, both events could be directly related to the spherical shape of the FA particles. The smooth, round particles would allow entrapped air to easily escape; unlike the crushed and jagged particles of the cement and GGBFS that would entrap more air.

4.3.1.4 Concrete Temperature

The concrete temperature values recorded are listed in Table 4.4 and shown in Chart 4.16. As described in Section 4.2.1.3, the concrete temperature was only recorded as a quality control value. The temperatures ranged from 61.0°F (16.1°C) to 89.8°F (32.1°C).

Chart 4.16 Temperature Values for SCM Study



4.3.2 Hardened Concrete Property Tests

The hardened concrete tests performed for the SCM study were compressive strength, rapid chloride ion penetrability test (RCPT), and freeze/thaw durability. The values listed in Table 4.5 are the mean values of six samples for compressive strength of cement A samples as described in Section 3.9. The values listed in Table 4.6 are the mean values of four samples each for RCPT and freeze/thaw durability for cement

A samples as described in Section 3.9. The grouping was based on the statistical analysis as described in Section 3.9.

4.3.2.1 Compressive Strength

Table 4.5 Compressive Strength (psi) for SCM Study

Mixture Design	1 Day	3 Days	7 Days	28 Days	90 Days
A/0/0	2280	5290	6520	7840	8250
A/20-120/0	2050	4260	5730	7120	8380
A/40-120/0	1320	3920	5830	7660	8890
A/60-120/0	810	3130	5150	6910	7920
A/0/20	1230	4120	6340	7910	9030
A/0/40	900	3650	6110	8090	9270
A/0/60	160	1010	4250	7610	9480
A/20-120/20	1240	4230	6510	8600	10020
A/20-120/40	250	2070	4680	7890	10110
A/20-120/60	0	90	1160	4500	7480
A/40-120/20	1980	2740	4660	7150	8730
A/40-120/40	0	0	3310	5770	7490
A/60-120/20	0	1890	3790	6730	7630
A/20-100/0	1840	4020	5720	6370	8630
A/40-100/0	1240	3510	7270	8430	9150
A/60-100/0	710	2320	4590	7270	8090
A/20-100/20	1160	3740	6050	9030	10170
A/20-100/40	320	2110	3860	7030	9800
A/20-100/60	0	0	830	2840	6350
A/40-100/20	560	-	4240	8350	9910
A/40-100/40	0	890	1840	5000	7610
A/60-100/20	0	1200	3180	7350	8480

Compression test results for the SCM study are listed in Table 4.5. Some of the one day and three day results were recorded as zero because these mixtures had not achieved enough strength to be demolded or tested. These mixture designs produced very weak early strength concrete mainly due to the high percentage (80%) replacements of cement with the SCMs. As noted in Section 2.6.1, the 80%

replacement of cement with GGBFS and FA reduced the early age strength of the concrete (Mindess et al. 2003).

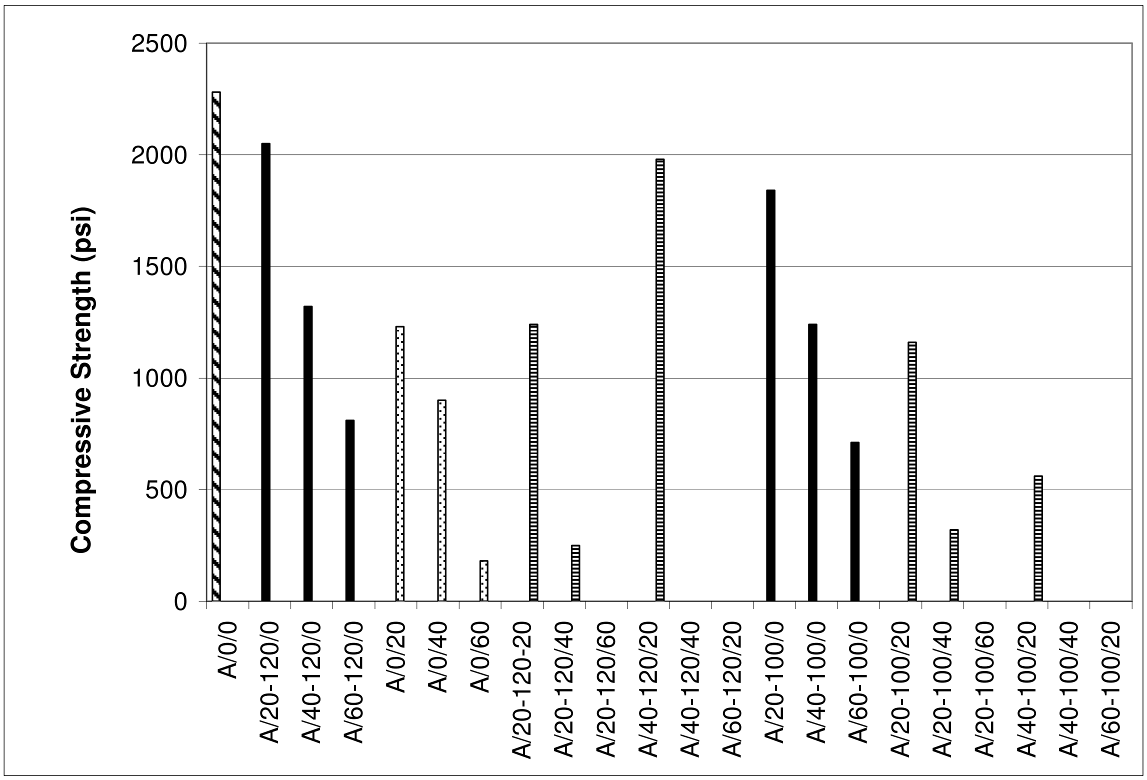
The one day control mixture (A/0/0) strengths were significantly higher than the mixtures with cement replacement. This trend follows the literature mentioned in Section 2.6.1. The second greatest strengths were mixtures A/20-120/0, A/40-120/20, and A/20-100/0 with a maximum difference of 440 psi from the control mixture. Small replacements (20%) of GGBFS had greater one-day strengths than the 20% FA mixtures and mixtures with greater than 20% SCM. At 1 day, the compressive strengths of mixtures with 40% GGBFS were not statistically different from the 20% FA mixtures. This shows that, for early age strength, a 40% replacement of GGBFS has a similar reduction in strength as 20% replacement of FA. The next to lowest mixtures were A/0/60, A/20-120/40, A/20-100/40, A/40-100/20, A/60-100/0, A/60-120/0, and A/0/40 with strengths ranging from 160 to 900 psi. These mixtures contained 60% SCM. The mixtures with the lowest one day strength of zero were A/60-120/20, A/20-120/60, A/20-100/60, A/40-120/40, A/40-100/40, and A/60-100/20. Theses mixtures contained 80% SCM and resulted in the least strength gain. The one-day compressive strength trends were observed as follows:

- the 100% cement mixture had the highest strength,
- the 20% GGBFS mixtures had higher strength than the 20% FA,
- the 20% FA, 40% FA, and 40% GGBFS mixtures had mid-range compressive strengths,
- 60% replacement of both SCM had lower strengths than the 20 to 40% replacements,

- the 80% replacements of cement had the lowest strength, and
- each 20% increase in replacement of either GGBFS or FA resulted in lower compressive strength (except the A/40-120/20 mixture).

The trend described was consistent with the literature for replacements of cement as discussed in Section 2.6.1.

Chart 4.17 One Day Compressive Strength Values for SCM Study

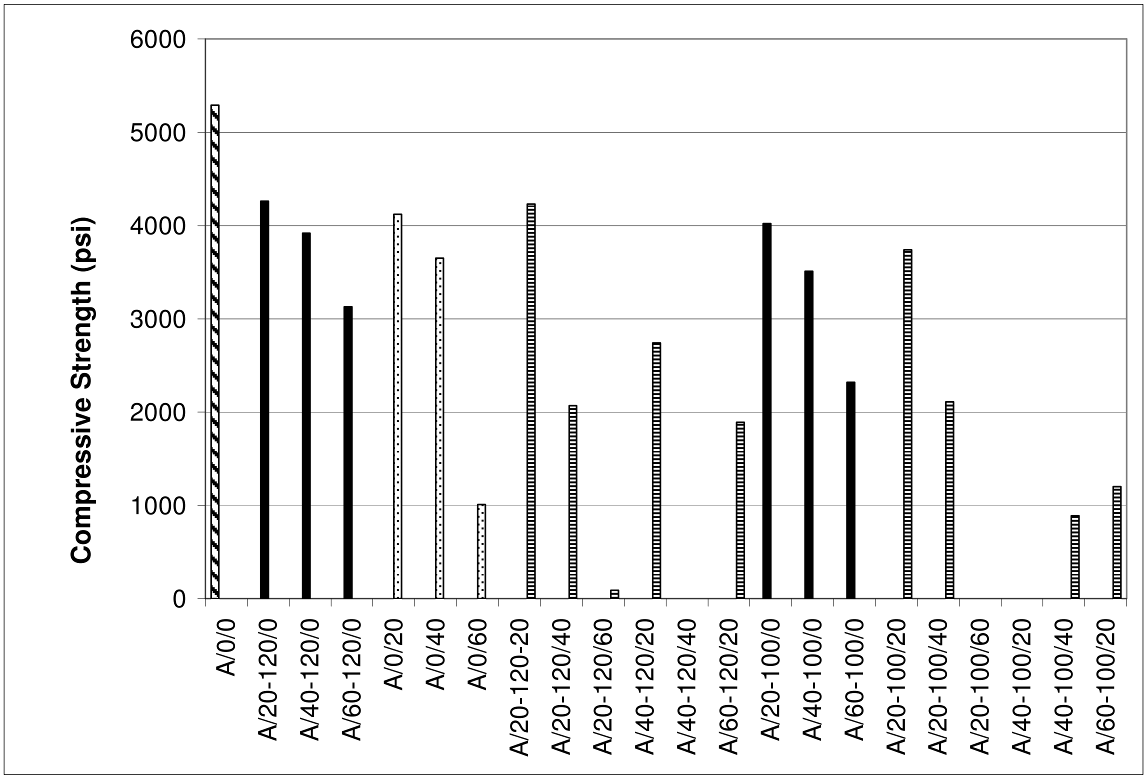


Three-day compressive strength values are listed in Table 4.5 except for the A/40-100/20 mixture. The six compressive strengths were not recorded for A/40-11/20. The highest three-day compressive strength was the control mixture (A/0/0) with a compressive strength of 5290 psi. The second highest three-day compressive strengths were recorded for A/20-120/0, A/0/20, A/20-120/20, and A/20-100/0 with compressive strengths ranging from 4260 to 4020 psi respectively. The next grouping of compressive strengths included A/40-120/0, with a compressive strength of 3920 psi, and A/20-100/20, with a compressive strength of 3740 psi. The smaller replacements of cement with SCM also had up to 80% of the three-day strength of the control mixture (100% portland cement). The exception to this trend was the ternary mixture A/20-120/20. This mixture has 40% total replacement but was statistically grouped within the 20% replacement mixtures and not with the next lower strength grouping of 40% replacements. The not statistically different grouping of the second lowest compressive strength included A/0/60 and A/40-100/40. The lowest three-day compressive strengths were recorded for mixtures A/40-120/40, A/20-120/60, and A/20-100/60. Two of which were not strong enough to be removed from the molds and the other had less than 100 psi. The trends in the three-day compressive strength test from the data and Chart 4.18 were observed to be as follows:

- the 100% cement mixture had the highest strength,
- the 20% replacements of SCM and the 20% GR 120 GGFBS/20% FA ternary mixtures had greater strengths than the other 40% replacements,
- each 20% increase in replacement of GGBFS or FA resulted in lower strength.

The trend for the three day compressive strength test was consistent with the literature as described in Section 2.6.1 except that the 20% GR 120 GGFBS/20% FA mixture had similar strength to the 20% replacements, not the 40% replacements.

Chart 4.18 Three Day Compressive Strength Values for SCM Study

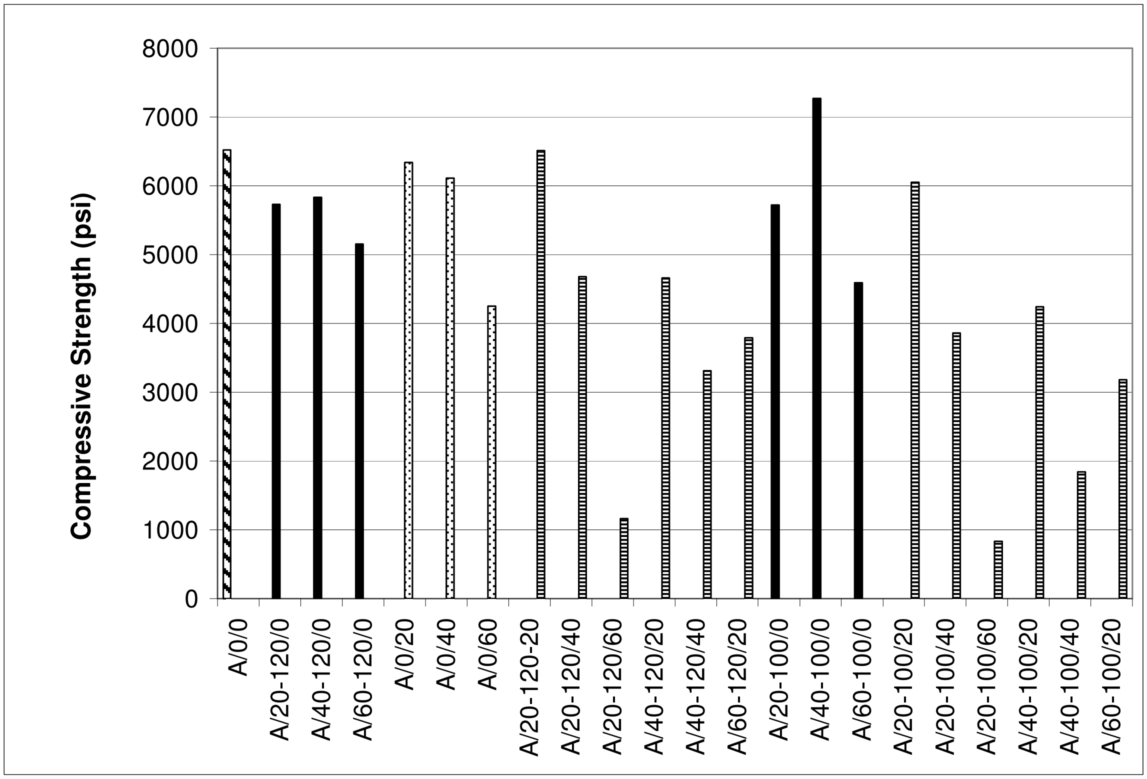


The statistically greatest compressive strength for one-day and three-day compressive strength was the 100% cement control mixture, but the seven-day compressive strength of mixture A/40-100/0 was the highest. The A/40-100/0 mixture was statistically different to the second highest compressive strength mixture, the control (A/0/0). The second grouping of not statistically different mixtures included A/0/0, A/20-120/20, A/0/20, and A/20-100/20 with compressive strengths of 6520 to 6050 psi respectively. The next group of mixtures with not statistically different compressive strengths included A/20-120/0, A/20-100/0, A/0/40, and A/60-120/0. The mixtures with the least seven-day compressive strengths were A/20-100/60, A/20-120/60, A/40-120/40. The trends in the seven-day compressive strength test were observed to be as follows from the data and Chart 4.19:

- the 100% cement mixture no longer had the highest strength,
- the 20/20 ternary mixtures and the 20% FA mixture had greater strength than the control mixture,
- mixtures containing 60% SCM (ternary mixtures and FA only or GGBFS only mixtures) ranged from 3860 to 5120 psi compared to 6520 psi for the control mixture,
- mixtures containing 40 % SCM (ternary mixtures and FA only or GGBFS only mixtures) ranged from 5830 to 7270 psi compared to 6520 psi for the control mixture,
- ternary mixtures containing 80% SCM had the lowest compressive strength, and
- the lowest compressive strength (mixture A/20-100/60) was 11% of the highest compressive strength.

At seven days of age mixtures SCM were achieving compressive strengths that were approaching, if not surpassing, the strength of the control mixture.

Chart 4.19 Seven Day Compressive Strength Values for SCM Study



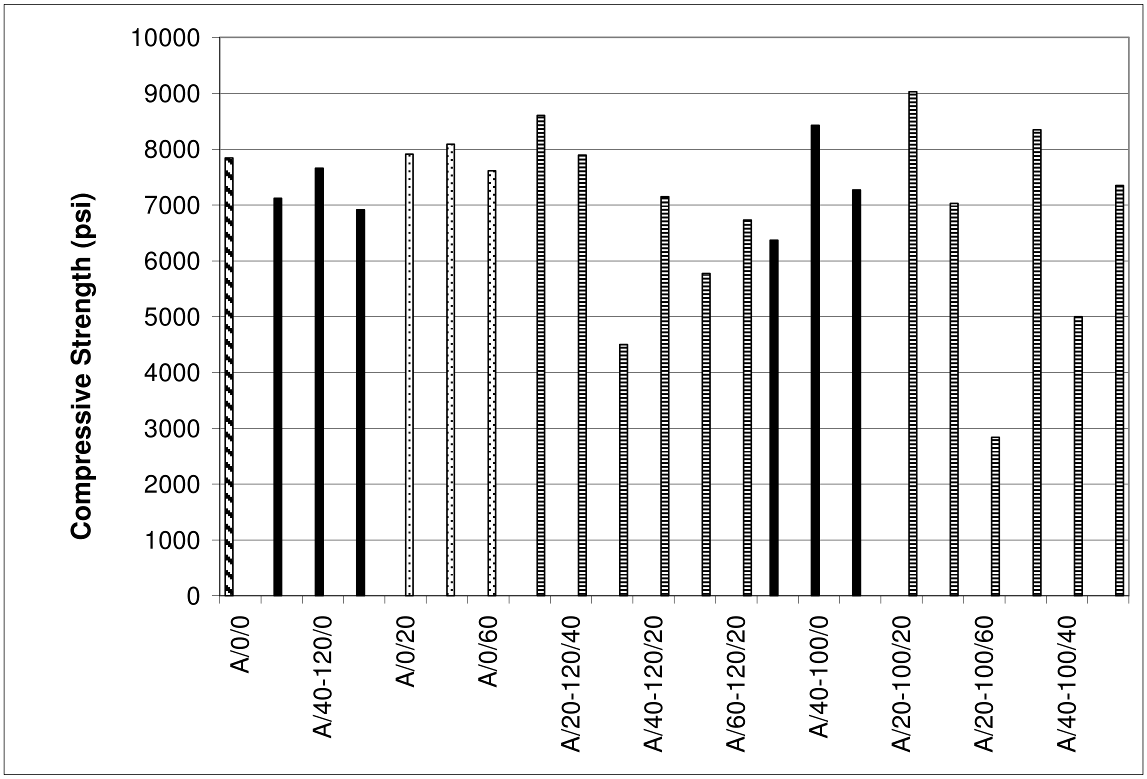
Mixtures with the greatest twenty-eight day compressive strength were A/20-100/20, A/20-120/20, A/40-100/0, and A/40-100/20, with values ranging from 9030 to 8350 psi. The grouping with the second highest twenty-eight day compressive strength included A/0/40, A/0/20, A/ 20-120/40, and A/0/0 with values ranging from 8090 to 7840 psi . The third group of mixtures included A/60-120/0, A/60-120/20, and A/40-120/40 with compressive strengths of 6910 to 5770 psi. The final group included A/40-100/40, A/20-120/60, and A/20-100/60 with compressive strengths of 5000 to 2840 psi. The trends in the data and Chart 4.20 were observed as follows:

- the 20% GGBFS and 20% FA ternary mixtures (for both grades of GGBFS) had the highest strength,

- about half of the mixtures made with GR 100 GGBFS had greater strength than like mixtures with GR 120 GGBFS,
- seven mixtures (including two 60% SCM mixtures) achieved higher twenty-eight day strengths than the control mixture,
- the data did not follow as distinct of a pattern for 20%, 40%, and 60% replacements of cement or for GGBFS vs. FA replacements as the seven day results,
- the 80% replacement mixtures had the lowest compressive strengths, (except for the A/60-100/20 mixture) and
- mixture A/20-100/60 had the lowest twenty-eight day strength, which was 44% of the control mixture.

The twenty-eight day compressive strength results show that a less definite range separated the 100% cement, GGBFS, FA, and ternary mixtures after early age strength tests. The trend of the replacement mixtures having greater later strength than the 100% cement mixture followed the literature as described in Section 2.6.1.

Chart 4.20 Twenty-eight Day Compressive Strength Values for SCM Study



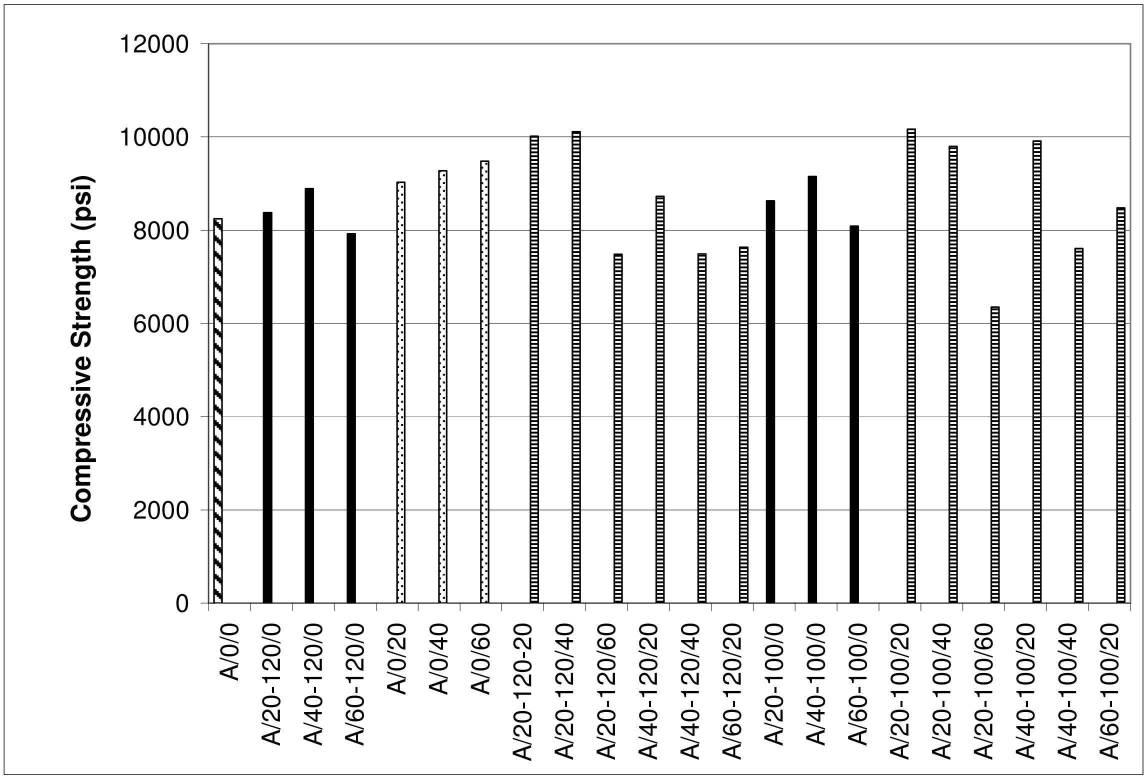
Mixture designs with the highest ninety-day compressive strengths were A/20-100/20, A/20-120/40, A/ 20-120/20, A/40-100/20, and A/20-100/40 with strengths ranging from 10170 to 9800 psi. The second highest strengths were mixtures A/0/60, A/0/40, and A/40-100/0 with ninety-day compressive strengths of 9480 to 9150 psi. The third group included A/60-120/20, A/40-100/40, A/40-120/40, and A/20-120/60 with strengths of 7630 to 7480 psi. The final group included mixture A/20-100/60 with 6350 psi. The trends observed in the ninety-day compressive strength data and Chart 4.21 were as follows:

- the control mixture, which had the highest one day strength, was in the bottom third at ninety days,

- the ternary mixtures with 20% GGBFS and 20 or 40% FA were in the top ¼ of the strengths measured,
- the 20% FA mixture had greater strength than the 20% GGBFS mixtures,
- 88% mixtures made with GR 120 GGBFS or with GR 100 GGBFS had higher strength when made with GR 100 GGBFS, and
- the 80% replacements with 40 and 60% replacements of FA had the lowest compressive strengths.

This trend was also consistent with the literature discussed in Section 2.6.1. The mixtures with SCM were observed to have higher strength than the control mixture in replacements up to 80%. The very high replacements (80%) with SCM possibly had less late age strength because of the lack of calcium hydroxide produced in the first reaction of the cement and water because of less cement in the mixture (as described in Section 2.7.3).

Chart 4.21 Ninety Day Compressive Strength Values for SCM Study



4.3.2.2 Rapid Chloride Ion Penetrability

The permeability of the hardened concrete mixtures was measured by the Rapid Chloride Ion Penetrability Test (RCPT) as described in Section 2.6.2. The results from the test are shown in Table 4.6. Also shown in Table 4.6 is the permeability classification based on the number of coulombs passed.

Table 4.6 Hardened Concrete Property Tests for SCM Study

Mixture	RCPT 28 Days, coulombs	Chloride Ion Penetrability	RCPT 90 Days, coulombs	Chloride Ion Penetrability	Freeze/ Thaw Durability, DF
A/0/0	4265	High	3611	Moderate	2
A/20-120/0	2442	Moderate	1433	Low	24
A/40-120/0	1719	Low	630	Very Low	23
A/60-120/0	937	Very Low	565	Very Low	23
A/0/20	4142	High	1477	Low	8
A/0/40	2079	Moderate	991	Very Low	10
A/0/60	2411	Moderate	1030	Low	19
A/20-120/20	1238	Low	735	Very Low	43
A/20-120/40	1639	Low	817	Very Low	16
A/20-120/60	3104	Moderate	495	Very Low	9
A/40-120/20	540	Very Low	642	Very Low	14
A/40-120/40	331	Very Low	420	Very Low	19
A/60-120/20	507	Very Low	357	Very Low	1
A/20-100/0	1957	Low	701	Very Low	10
A/40-100/0	1035	Low	625	Very Low	6
A/60-100/0	480	Very Low	398	Very Low	1
A/20-100/20	1235	Low	866	Very Low	1
A/20-100/40	3352	Moderate	867	Very Low	6
A/20-100/60	6124	High	1162	Low	2
A/40-100/20	824	Very Low	328	Very Low	23
A/40-100/40	1128	Low	337	Very Low	27
A/60-100/20	265	Very Low	342	Very Low	6

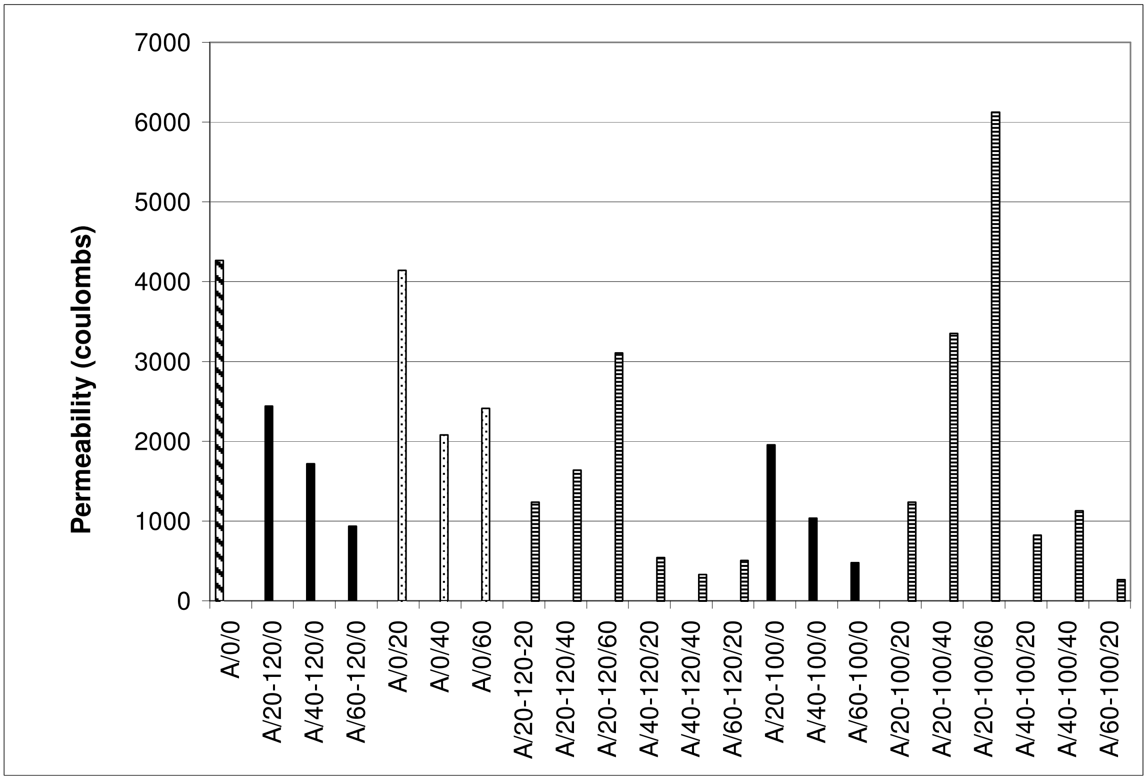
The group of mixtures with the highest twenty-eight day chloride ion penetrability included A/20-100/60, A/0/0, A/0/20, and A/20-100/40 with 6124 to 3352 coulombs passed. The next highest permeability mixtures included A/20-120/60 and A/20-120/0 with 3104 and 2442 coulombs. This range of mixtures decreased the permeability of the control mixture by 27% to 43%. The mixtures with the next to lowest chloride ion penetrability were A/40-100/40, A/40-100/0, A/40-120/20, A/60-120/0, and A/40-100/20 with coulombs passed of 1128 to 824. These mixtures lowered the permeability of the control mixture by 74% to 81%. The mixtures with the lowest twenty-eight day chloride ion penetrability were A/40-120/20, A/40-120/40, and A/60-100/20 with coulombs passed of 507 to 265. These mixtures lowered the permeability of the control by 88% to 94%.

The 20%, 40%, and 60% replacements of GR 120 GGBFS decreased the permeability 43%, 60%, and 78% from the control mixture. 20% FA decreased the permeability 3% from the control mixture and the 40% and 60% replacements of FA reduced the permeability by approximately 50% when compared to the control mixture. The 20%, 40%, and 60% replacements of GR 100 GGBFS decreased the permeability 54%, 76%, and 89% from the control mixture. The ternary mixtures with 20% of GGBFS (either grade) showed an increase in permeability for each additional 20% of FA replacement. The ternary mixtures with 20% FA show a decrease in permeability for each additional 20% of either grade GGBFS. The trends observed from the twenty-eight day RCPT and Chart 4.22 were as follows:

- the 100% cement mixture had the second highest permeability,
- the mixtures that passed more coulombs, and therefore were considered as having higher permeability, had 0 to 20% replacements of both GR 100 and GR 120 GGBFS and a range of replacements of FA,
- each 20% increase in replacement of GGBFS lowered the permeability,
- each 20% increase in replacement of FA to ternary mixtures increased permeability,
- the mixtures with low permeability had 40 to 60% replacements of both grades of GGBFS and a range of FA replacement, and

- higher replacements of GGBFS had a lowering effect on permeability unlike higher replacements of FA at twenty-eight days.

Chart 4.22 Twenty-eight Day Permeability Values for SCM Study

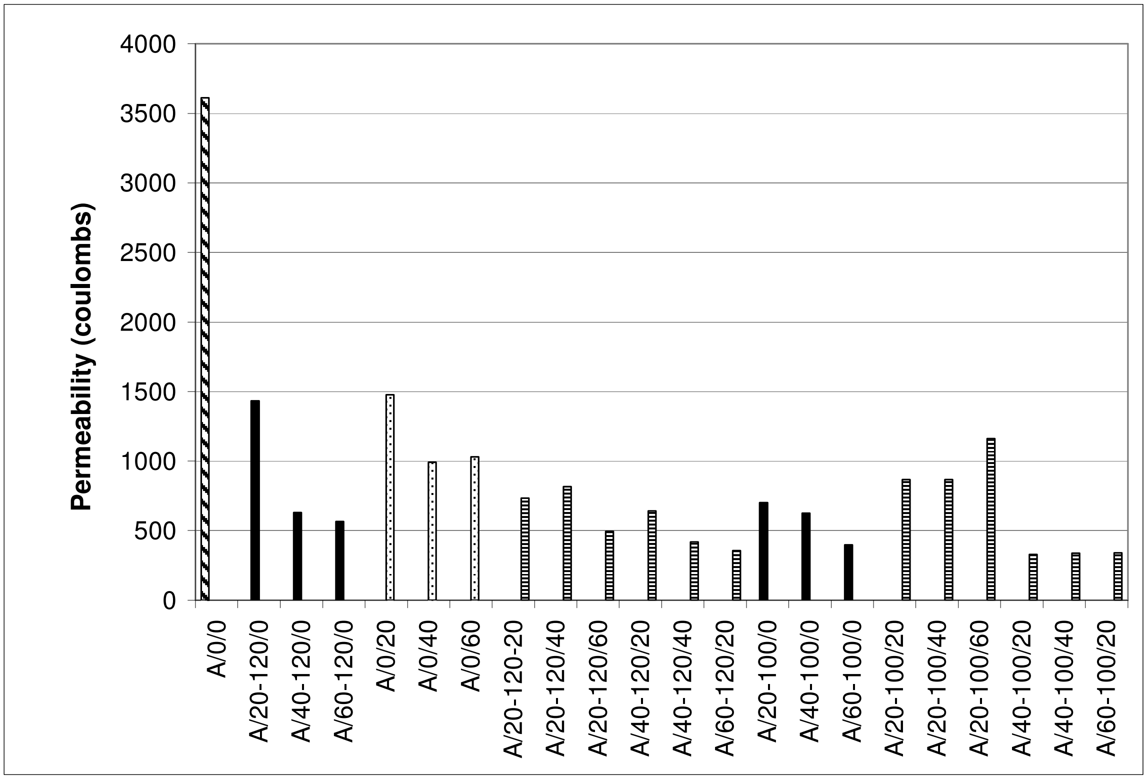


Mixture A/0/0 had the highest ninety-day chloride ion penetrability. The control mixture passed 3611 coulombs. Mixtures A/0/20, A/20-120/0, A/20-100/60, and A/0/60, with coulombs passed ranging from 1477 to 1030, decreased the permeability of the control mixture by 59% to 71%. The third group of mixtures included A/0/40, A/20-100/0, A/20-100/40, A/20-100/20, and A/20-120/20 with coulombs passed of 991 to 735. This group reduced the permeability of the control mixture by 73% to 80%. The fourth group included A/40-120/20, A/40-100/0, A/60-120/0, A/20-120/60, and A/60-100/0 with coulombs passed of 642 to 398. These mixtures reduced the permeability of the control mixture by 82% to 89%. The mixtures with the lowest permeability were A/40-120/40, A/60-120/20, A/60-100/20, A/40-100/40, and A/40-100/20 with coulombs passed of 369 to 328. This group of mixtures lowered the permeability of the control mixture by 90% to 91%.

Adding 20% SCM (GR100 GGBFS, GR 120 GGBFS, or FA) reduced the permeability approximately 60 to 70% from the control mixture. An additional 20% of FA or GGBFS (to make 40 % FA, 40% GGBFS or 20/20 ternary mixtures) reduced the permeability by 72 to 82% from the control mixture. Replacements with 60 to 80% SCM lowered the permeability up to 90% form the control mixture at 90 days. Therefore, the greatest improvement (60%) was observed within the first 20% SCM mixtures and an additional 10 to 20% reduction was observed with up to 40% SCM mixtures. SCM replacements greater than 40% only reduced the permeability at 90 days by a maximum of 10% more than the 40% mixtures, which does not represent a great benefit. The ninety-day permeability trends were observed to be as follows from the data and Chart 4.23:

- the 100% cement mixture had moderate permeability,
- the mixtures with the highest ninety-day permeability had 0 to 20% replacements of GGBFS and 40% to 60% replacements of FA,
- the mixtures with the lowest ninety-day permeability had 40% to 60% replacements of GGBFS and 20% to 40% replacements of FA, and
- the ninety-day permeability trends were not as clearly defined between the different combinations of replacements as the twenty-eight day permeability trends.

Chart 4.23 Ninety Day Permeability Values for SCM Study



Overall trends were observed as follows:

- the control mixture dropped one level of permeability (high to moderate) from twenty-eight day tests to ninety-day tests,
- 27% of the mixtures did not change permeability level from 28 to 90 days because they were classified as very low permeability at 28 days,
- 50% of the mixtures lowered one level of permeability from 28 to 90 days,
- 23% of the mixtures lowered two levels of permeability from 28 to 90 days,
- each 20% addition of GGBFS replacement lowered the 28 and ninety-day permeability one level,

- the replacement of 20% FA did not lower the twenty-eight day permeability but lowered the ninety-day permeability by one level,
- the replacement of 40 and 60% FA lowered the 28 and ninety-day permeability by one level,
- the ternary mixtures decreased the twenty-eight day permeability by at least 1 level, with the exception of the A/20-100/60 mixture, and
- the ternary mixtures decreased the ninety-day permeability by two levels (to very low), with the exception of the A/20-100/60 mixture.

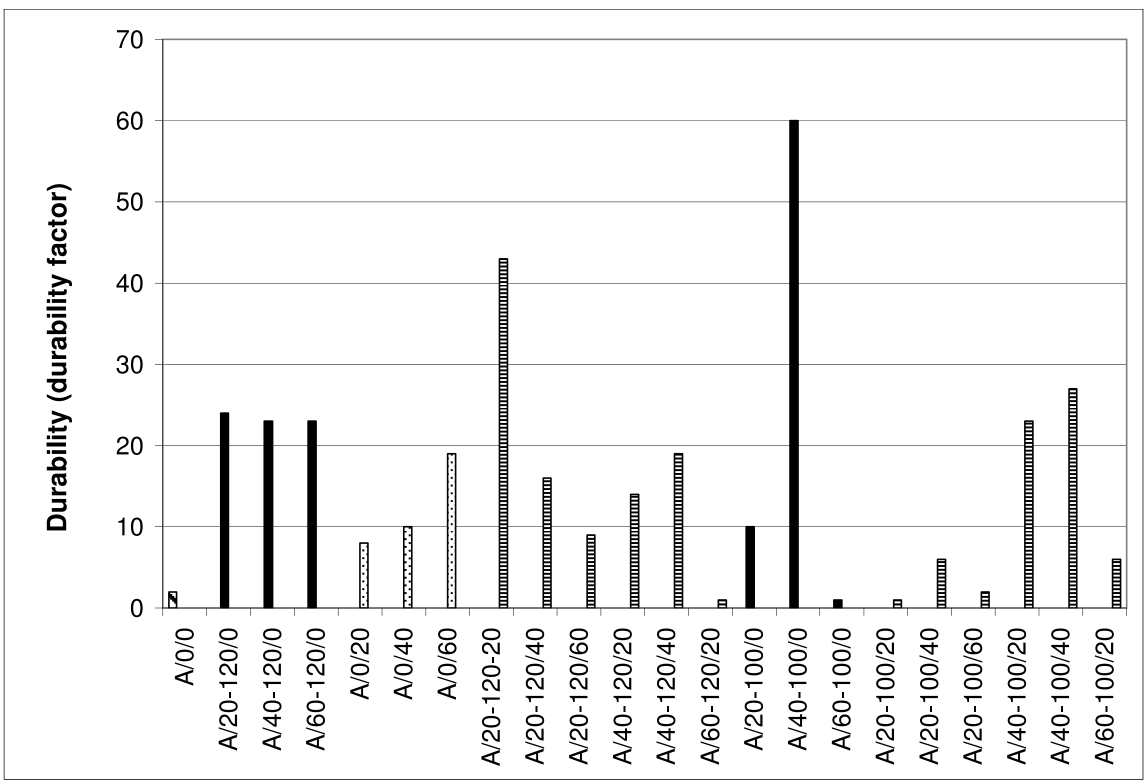
4.3.2.3 Freeze/Thaw Durability

The resonance frequency was monitored for each sample at each test and recorded as shown in Appendix A. The durability factor was determined from the last frequency recorded from each sample as per ASTM 666 (AASHTO T 161). Pictures of the freeze/thaw samples at end of testing or failure are shown in Appendix B. The mixtures with the lowest durability factors, representing the mixtures with the lowest durability, were A/60-120/20, A/60-100/0, A/20-100/20, A/0/0, A/20-100/60, A/40-100/0, A/20-100/40, and A/60-100/20. These mixtures had durability factors of 1 to 6. The mixtures with the highest durability factors were A/40-100/20, A/40-120/0, A/60-120/0, A/20-120/0, A/40-100/40, and A/20-120/20 with durability factors of 23 to 43. The addition of GGBFS increased the durability factor from the control mixture twelve fold. The 20% FA replacement increased the durability of the control mixture by a factor of 4. The 40% FA replacement increased the durability of the control mixture by a factor of 5. And the 60% FA replacement increased the durability of the control mixture by a factor of 9.5. The ternary mixture of 20% replacement of GR

120 GGBFS and 20% replacement of FA had the highest durability factor of 43. The trends observed from the data and Chart 4.24 were as follows:

- the durability factors of the GR 100 GGBFS mixtures were less than GR 120 GGBFS mixtures for all but two like mixtures,
- the durability factors of the GR 120 GGBFS mixtures were similar to each other,
- each 20% increase in FA replacement increased the durability factor in FA only mixtures, and
- 20% increase in FA decreased the durability factor in ternary mixtures.

Chart 4.24 Freeze/Thaw Durability Values for SCM Study



4.4 Ground Granulated Blast Furnace Slag Study

The purpose of the GGBFS study was to determine if differences in GR 100 and GR 120 GGBFS affects concrete performance. The two grades came from different locally available sources and may have different properties because of the raw material source, refinement process, and quality control standards. The fresh and hardened properties of mixtures made with GR 100 GGBFS were compared to the mixtures made with GR 120 GGBFS. Nine mixtures were batched with each grade of GGBFS as discussed in Section 3.6. The control mixture design was made as described in Section 4.1.

4.4.1 Fresh Concrete Tests

The fresh concrete tests performed for the GGBFS study were slump, air content, concrete temperature, and unit weight. The values listed in Table 4.7 are the mean values of two batches for each grade of GGBFS as described in Section 3.9. The grouping was based on the statistical analysis as described in Section 3.9.

Table 4.7 Fresh Concrete Tests for Ground Granulated Blast Furnace Slag Study

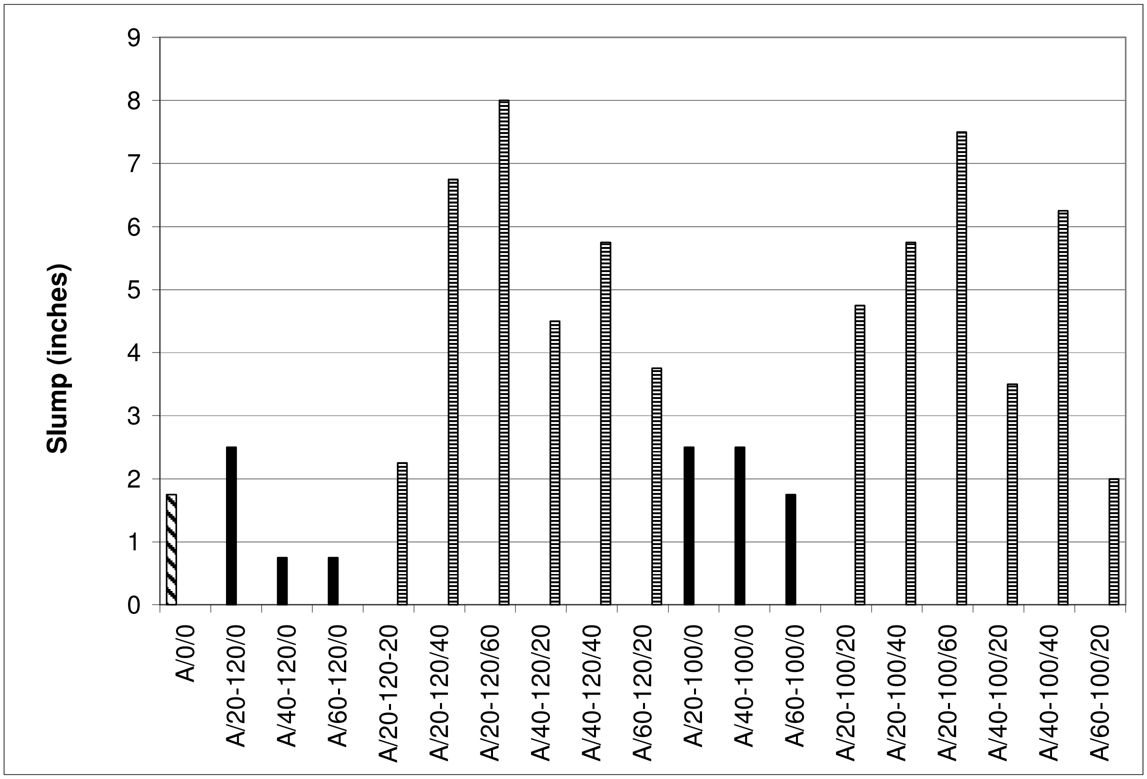
Mixture	Slump, in. (mm)	Unit Weight, lb/ft^3 (kg/m^3)	Air Content, %	Temperature, °F (°C)
A/0/0	1.75 (45)	151.5 (2426)	1.4	89.8 (32.1)
A/20-120/0	2.50 (65)	149.6 (2397)	1.5	81.8 (27.6)
A/40-120/0	0.75 (20)	150.5 (2410)	1.5	68.5 (20.3)
A/60-120/0	0.75 (20)	149.8 (2399)	1.6	72.5 (22.5)
A/20-120/20	2.25 (60)	150.1 (2404)	1.5	67.4 (19.6)
A/20-120/40	6.75 (70)	150.8 (2416)	1.1	61.1 (16.2)
A/20-120/60	8.00 (205)	149.8 (2399)	0.5	61.0 (16.1)
A/40-120/20	4.50 (115)	149.1 (2388)	1.5	69.6 (20.9)
A/40-120/40	5.75 (205)	149.7 (2398)	1.1	81.5 (27.5)
A/60-120/20	3.75 (95)	149.2 (2390)	1.3	69.4 (20.8)
A/20-100/0	2.50 (65)	151.5 (2428)	1.6	82.4 (28.0)
A/40-100/0	2.50 (65)	149.5 (2395)	1.3	80.4 (26.9)
A/60-100/0	1.75 (45)	148.8 (2384)	1.5	83.0 (28.3)
A/20-100/20	4.75 (120)	150.5 (2412)	1.3	85.2 (29.6)
A/20-100/40	5.75 (145)	150.0 (2403)	0.8	77.0 (25.0)
A/20-100/60	7.50 (190)	150.1 (2405)	0.5	79.0 (26.1)
A/40-100/20	3.50 (90)	148.8 (2384)	1.2	84.0 (28.9)
A/40-100/40	6.25 (160)	149.5 (2395)	0.8	84.8 (29.3)
A/60-100/20	2.00 (50)	149.7 (2399)	1.4	76.5 (24.7)

4.4.1.1 Slump

Slump values for the ground granulated blast furnace slag study are listed in Table 4.7. The slumps ranged from 0.75 to 8.0 inches (20 to 205 mm). The trends in the slump were observed as follows from the data and Chart 4.25:

- four out of the 9 mixtures had greater slumps with GR 120 GGBFS,
- one out of the 9 mixtures had the same slump, and
- four out of the 9 mixtures had greater slumps with GR 100 GGBFS.

Chart 4.25 Slump Values for GGBFS Study



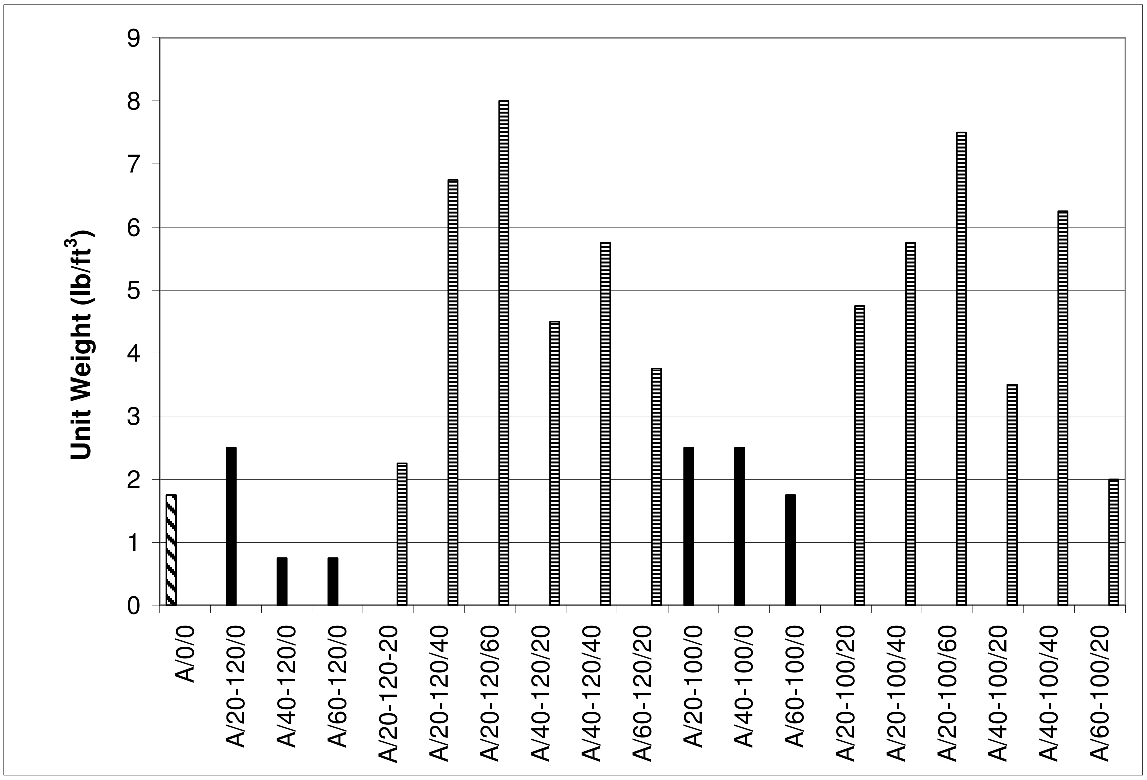
4.4.1.2 Unit Weight

Unit weight values for the ground granulated blast furnace slag study are listed in Table 4.7. The unit weights for the GGBFS study ranged from 148.8 to 151.5 lb/ft^3 (2384 to 2426 kg/m^3). All of the mixtures were not statistically different whether they were made with GR 100 or GR120 GGBFS, except the 20 % replacement with GGBFS. This means that if unit weight was part of the design criteria for mixtures with GGBFS the grade of GGBFS used would not be a factor. The following trends were observed from the data and Chart 4.26:

- the control mixture, A/0/0, had higher unit weight than the other mixtures,

- the unit weights were consistent between the mixtures made with GR 100 GGBFS and the mixtures made with GR 120 GGBFS.

Chart 4.26 Unit Weight Values for GGBFS Study



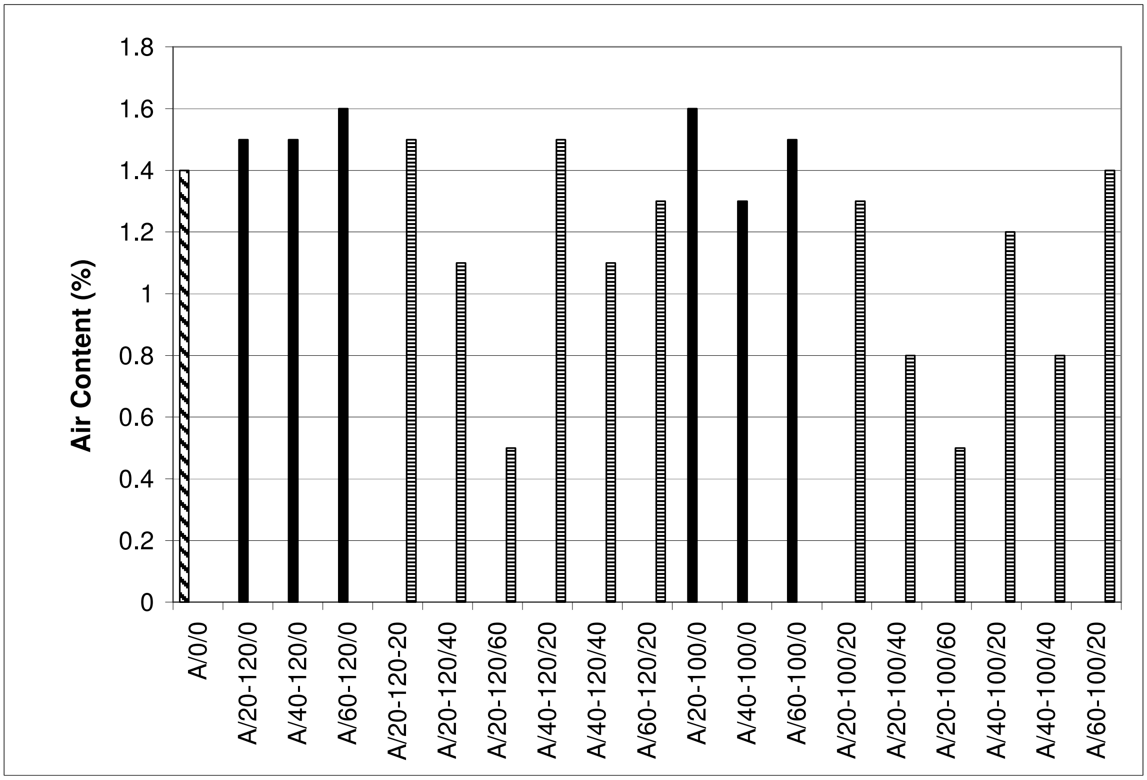
4.4.1.3 Air Content

Air content for the ground granulated blast furnace slag study are listed in Table 4.7. The air contents ranged from 0.5 to 1.6% with the majority of samples having a 1.1 to 1.6 % air content. As described in Section 3.7.1, the air content in the concrete was the result of entrapped air and not entrained air. Mixtures without AEA normally entrap 1.0 to 2.0% air. The trends observed from the data and Chart 4.27 were as follows:

- 67% of the air contents were not statistically different when made with different grades of GGBFS, and

- the other mixtures had higher air content when made with GR 120 GGBFS.

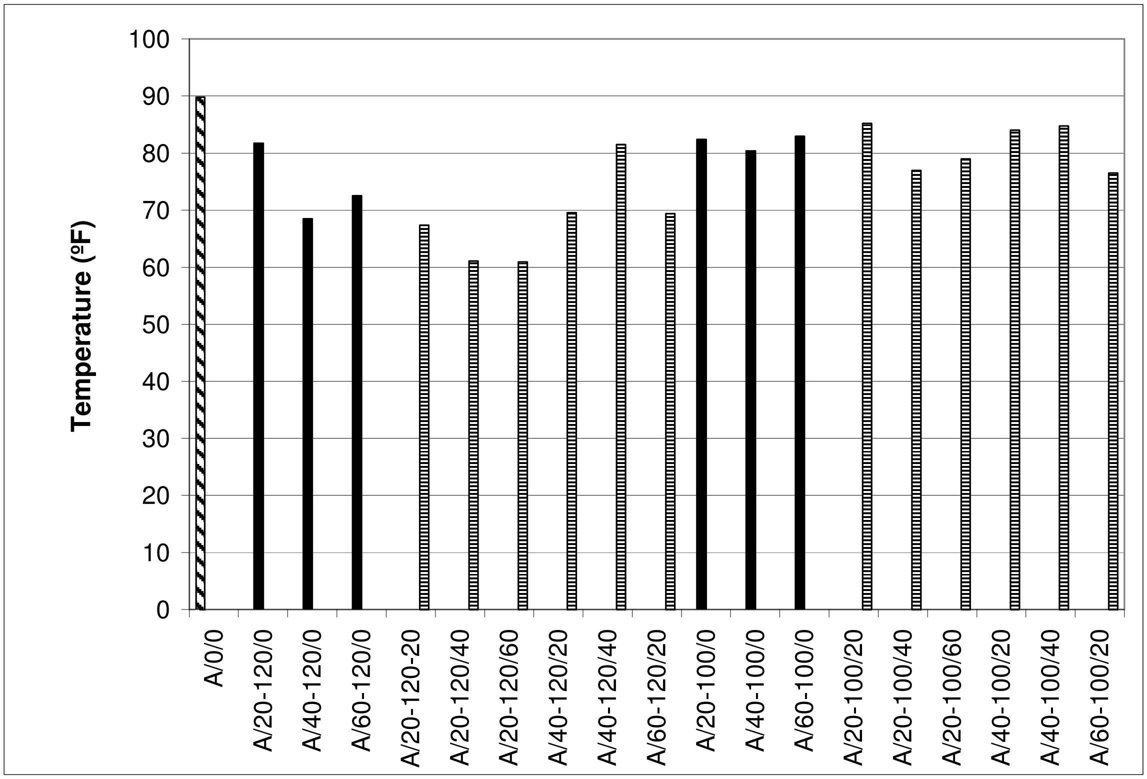
Chart 4.27 Air Content Values for GGBFS Study



4.4.1.4 Concrete Temperature

As mentioned in the other studies, the concrete temperature listed in Table 4.7 was only taken as a quality control measure. The fresh concrete temperature ranged from 60.95 to 89.8ºF (16.1 to 32.1ºC) as shown in the data and Chart 4.28.

Chart 4.28 Temperature Values for GGBFS Study



4.4.2 Hardened Concrete Tests

The hardened concrete tests performed during the ground granulated blast furnace slag study were compressive strength, rapid chloride ion penetrability test (RCPT), and freeze/thaw durability. The values listed in Table 4.8 are the mean values of six compressive strength samples as described in Section 3.9. The values listed in Table 4.9 are the mean values of four samples each for RCPT and freeze/thaw durability, two from each trial batch as described in Section 3.9. The grouping was based on the statistical analysis as described in Section 3.9.

4.4.2.1 Compressive Strength

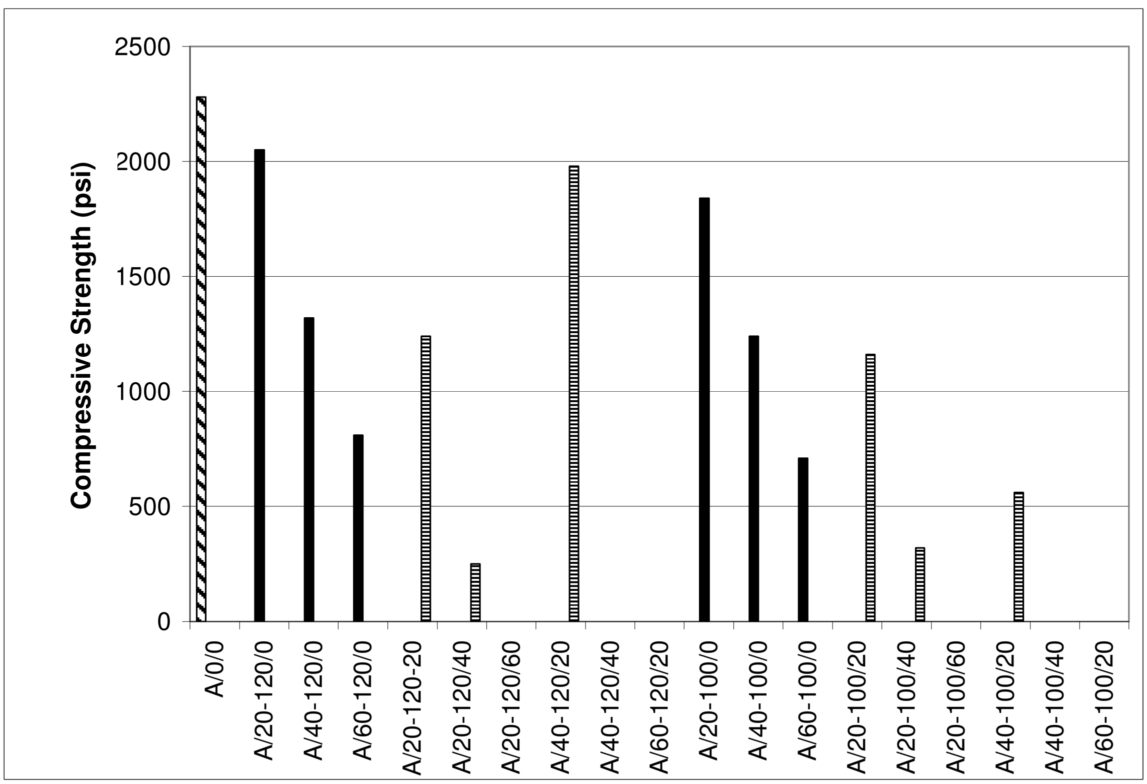
Table 4.8 Compressive Strength (psi) for GGBFS Study

Mixture Design	1 Day	3 Days	7 Days	28 Days	90 Days
A/0/0	2280	5290	6520	7840	8250
A/20-120/0	2050	4260	5730	7120	8380
A/40-120/0	1320	3920	5830	7660	8890
A/60-120/0	810	3130	5150	6910	7920
A/20-120/20	1240	4230	6510	8600	10020
A/20-120/40	250	2070	4680	7890	10110
A/20-120/60	0	90	1160	4500	7480
A/40-120/20	1980	2740	4660	7150	8730
A/40-120/40	0	0	3310	5770	7490
A/60-120/20	0	1890	3790	6730	7630
A/20-100/0	1840	4020	5720	6370	8630
A/40-100/0	1240	3510	7270	8430	9150
A/60-100/0	710	2320	4590	7270	8090
A/20-100/20	1160	3740	6050	9030	10170
A/20-100/40	320	2110	3860	7030	9800
A/20-100/60	0	0	830	2840	6350
A/40-100/20	560	-	4240	8350	9910
A/40-100/40	0	890	1840	5000	7610
A/60-100/20	0	1200	3180	7350	8480

Results of the compression test for the ground granulated blast furnace slag study are listed in Table 4.8. The mixtures that had not statistically different one day compressive strengths whether they were made with GR 100 GGBFS or GR 120 GGBFS were A/20/0, A/40/0, A20/20, A/20/60, A/40/40, and A/60/20. The mixture made with 60% GGBFS had a 12% decrease in compressive strength when made with GR 100 GGBFS. The ternary mixture made with 40% GGBFS and 20% FA had a 71% decrease in one day compressive strength when made with GR 100 GGBFS. The only mixture that had statistically greater compressive strength when made with GR 100 GGBFS was A/20-100/40. The GR 120 mixture (A/20-120/40) decreased the compressive strength by 22%. The trends in the one day compressive strength data and Chart 4.29 were observed as follows:

- each 20% increase in replacement (amount of FA held constant) resulted in lower strength,
- 67% of the mixtures had not statistically different compressive strengths with either GR 100 or GR 120 GGBFS,
- 22% had greater compressive strengths with GR 120 GGBFS, and
- 11% had greater compressive strengths with GR 100 GGBFS.

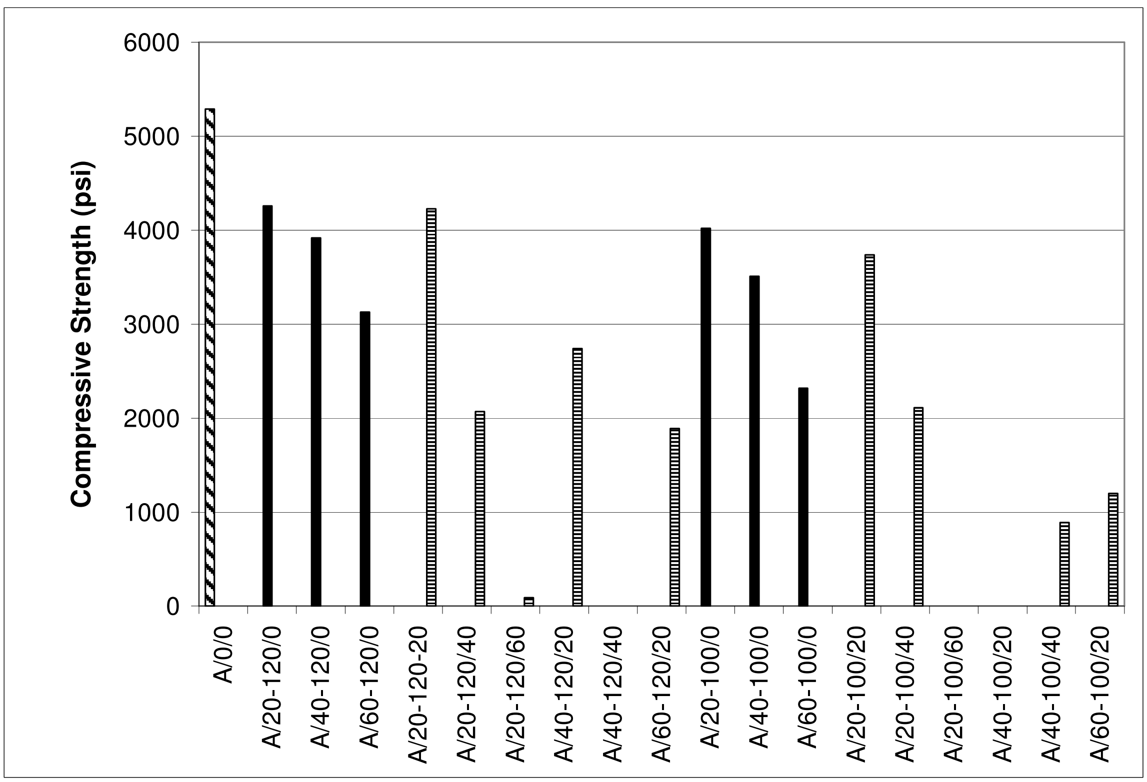
Chart 4.29 One Day Compressive Strength Values for GGBFS Study



At three days of age, mixtures that had not statistically different compressive strengths were A/20/0, A/20/40, A/20/60, A/40/40, and A/60/20. The A/40/0, A/60/0, and A/20/20 mixtures had an average of 14% less three-day compressive strength when made with GR 100 GGBFS. The A/40-100/20 mixture did not have three-day compressive strength data recorded and therefore could not be compared to the A/40-120/20 mixture. The trends observed in the GGBFS three day compressive strength data and Chart 4.30 were as follows:

- 56% of the mixtures had not statistically different compressive strengths with either GR 100 or GR 120 GGBFS,
- 33% had greater compressive strengths with GR 120 GGBFS, and
- 11% had greater compressive strengths with GR 100 GGBFS.

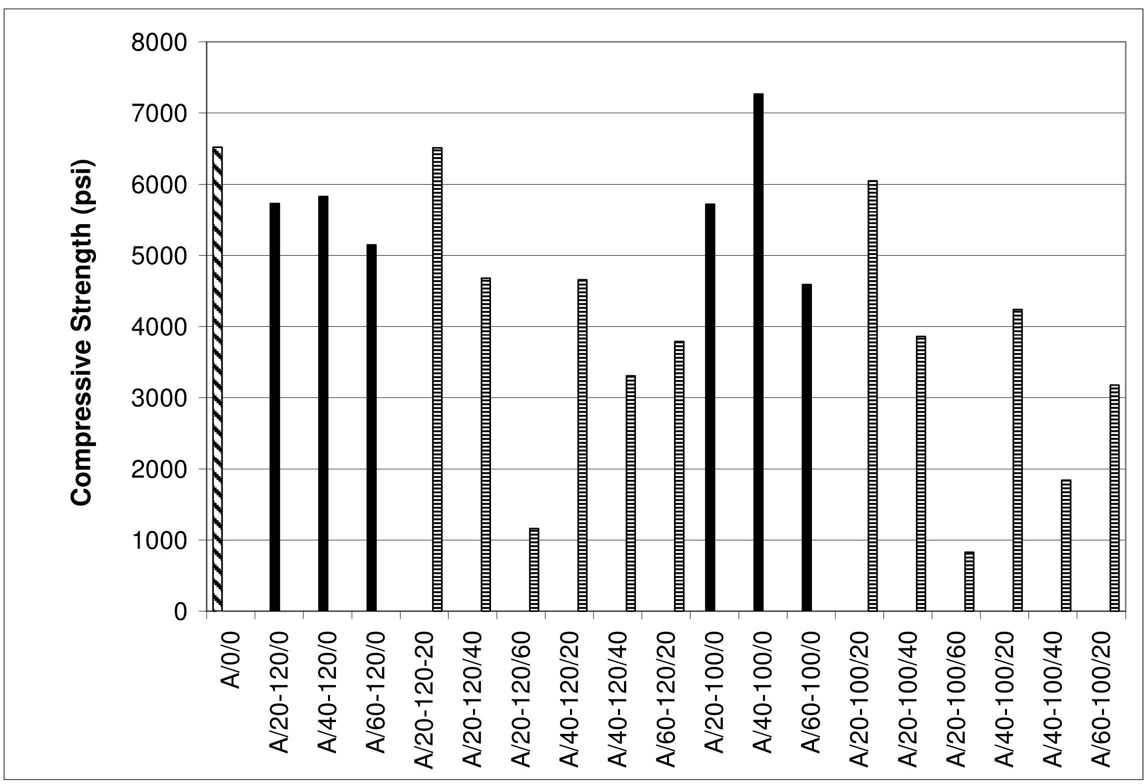
Chart 4.30 Three Day Compressive Strength Values GGBFS Study



At seven days of age, the A/20/0, A/20/60, A/40/40, and A/60/20 mixtures had not statistically different compressive strengths between the GR 100 and GR 120 GGBFS mixtures. The A/60/0, A/20/20, A/20/40, and A/40/20 mixtures saw a 11%, 7%, 2%, and 9% decrease in compressive strength with GR 100 GGBFS. The A/40/0 mixture had a 20% decrease in strength when made with GR 120 GGBFS. The 7day compressive strength trends were observed to be as follows from the data and Chart 4.31:

- the 40% GR 100 mixture had the highest strength and higher strength than the like GR 120 mixture,
- 44% of the mixtures had not statistically different compressive strengths with either GR 100 or GR 120 GGBFS,
- 44% had greater compressive strengths with GR 120 GGBFS, and
- 12% had greater compressive strengths with GR 100 GGBFS.

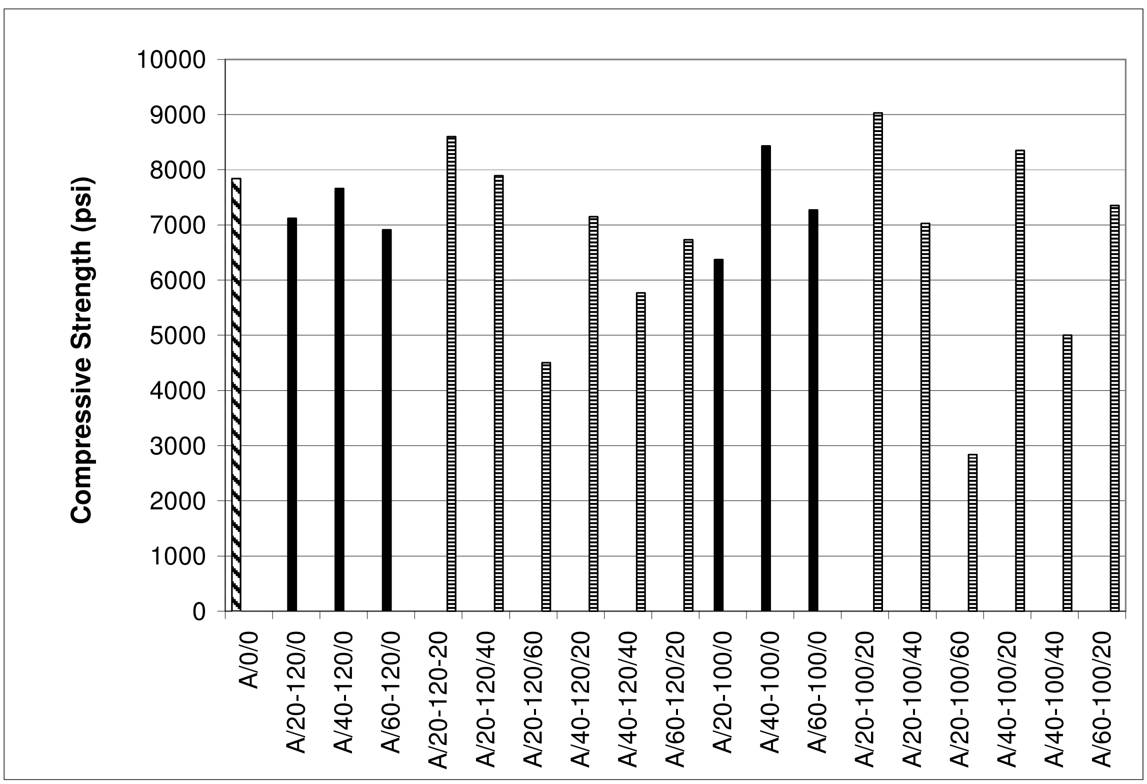
Chart 4.31 Seven Day Compressive Strength Values for GGBFS Study



The mixtures that had not statistically different twenty-eight day strengths whether they were made with GR 100 or GR 120 GGBFS were A/20/0, A/20/20, A/20/60, and A/40/40. Four of the remaining five mixtures had greater twenty-eight day compressive strength when made with GR 100 GGBFS. These mixtures were A/40/0, A/60/0, A/20/20, A/40/20, and A/60/20. The trends in twenty-eight day compressive strength data and Chart4.32 were observed to be as follows:

- 44% of the mixtures had not statistically different compressive strengths with either GR 100 or GR 120 GGBFS,
- 44% had greater compressive strengths with GR 100 GGBFS, and
- 12% had greater compressive strengths with GR 120 GGBFS.

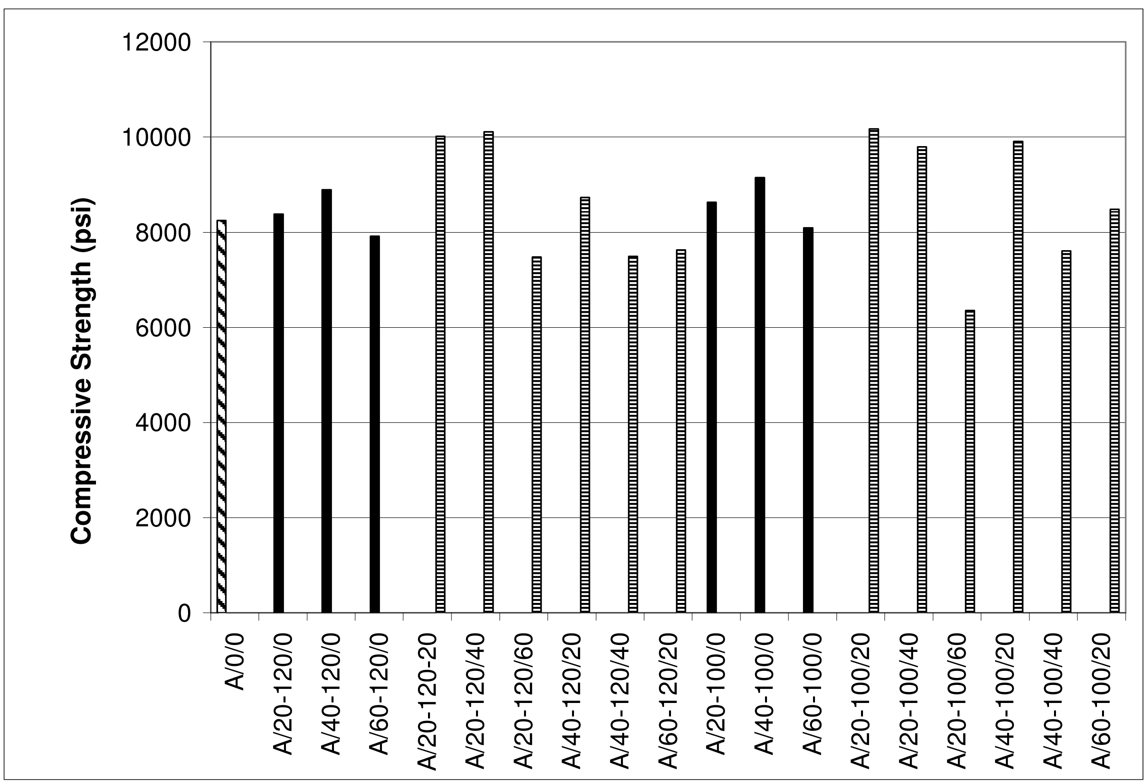
Chart 4.32 Twenty-eight Day Compressive Strength Values for GGBFS Study



Not statistically different mixtures in ninety-day compressive strength between GR 100 GGBFS and GR 120 GGBFS were: A/20/0, A/40/0, A/60/0, A/20/20, A/20/40, and A/40/40. The A/40/20 and A/60/20 mixtures were decreased by 11% when made with GR 120 GGBFS. The A/20/60 mixture had a 15% decrease in ninety-day compressive strength when made with GR 100 GGBFS. The 90 day compressive strength trends observed were as follows from the data and Chart 4.33:

- 67% of the mixtures had not statistically different compressive strengths with either GR 100 or GR 120 GGBFS,
- 22% had greater compressive strengths with GR 100 GGBFS, and
- 11% had greater compressive strengths with GR 120 GGBFS.

Chart 4.33 Ninety Day Compressive Strength Values for GGBFS Study



Overall, half of the like mixtures were not statistically different when compared to each other for compressive strength. Two thirds were similar at one day and two thirds were similar at ninety days. At 1, 3, and 7 days, one third of the like mixtures had higher compressive strength when made with GR 120 GGBFS. At 28 and 90 days one third of the like mixtures had higher compressive strength when made with GR 100 GGBFS. The GR 100 GGBFS reactivity index was 87% of the GR 120 GGBFS reactivity index at 7 days, but by 28 days the GR 100 GGBFS reactivity index was 98% the GR 120 GGBFS reactivity index. The convergence of the two SCMs reactivity indexes would account for the shift in more mixtures with greater compressive strengths from GR 120 at 1, 3, and 7 days to GR 100 at 28 and 90 days.

4.4.2.2 Rapid Chloride Ion Penetrability

The permeability of the hardened concrete mixtures was measured by RCPT as described in Section 2.6.2. The results from the test are shown in Table 4.9. Also shown in Table 4.9 is the permeability classification based on the number of coulombs passed.

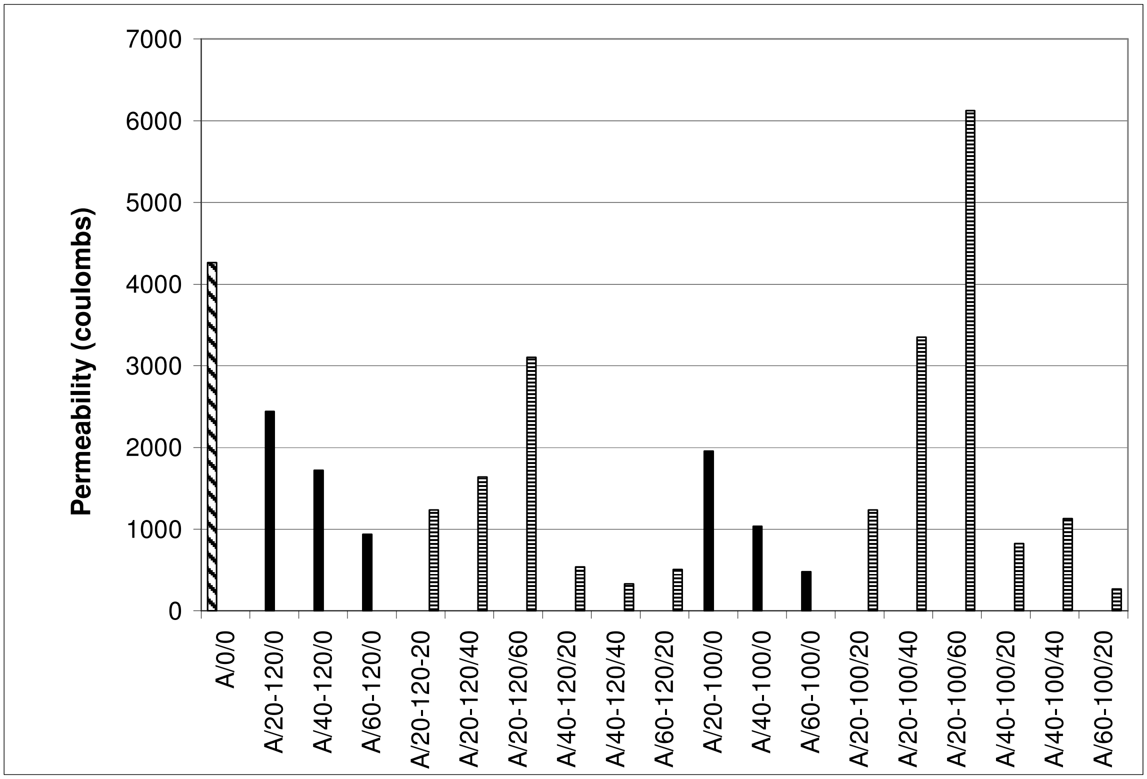
Table 4.9 Hardened Concrete Property Tests for GGBFS Study

Mixture	RCPT 28 Days, coulombs	Chloride Ion Penetrability	RCPT 90 Days, coulombs	Chloride Ion Penetrability	Freeze/Thaw Durability, DF
A/0/0	4265	High	3611	Moderate	2
A/20-120/0	2442	Moderate	1433	Low	24
A/40-120/0	1719	Low	630	Very Low	23
A/60-120/0	937	Very Low	565	Very Low	23
A/20-120/20	1238	Low	735	Very Low	43
A/20-120/40	1639	Low	817	Very Low	16
A/20-120/60	3104	Moderate	495	Very Low	9
A/40-120/20	540	Very Low	642	Very Low	14
A/40-120/40	331	Very Low	420	Ver`y Low	19
A/60-120/20	507	Very Low	357	Very Low	1
A/20-100/0	1957	Low	701	Very Low	10
A/40-100/0	1035	Low	625	Very Low	6
A/60-100/0	480	Very Low	398	Very Low	1
A/20-100/20	1235	Low	866	Very Low	1
A/20-100/40	3352	Moderate	867	Very Low	6
A/20-100/60	6124	High	1162	Low	2
A/40-100/20	824	Very Low	328	Very Low	23
A/40-100/40	1128	Low	337	Very Low	27
A/60-100/20	265	Very Low	342	Very Low	6

The mixtures with not statistically different twenty-eight day permeability whether made with GR 100 or GR 120 GGBFS were A/20/0, A20/20, A/40/20, and A60/20. The mixtures that had lower permeability when made with GR 100 GGBFS were A/40/0 and A/60/0. When these mixtures were made with GR 100 GGBFS the permeability decreased by 40% and 49% respectively. The mixtures that had lower permeability when made with GR 120 GGBFS were A/20/40, A/20/60, and A/40/40. When these mixtures were made with GR 120 GGBFS the permeability decreased by 51%, 49%, and 70% respectively. The twenty-eight day permeability trends from the data and Chart 4.34 were observed to be as follows:

- when combined with FA, GR 100 GGBFS mixtures had higher permeability than like GR 120 mixtures,
- 44% of the mixtures had not statistically different permeability with either GR 100 or GR 120 GGBFS,
- 22% had lower permeability with GR 100 GGBFS, and
- 34% had lower permeability with GR 120 GGBFS.

Chart 4.34 Twenty-eight Day Permeability Values for GGBFS Study

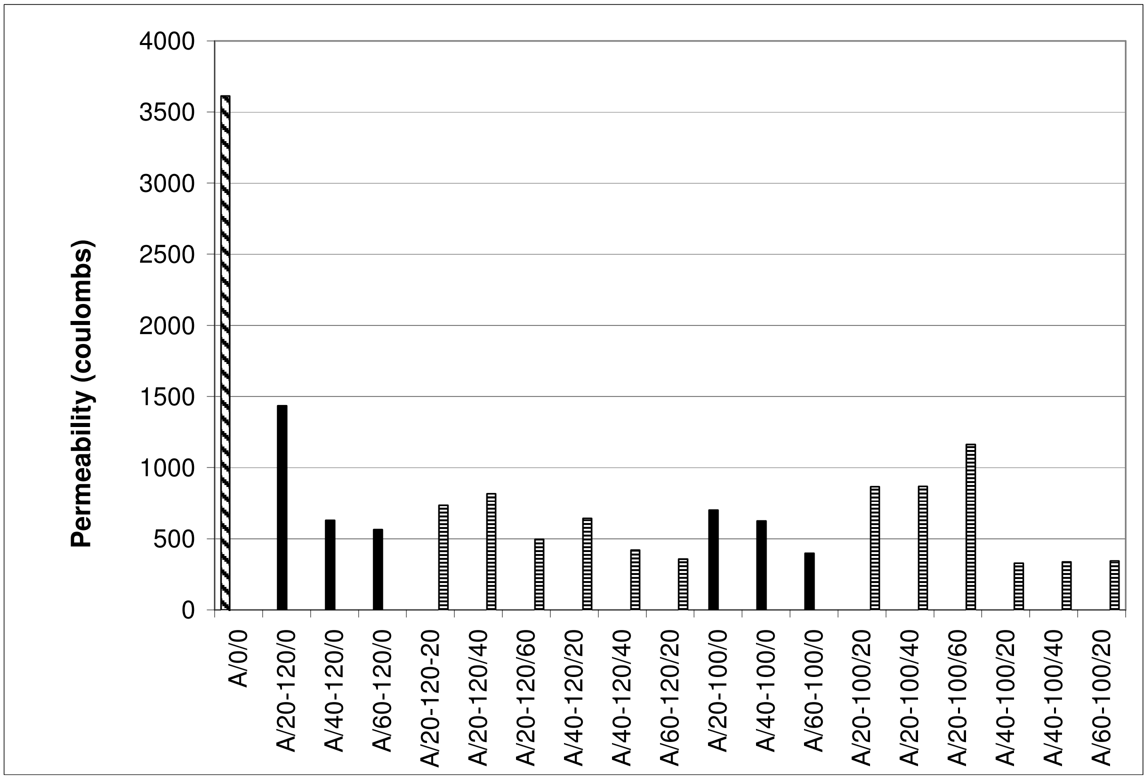


Not statistically different mixtures for ninety-day permeability were A/40/0, A/60/0, A/20/20, A20/40, and A/60/20. One of the nine mixtures in the GGBFS study, A/20/60, had a 57% decrease in permeability when made with GR 120 GGBFS. Three mixtures, A/20/0, A/40/20, and A/40/40, had a decrease of 51%, 50%, and 20% when made with GR 100 GGBFS. The trends in the ninety-day permeability data and Chart 4.35 were observed to be as follows:

- at ninety days the difference between ternary GR 100 and GR 120 mixtures was not as pronounced as twenty-eight day results,
- 56% of the mixtures had not statistically different permeability with either GR 100 or GR 120 GGBFS,
- 33% had lower permeability with GR 100 GGBFS, and

- 11% had lower permeability with GR 120 GGBFS.

Chart 4.35 Ninety Day Permeability Values for GGBFS Study



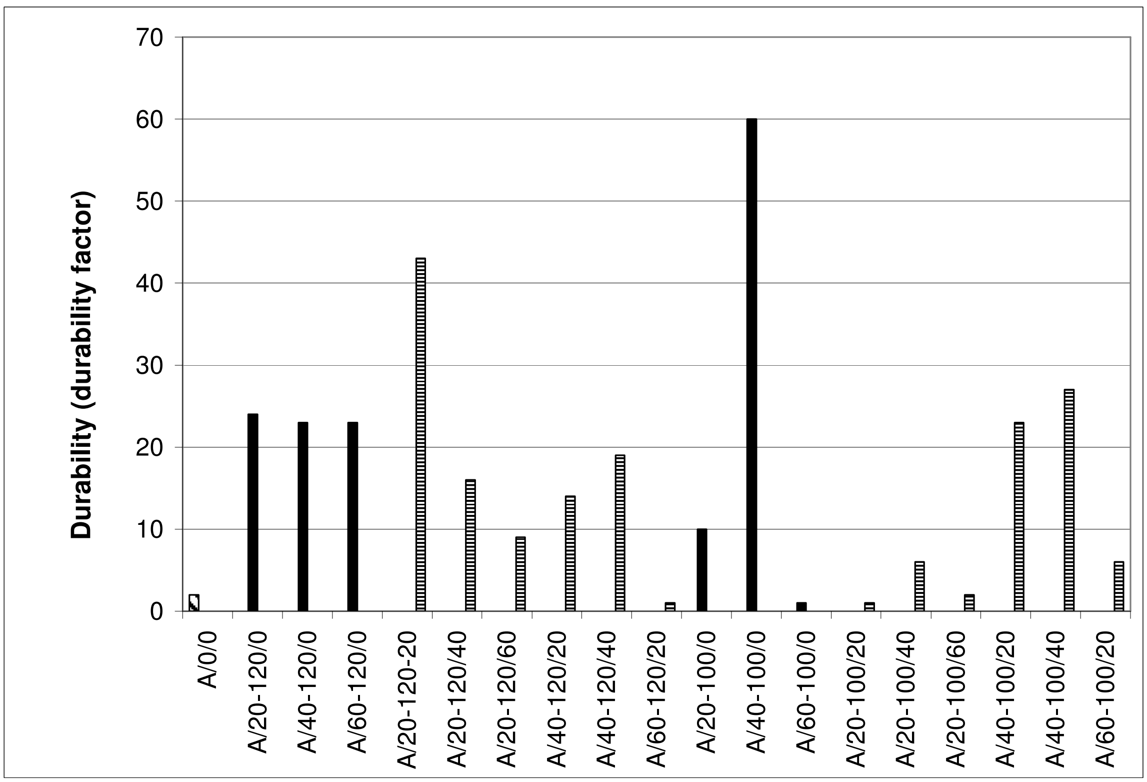
4.4.2.3 Freeze/Thaw Durability

The resonance frequency was monitored for each sample at each test and recorded as shown in Appendix A. The durability factor was determined from the last frequency recorded from each sample as per ASTM 666 (AASHTO T 161). Pictures of the freeze/thaw samples at end of testing or failure are shown in Appendix B. Three of the nine mixtures had not statistically different durability factors for freeze/thaw durability. The mixtures were A/20/0, A/20/60, and A/40/40. The mixtures with greater durability when made with GR 120 GGBFS were A/40/0, A/60/0, A/20/20, and A/20/20. The mixtures that had greater durability with GR 100

GGBFS were A/40/20 and A/60/20. The trends observed from the data and Chart 4.36 were as follows:

- the durability factors of the GR 100 GGBFS mixtures less consistent than GR 120 mixtures, and
- the durability factors of the GR 120 GGBFS mixtures were similar to each other.

Chart 4.36 Freeze/Thaw Durability Values for GGBFS Study



Chapter 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 General

The research program described in Sections 3.5 and 3.6 was designed to examine the fresh and hardened properties of concrete mixtures containing GGBFS and FA. The replacement rates encompass the range defined conservatively by a replacement below that allowed by AHTD (20%) and liberally by greater replacement rates (80%) than recommended in previous studies. The following sections present the conclusions and recommendations from the cement, SCM, and GGBFS studies with the fresh concrete properties followed by the hardened concrete properties.

5.2 Cement Study

Section 3.5 described the cement study portion of the research program. Section 4.2 presented the results from the study. The purpose of the study was to determine if the SCM produced similar properties when combined with different locally available Type I cement sources.

5.2.1 Fresh Concrete Properties

Slumps were statistically different between the two cement sources. The slump values for cement B were greater than the slump values for cement A. The two cements did show a similar trend in slump with higher FA replacement rates producing greater slump and higher GGBFS contents decreasing the slump.

Unit weights of mixtures made with cement A were higher than the unit weights of mixtures made with cement B. Unit weight was tested as a quality control method to check the amounts of materials in the concrete.

This study did not include adding air entraining admixtures; therefore the air content was due only to entrapped air. The air contents were observed to be within 1 to 2%, which is typical of mixtures containing only entrapped air. Literature suggests mixtures with SCMs require more attention and testing with air-entraining admixtures to achieve higher air contents. The literature also suggests that the unburned carbon in FA will have a detrimental effect on the air content and that observations in the air content should be monitored for fluctuation.

5.2.2 Hardened Concrete Properties

Even though cement A mixtures generally had higher strength than like cement B mixtures; they followed the same trend and therefore react similarly to the addition of SCMs. For all ages, only 8 of the 25 mixtures were not statistically different, meaning that cement A and cement B produce different compressive strengths in 68% of the mixtures. Even though there were differences, both mixtures (cement A and cement B) benefited from the addition of SCM. Mixtures from both cement sources met the AHTD twenty-eight day strength requirement of 4,000 psi.

At all ages, cement A mixtures generally produced higher compressive strengths than cement B mixtures but similar trends were observed between the two sources. Cement A reacted differently with SCMs than cement B to lower permeability from the control mixture for 28 and 90 days. The freeze/thaw results were not as consistent between cement A and cement B mixtures, however, the addition of SCM generally improved the durability when compared to the control mixtures.

5.3 Supplementary Cementitious Material Study

Section 3.6 described the SCM study portion of the research program. Section 4.3 presented the results from the study. The SCM study analyzed the fresh and hardened properties of concrete mixtures with differing amounts of GGBFS, FA, or combinations of both materials.

5.3.1 Fresh Concrete Properties

Slump increased as FA content increased, and decreased as GGBFS content increased. These two trends were also observed in the ternary mixtures. The slump data were taken at a variety of mixing temperatures but the trends in slump were not dependent on the temperature. Mixtures containing more than 20% GGBFS had a reduced slump from the control mixture. Reduction in slump observed in the GGBFS mixtures can be offset by the addition of a high range water reducer.

5.3.2 Hardened Concrete Properties

One of the main concerns with the use of SCM is the reduction of strength associated with replacing cement. The compressive strength results for the SCM study repeated the trend noted from the literature in Section 2.8.1 that cement only mixtures had higher early strength than mixtures containing SCM. The study also showed that some mixtures with cement replacements obtained higher later strength than the cement only mixture. The statistical analysis, described in Section 3.9, determined the differences and similarities between the compressive strengths.

At one day, the cement only mixture had statistically higher compressive strength than mixtures containing SCM. The control mixture also had the greatest three-day compressive strength. Three of the 20% replacement mixtures and the 20%

GGBFS/ 20% FA mixture were not statistically different and had the second highest strengths. Mixtures with greater than 40% replacements (of either SCM) had the lowest strengths.

AHTD specifications require at least 3000 psi (21.0 MPa) compressive strength at seven days to open a roadway to traffic. At seven days, 19 of 22 mixtures in the SCM study had over 3000 psi compressive strength. Even the 60% replacement of GGBFS, FA, and ternary mixtures with 60% total replacement met the seven day compressive strength requirement. The control mixture did not have a statistically greater strength than the 20% GGBFS/20% FA and 20% FA mixtures; meaning that the three mixtures are interchangeable at seven-days. The mixtures with a seven day compressive strength less than 3000 psi were the ternary mixtures with 40 or 60% FA replacements combined with GGBFS replacements to total 80% SCM. Such high replacements of cement generally have very low early strength as described in Section 2.6.1.

The twenty-eight day compressive strength is widely used as the design strength of concrete mixtures. As described in Section 3.2 and Section 3.3, the AHTD specifications for concrete pavement require 4000 psi (28.0 MPa) as the minimum twenty-eight day compressive strength. Twenty-one of the 22 mixtures in the SCM study resulted in greater than 4000 psi strength at 28 days. Three ternary mixtures and a 40% GGBFS mixture had statistically higher 28 day compressive strength than the control mixture containing only portland cement. The lone mixture with the 28 day compressive strength less than 4000 psi was the 20% Gr. 100 and 60% FA mixture. The literature review suggests that GGBFS and FA replacement mixtures could gain more strength than cement only mixtures in later strength tests as described in Section 2.6.1.

Eight mixtures made with 40 or 60% SCM replacements had statistically higher ninety-day compressive strength than the control mixture. The 8 mixtures had a compressive strength that was at least 1000 psi greater than the control mixture. The 80% replacement ternary mixtures had the lowest 90 day strength with 5 out of 6 mixtures having less than 8000 psi compared to 8250 psi for the control mixture. These results show that SCM mixtures, containing up to 60% SCM, have greater or comparable later strength when compared to cement only mixtures as described in the literature in Section 2.6.1.

Three mixtures, including the control mixture, are classified as having high permeability at 28 days based on the RCPT results. FA only mixtures, 20% GGBFS only mixtures, and ternary mixtures with 20% GGBFS and 60% FA had high or moderate permeability. For permeability at 28 days, GGBFS was a better mixture design component than FA because an increase in GGBFS decreased permeability while an increase in FA increased permeability. But at 90 days of age, the FA mixtures would also be classified as having low permeability. All mixtures experienced a reduction in permeability from 28 to 90 days.

The freeze/thaw durability is greatly dependent on the air content, especially entrained air as described in Section 2.5.4. Mixtures with air contents of approximately 7 to 9% have the highest durability factors from freeze/thaw tests (Mindess et al. 2003). Without AEA, the mixtures in this study did not meet the AHTD specifications. Due to the addition of FA and GGBFS, seventeen of the 21

SCM mixtures had greater durability than the control mixture. However, none of the mixtures had a DF over 60, the value recognized as having acceptable freeze/thaw resistance.

5.4 Ground Granulated Blast Furnace Slag Study

The ground granulated blast furnace slag study was described in Section 3.6. The results from the study were presented in Section 4.4. The purpose of the GGBFS study was to determine if the proposed replacement rates of Gr. 120 GGBFS would be acceptable for Gr. 100 GGBFS.

5.4.1 Fresh Concrete Properties

Mixtures containing only GGBFS (no FA) had comparable slump to the control mixture within 1". The ternary mixtures had statistically higher slump than the control mixture in 10 of the 12 ternary mixtures. The slump results for the GGBFS were not consistent. Four of 9 mixture designs had greater slump when made with GR 120 GGBFS, and 4 of 9 mixture designs had greater slump when made with GR 100 GGBFS.

5.4.2 Hardened Concrete Properties

The early strength tests on 1, 3, and 7 days show a trend of greater compressive strength in mixtures made with GR 120 GGBFS when compared to like GR 100 mixtures. The one day compressive strength tests showed that 6 of the 9 designs were not statistically different, 2 of 9 had greater strength with GR 120 GGBFS, and 1 of 9 had greater strength with GR 100 GGBFS. With the exception of the A/40-120/20 mixture, the mixtures showed similar trends in strength. Three day compressive strength results showed 5 of 9 mixtures with not statistically different strength, 3 of 9 had greater strength with GR 120 GGBFS and 1 of 9 had greater strength with GR 100 GGBFS. At 7 days of age, the compressive strengths for 4 of 9 mixtures were not statistically different strength, another 4 mixtures had greater strength with GR 120 GGBFS, and 1 mixture had greater strength with GR 100 GGBFS.

The results from the twenty-eight day compressive strengths showed that 4 of 9 mixtures were not statistically different strength, 4 of 9 had greater strength when made with GR 100 GGBFS, and 1 of 9 had greater strength when made with GR 120 GGBFS. This trend was opposite of the seven-day results and contrary to the trend from 1 to seven-day results. The twenty-eight day strength is used in the industry to determine the grade of GGBFS, as described in Section 2.2. The GR 120 GGBFS should have greater strength than the GR 100 GGBFS based on the method used to grade the material. The GR 100 GGBFS used in this study could fall just short of the requirements for GR 120 for the seven-day strength requirements, as suggested by the seven-day results. The GGBFS has to meet both 7 and twenty-eight day requirements according to the ASTM C989 to be considered GR 100 or GR 120.

The 90 day compressive strengths results show that the mixtures with different grades of GGBFS became more similar. Six of 9 mixtures were not statistically different, the highest number of similar results in the GGBFS study. The strengths were greater for GR 100 GGBFS in 2 of 9 mixtures and greater for GR 120 GGBFS in 1 of 9 mixture designs.

The similarity in permeability between the GR 100 and GR 120 mixtures also increased from 28 to 90 days. At 28 days, 4 of 9 mixture designs were not statistically different, 2 had lower permeability with GR 100 GGBFS, and 3 had lower permeability with GR 120 GGBFS. At 90 days, 5 of 9 mixture designs were not statistically different, 3 had lower permeability with GR 100 GGBFS, and 1 had lower permeability with GR 120 GGBFS. All mixtures were statistically different in durability factor between GR 100 GGBFS and GR 120 GGBFS mixtures, but the similarly poor freeze/thaw performance was due to the lack of AEA.

5.5 Recommendations

The purpose of the cement study was to determine if the SCMs produced similar properties when combined with different locally available Type I cement sources. The results of the fresh and hardened concrete tests for the cement study showed that some of the properties were not statistically different while some were. The properties that were not similar between the two cements showed similar trends. The two different portland cement sources did not produce extremely varying results. The recommendations from the cement study results are as follows:

- the differences in properties between cement A and cement B can be attributed to the differences in cement source, not varying reactions to the SCMs,
- cement source did not cause extreme variance in the fresh and hardened concrete properties, and
- GR 100 GGBFS, GR 120 GGBFS, and FA can be used in mixtures with different cement sources available in Arkansas.

The purpose of the SCM study was to analyze the fresh and hardened properties of concrete mixtures with differing amounts of GGBFS, FA, or combinations of both materials. The results of the fresh and hardened concrete tests for the GGBFS study showed that SCM replacements can improve the properties of concrete mixtures. Because the GGBFS study resulted in viable mixture design properties from concrete with at least 40% SCM replacements, the recommendations are as follows:

- add AEA to the mixtures for the air contents to be within AHTD specifications while observing for lower strengths and slump increases typical of adding AEA,
- compressive strengths at one day suggest that up to 40% SCM (as FA and GGBFS only or ternary mixtures) can be used with a strength of at or above 900 psi for joint construction within two days of pour,
- compressive strengths at three days suggest that up to 40 % SCM (as FA and GGBFS only or ternary mixtures) can be used with a strength of at or above 3510 psi (nearly AHTD 28 day design criteria) for form removal,
- 90 day permeability results suggest that the greatest benefit is at 20% SCM, but that additional 20% SCM lowers permeability slightly,
- freeze/thaw results show that SCMs improve the freeze/thaw durability of concrete mixtures over the control mixtures even without AEA, and therefore,
- it is recommended that up to 40% maximum replacements with SCM (GR 100 and GR 120 GGBFS, FA, and ternary mixtures) be allowed for concrete pavement design in Arkansas.

The purpose of the GGBFS study was to determine if the proposed replacement rates produced the same properties using GR 100 and GR 120 GGBFS. Either grade (GR 100 or GR 120) GGBFS could be used in concrete mixtures without widely varying fresh concrete properties. At three days the difference in strength, between GR 100 and GR 120 mixtures, is not so great that one, and not the other, would have sufficient strength for cutting joints without tearing and raveling (AHTD requirement for joint sawing). GR 120 GGBFS produced greater strength because the seven day reactivity index of the GR 100 is 87% of the GR 120. In this study, the reactivity index of the GR 100 GGBFS converged on that of the GR 120 GGBFS (87% to 98%) so that the mixtures produced more similar compressive strength results at later age. Mixtures with both grades met the AHTD twenty-eight day compressive strength requirement of 4000 psi. Both grades also produced mixtures with permeability values lower than the control mixture and similar freeze/thaw durability greater than the control mixture. The GGBFS Study recommendations are as follows:

- GR 100 and GR 120 produced similar and acceptable fresh and hardened concrete properties,
- recommended replacements rates for GR 100 and GR 120 are interchangeable, and
- GR 100 and GR 120 GGBFS should be allowed.

BIBILIOGRAPHY

ACI Committee 233. Slag Cement in Concrete and Mortar. Farmington Hills: American Concrete Institute, 2003.

Agnes, Michael, and David Guralnik. *Webster's New World College Dictionary*. 4th ed. Foster City: IDG Books Worldwide, Inc., 2000.

American Coal Ash Association (ACAA). Fly Ash Facts for Highway Engineers. Springfield: National Technical Information Service, 1995.

Arkansas Highway and Transportation Department. Standard Specifications for Highway Construction. Little Rock: Arkansas Highway and Transportation Department, 2003.

Babu, K. Ganesh, and G. Siva Nageswara Rao. "Early Strength Behaviour of Fly Ash Concretes." Cement and Concrete Research. Vol. 24. No. 2 (1994): 277-284.

"Blast Furnace Slag-Material Description." Blast Furnace Slag-Material Description. Turner-Fairbanks Highway Research Center. 21 Dec. 2004 <http://www.tfhrc.gov/hnr20/recycle/waste/bfs1.htm>.

"Blast Furnace Slag – User Guideline – Portland Cement Concrete." Blast Furnace Slag – User Guideline – Portland Cement Concrete. Turner-Fairbanks Highway Research Center. 21 Dec. 2004 <http://www.tfhrc.gov/hnr20/recycle/waste/bfs3.htm>.

"Coal Fly Ash-Material Description ." Coal Fly Ash-Material Description. Turner-Fairbanks Highway Research Center. 21 Dec. 2004 <http://www.tfhrc.gov/hnr20/recycle/waste/cfa51.htm>.

"Coal Fly Ash-User Guideline." Coal Fly Ash-User Guideline. Turner-Fairbanks Highway Research Center. 21 Dec. 2004 <http://www.tfhrc.gov/hnr20/recycle/waste/cfa53.htm>.

Duchesne, Josée, and Marc-André Bérubé. "Long-term Effectiveness of Supplementary Cementing Materials Against Alkali-Silica Reaction." Cement and Concrete Research. Vol. 31. No. 7 (2001): 1057-1063.

"Fly Ash-Materials Group." Fly Ash-Materials Group. United States Department of Transportation; Federal Highway Administration. 23 Dec. 2004 <http://www.fhwa.dot.gov/infrastructure/materialsgrp/flyash.htm>.

Gillott, J. E. "Review of Expansive Alkali-Aggregate Reactions in Concrete." Journal of Materials in Civil Engineering. Nov. 1995: 278-282.

"Ground Granulated Blast-Furnace Slag-Materials Group." Ground Granulated Blast-Furnace Slag-Materials Group. United States Department of Transportation; Federal Highway Administration. 21 Dec. 2004 <http://www.fhwa.dot.gov/infrastructure/materialsgrp/ggbfs.htm>.

Hogan, Frank, Jerry Meusel, and Lou Spellman. "Breathing Easier with Blast Furnace Slag." Cement Americas. December 23, 2004. <http://cementamericas.com/mag/cement_breathing_easier_blast/index.html> July 2001.

Irassar, E. F., and A. Di Maio, and O. R. Batic. "Sulfate Attack on Concrete with Mineral Admixtures." Cement and Concrete Research. Vol. 26. No. 1. (1996): 113-123.

Khatri, R. P., V. Sirivivatnanon,, and W. Gross. "Effect of Different Supplementary Cementitious Materials on Mechanical Properties of High Performance Concrete." Cement and Concrete Research. Vol. 25. No. 1 (1995): 209-220.

Külaots, Indrek, Robert H. Hurt, and Eric M. Suuberg. "Size Distribution of Unburned Carbon in Coal Fly Ash and its Implications." Fuel. Vol. 83. No. 2 (2004): 223-230.

"Leadership in Energy & Environmental Design." Leadership in Energy & Environmental Design. United States Green Building Council. 21 Dec. 2004 <http://www.usgbc.org/LEED/LEED_main.asp>.

Leng, Faguang, Naiqain Feng, and Xinying Lu. "An Experimental Study on the Properties of Resistance to Diffusion of Chloride Ions of Fly Ash and Blast Furnace Slag Concrete." Cement and Concrete Research. Vol. 30. (2000): 989-992.

Li, Gengying, and Xiaohua Zhao. "Properties of Concrete Incorporating Fly Ash and Ground Granulated Blast-Furnace Slag." Cement and Concrete Composites. Vol. 25. No. 3 (2003): 293-299.

Luther, M. D., W. J. Mikols, A. J. De Maio, and J. I. Whitlinger 1994, "Scaling Resistance of Ground Granulated Blast Furnace Slag (GGBFS) Concretes," *Durability of Concrete*, Proceedings of the Third International Conference, SP-145, V. M. Malhotra, ed., American Concrete Institute, Farmington Hills, Mich., pp.47-64.

Mehta, P. Kumar. “Greening of the Concrete Industry for Sustainable Development.” Concrete International. Vol. 24. No.7 July (2002): 23-28.

Mindess, Sidney, J. Francis Young, and David Darwin. Concrete. 2nd ed. Upper Saddle River: Pearson Education, Inc., 2003.

Nobata, Kenji, and Yasutomo Ueki. “Basic Property and the Method of Effective Use on Portland Blast-Furnace Slag Cement and Ground Granulated Blast Furnace Slag.” Nippon Steel technical report. No. 86. (2002): 44-47.

Nocuń-Wczelik, W. “Heat Evolution in Hydrated Cementitious Systems Admixtured with Fly Ash.” Journal of Thermal Analysis and Calorimetry. Vol. 65 (2001): 613-619.

Ostrowski, Christopher. “Fly Ash, Slag put ‘Green’ Concrete on the Map.” Intermountain Contractor. Vol. 58. No. 7 20 July (2002): 48.

Penttala, Vesa. “Concrete and Sustainable Development.” ACI Materials Journal. Vol. 94. No. 5 Sept.-Oct. (1997): 409-416.

Pigeon, Michel, and Micheline Regourd. “Freezing and Thawing Durability of Three Cements with Various Granulated Blast Furnace Slag Contents.” American Concrete Institute SP 79-52. Vol. 2. (1983):.979-998.

“P-Value.” iSix Sigma Dictionary. 7 July 2003. iSix Sigma. 27 July 2005 <http://www.isixsigma.com/dictionary/P-Value-301.htm>.

Schriefer, John. “Reaping the Value from Dust and Slag.” New Steel. 21 Dec. 2004. <http://www.newsteel.com/features/Ns9702f3.htm> Feb. (1997).

Schutter, G. De. “Hydration and Temperature Development of Concrete Made with Blast-Furnace Slag Cement.” Cement and Concrete Research. Vol. 29. No. 1 (1999): 143-149.

Shi, Caijun, Julia A. Stegemann, and Robert J. Caldwell. “Effect of Supplementary Cementing Materials on the Specific Conductivity of Pore Solution and its Implications on the Rapid Chloride Permeability Test (AASHTO T277 and ASTM C 1202) Results.” ACI Materials Journal. Vol. 95. No. 4 July-Aug. (1998) 389-394.

Sullivan, Ed, and Dave Czechowski. “Cement Shortage Assessment.” The Monitor: Flash Report. Portland Cement Association. 13 May (2004).

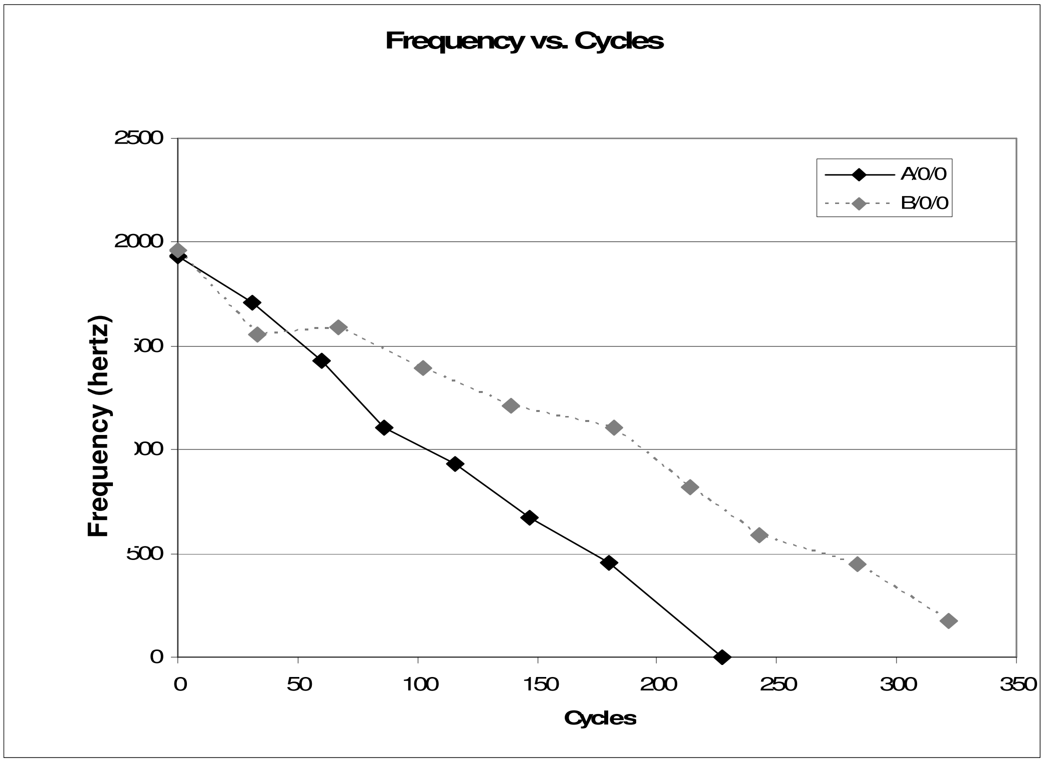
Taylor, Peter C., Willy Morrison, and Victoria A. Jennings. “Effect of Finishing Practices on Performance of Concrete Containing Slag and Fly Ash as

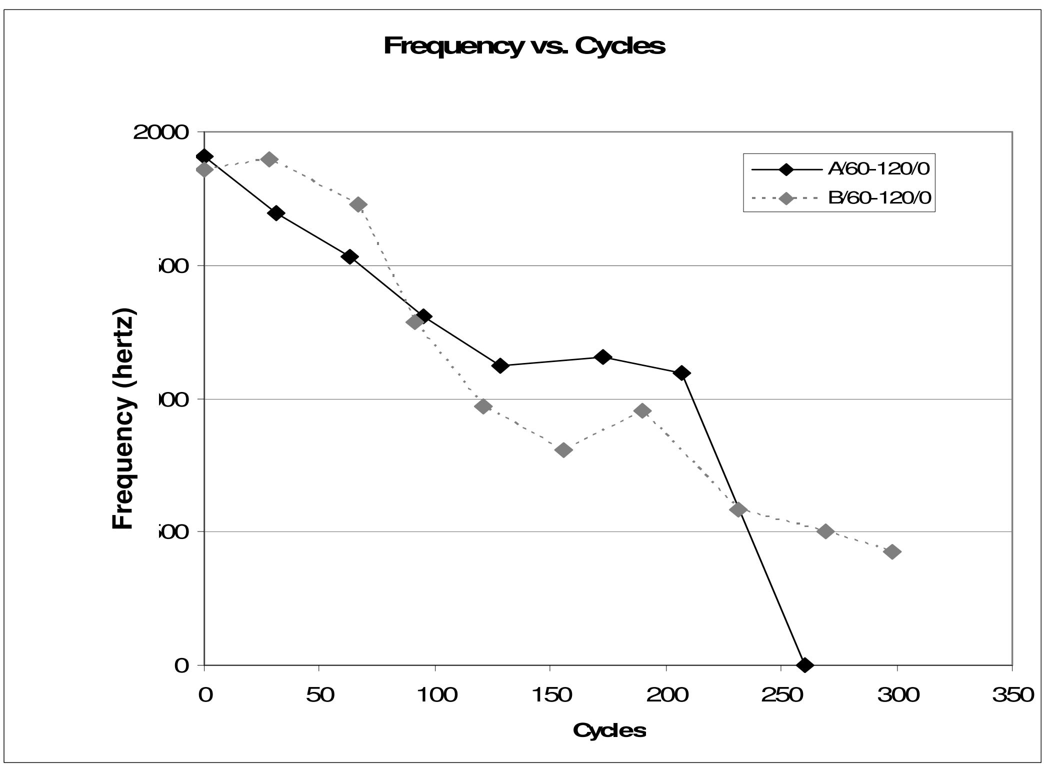
Measured by ASTM C 672 Resistance to Deicer Scaling Tests." Cement, Concrete, and Aggregates. Vol. 26. No. 2 Dec.(2004): 155-159.

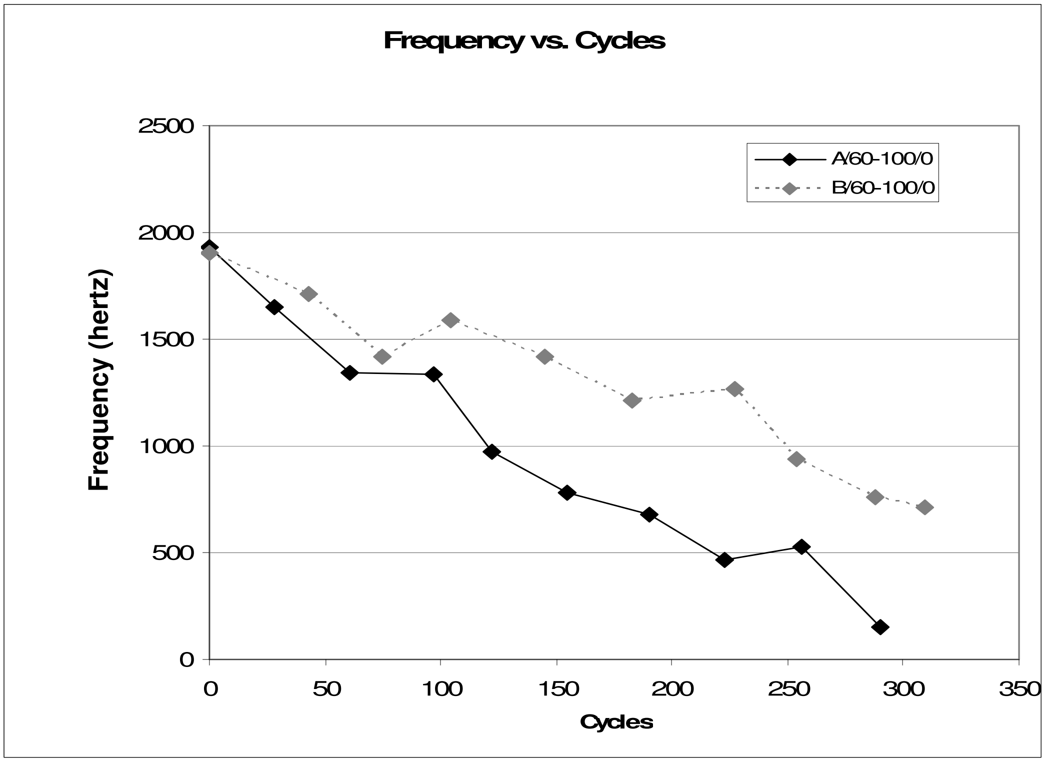
VanGeem, Martha, and Medgar Marceau. "Using concrete to maximize LEED points." Concrete International. November (2002): 69-73.

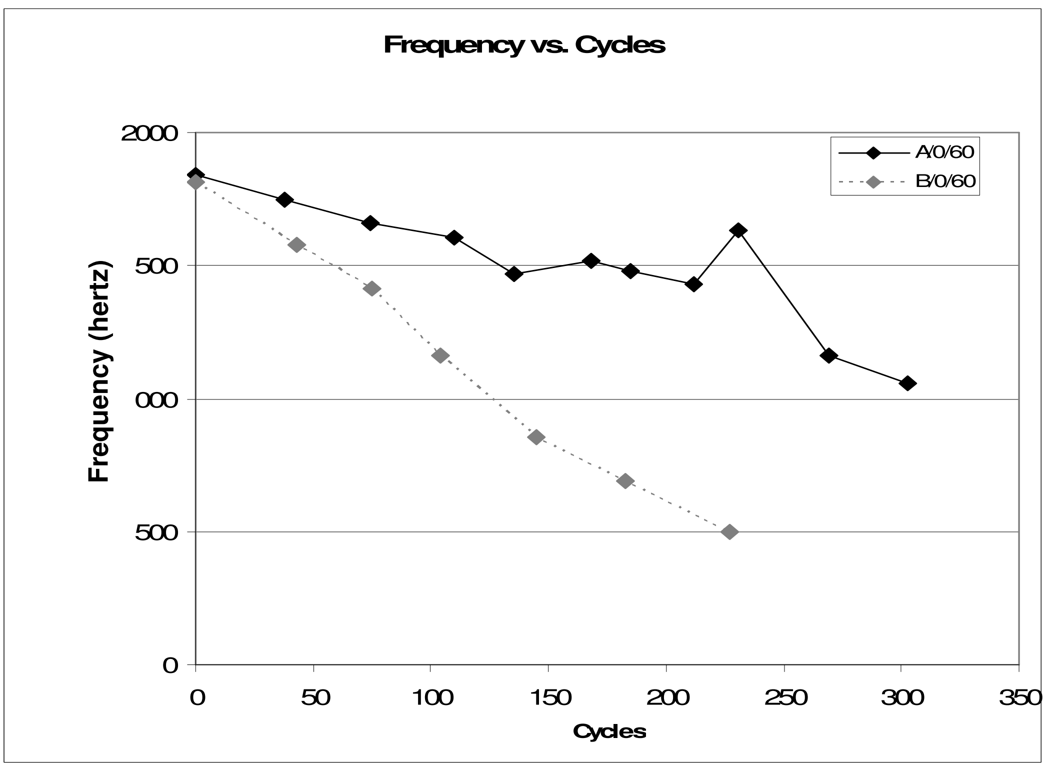
APPENDIX A: FREQUENCY VS CYCLES GRAPHS

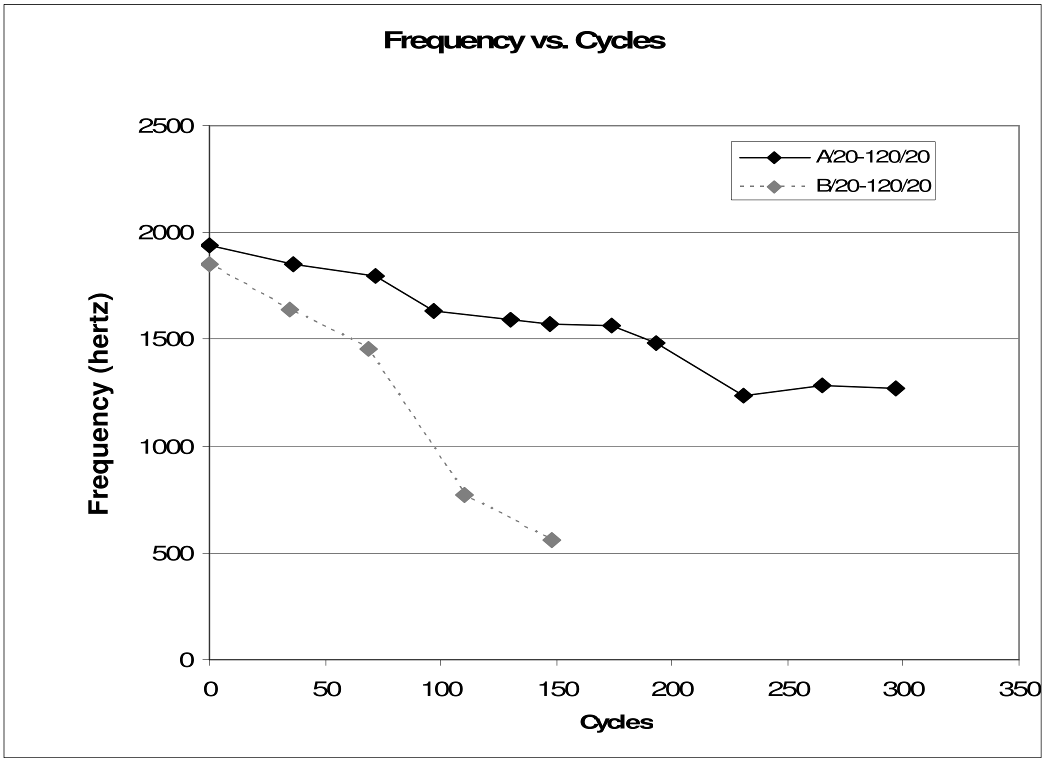
A.1 Cement A and Cement B Batches for Cement Study



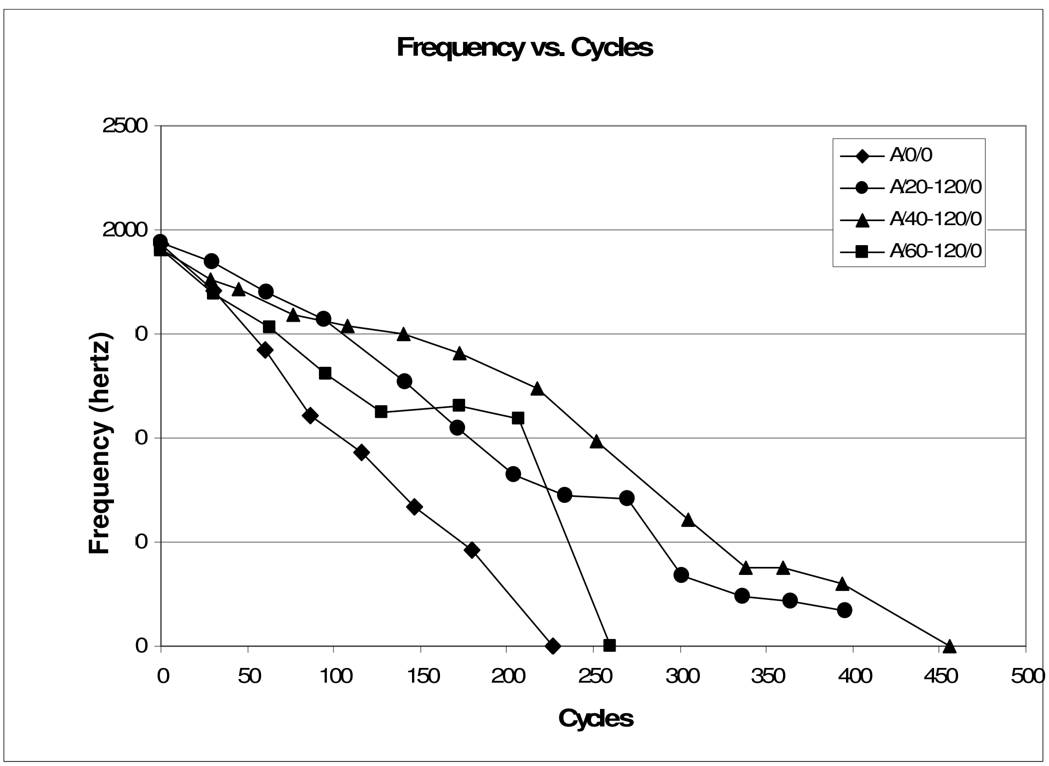


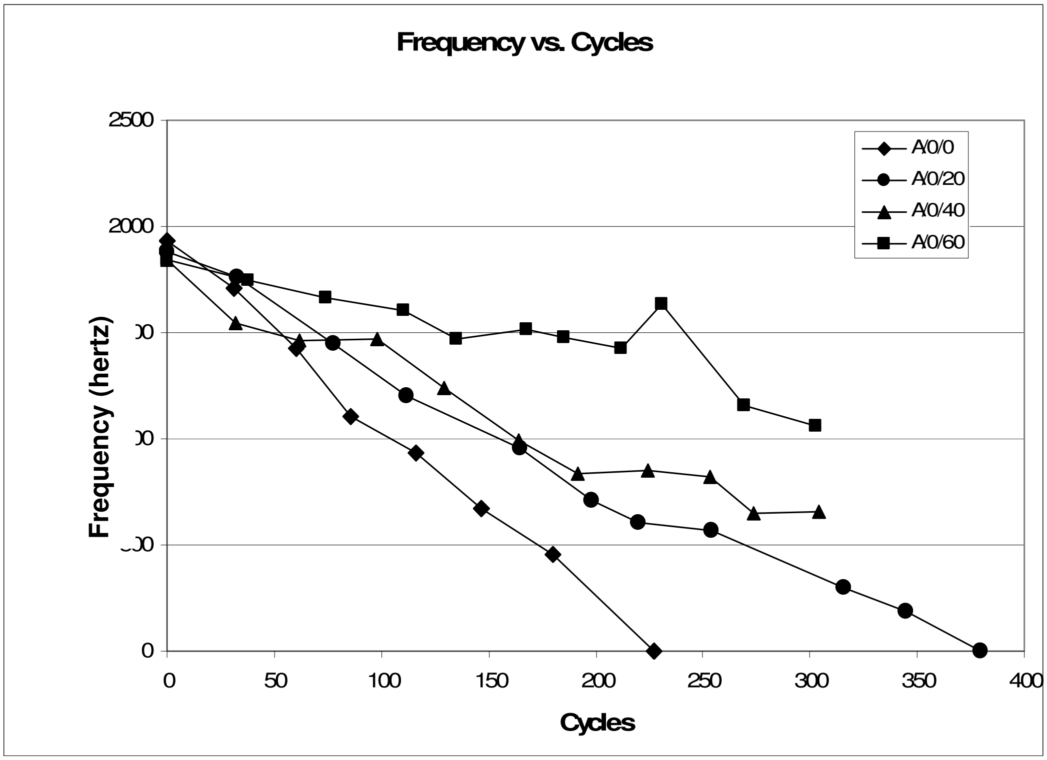

Frequency vs. Cycles
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
350
Frequency (hertz)
Cycles
A/60-100/0
B/60-100/0


Frequency vs. Cycles
2000
500
000
500
0
0
50
100
150
200
250
300
350
Frequency (hertz)
Cycles
A/0/60
B/0/60

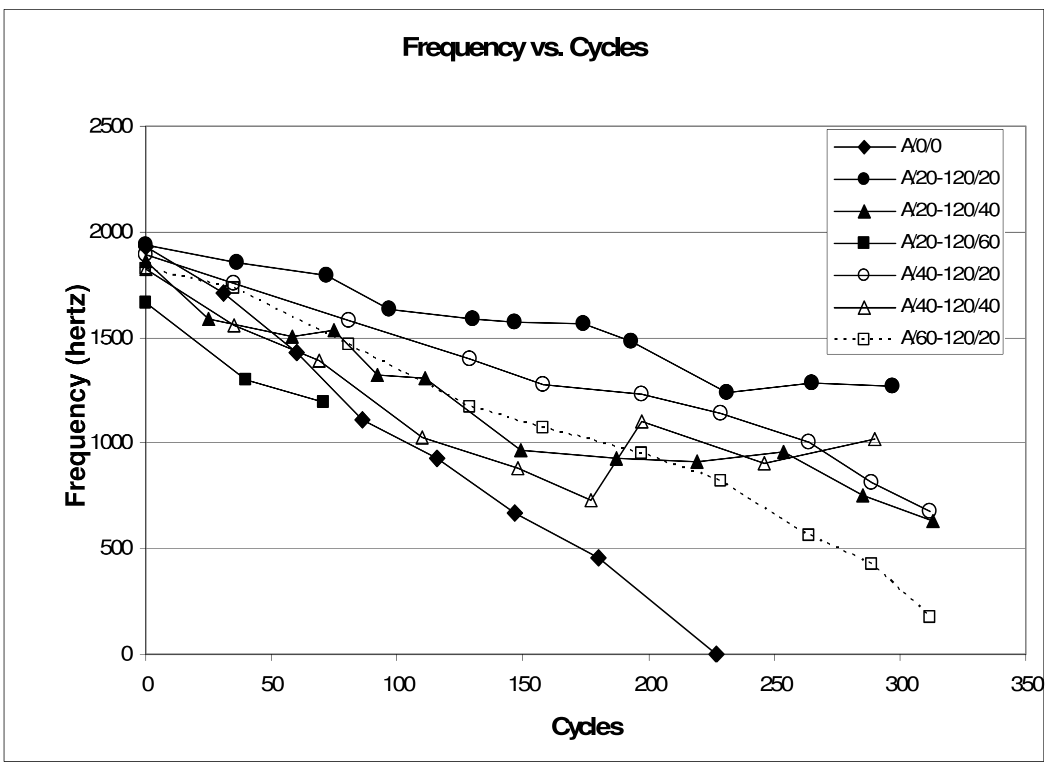


A.2 Cement A Batches with GGBFS and FA for SCM Study

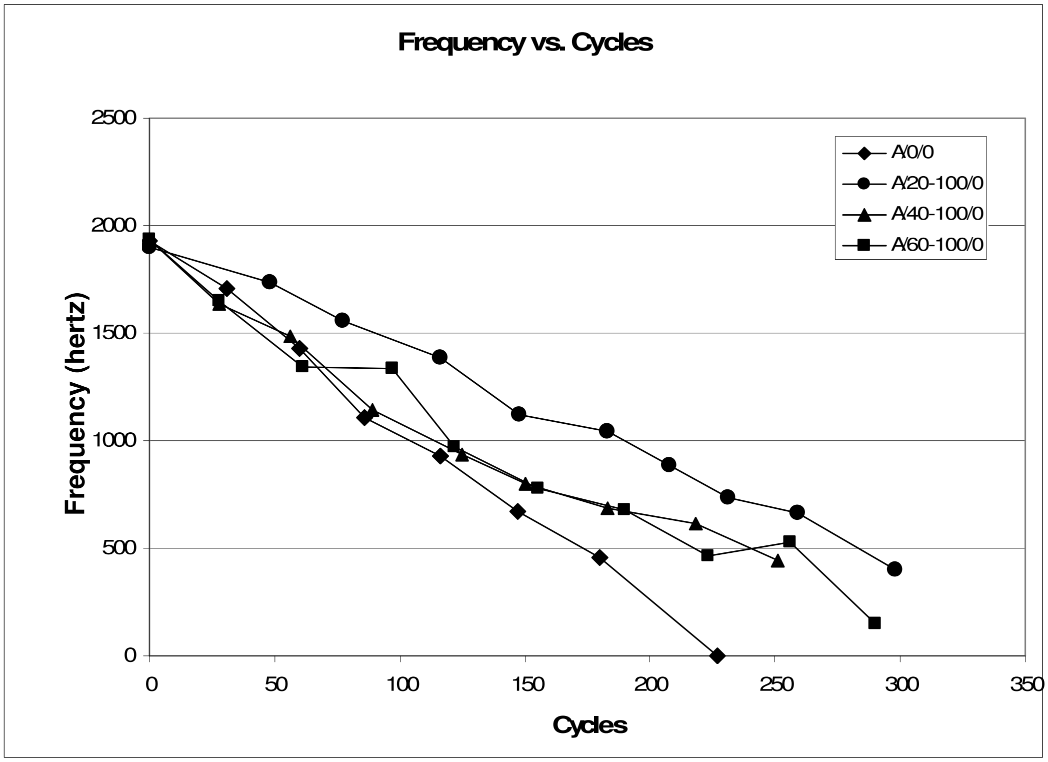


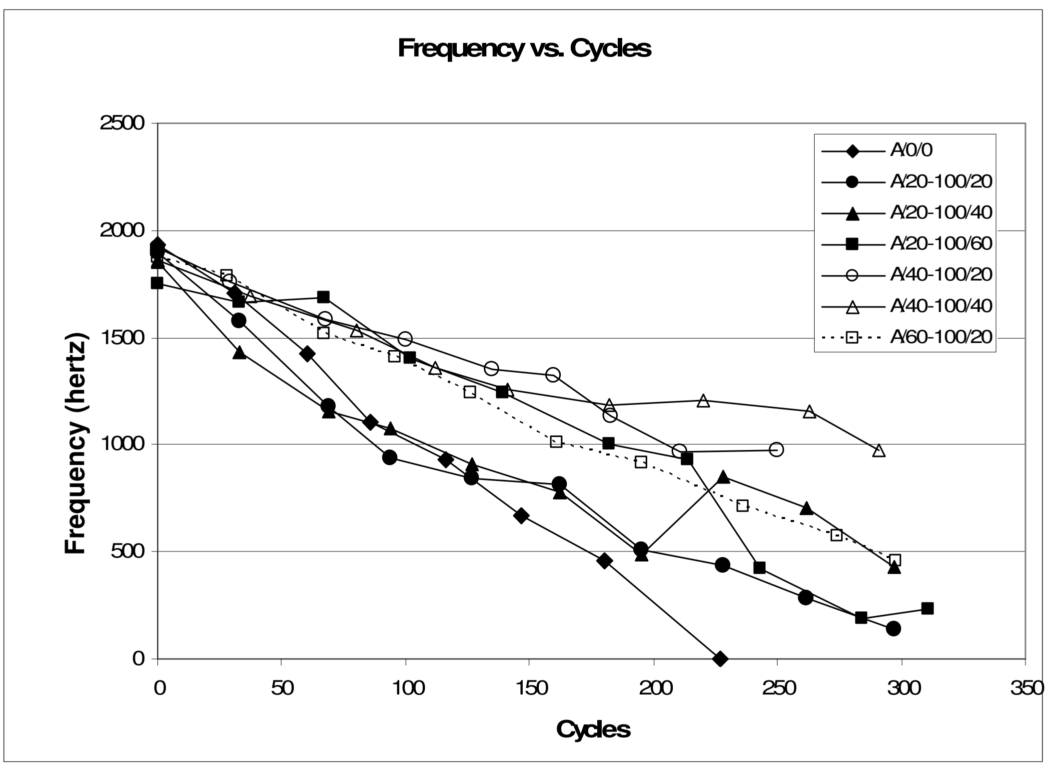


Frequency vs. Cycles
A/0/0
A/0/20
A/0/40
A/0/60
Frequency (hertz)
Cycles
2500
2000
0
0
50
100
150
200
250
300
350
400

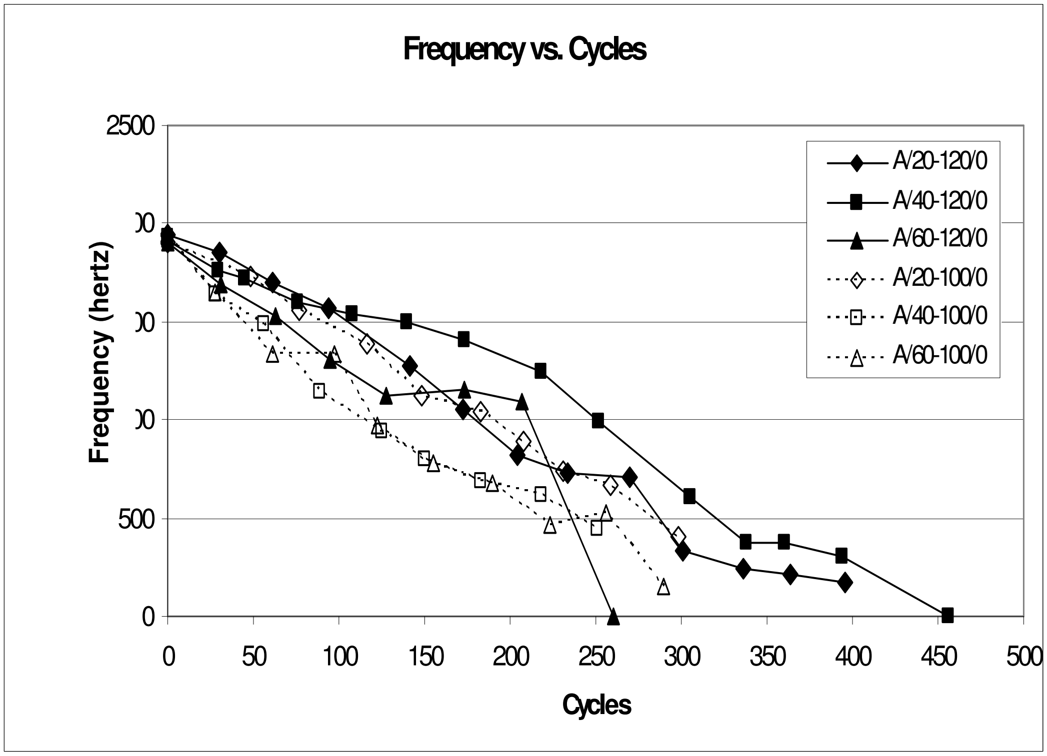


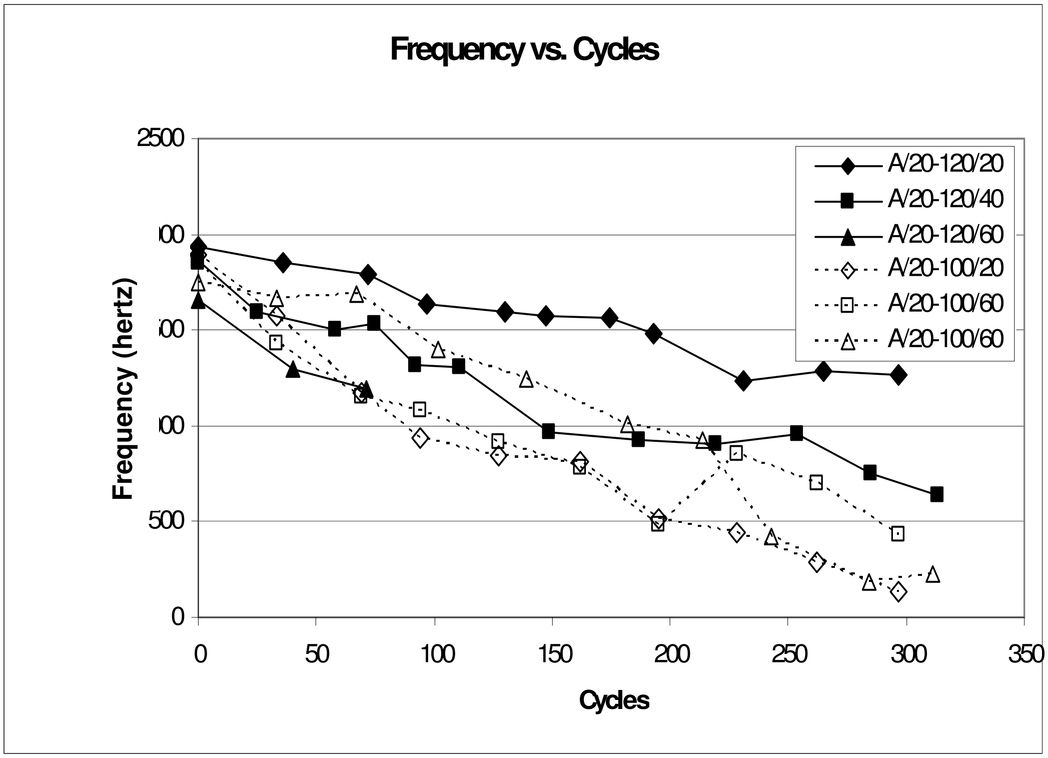
Frequency vs. Cycles
A/0/0
A/20-120/20
A/20-120/40
A/20-120/60
A/40-120/20
A/40-120/40
A/60-120/20
Frequency (hertz)
Cycles
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
350


Frequency vs. Cycles
Frequency (hertz)
Cycles
A/0/0
A/20-100/0
A/40-100/0
A/60-100/0
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
350

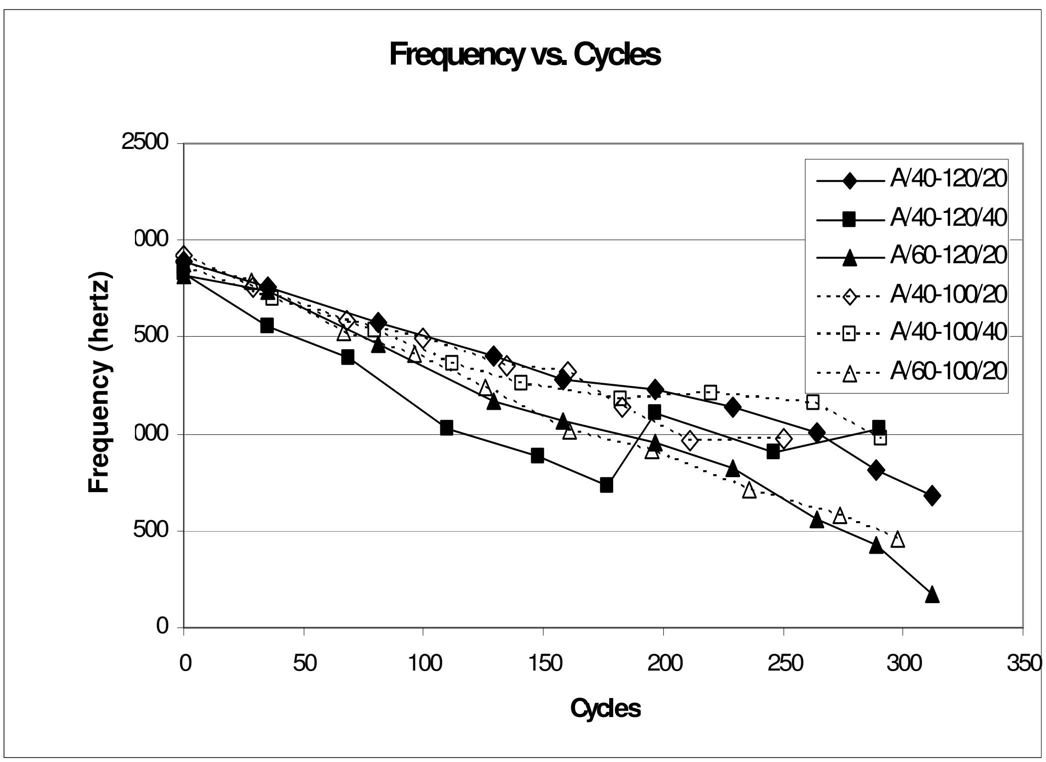

Frequency vs. Cycles
Frequency (hertz)
Cycles
A/0/0
A/20-100/20
A/20-100/40
A/20-100/60
A/40-100/20
A/40-100/40
A/60-100/20
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
350

A.3 Cement A Batches with GR 120 and GR 100 GGBFS for GGBFS Study





Frequency vs. Cycles
2500
000
500
000
500
0
0
50
100
150
200
250
300
350
Frequency (hertz)
Cycles
A/20-120/20
A/20-120/40
A/20-120/60
A/20-100/20
A/20-100/60
A/20-100/60



Frequency vs. Cycles
2500
000
500
000
500
0
0
50
100
150
200
250
300
350
Frequency (hertz)
Cycles
A/40-120/20
A/40-120/40
A/60-120/20
A/40-100/20
A/40-100/40
A/60-100/20

APPENDIX B: FREEZE/THAW SAMPLES AT FAILURE OR END OF TEST

Figure B.1 A/0/0

Figure B.2 A/0/0

Figure B.3 A/20-120/0

Figure B.4 A/40-120/0

Figure B.5 A/40-120/0

Figure B.6 A/40-120/0

Figure B.7 A/60-120/0

Figure B.8 A/60-120/0

Figure B.9 A/0/20

Figure B.10 A/0/20

Figure B.11 A/0/40

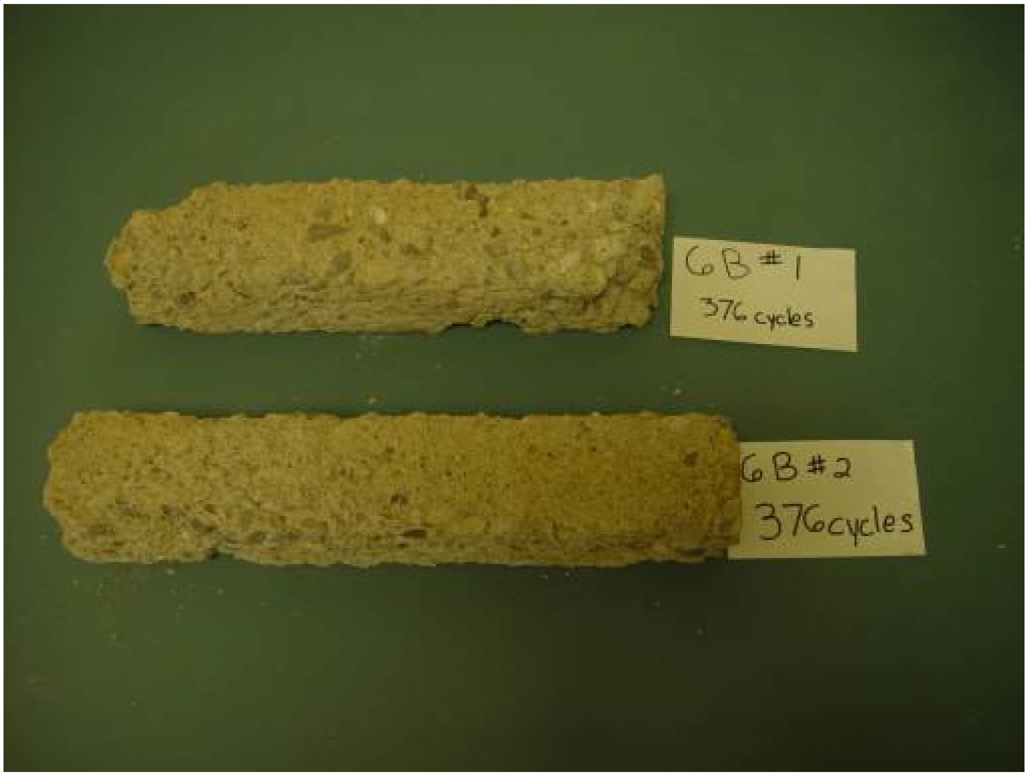


Figure B.12 A/0/60

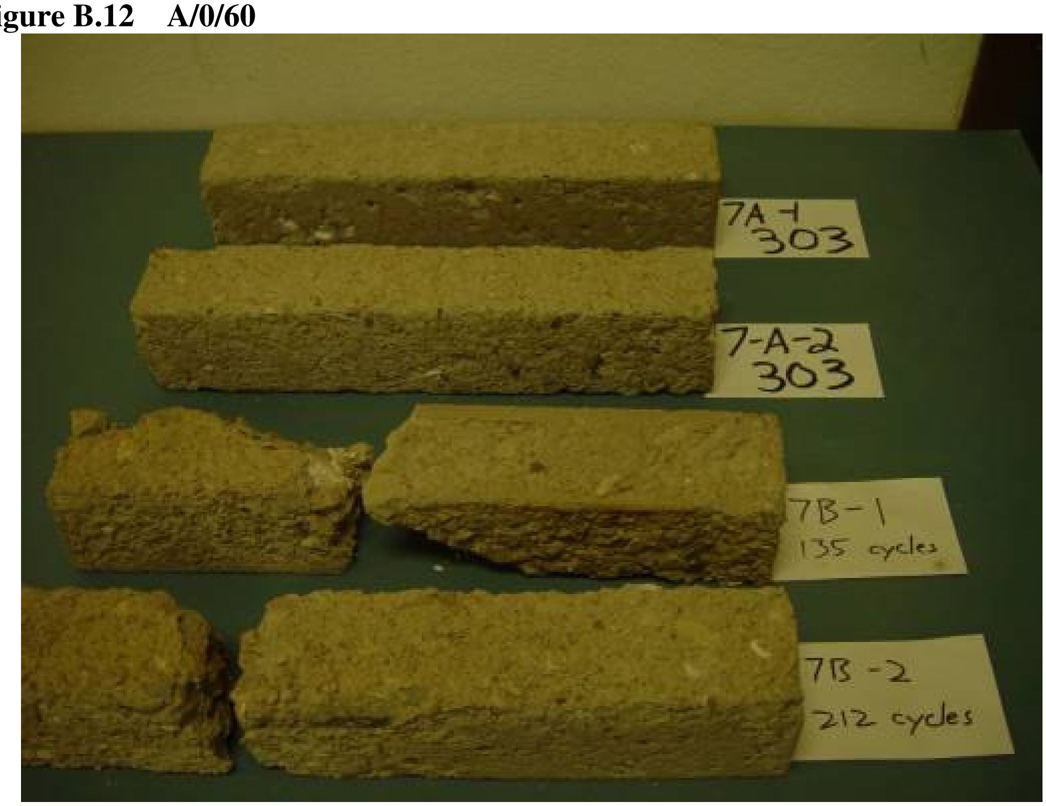


Figure B.13 A/20-120/20

Figure B.14 A/20-120/40

Figure B.15 A/20-120/60

Figure B.16 A/40-120/20

Figure B.17 A/40-120/40

Figure B.18 A/60-120/20

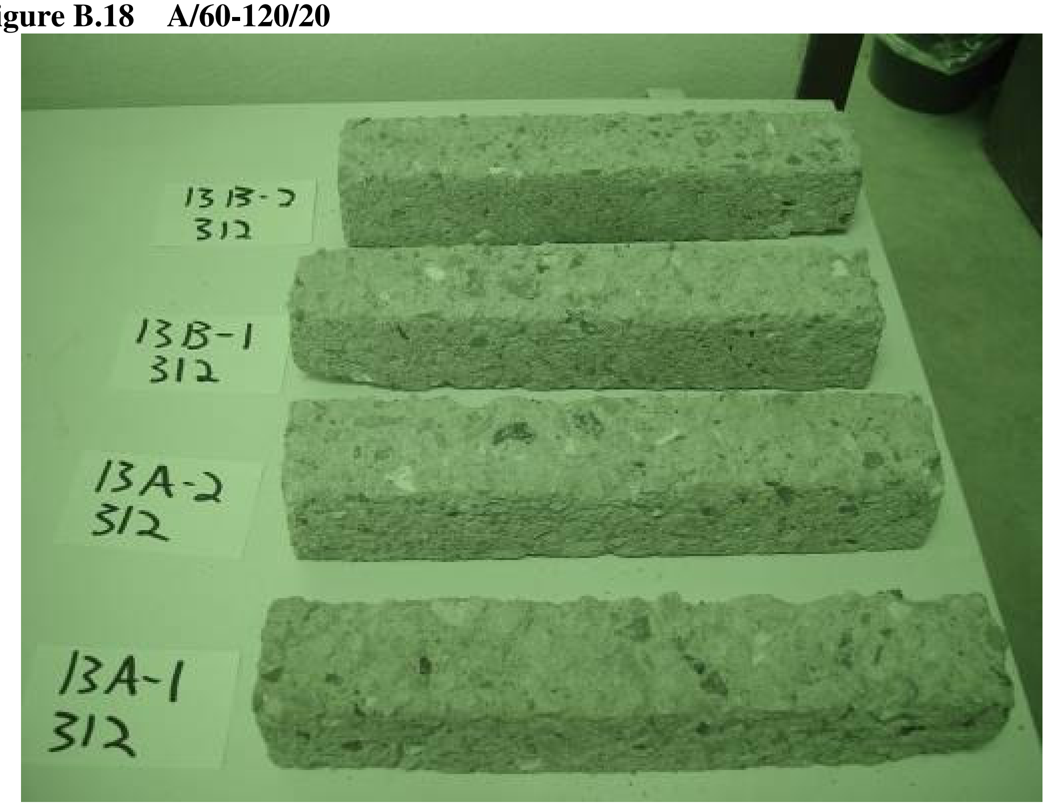


Figure B.19 A/20-100/0

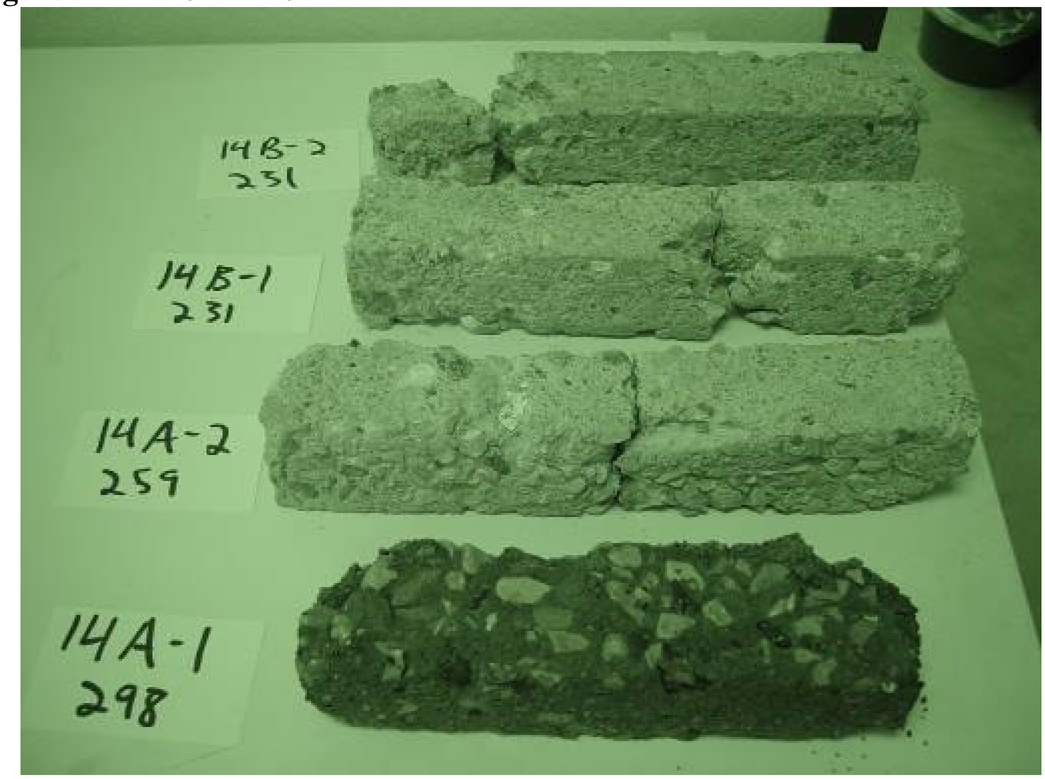


Figure B.20 A/40-100/0

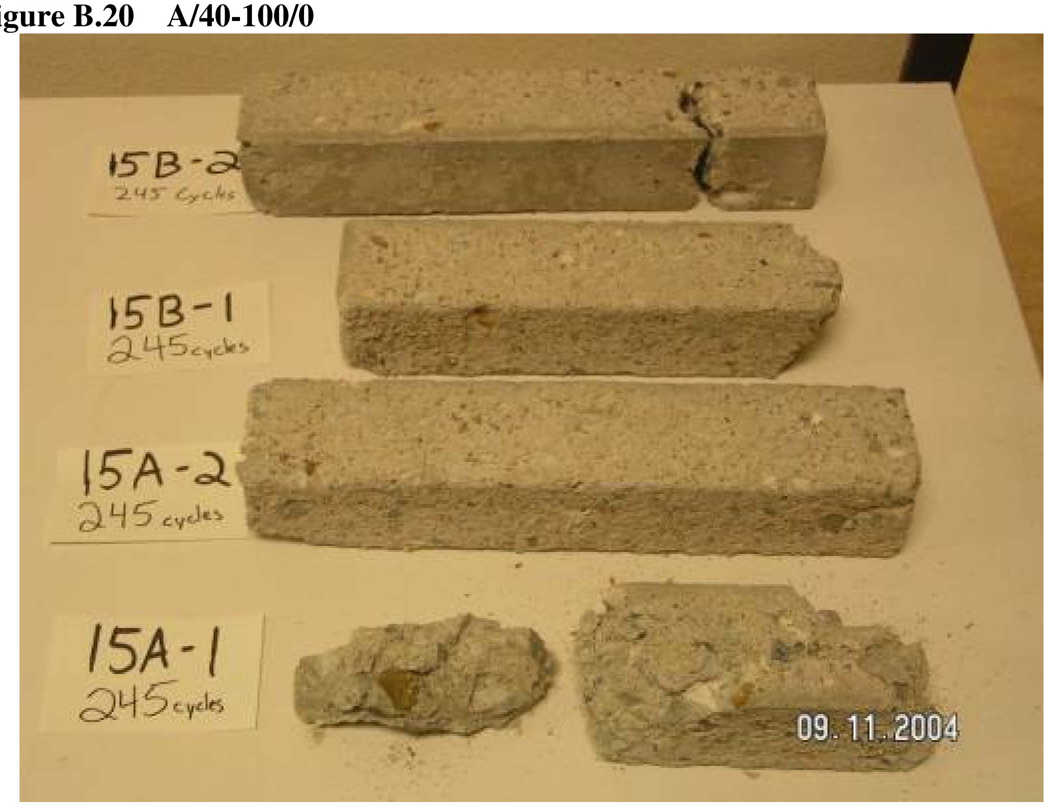


Figure B.21   A/60-100/0

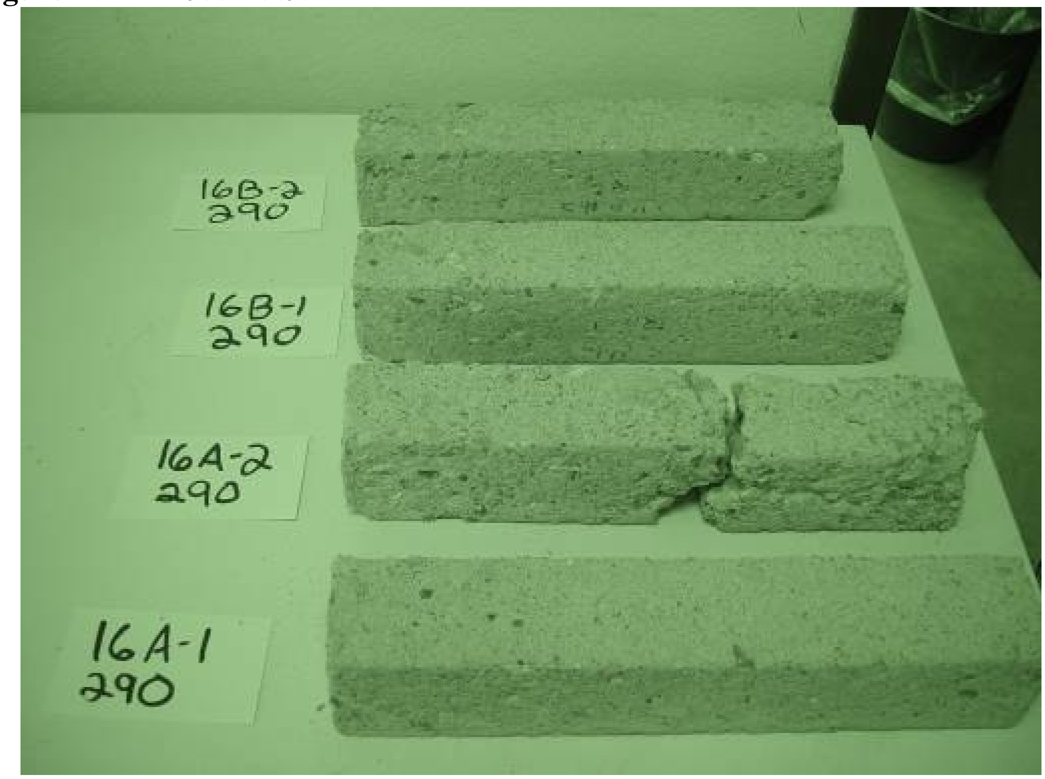


Figure B.22   A/20-100/20

Figure B.23 A/20-100/40

Figure B.24 A/40-100/20

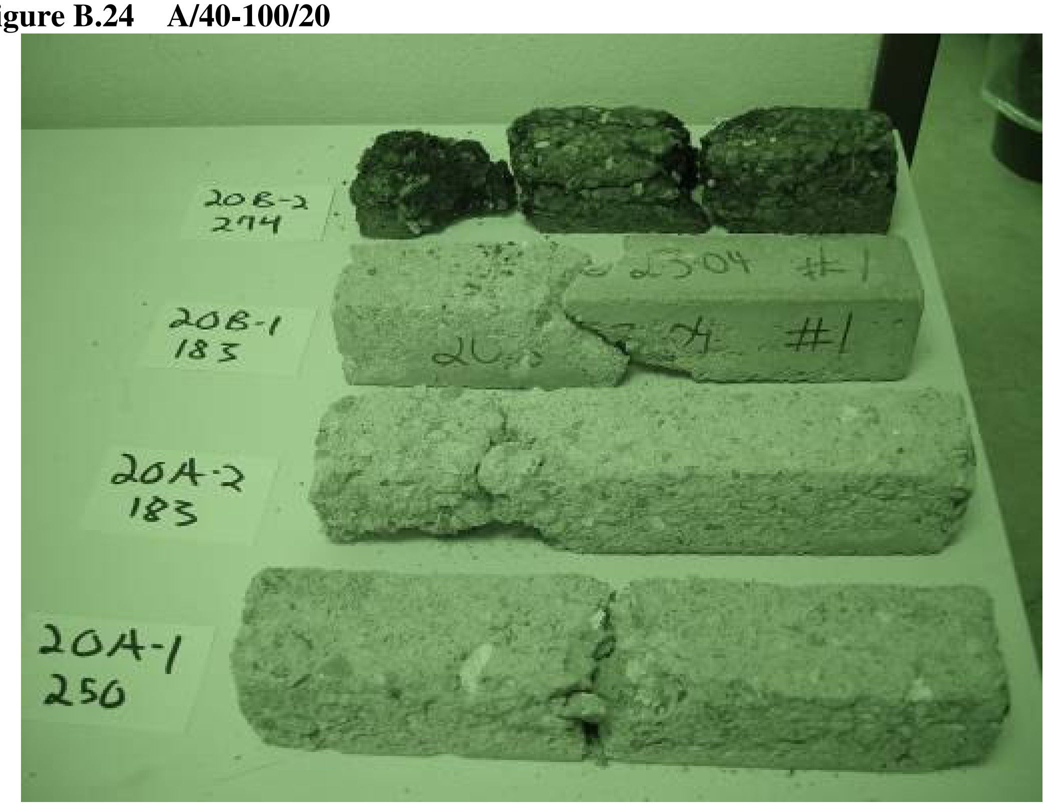


Figure B.25 A/40-100/40

Figure B.26 A/60-100/20

Figure B.27 B/0/0

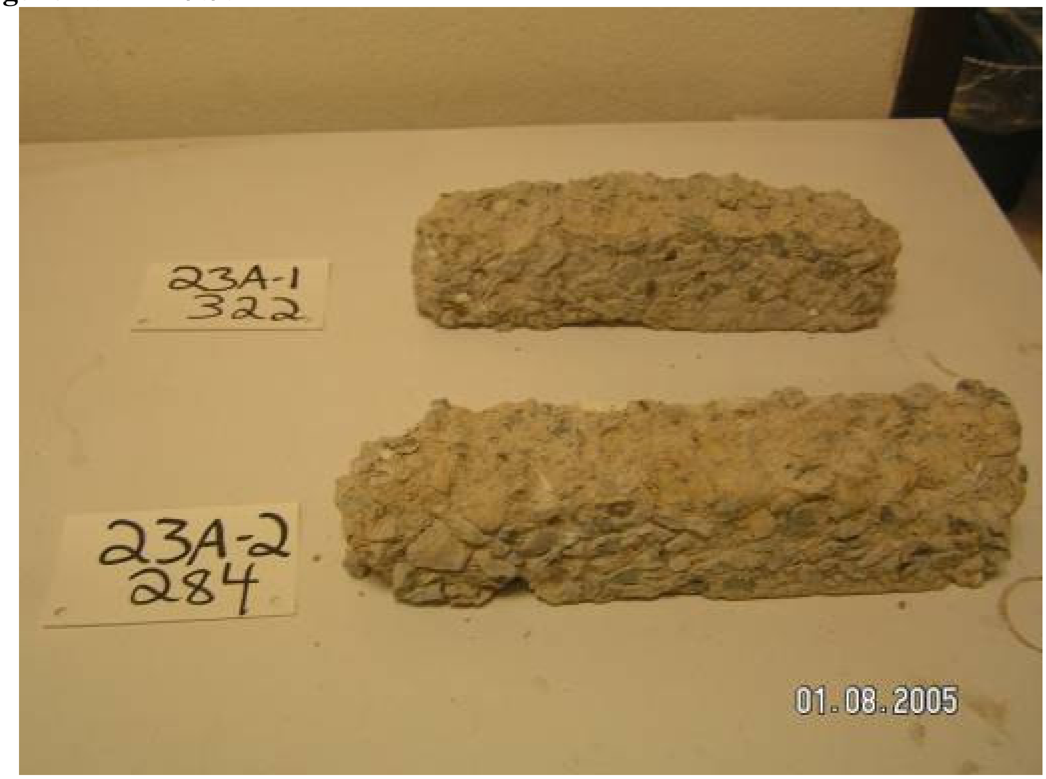


Figure B.28 B/60-120/0

Figure B.29   B/0/60

Figure B.30   B/20-120/20

Figure B.31 B/60-100/0

APPENDIX C: FRESH CONCRETE PROPERTY DATA

Table C.1 Slump (inches)

Mixture Design	Batch	Slump	Batch	Slump
A/0/0	A	1.75	B	1.5
A/20-120/0	C	2.25	D	2.5
A/40-120/0	A	0.75	B	0.75
A/60-120/0	A	0.75	B	0.75
A/0/20	A	2.75	B	4
A/0/40	A	6.5	B	5.5
A/0/60	A	7	B	7.5
A/20-120/20	A	2.25	B	2
A/20-120/40	A	6.5	B	6.75
A/20-120/60	C	7.75	D	8.25
A/40-120/20	A	4	B	5
A/40-120/40	C	3.25	D	8
A/60-120/20	A	4	B	3.25
A/20-100/0	A	2.5	B	2.5
A/40-100/0	A	2.5	B	2.25
A/60-100/0	A	1.75	B	1.75
A/20-100/20	A	4.25	B	5
A/20-100/40	A	5.25	B	6
A/20-100/60	A	7.25	B	7.5
A/40-100/20	A	4.25	B	2.75
A/40-100/40	A	7	B	5.5
A/60-100/20	A	2.5	B	1.25
B/0/0	A	3	-	-
B/60-120/0	A	2.75	-	-
B/0/60	A	8.75	-	-
B/20-120/20	A	3.75	-	-
B/60-100/0	A	3	-	-

Table C.2 Unit Weight (lb.ft^3)

Mixture Design	Batch	Unit Weight	Batch	Unit Weight
A/0/0	A	151.1	B	151.8
A/20-120/0	C	149.7	D	149.6
A/40-120/0	A	150.7	B	150.2
A/60-120/0	A	149.8	B	149.8
A/0/20	A	150.1	B	150.6
A/0/40	A	151.1	B	151.1
A/0/60	A	150.9	B	150.3
A/20-120/20	A	150.3	B	149.8
A/20-120/40	A	150.8	B	150.8
A/20-120/60	C	150.5	D	149.1
A/40-120/20	A	149.0	B	149.2
A/40-120/40	C	150.3	D	149.0
A/60-120/20	A	149.0	B	149.4
A/20-100/0	A	152.4	B	150.7
A/40-100/0	A	149.8	B	149.3
A/60-100/0	A	149.0	B	148.6
A/20-100/20	A	150.1	B	151.0
A/20-100/40	A	149.8	B	150.2
A/20-100/60	A	150.0	B	150.2
A/40-100/20	A	148.9	B	148.8
A/40-100/40	A	149.5	B	149.5
A/60-100/20	A	149.6	B	149.9
B/0/0	A	150.0	-	-
B/60-120/0	A	148.7	-	-
B/0/60	A	148.9	-	-
B/20-120/20	A	149.3	-	-
B/60-100/0	A	148.9	-	-

Table C.3 Air Content (%)

Mixture Design	Batch	Air Content	Batch	Air Content
A/0/0	A	1.4	B	1.3
A/20-120/0	C	1.5	D	1.5
A/40-120/0	A	1.4	B	1.6
A/60-120/0	A	1.5	B	1.7
A/0/20	A	1.0	B	1.0
A/0/40	A	0.7	B	1.1
A/0/60	A	0.6	B	0.5
A/20-120/20	A	1.4	B	1.5
A/20-120/40	A	1.2	B	0.9
A/20-120/60	C	0.5	D	0.5
A/40-120/20	A	1.5	B	1.5
A/40-120/40	C	1.2	D	1.0
A/60-120/20	A	1.2	B	1.3
A/20-100/0	A	1.6	B	1.5
A/40-100/0	A	1.2	B	1.3
A/60-100/0	A	1.4	B	1.5
A/20-100/20	A	1.3	B	1.2
A/20-100/40	A	0.7	B	0.9
A/20-100/60	A	0.4	B	0.5
A/40-100/20	A	0.9	B	1.4
A/40-100/40	A	0.7	B	0.9
A/60-100/20	A	1.2	B	1.5
B/0/0	A	1.7	-	-
B/60-120/0	A	1.5	-	-
B/0/60	A	0.4	-	-
B/20-120/20	A	1.3	-	-
B/60-100/0	A	1.2	-	-

Table C.4 Temperature (°F)

Mixture Design	Batch	Temperature	Batch	Temperature
A/0/0	A	88.7	B	90.9
A/20-120/0	C	82.5	D	81.0
A/40-120/0	A	69.7	B	67.3
A/60-120/0	A	73.5	B	71.5
A/0/20	A	76.5	B	74.8
A/0/40	A	74.0	B	74.1
A/0/60	A	75.2	B	68.2
A/20-120/20	A	70.0	B	64.7
A/20-120/40	A	65.1	B	57.1
A/20-120/60	C	64.8	D	57.1
A/40-120/20	A	70.2	B	69.0
A/40-120/40	C	81.0	D	82.0
A/60-120/20	A	71.4	B	67.4
A/20-100/0	A	82.0	B	82.9
A/40-100/0	A	80.8	B	80.1
A/60-100/0	A	82.4	B	83.6
A/20-100/20	A	83.5	B	86.9
A/20-100/40	A	77.1	B	76.9
A/20-100/60	A	79.3	B	78.6
A/40-100/20	A	84.0	B	84.0
A/40-100/40	A	84.5	B	85.0
A/60-100/20	A	78.0	B	75.0
B/0/0	A	80.0	-	-
B/60-120/0	A	78.0	-	-
B/0/60	A	80.0	-	-
B/20-120/20	A	80.0	-	-
B/60-100/0	A	82.0	-	-

APPENDIX D: HARDENED CONCRETE PROPERTY DATA

Table D.1 One Day Compressive Strength (psi)

Mixture Design	A	A	A	B	B	B
A/0/0	2250	2142	2255	2286	2400	2344
A/20-120/0	2282	2242	2099	1949	1845	1877
A/40-120/0	1555	1567	1481	1066	1099	1174
A/60-120/0	832	844	866	765	819	744
A/0/20	1272	1214	1370	1263	1105	1157
A/0/40	913	904	956	902	914	821
A/0/60	144	156	136	178	187	174
A/20-120/20	1347	1395	1372	1168	1127	1051
A/20-120/40	253	253	232	246	274	229
A/20-120/60	0	0	0	0	0	0
A/40-120/20	2040	2003	2087	1907	1969	1896
A/40-120/40	0	0	0	0	0	0
A/60-120/20	0	0	0	0	0	0
A/20-100/0	1935	1984	2187	1604	1713	1629
A/40-100/0	1250	1244	1296	1167	1207	1275
A/60-100/0	744	688	727	736	677	703
A/20-100/20	1292	1222	1160	1124	1055	1128
A/20-100/40	320	282	318	328	317	346
A/20-100/60	0	0	0	0	0	0
A/40-100/20	573	519	575	547	544	575
A/40-100/40	0	0	0	0	0	0
A/60-100/20	0	0	0	0	0	0
B/0/0	2163	2088	2005	-	-	-
B/60-120/0	0	0	0	-	-	-
B/0/60	1740	1870	1709	-	-	-
B/20-120/20	1393	1433	1283	-	-	-
B/60-100/0	0	0	0	-	-	-

Table D.2 Three Day Compressive Strength (psi)

Mixture Design	A	A	A	B	B	B
A/0/0	5123	5018	4660	5757	5612	5568
A/20-120/0	3352	4583	4583	4415	4118	4530
A/40-120/0	4070	4191	4260	3458	3718	3816
A/60-120/0	3046	2885	3288	3389	3045	3108
A/0/20	3996	4044	3766	4035	4452	4441
A/0/40	3389	3532	3587	3798	3755	3836
A/0/60	925	897	857	1081	1078	1222
A/20-120/20	4120	4245	4226	4347	4233	4210
A/20-120/40	2073	2088	2119	2007	2058	2084
A/20-120/60	92	92	96	92	97	92
A/40-120/20	2371	2683	2549	2942	2968	2920
A/40-120/40	0	0	0	0	0	0
A/60-120/20	1773	1802	1775	2059	2011	1943
A/20-100/0	4419	4374	4154	3836	3637	3676
A/40-100/0	3519	3536	3372	3513	3599	3514
A/60-100/0	2357	2338	2244	2329	2240	2440
A/20-100/20	3810	3551	3890	3646	3863	3686
A/20-100/40	2033	2034	1935	2253	2183	2223
A/20-100/60	0	0	0	0	0	0
A/40-100/20	-	-	-	-	-	-
A/40-100/40	873	832	804	949	914	957
A/60-100/20	1245	1227	1132	1223	1166	1185
B/0/0	3801	4335	3759	-	-	-
B/60-120/0	2794	2759	3189	-	-	-
B/0/60	1740	1870	1709	-	-	-
B/20-120/20	4200	4237	3927	-	-	-
B/60-100/0	1923	1884	1666	-	-	-

Table D.3 Seven Day Compressive Strength (psi)

Mixture Design	A	A	A	B	B	B
A/0/0	6087	6063	6350	6995	6745	6886
A/20-120/0	-	-	-	5672	5696	5834
A/40-120/0	5734	6004	6236	6094	5255	5634
A/60-120/0	5099	5091	5340	5461	5026	4869
A/0/20	6308	6175	6015	6324	6864	6368
A/0/40	6030	6122	5613	6419	6162	6329
A/0/60	4491	4576	4227	4008	4149	4062
A/20-120/20	6253	6248	6749	6540	6603	6685
A/20-120/40	4821	4814	4703	4528	4598	4619
A/20-120/60	1150	1058	1100	1200	1292	1155
A/40-120/20	4997	4918	4775	4626	4377	4269
A/40-120/40	3634	3671	3786	2940	2866	2936
A/60-120/20	3664	3603	3774	3748	3938	4010
A/20-100/0	6001	5524	5975	5454	5677	5699
A/40-100/0	7127	7444	7291	7407	7241	7131
A/60-100/0	4396	4600	4338	4877	4629	4697
A/20-100/20	6076	5975	5807	6377	6082	6005
A/20-100/40	3591	3766	3736	4021	4043	3986
A/20-100/60	762	802	832	791	864	938
A/40-100/20	4452	3918	3934	4387	4370	4355
A/40-100/40	1675	1716	1694	1943	1982	2016
A/60-100/20	3286	2958	3002	3311	3202	3300
B/0/0	5072	4844	5033	-	-	-
B/60-120/0	4455	4680	4755	-	-	-
B/0/60	3562	3769	3786	-	-	-
B/20-120/20	5632	5372	5917	-	-	-
B/60-100/0	4393	4227	4364	-	-	-

Table D.4 Twenty-eight Day Compressive Strength (ºF)

Mixture Design	A	A	A	B	B	B
A/0/0	7377	7092	7950	8303	7982	8352
A/20-120/0	7009	7043	6926	7168	7296	7251
A/40-120/0	7803	7663	8345	7572	7284	7291
A/60-120/0	6880	6942	6782	6953	7209	6677
A/0/20	7751	7762	8009	8113	7915	7910
A/0/40	8260	7757	7870	8142	8032	8490
A/0/60	7783	7766	7389	7401	7536	7762
A/20-120/20	8519	8757	7911	8750	9076	8581
A/20-120/40	8403	7908	7942	7657	7854	7566
A/20-120/60	4655	4612	4575	4317	4349	4506
A/40-120/20	7129	6969	7366	7144	7307	6969
A/40-120/40	6451	6308	6053	5476	5044	5279
A/60-120/20	6259	6799	6895	6853	6587	7004
A/20-100/0	7431	8059	7250	5696	4400	5373
A/40-100/0	8656	8404	8350	8220	8403	8540
A/60-100/0	7518	7680	7047	7240	6965	7150
A/20-100/20	8553	9390	9237	8754	8800	9451
A/20-100/40	6778	7174	6628	6988	7289	7337
A/20-100/60	2907	2882	2947	2718	2817	2748
A/40-100/20	8372	8075	8146	8524	8309	8689
A/40-100/40	4648	4788	4904	5622	4859	5195
A/60-100/20	7174	7797	7172	7155	7607	7169
B/0/0	6216	6223	6597	-	-	-
B/60-120/0	6599	5928	6681	-	-	-
B/0/60	5815	6182	6026	-	-	-
B/20-120/20	7442	7186	7235	-	-	-
B/60-100/0	5680	5856	5946	-	-	-

Table D.5 Ninety Day Compressive Strength (ºF)

Mixture Design	A	A	A	B	B	B
A/0/0	7857	8526	7935	8524	8676	7992
A/20-120/0	8613	8617	8356	8671	7881	8157
A/40-120/0	8985	8999	9078	8635	8755	8899
A/60-120/0	8098	8062	7737	7679	7978	7972
A/0/20	8620	9120	8984	9096	9139	9200
A/0/40	9381	9248	8918	9782	8964	9323
A/0/60	9518	9691	9554	9245	9358	9502
A/20-120/20	10299	9402	9492	10445	10029	10468
A/20-120/40	10108	10258	10248	9860	9814	10359
A/20-120/60	7543	7530	7873	7270	6970	7682
A/40-120/20	8902	8829	8392	8564	8769	8917
A/40-120/40	8093	7896	7900	6840	7309	6925
A/60-120/20	7616	7631	7405	7275	7895	7958
A/20-100/0	8146	9095	9260	8679	8614	7960
A/40-100/0	8887	8789	8777	9431	9465	9576
A/60-100/0	7758	7533	7986	8613	8062	8561
A/20-100/20	9664	10480	10180	10071	10589	10020
A/20-100/40	9685	9301	9634	10246	10137	9777
A/20-100/60	6527	6586	6491	6260	6039	6185
A/40-100/20	10039	9214	9646	10210	10605	9739
A/40-100/40	7433	7494	7764	7479	7619	7874
A/60-100/20	8622	8190	8480	8808	8336	8421
B/0/0	8053	7392	8114	-	-	-
B/60-120/0	6669	7500	6688	-	-	-
B/0/60	7889	7737	7718	-	-	-
B/20-120/20	8189	8719	8088	-	-	-
B/60-100/0	7720	7967	7922	-	-	-

Table D.6 Twenty-eight Day Permeability (adjusted coulombs)

Mixture Design				
A/0/0	6131	5021	2958	2951
A/20-120/0	2634	2258	2459	2415
A/40-120/0	1860	1727	1696	1591
A/60-120/0	857	1027	1032	831
A/0/20	4132	3790	4505	0
A/0/40	1985	2540	1713	0
A/0/60	1111	2555	3568	0
A/20-120/20	1251	1473	1586	641
A/20-120/40	1795	2138	1589	1034
A/20-120/60	3144	3281	2887	0
A/40-120/20	59	1021	0	0
A/40-120/40	419	433	221	250
A/60-120/20	422	504	595	0
A/20-100/0	1807	1636	2297	2088
A/40-100/0	1069	1025	1014	1034
A/60-100/0	489	475	0	477
A/20-100/20	1100	0	1420	185
A/20-100/40	3270	3146	0	3642
A/20-100/60	6387	5744	6240	0
A/40-100/20	0	848	807	818
A/40-100/40	1101	0	1022	1260
A/60-100/20	272	229	297	260
B/0/0	1670	1465	-	-
B/60-120/0	832	810	-	-
B/0/60	1193	1280	-	-
B/20-120/20	1253	1693	-	-
B/60-100/0	555	511	-	-

Table D.7 Ninety Day Permeability (adjusted coulombs)

Mixture Design				
A/0/0	3783	3439	0	0
A/20-120/0	1816	1416	1078	1423
A/40-120/0	889	221	782	0
A/60-120/0	690	686	218	667
A/0/20	1535	1458	1439	0
A/0/40	991	915	1027	1032
A/0/60	1097	1055	1220	749
A/20-120/20	729	722	753	0
A/20-120/40	800	789	941	737
A/20-120/60	589	410	488	0
A/40-120/20	588	563	773	0
A/40-120/40	345	412	332	388
A/60-120/20	0	362	334	376
A/20-100/0	0	826	1048	929
A/40-100/0	652	605	591	654
A/60-100/0	449	376	375	393
A/20-100/20	845	991	897	731
A/20-100/40	770	974	967	757
A/20-100/60	1161	1088	1053	1345
A/40-100/20	341	313	317	340
A/40-100/40	346	288	359	354
A/60-100/20	346	298	340	382
B/0/0	1754	1129	-	-
B/60-120/0	725	613	-	-
B/0/60	1447	1425	-	-
B/20-120/20	539	750	-	-
B/60-100/0	244	439	-	-

Table D.8 Freeze/Thaw Durability

Mixture Design	N at 0 cycles (Hz)	N1 at c cycles (Hz)	Cycles	Durability Factor
A/0/0	1963	455	180	3.22
	1916	476	180	3.70
	1925	327	180	1.73
	1925	165	258	0.63
A/20-120/0	1895	527	298	7.68
	1881	677	298	12.87
	1893	1040	298	29.98
	1860	1265	298	45.95
A/40-120/0	1891	1068	252	26.79
	1932	852	252	16.34
	1941	818	252	14.92
	1881	1210	252	34.76
A/60-120/0	1995	1012	207	17.76
	1863	1232	207	30.17
	1950	1073	207	20.89
	1811	1057	207	23.51
A/0/20	1882	393	254	3.69
	1852	667	254	10.98
	1903	606	254	8.59
	1894	590	254	8.22
A/0/40	1834	1277	62	10.02
	1817	996	62	6.21
	1903	695	304	13.52
	1829	625	304	11.83
A/0/60	1874	1099	303	34.74
	1870	1017	303	29.87
	1856	1236	74	10.94
	1775	142	185	0.39
A/20-120/20	1899	1300	297	46.40
	1975	1235	297	38.71
	1918	1176	297	37.22
	1965	1365	297	47.77
A/20-120/40	1865	655	313	12.87
	1890	991	313	28.68
	1831	631	313	12.39
	1888	614	313	11.03

Mixture Design	N at 0 cycles (Hz)	N1 at c cycles (Hz)	Cycles	Durability Factor
A/20-120/60	1640	1191	71	12.48
	1647	1362	40	9.12
	1705	1326	40	8.06
	1652	1164	40	6.62
A/40-120/20	1891	779	312	17.65
	1900	892	312	22.92
	1892	543	312	8.57
	1885	493	312	7.11
A/40-120/40	1764	680	289	14.32
	1747	968	289	29.58
	1789	637	289	12.21
	-	-	-	-
A/60-120/20	1953	191	312	0.99
	1793	173	312	0.97
	1754	172	312	1.00
	1791	166	312	0.89
A/20-100/0	1911	402	298	4.40
	1863	653	231	9.46
	1928	890	208	14.77
	1911	786	231	13.03
A/40-100/0	1876	684	218	9.66
	1933	470	251	4.95
	1974	501	251	5.39
	1959	363	251	2.87
A/60-100/0	1947	153	290	0.60
	1911	151	290	0.60
	1975	161	290	0.64
	1904	145	290	0.56
A/20-100/20	1958	139	297	0.50
	1853	136	297	0.53
	-	-	-	-
	1870	137	297	0.53
A/20-100/40	1864	652	297	12.11
	1835	342	297	3.44
	1880	352	297	3.47
	1841	376	297	4.13

Mixture Design	**N at 0 cycles (Hz)**	**N1 at c cycles (Hz)**	**Cycles**	**Durability Factor**
A/20-100/60	-	-	-	-
	-	-	-	-
	1707	211	311	1.58
	1796	248	311	1.98
A/40-100/20	1864	980	211	19.44
	1932	1358	183	30.14
	1925	1259	160	22.81
	1951	976	250	20.85
A/40-100/40	1846	837	291	19.94
	1841	1102	291	34.76
	1898	987	291	26.23
	-	-	-	-
A/60-100/20	1936	588	303	9.32
	1946	562	303	8.42
	1893	447	298	5.54
	1838	230	298	1.56
B/0/0	2015	176	322	0.82
	1900	494	243	5.48
B/60-120/0	1856	689	298	13.69
	1863	156	298	0.70
B/0/60	1809	500	227	5.78
	1815	912	145	12.20
B/20-120/20	1857	611	148	5.34
	1851	508	148	3.72
B/60-100/0	1891	570	309	9.36
	1914	850	309	20.31