Final Report

Development of Class P-SCC (Self-Consolidating Concrete) and Class A-SCC Concrete Mixtures

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16. Abstract

Self-consolidating concrete, also known as self-compacting concrete (SCC), is a highly flowable concrete that spreads into place and fills formwork without the need for mechanical vibration. SCC reduces the time and labor costs needed for concrete placement. This project was proposed by the Tennessee Department of Transportation (TDOT) and carried out by The University of Tennessee at Chattanooga (UTC). The aim of the proposed project was to develop four new SCC mixtures (two Class P-SCC and two Class A-SCC), and ensured they met the minimum strength and durability requirements for TDOT Class P and Class A mixtures. The proposed research program ensured that desired fresh properties are achievable with materials available in Tennessee. With the approval of TDOT management, Class P-SCC and Class A-SCC (with specified fresh and hardened properties) would appear as options in TDOT specifications. Four groups of mixtures were prepared, two of them were used to develop Class P-SCC mixtures and the other two were used to develop Class A-SCC mixtures. Each group consisted of twelve mixtures. The mixtures were subjected to testing to assess their fresh and hardened properties. Finally, the results of this study were evaluated to recommend performance specifications for Class P-SCC and Class A-SCC for TDOT adoption of SCC standard operating procedures.

17. Key Words
Self-Consolidating Concrete, Two Class SCC, Concrete Strength, Concrete Durability, Concrete Properties, Concrete Procedures

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Development of Class P-SCC (Self-Consolidating Concrete) and Class A-SCC Concrete Mixtures

The University of Tennessee at Chattanooga
Chattanooga, Tennessee

January 2016

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Chapter 1 INTRODUCTION

1.1 Background

Self-consolidating concrete (SCC), also known as self-compacting concrete, is a highly flowable, non-segregating concrete; it can fill formwork under its own weight without the need of conventional vibration techniques. Generally, SCC is made with conventional concrete components with the addition of chemical admixture such as viscosity-modifying admixture (VMAs) to enhance cohesion and control the tendency of segregation resulting from the highly flowable SCC (ACI, 2007). Also, the amount of SCC fine aggregate is usually higher than that for conventional concrete to provide better lubrication for course aggregates to enhance the workability of the mixture (Adekunle, 2012). The use of SCC was first used in Japan and has gained acceptance elsewhere since the late 1980s (ACI, 2007). During that time the durability of concrete structures became an important issue in Japan; thus an adequate compaction by skilled labors was required to obtain durable concrete structures. This requirement led to the development of SCC, and its first use was reported in 1989 (Okamura & Ouchi, 2003). SCC was initially used to provide proper consolidation in applications where concrete durability and service life were of concern. Later, SCC was also proven to be economically beneficial because of some factors as noted below (EFNARC, 2002):

- Accelerating construction times.
- Reduction in site manpower and equipment.
- Improved finished surfaces
- Improved ease of placement
- Improved durability
- Greater freedom in design
- Thinner concrete sections
- Reduced noise levels, absence of vibration
- Safer working environment

The use of SCC has been an excellent solution for the precast/prestressed concrete industry. In the precast industry, congested reinforcement and complex geometrical shapes make proper filling and consolidation using conventional concrete more difficult. Also, due to the relative ease of construction using SCC and superior quality control environment that is required in the precast industry SCC use has been a relatively easy transition. In North America, the use of SCC in the precast industry has grown dramatically since 2000. In 2000, the volume of SCC in the precast market was approximately 177,000 yd^3 (135,000 m^3), and it increased to 2.3 million yd^3 (1.8 million m^3) in 2003 (ACI, 2007). In 2002, 40% of precast manufacturers in the United States had used SCC, and in some cases, new plants are currently being built around the idea of using SCC technology (Vachon & Daczko, 2002).

Besides the above advantages, SCC has also been proven to have some disadvantages related to its fluid nature. SCC is a highly flowable concrete; therefore, formwork must be properly sealed and strong enough to inhibit leaking of the SCC paste and resist the higher hydrostatic pressures that are expected with fluid SCC (Keske, Schindler, & Barnes, 2013). Also, more studies are needed to examine the effects of adding chemical admixtures that give SCC its fluid nature, higher paste contents, and higher fine contents that may significantly change the fresh and hardened properties of the SCC compared to conventional concrete mixes (Missouri DOT, 2012).

1.2 Objectives and Scope of work

Self-consolidating concrete (SCC) is a concrete technology that is growing in popularity with the precast/prestressed industry and contractors. SCC achieves the ability to flow and self-consolidate through modified aggregate gradations, increased cementing materials, and chemical admixtures; therefore, its hardened properties are similar to conventional concretes. This project is funded by Tennessee Department of Transportation (TDOT) carried out by University of Tennessee at Chattanooga (UTC) to develop four new SCC mixtures; two Class P-SCC (precast) and two Class A-SCC (general use), and ensure they meet the minimum strength and durability requirement for TDOT Class P and Class A mixtures, respectively. The research program will ensure that desired fresh properties are achievable with materials available in Tennessee. With the approval of TDOT management, Class P-SCC and Class A-SCC (with specified fresh and hardened properties) would appear as an option in TDOT specifications. Using SCC mixtures can potentially save TDOT money by allowing TDOT suppliers and contractors to utilize this cost and time-saving technology. Also, greater use of supplementary cementing materials (SCMs) will improve TDOT's environmental stewardship.

As stated previously this study is funded by TDOT to research the fresh and hardened properties of SCC. The primary objectives of this study were to:

- Investigate the fresh properties of SCC in comparison to conventional concrete.
- Investigate the relationship between Visual Stability Index (VSI) and fresh-segregation of SCC.
- Investigate the effect on fresh properties of Class F & C fly ash, and various gradations of coarse and fine aggregates.
- Investigate the effect of accelerated curing process on the hardened properties represented by compressive strength, tensile strength and Modulus of elasticity.
- Recommend a specification for fresh and hardened performance requirements for Class-P and Class-A SCC that TDOT could use.

To achieve the above objectives the following scope of work was implemented: (1) review other states specifications and relevant studies and literature; (2) develop a research approach; (3) investigate the fresh properties of general use SCC mixes; (4) investigate the effects of VSI on fresh and hardened segregation of SCC mixes; (5) investigate the effects of VSI on permeability of SCC mixtures; (6) compare the fresh and hardened properties of SCC mixtures with conventional concrete mixtures; (7) analyze and study the information obtained throughout the mixing and testing to develop findings, conclusions, and recommendations; and (8) prepare this report in order to document the information obtained during this investigation, and provide the TDOT with the specification of fresh performance requirements for SCC. Finally, training was provided to TDOT Materials & Tests staff at all four regional offices to help familiarize them with SCC and its testing procedures. This training took place near the conclusion of the research project.

1.3 Research Approach

The study was divided into six major activities which were:

1. To conduct a comprehensive literature review of the state-of-the-art of SCC in the United States and the rest of the world. The literature review focuses on the current practices, types of materials used, and the types of tests used. Also, a survey of state specifications was conducted.
2. Typical Class P and Class A materials such as coarse aggregate, fine aggregates, cement, Class F and Class C fly ash, and some chemical admixtures were acquired from local TDOT suppliers. Also in this activity, the test specimens molds and experimental accessories were prepared as well as necessary equipment calibration was conducted.
3. Development of candidate Class P-SCC and Class A-SCC mixtures. Two Class P-SCC mixtures were developed, with 20% replacements of cement with Class F and the other mix without any replacement. These mixture proportions were developed based on the trial minimum requirement determined in activity one. Conventional concrete mixtures were prepared for the Class P to evaluate the performance of the SCC mixtures in comparison to conventional concrete. Also, two Class A-SCC mixtures were developed, with 20% replacements of cement with Class F fly ash and Class C fly ash. These mixture proportions were developed based on the trial minimum requirement determined in activity one. Several conventional concrete mixtures were developed for the Class A to evaluate the performance of the SCC mixes in comparison to conventional concrete. A total of 12 batches of each candidate mixture were produced using different coarse aggregate gradations, natural and manufactured sand.
4. The 48 candidate mixtures were tested with a variety of fresh consistencies and aggregate blends. Each Conventional mixture underwent standard fresh property testing which includes: slump (ASTM C 143); Unit Weight and Gravimetric Air Content (ASTM C 138); Air Content by Pressure Method (ASTM C 231). Also, SCC mixtures were subjected to the same fresh test except slump and underwent additional fresh tests which include: Slump Flow and Visual Stability Index (ASTM C 1611); Consolidating ability by J-Ring (ASTM C 1621); Static Segregation by Column Test (ASTM C 1610); and L-Box.
5. Casting of SCC specimens for the proposed hardened tests on the candidate mixtures after being cured under the accelerated curing process for Class P-SCC and standard curing for Class A-SCC. Each Class P-SCC mixture was tested at 18 hours, 28, and 56 days, while Class A-SCC mixtures were tested at 7 days, 28, and 56 days. Each mixture underwent standard hardened property testing which includes: compressive strength, splitting tensile strength, modulus of elasticity, rapid chloride permeability, and hardened concrete segregation by ultrasonic pulse velocity.
6. In the final activity, the fresh and hard properties data were compiled, analyzed and the effects of Visual Stability Index (VSI) on fresh segregation of SCC and compressive strength was investigated.

1.4 Study Outline

This study consists of six chapters. The first chapter discusses the historical background of SCC, The advantages of using SCC. Also, the chapter includes the objectives of the study and research approach to perform the study.

The second chapter will summarize a literature review about all the aspects of SCC and on the accelerated curing performed in the project. The mixture proportioning, fresh and hardened properties of SCC will be discussed. Also, a summary of the methods used to assess the fresh and hardened properties are addressed.

Chapter 3 summarizes the survey of state Departments of Transportation (DOTs) that was conducted to gather specifications related to SCC use in other states. The survey addresses the mixture parameters, fresh performance, and hardened performance requirements. The results of the survey were summarized and discussed in chapter 3.

Chapter 4 documents the development of the 32 SCC mixtures and 16 conventional concrete mixtures. A detailed description of these mixtures is provided which includes, but is not limited to, the selection of aggregate gradation, cementitious materials, chemical admixtures, and air entraining admixture. Also, the mixing procedure is documented, followed by descriptions of the fresh and hardened properties measured during this study.

The results of the fresh and hardened SCC tests are presented in Chapter 5. All conclusions and recommendations derived from the study are then summarized in Chapter 6.

Chapter 2 LITERATURE REVIEW

2.1 Introduction

Self-consolidating concrete (SCC) is a rapidly growing technology in the construction market and the precast industry because of its economic benefits and due to the relative ease of construction and superior quality control environment in that industry segment. SCC has been described as "the most revolutionary development in concrete construction for several decades (Vachon & Daczko, 2002). As mentioned earlier, SCC is highly flowable, and it is made with conventional concrete components and with chemical admixture such as viscosity-modifying admixture (VMAs) to enhance cohesion and to control the tendency of segregation resulting from the high flowability. SCC achieves the ability to flow and self-consolidate through modified aggregate gradations, increased paste or powders, and chemical admixtures; therefore, its hardened properties are similar to conventional concretes but its fresh properties differentiate it from conventional concrete. SCC should be designed to provide high levels of deformations while maintaining high stability. Therefore, the fresh properties of SCC are vital in determining whether or not it can be placed satisfactorily and with the required characteristics. The main four characteristics that should be met for SCC are mentioned below (ACI, 2007):

- Filling ability (unconfined flowability): The ability of the SCC to flow and completely fill all spaces in a mold or form under only self-weight.
- Passing ability (confined flowability): The ability to flow through reinforcing bars or other obstacles without segregation or mechanical vibration.
- Segregation resistance (stability): The ability to remain homogeneous in composition during transport and placing.
- Surface quality and finishing.

Throughout this chapter, the most commonly used test methods that are conducted to measure the SCC characteristics are briefly described. Also, a brief description of material proportion and hardened properties of SCC are discussed.

2.2 Test Methods for Measuring SCC Fresh Characteristics

Most of the conventional fresh property tests are not applicable to SCC due to its high flowable nature. Thus, many methods were derived to test the fresh properties and characteristics of SCC, which are briefly described below:

2.2.1 Slump Flow Test (ASTM C 1611)

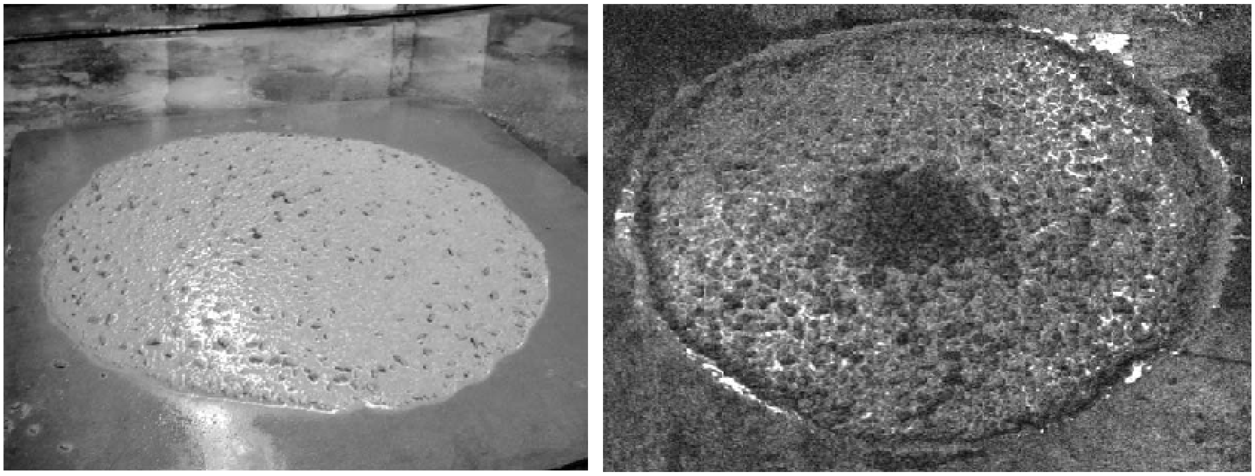
The slump flow is the most widely used test to measure the filling ability and flowability of SCC (ASTM, 2005). It was first developed in Japan to characterize fresh concrete mixtures for underwater placement (ACI, 2007). The test method is based on the conventional slump test. The diameter of an SCC "patty" is measured. This patty is formed from SCC free flowing from an inverted slump cone onto a level surface. The common range of slump flow that is reported by ACI Committee 237 is 18 to 30 inches (450 to 760 mm) for SCC. The higher the slump flow value, the greater ability to fill a formwork or mold, and the farther the SCC can travel from a discharge point under self-weight. An example of a slump flow test is shown in Figure 2.1.

Figure 2.1 Slump flow test

2.2.2 Visual Stability Index (ASTM C 1611)

The Visual Stability Index (VSI) is a method for determining the segregation stability of the mixture, and to evaluate the relative stability of batches of the same SCC mixture. The VSI is determined through visually rating apparent stability of the slump flow patty based on specific visual properties of the spread. The SCC mixture is considered stable and suitable for the intended use when the VSI rating is 0 or 1, and a VSI rating of 2 or 3 gives an indication of segregation potential (ACI, 2007). Assigning a Visual Stability Index (VSI) value to the concrete spread using the criteria shown Figure 2.2 (ASTM, 2005).

(a) (b)



(c) (d)

Figure 2.2 Visual Stability Index, (a) VSI = 0 – Concrete Mass is Homogeneous and No Evidence of Bleeding. (b) VSI = 1 – Concrete Shows Slight Bleeding Observed as a Sheen on the Surface. (c) VSI = 2 – Evidence of a Mortar Halo and Water Sheen. (d) VSI = 3 – Concentration of Coarse Aggregate at Center of Concrete Mass and Presence of a Mortar Halo.

2.2.3 T50 (ASTM C 1611)

The T50 value is another fresh property to quantify the flowing ability of SCC and provides a relative index of the viscosity. The test measures the time for the slump flow paddy to reach a diameter of 20 in (50 cm). A longer T50 time indicates a higher viscosity mixture, and a shorter T50 results from a lower viscosity mixture (ACI, 2007). ACI Committee 237 reports that an SCC mixture can be characterized as a lower viscosity mixture when the T50 time is 2 seconds or less, and as a higher viscosity mixture with T50 time greater than 5 seconds. The T50 test and slump flow test are typically performed with the same paddy.

2.2.4 J-ring (ASTM C 1621)

The test is used to determine the passing ability of SCC through reinforcement steel and obstacles. A sample of fresh SCC is placed in a standard slump cone with J-ring based, which contains steel bars. The mold is raised, the SCC passes through J-ring, and the J-ring patty diameter is measured (ASTM, 2009a). The higher the J-ring slump flow value, the greater ability the SCC has to fill a steel reinforced form or mold, and the farther SCC can travel through a reinforcing bar from a discharge point under its own weight (ACI, 2007). The difference between the unconfined slump flow and the J-ring slump flow is used to identify the restriction degree of SCC to pass through reinforcing bars. The mixtures passing ability and the blocking tendency could be determined according to the ASTM C1621 standard classification shown in Table 2.1. An example of a J-Ring test is shown in Figure 2.3.

Table 2.1Blocking assessment using J-ring

Difference Between Slump Flow and J-Ring Flow	**Blocking Assessment**
0 to 1 in.	No visible blocking
>1 to 2 in.	Minimal to noticeable blocking
>2 in	Noticeable to extreme blocking

Figure 2.3 J-Ring test

2.2.4 L-box Test

The L-box test is based on a Japanese design for underwater concrete (EFNARC, 2002). The test assesses the flow of the concrete, and also the extent to which it's subject to blocking by reinforcement. The apparatus consists of a rectangular-section box in the shape of an ‘L', with a vertical and horizontal section, separated by a movable gate, in front of which vertical lengths of reinforcement bar are fitted. The SCC is placed in the vertical section, and the gate is lifted to let the concrete flow into the horizontal section. When the flow stops, the heights of the concrete are measured at the end of the horizontal section and in the vertical section. The L-Box result is the ratio of the height of concrete in the horizontal section to remaining in the vertical section. ACI Committee 237 specified the minimum ratio of the heights to be 0.8, and the nearer this ratio to 1.0 is the better flow potential of the SCC mixture. An example of L-Box testing apparatus is shown in Figure 2.4.

Figure 2.4 L-Box testing apparatus

2.2.5 Column Segregation (ASTM C 1610)

This test is used to assess the segregation resistance of SCC. A sample of freshly SCC is placed in one lift in a cylindrical mold without tamping or vibration. The mold is allowed to rest for 15 minutes, and then the cylindrical mold is divided into three sections to represent different levels of the column. The SCC from the top and bottom sections is washed through a No.4 (4.75 mm) sieve, leaving the coarse aggregate on it. The mass of the coarse aggregate from the top and the bottom levels of the column are measured to calculate the percentage of segregation (ASTM, 2009b). The SCC is considered to be accepted if the percent segregation is less than 10% (ACI, 2007). An example of a column segregation test apparatus is shown in Figure 2.5.

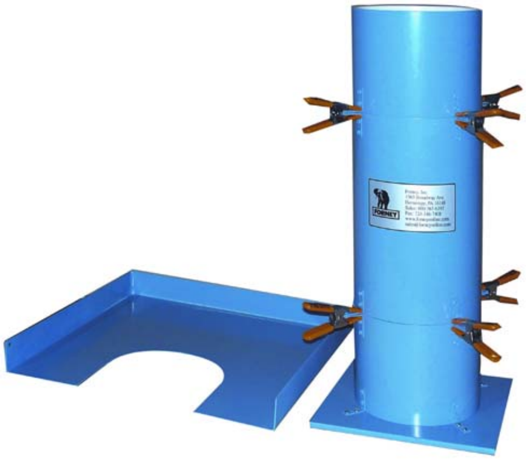


Figure 2.5 Column segregation apparatus

2.3 Constituent Materials and Mixture Proportions of SCC Mixtures

SCC is made with conventional concrete components which includes, coarse and fine aggregate, cement, supplementary cementing materials, water, air, and with some chemical admixture such as high-range water reducers and VMAs (ACI, 2007). In addition, SCC contains larger amount of powder and supplementary cementitious materials such as fly ash, silica fume, GGBFS, limestone powder, etc. in order to enhance the behavior of SCC.

2.3.1 Powders and Water Content

Powder includes cement, Ground Granulated Blast Furnace Slag (GGBFS), fly ash, Limestone powder, and any material that grinds to less than 0.125 mm (No.100 sieve) (ACI, 2007). SCC is comprised of a larger amount of powders than conventional concrete that can improve the characteristics of SCC, particle distribution, and packing, and ensuring highly cohesive SCC.

2.3.1.1 Portland Cement

The selection of the type of cement based on the overall requirements of SCC such as strength, durability, and the application (Keske et al., 2013; PCI, 2003). For general use concrete, the cement should not contain more than 10% of C_3A to avoid the problems of poor workability and quick hydration (Hameed, 2005). Therefore, most types of the five primary types of Portland cement can be used in SCC, and they should meet one of the following specifications: ASTM C 150, C 595, or C 1157 (ACI, 2007). For precast/prestressed concrete, ASTM C 150 type III cement is preferred due to its high early-age strength characteristics (K. H. Khayat, 1999).

2.3.1.2 Fly Ash

Fly ash is spherical with smooth surface particles, resulting from the burning of coal in coal-fired power plants. ASTM C 618 separates fly ash into two classes based on the calcium oxide content, Class C which contains 15 – 40 percent of calcium oxide, and Class F, which has less than 10 percent calcium oxide (ASTM C 618, 2003). Fly ash is used to replace portland cement to decrease the cost and heat of hydration associated with cement. According to ACI 2007 and Khayat et al. (2003), a replacement between 20 and 40% Class F fly ash in an SCC mixture led to good workability, with acceptable strength development and frost durability. However some studies showed using Class F fly ash can reduce the early strength at three and seven days (Keske et al., 2013; Mehta & Monteiro, 2006). Optimum replacement value is determined by job specification, material availability, cost, and the strength-gain needs of the application (ACI, 2007; Keske et al., 2013).

2.3.1.3 Mixing Water

The relationship between the water-to-cementitious-material ratio (w/cm) and the strength of concrete is an inverse relationship; the strength increases if the w/cm decreases (Keske et al., 2013; Mehta & Monteiro, 2006). For precast concrete high early-age strengths are desirable, thus a lower w/cm should be used, typically between 0.34 and 0.40 (Keske et al., 2013; Kamal Khayat & Mitchell, 2009). Therefore, high range water reducer admixtures (HRWRA) are used to increase the workability of SCC mixtures. Also, the stability of SCC could be increased by reducing the water content; thus, a suitable amount of water and water reducer is needed to maintain higher level workability and stability.

2.3.2 Coarse Aggregate and Fine Aggregate

The coarse aggregate size and volume should be chosen according to the required SCC characteristics (passing ability and stability of the plastic concrete) (ACI, 2007). The passing ability of SCC is very sensitive to the size and volume of coarse aggregate. Therefore, ACI Committee 237 recommends the nominal maximum size of the coarse aggregate to be one size smaller than suggested in (ACI Committee 301, 1994) to enhance the passing ability. The particle shape of coarse aggregate also affects the workability of SCC. A rounded coarse aggregate provides more filling ability than a crushed-stone of similar size (ACI, 2007). The fine aggregate, on the other hand, should be well-graded natural or manufactured sand. In general, it is recommended to blend natural and manufactured sand to improve the stability of SCC (ACI, 2007).

The decrease in total coarse aggregate volume enhances the passing and filling ability of SCC mixtures (Keske et al., 2013; Koehler et al., 2007). In precast/prestressed applications, where a high passing and filling ability is required, each of the coarse and fine aggregate could occupy one-third of SCC mixture by volume (Keske et al., 2013; Kamal Khayat & Mitchell, 2009; Koehler et al., 2007).

Aggregate angularity affects mortar and concrete properties primarily by changing water demand. Lower angularity fine aggregates are typically desired, if available. Manufactured sands tend to be more angular than natural sands due to the crushing operations needed to produce the sand and to the lack of abrading occurring with natural sands. The crushing process also tends to produce a considerable quantity of fines that must be wasted unless permitted to remain in the manufactured sand. Since the fines are primarily stone dust rather than clay or other contaminants, a higher percentage is allowed in manufactured sand specifications. The higher fines content will also increase water demand, all else being equal. The angularity of fine aggregate is usually quantified as the void content using the method proposed by the National Aggregates Association and standardized as ASTM C 1252. Particle shape will clearly affect the void content, but individual particle shape analysis has been conducted on coarse aggregate constituents. A similar analytical tool for fine aggregate would be useful (Dilek, 2004).

2.3.3 Admixtures

Admixtures are an essential component of SCC mixtures. Many types of admixtures are used to enhance the fresh properties of SCC mixtures such as, but are not limited to, HRWRAs, Viscosity-Modifying Admixtures (VMAs), and Air –Entraining Admixtures (AEAs).

HRWRAs are the most common admixtures that can be used to develop SCC mixtures. Generally, HRWRAs increase the fluidity of SCC, which helps to keep the water-cement ratio as low as possible (ACI, 2007). HRWRAs can affect the fresh properties of SCC through increasing the workability, and the hardened properties, especially strength, are affected by reducing the w/cm as a result of using HRWRAs (Keske et al., 2013).

Viscosity-Modifying Admixtures are beneficial components for controlling the viscosity and stability of SCC. A lower viscosity, lower resistance to flow, is required to increase the traveling distance of SCC during the placement (Keske et al., 2013; Koehler et al., 2007). VMAs can also be used with HRWRs to maintain a uniform stability at a lower viscosity (Keske et al., 2013; K. H. Khayat, 1999)

In general, the use of VMAs is not always necessary. The viscosity of SCC mixture can be adjusted through aggregate selection and graduation, or by controlling the amount of HRWRAs and/or VMAs. (Keske et al., 2013; KH Khayat, Ghezal, & Hadriche, 2000; Koehler et al., 2007).

AEAs are added to concrete to form macroscopic voids and microscopic bubbles in the concrete volume to provide space for expansion due to the cyclic freezing and thawing of water caught inside the concrete. AEA provides a uniform structure of voids, thus making their use widespread in precast SCC mixtures (Keske et al., 2013). AEA is typically added in small dosages; the dosage must be adjusted based on the concrete fluidity and production techniques employed (Keske et al., 2013).

2.4 Hardened Properties Tests

The hardened properties and behavior of SCC are similar to conventional concrete. The tests that are used to assess the performance of hardened properties are normally Compressive Strength (ASTM C 39), Static Modulus of Elasticity (ASTM C 469) and Splitting Tensile Strength (ASTM C 496). SCC may have a lower modulus of elasticity due to lower coarse aggregate content, which may affect deformation characteristics of pre-stressed concrete members. Additionally, creep and shrinkage are expected to be higher for SCC due to its high paste content, affecting pre-stress loss and long term deflection, although this may be offset in part due to relatively low w/cm of SCC commonly used in precast operations (Mata, 2004).

Other tests may be used to assess the hardened segregation of the concrete like Ultra-Sonic Pulse Velocity, which is testing a hardened column using the ultrasonic pulse velocity equipment. The test is measuring the velocity of an induced sound wave on the top and the bottom of the column. Differences in pulse velocity indicate greater segregation occurred in the concrete.

Another hardened property tests may be performed to assess the performance of SCC, such as the permeability. Several types of tests used to assess the permeability of the concrete like (AASHTO T 277 and ASTM C1202) or commonly known as the Rapid Chloride permeability test (RCPT), which uses an electric indication of concrete's ability to resist chloride ion penetration. Another test for permeability is Surface resistivity (SR) test (AASHTO TP 95) which takes less time and cost to prepare (Tanesi, 2012).

2.4.1 Rapid Chloride Permeability Test (ASTM C1202 / AASHTO T277)

This test method was originally developed by the Portland Cement Association, under a research program paid for by the Federal Highway Administration (FHWA). The original test method may be found in FHWA/RD-81/119, "Rapid Determination of the Chloride Permeability of Concrete." Since the test method was developed, it has been modified and adapted by various agencies and standard's organizations. These include:

- AASHTO T277, "Standard Method of Test for Rapid Determination of the Chloride Permeability of Concrete."
- ASTM C1202, "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration."

Many concrete structures are built today with specifications calling for low-permeability concrete. The construction industry accepts this test procedure as a measurement for determining chloride permeability.

2.5 Accelerated Curing of SCC

Accelerated curing is a way to achieve high early age strength. This practice is most common in the precast industry, where there is a need for concrete elements to be cast and removed from casting bed quickly for production purposes. The idea behind the accelerated curing is by increasing the concrete temperature, the rate of hydration increases and a larger portion of the later-age properties of the concrete can be attained during the short curing period compared with standard temperature curing. Different curing methods are being used to accelerate the curing process. Warm water, boiling water, and steam curing are all curing methods that have been used for a long time to cure concrete. With these techniques, concrete is subjected to boiling water or steam after 6 hours of being cast for about 12 hours to achieve high early age strength.

A new technique for accelerated curing was developed by a company called Products Engineering based Colorado. The method is based on generating the heat needed for curing the concrete using electricity; the system developed based on that idea is known as the SURE CURE system. The company developed both on-site systems to cure concrete in production and cylinders which are used for research. The SURE CURE Curing Control System is a computer-based concrete curing controller which allows entering the desired temperature profile for your concrete cylinders. Figure 2.6 below describes how the approach and connectivity of the different parts of the curing elements.

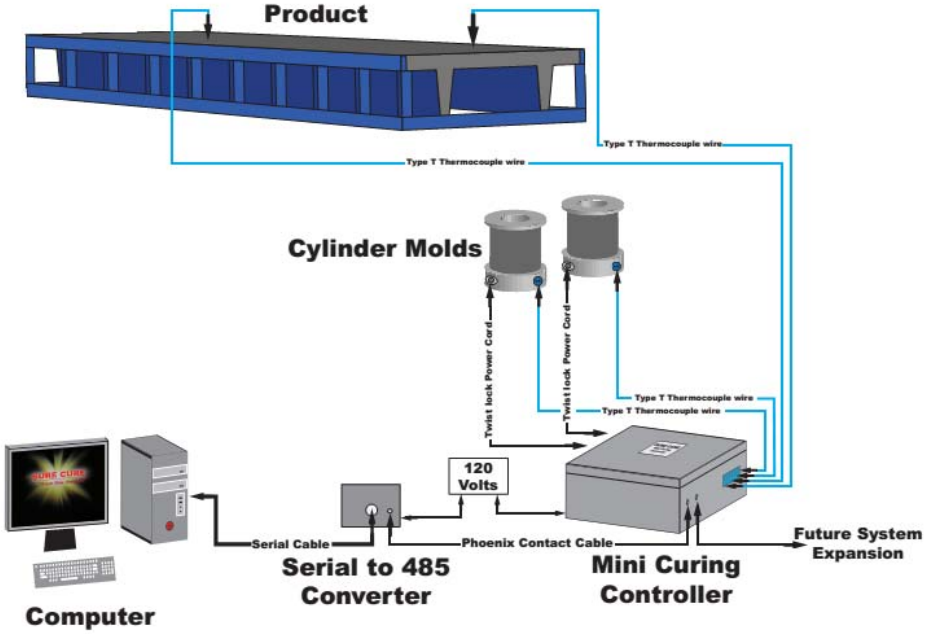


Figure 2.6 SURE CURE System

Chapter 3 SURVEY OF THE STATE SCC MATERIAL SPECIFICATIONS

3.1 Introduction

A survey of state Departments of Transportation (DOTs) was conducted to gather specifications related to SCC use in other states. The survey addresses the mixture parameters, fresh performance requirements, and the hardened performance requirements. The results of the survey are summarized and discussed in this chapter. In the summary, the term "general" will be used to describe specifications that allow for multiple uses or where a particular use is not explicitly stated.

3.2 Survey Requirements

The survey was distributed to the state DOTs in the US to gather information related to SCC specifications. The survey addresses the mixture parameters, fresh performance, and hardened performance requirements; the items specifically addressed by the survey are:

3.1.1 Mixture Parameters

- Maximum and minimum cement contents.
- Fly ash (and other SCM) usage allowances.
- Coarse aggregate gradation (maximum size) limits.
- Fine-to-total aggregate ratio limits (FA/TA).
- Air entrainment requirements (AE).
- Water-to-cement ratio requirements.

3.1.2 Fresh Performance

- Slump flow maximum/minimum limits.
- T-50 limit.
- Visual stability (VSI) limit.
- J-Ring, L-Box, segregation column, and other fresh performance requirements.

3.1.3 Hardened Performance

- Compressive strength requirements.
- Flexural/tensile strength requirements.
- Modulus of elasticity requirements.
- Permeability requirements.

3.3 Summary of The Survey

A summary of the 24 state DOTs that responded to the survey is shown in Figure 3.1. Oregon and Michigan responded that they do not allow SCC on their projects, and South Carolina responded that there was no industry demand for SCC. Of the states that use SCC, the survey results showed that 12 states allow for SCC in precast applications through specification or special provision. Seven states allow SCC for general use through specification or special provision. SCC in drilled shaft foundations is allowed in 4 states through special provision or specification. Three states allow SCC for other uses (caissons, bridges, and composite arch).

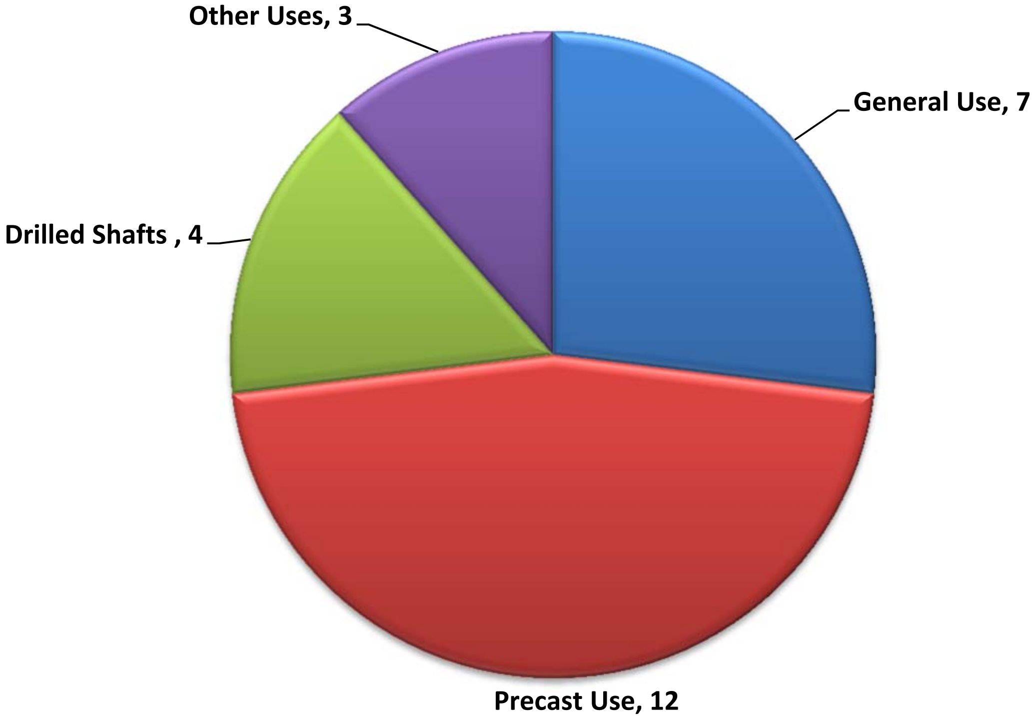


Figure 3.1Summary of SCC usage type among responding states

3.3.1 Summary of the Respondents

The survey was sent to 50 states; responses were received from 24 states. The specifications of the states that Departments of Transportation responded are briefly summarized in the next section and details are provided in Tables 3.1 - 3.5. The respondents generally indicated they do have some specifications for mixture parameters and fresh performance requirements; however, hardened properties, especially flexural strength, tensile strengths, and permeability were reported to be project-specific.

Alabama (ALDOT)

The SCC specifications for ALDOT are in the process of being finalized. However, they provided parameters which are applicable for SCC use in prestressed concrete. The parameters include the mixture proportions, fresh performance requirements, and the hardened performance requirements for SCC for precast use. They have specified 5000 psi compressive strength unless otherwise specified. For their permeability requirement, they have specified a maximum 2,000 coulombs in marine environments. Currently, ALDOT is considering the use of SCC for use in drilled shafts and columns.

Arizona (ADOT)

ADOT responded with the requirements they are using to approve SCC for precast. The parameters include the mixture proportions, in which they base the cement content loosely off of the requirements for structural concrete. The SCM content is up to the manufacture, but ultimately has to be reviewed and approved by the department. They do not require air entrained in precast or prestressed items. They do not have a Fine Aggregate to Total Aggregate (FA/TA) limit, but they stated they have not approved a mixture with an FA/TA of more than 0.48. There are no requirements for maximum aggregate size, but they report a #7 stone is typical. Column segregation is required during trial batching, and typically monthly during production. Compressive strength is the only hardened performance requirement, and it is as per specification.

California (Caltrans)

Caltrans provided general specifications for SCC, and it applies only where the job specifications allow the use of SCC. The provided specification allows for SCC use in several applications and is labeled general purpose for this report. The specifications contain the fresh performance requirements, the coarse aggregate gradation limits, and the SCMs usage allowance which include: fly ash, GGBFS, ultra-fine fly ash (UFFA), and metakaolin.

Colorado (CODOT)

Colorado State provided information on their specifications for SCC for use in caissons and precast. However, there were no specifications for precast use.

Florida (FLDOT)

FLDOT provided their specifications for the precast/prestressed concrete fabrication facilities that are involved in the manufacturing of the products using SCC. The specifications contain the mixture parameters requirements in which they do not mandate a coarse aggregate maximum size. Producers are using #67, #78 or #89 and may include additional blending of these; however, to avoid shrinkage concerns producers are trying to use #67 and #78 maximum sizes. The cementing and SCM requirements are the same as that of conventional concrete. The air entrainment requirement is 1% to 6%. The specifications also provide the fresh and hardened performance requirements which are a project-specific.

Idaho (ID DOT)

Idaho State SCC specifications are a modification of the Portland cement concrete specifications. The SCC specification provided is for Class 30 (3000psi) and Class 35 and greater (3500psi and greater) concrete. It contains the mixture parameter requirements and the fresh performance requirements.

Kentucky (KY DOT)

Kentucky DOT reported that SCC is only permitted for qualified precast plants. The SCC strength requirement is 3500psi for 28 days unless otherwise indicated in project plans. They specified the cement content, air entrainment, and the water-to-cement ratio requirements in the mixture parameters section.

Maine (ME DOT)

Maine DOT reported in their draft specifications that SCC can be used for Class A (general use), LP (Structural Wearing Surfaces) or P (Precast) mixes when approved by the Resident Engineer. The SCC should meet the requirements of strength, entrained air and permeability for the respective concrete Class.

ME DOT also provided a special provision for SCC that they used on bridge project using carbon-fiber composite arches. The special provision contains the mixture parameters, fresh performance requirements, and the compressive strength.

Maryland (MD SHA)

Maryland Department of Transportation's State Highway Administration (SHA) has been conducting a pilot program using SCC in a selected number of precast plants producing low-risk drainage structures for some years. Recently the Maryland Transportation Authority (Maryland's tolling authority) completed a large-scale project, the Inter-County Connector, which incorporated some prestressed beams utilizing SCC. SHA provided their current draft specification for SCC in precast and prestressed structures which contain the mixture parameters, fresh performance requirements, and the hardened performance requirements.

MD SHA administers some 30+ precast/prestressed plants over a ten state region. Due to the degree of variance in aggregate properties and variable needs for ASR mitigation, MD SHA does not set absolute aggregate limits. Trial batch results will indicate the need for adjustment to aggregates and SCM. MD SHA reports none of their producers are currently manufacturing an SCC mixture with any stone or gravel larger than #67.

Michigan (MI DOT)

MIDOT stated they do not allow SCC usage in their projects.

Minnesota (MN DOT)

Minnesota State DOT provided their draft performance specifications for SCC. They do not have a standard specification for SCC at the present. They have used SCC on a couple of projects when there were concerns about achieving consolidation around heavily reinforced locations. In those cases, they use conventional concrete specifications and added requirements for a VSI of less than 1 and a maximum spread of 28".

Mississippi (MS DOT)

Mississippi DOT provided information regarding SCC specifications for general use and drilled shafts concrete. The specifications are comprised of the mixture parameter requirements which include SCM usage, maximum size aggregate, air content and w/c. For fresh properties, they specify slump flow separately for precast and general use. Also, they specify J-ring, static segregate (column test) and bleeding capacity.

New Hampshire (NH DOT)

New Hampshire DOT has used SCC in precast operations, and they have an Alkali–silica reaction (ASR) and permeability requirement in which suppliers must use SCMs. For the fresh performance requirements, they responded that all the mixtures used for NHDOT have been developed by precast manufacturers with the assistance of admixture suppliers. A field test is required before placement to ensure the adequacy of the mixture. However, they do not report specific requirements for the fresh performance properties. NHDOT reported they have minimum compressive strength and permeability requirement for the hardened performance requirements, but they did not specify their values.

New Jersey (NJDOT)

New Jersey provided their SCC specifications for drilled shafts and precast concrete. The specifications contain the mixture parameters and the fresh performance requirements, and they specified the compressive strength and the permeability in the hardened performance requirements.

North Carolina (NCDOT)

NCDOT provided the standard special provision for SCC for Precast / Prestressed use. It contains the mixture parameters, fresh performance requirements, and specifies the compressive strength for hardened performance requirements.

Nevada (NV DOT)

Nevada Department of Transportation allows SCC only in drilled shafts. A minimum of 20% fly ash is required. There is no requirement for maximum aggregate size, but 1/2 inch is typical. There is no specification for FA/TA, but the mixtures range from0.57-0.43.

Oregon (OR DOT)

Oregon DOT reported they do not allow SCC usage in their projects.

Rhode Island (RIDOT)

RIDOT provided the general specification for SCC, which covers the requirements for modifying all classes of concrete mix designs, except classes B (General Use) and Z (Precast Elements) for self-consolidating applications. RIDOT does not have different requirements for conventional and SCC mixtures except for the maximum water/cement ratio, slump and placement methods.

South Carolina (SCDOT)

SCDOT does not have specifications for SCC in their standard specifications. They stated that the prestressed concrete producers in their state are not interested in working with SCC mixes, and that they would rather work with a high slump conventional concrete. However, a few years ago, University of South Carolina (USC) conducted a research study of SCC funded by SCDOT to investigate the performance, and the benefits of lightweight SCC prestressed concrete bridge girders.

South Dakota (SDDOT)

South Dakota DOT provided their current special provision for cast-in-place SCC, which is a modification of the SDDOT Standard Specifications for Roads and Bridges for conventional concrete. The specification addresses the mixture parameters and the performance requirements for general use.

Texas (TXDOT)

TxDOT provided their 2014 concrete specifications. They have allowed SCC concrete in precast concrete plants that produce girders, retaining walls, and coping for several years. Currently, they don't allow SCC concrete on the job sites, but they might start next year (2014) to allow SCC in drill shaft foundations. The 1500 coulombs permeability requirement reported in the table is only a required for mixture Option 8 (less than 20% SCM replacement).

Virginia (VADOT)

The Virginia DOT reported they were using SCC mixes with little specification differences from conventional concrete mix designs. The main differences are specifying a slump flow (ASTM 1611) rather than a slump, using the J-ring test (ASTM 1621) to check for flowability around steel and a different fine aggregate/coarse aggregate ratio. The specified SCC parameters are considered for general use.

Washington (WSDOT)

Washington State provided a specification for precast elements which allows for SCC use. SCC is only used on a case-by-case basis for other applications and would have to meet the requirements for testing and submittals of that class of concrete. The Mix design parameters are the same for SCC as for conventional precast concrete. The aggregate size is limited either by intended use (form work and rebar spacing) or limits in the specification by class of mix. Also, they also specify the fresh performance parameters and the compressive strength for hardened performance.

West Virginia (WVDOT)

West Virginia reported they do not have a specification for the SCC in their standards. When SCC has been used, it has either been specified by special provision or on a case-by-case approval with direct coordination with the precast fabricator. West Virginia provided their special provision specifications that they used on projects in which prestressed concrete box beams, prestressed beams, and drilled shafts that were constructed with SCC.

3.3.2 Summary of the specifications

The information provided by the respondents are tabulated and presented in Tables 3.1 - 3.5. The respondents addressed the mixture parameters, fresh performance requirements, and the hardened performance requirements for SCC which are summarized below:

Mixture Parameters

Selection of the maximum and minimum cement contents depends on the overall requirements for concrete, such as strength and durability. Of the responding states, 75% (18 states) provided cement content requirements which ranged between 470 -850 lb/yd3 for precast and 317 – 800 lb/yd3 for general use.

Of the states that responded 79% (19 states) allow fly ash, silica fume, and/or ground granulated blast furnace slag (GGBFS).

The maximum size of the aggregates depends on the particular application. Of the responding agencies, 62.5% (15 states) specify coarse aggregate gradation (maximum size or Nominal maximum size) limits, and about 46.7% of these agencies (7 of 15 states) specified ¾ inch as a maximum aggregate size.

The fine aggregate volume to total aggregate volume ratio is an important parameter for SCC. Eleven of the responding states (45.8%) provided a fine-to-total aggregate ratio limit, which is ranged between 0.4 to 0.5 for general use and 0.4 to 0.6 for precast use. In addition, 5 of the 11 (45.5%) states specified a 0.5 as a maximum fine-to-total aggregate ratio.

When a proper air-void system is provided, SCC can exhibit excellent resistance to freezing and thawing cycles and to deicing salt scaling. Of the responding agencies, 18 (75%)

specified ranges of air entrainment requirements, which ranged between 0 to 9%. In addition, 10 of 18 states (55.5%) reported 6.0± 1.5 % as air entrainment requirements.

Higher strengths in the SCC are typically achieved by lowering the water-cement ratio (w/c) of the concrete mixture. Of the respondents, 83.3% (20 states) addressed w/c limits, and 8 of the 20 (40%) specified 0.45 as a maximum w/c limit. Generally, w/c ranged from 0.30 to 0.50 for both precast and general use.

Fresh Performance

SCC in its fresh state exhibits different characteristics than conventional concrete. SCC by definition must flow under its own weight without the need for mechanical vibration. Also, it must display filling ability, passing ability, and segregation stability, so that when SCC consolidates it completely fill formwork and surround any steel reinforcement or prestressing strands.

The slump flow is the most widely used test to measure the filling ability of the SCC. Of the responding agencies, 19 (79.2%) specified a slump flow limits; it is ranged between 25 ±7in for general use and 26±3in for precast use.

The T50 is a method to quantify the flowing ability of SCC, and gives a relative index of the viscosity. The test measures the time for the concrete spread paddy to reach the 20 in. (50 cm). Seven states (29.1%) provided a T50 limits. Of these states, 4 out of 7 (57.1%) specified 2 to 7 sec for T50 test for the both precast and general use.

The Visual Stability Index (VSI) is a method for determining the stability of the mix and is determined by rating apparent stability of the slump flow patty. Of the responding agencies, 16 (66.7%) addressed a VSI limit, and 12 out of 16 agencies (75%) stated that a VSI of one or less would result in a stable batch.

The J-ring and L-Box are tests to measure the passing ability of SCC. The results show the J-ring is more commonly used by the responding states compared to L-Box test. The survey showed that 15 states (62.5%) are using the J-ring test, and 6 out of 15 states (40%) specified the difference between the conventional slump flow and the J-ring slump flow to be less than 2 inches for general use, and two states specified 3 inches as a difference for precast use. Also, 5 out of 15 states (33.3%) stated the J-ring slump flow to be less than 2 inches for the both general and precast use. Only one state (North Carolina) specified limits for the L-Box test which is 0.8 to 1.0 as the ratio of the height in the horizontal section relative to the vertical section.

Column segregation is a test to evaluate the static stability of a concrete mixture by quantifying aggregate segregation. Of the respondents, 10 states (41.6%) use this test to measure the stability of SCC, and 4 out of 10 states (40%) reported 10% as a maximum column segregation limit, and 3 out of 10 (30%) specified 15% as a maximum limit.

Hardened Performance

The Hardened properties of SCC may be engineered through the mixture proportion to be similar to those of a conventional concrete mixture. The hardened properties addressed in this survey are compressive strength (fc), modulus of elasticity (Ec), flexural/tensile strength, and permeability. Of the respondents, 17 (70.8%) states have compressive strength requirements, and 9 states (37.5%) have permeability requirements. The average of minimum compressive strength ranged between 3,000 to 8,000 psi among the states, and the maximum current (permeability) ranged from 1500-3000 coulombs for general use and 1500-4000 coulombs for precast use. Modulus of elasticity and tensile strengths were not specified.

Table 3.1 Summary of State DOTs specifications of the mixture parameter for SCC Alabama - New Hampshire:

State	Type	Mixture Parameters						Notes
		Cement (lb/yd^3)	SCMS	Max Agg.	FA/TA	AE%	W/C	
AL	**Precast**	600-850	Fly Ash, GGBFS, Silica Fume	3/4 in	0.45 - 0.55	4 - 6	0.40 max	
AZ	**Precast**	715	Fly Ash, GGBFS, Silica Fume	½ in	0. 48 max	NS	0.40 max	
CA	**General**	NS	Fly Ash, GGBFS, UFFA, Metakaolin, Silica fume	2 in	NS	NS	NS	
CO	**Caissons**	610 min	Fly Ash	NS	0.50	8 max	0.38-0.45	
	Precast	NS	NS	NS	NS	NS	NS	
FL	**Precast**	470- 752 min	Fly Ash, GGBSF	NS	0.50 max	1- 6	0.45	
ID	**General**	560 min	Fly Ash, GGBFS, Silica Fume	NS	NS	6.5±1.5	Max 0.40 - 0.45	
KY	**Precast**	564 min	NS	NS	NS	6± 2	0.46 max	
ME	**Composite Arch Tube**	850 min	Fly Ash, GGBFS,	3/8 in	0.50 min	3 (±3)	0.43 max	Special provision
	General	660 max		NS	NS	7.50	NS	
MD	**Precast**	615 min	DC	DC	DC	6.5± 1.5	0.32-0.50	
MI	Not allowed							
MN	**Bridge**	NS	Fly ash GGBFS Silica Fume	NS	NS	6 ± 2	0.45 max	Special provision
MS	**General**	NS	Fly ash GGBFS	1 in	NS	3-6	0.45 max	
	Drilled Shafts	NS	Fly ash (F) GGBFS	¾ in	NS	NS	0.45 max	
NH	**Precast**	NS	NS	¾ in	NS	NS	0.45 max	

NS = not specified.
DC = as per design criteria.

Table 3.2 Summary of State DOTs specifications of the mixture parameter for SCC New Jersey - West Virginia

State	Type	Mixture Parameters						Notes
		Cement (Ib/yd)	**SCMS**	**MAX agg**	**FA/TA**	**AE%**	**W/C**	
NJ	**Drilled Shafts**	611	Fly Ash, GGBFS, Silica fume	3/8 in	0.5 max	7.5 ± 2.0	0.443	
	Precast	564 - 658					0.4	
NC	**Precast**	639 - 850	Fly Ash, GGBFS, silica fume,	NS	0.40- 0.60	6.0±1.5	0.48	Special provision
NV	**Drilled Shafts**	639-925	fly ash, silica fume, GGBFS	NS	0.57-0.43	4-7	0.4	Special provision
OR	Not allowed							
RI	**General**	400 – 700	Fly Ash, GGBFS, Silica Fume	3/4 in	NS	5 - 9	0.36 max	aggregate of 1.5 in. allowed by special provision
SC	No interest from industry or vendors							
SD	**General**	700-800	Fly Ash	3/4 in	0.55 max	5.0 -7.5	0.45 max	Special Provision
TX	**Precast**	700 max	Fly Ash, GGBFS, Silica fume, Metakaolin	1 in	NS	NS	0.45	
VA	**General**	423 - 800	Fly Ash (F), GGBFS, Silica fume, Metakaolin	NS	0.40-0.50	4 - 8	0.45	
WA	**Precast**	564 - 660	Fly Ash GGBFS	3/4 in	NS	4.5 - 7.5	NS	
WV	**Drilled Shafts**	566-752	Fly Ash(F), GGBFS, Silica fume, Metakaolin	3/4 in	0.50 max	4.5 -7.5	0.42	Special provision
	Precast	NS				4 - 6	0.42 max	Special provision

NS = not specified.
DC = as per design criteria.

Table 3.3 Summary of State DOTs specifications of the fresh performance for SCC Alabama - New Hampshire

State	Type	Fresh Performance				Notes
		Slump flow limits	T-50 sec	VSI	J-Ring/L-Box /column	
AL	**Precast**	27” ± 2”	NS	< 2.0	Δ slump flow J-Ring flow <3.0 in	
AZ	**Precast**	30” max	NS	< 2	Column Segregation under 8%	
CA	**General**	20"min	2 - 7	≤ 1	Δ slump flow J-Ring flow <2.0 in, Column Segregation< 15%, Bleeding Capacity < 2.5 %	
CO	**Caissons**	21” ± 3”	NS	NS	Δ slump flow J-Ring flow ≤ 2.0 in,	Static Segregation <10%
	Precast	NS	NS	NS	NS	NS
FL	**Precast**	27” ± 2.5”	2 - 7	≤ 1	Δ slump flow J-Ring flow <2.0 in, Column Segregation <15%	
ID	**General**	25” ± 7”	NS	1.5max.	Δ slump flow J-Ring flow ≤1.5 in, Column Segregation ≤10%	
KY	**Precast**	NS	NS	NS	NS	
ME	**Composite Arch Tube**	27” ± 3”	NS	1.5max.	NS	Special provision
	General	NS		0 - 1		
MD	**Precast**	25” ± 3”	6 ± 4	0 -1	J-ring Column segregation	
MI	Not allowed					
MN	**Bridge**	Max 28”	NS	≤ 1	NS	Special provision
MS	**General**	28” ±4”	NS	NS	Δ slump flow J-Ring flow <1.5 or 2.0 in, Column Segregation <15%, Bleeding capacity < 2.5 %	
	Drilled Shaft	21” ±3”	NS	NS	Column Segregation <10%	Special provision
NH	**Precast**	NS	NS	NS	NS	

NS = not specified.
DC = as per design criteria.

Table 3.4 Summary of State DOTs specifications of the fresh performance for SCC New Jersey - West Virginia

State	Type	Fresh Performance				Notes
		Slump flow limits	**T-50 sec**	**VSI**	**J-Ring/L-Box /column**	
NJ	**Drilled Shafts**	21" ± 3"	NS	≤ 1	NS	Special provision
	Precast	26" ± 2"	NS	≤ 1	NS	
NC	**Precast**	27" ± 3"	NS	NS	Δ slump flow J-Ring flow <3.0 in, L-box Ratio: 0.8 - 1.0	Special provision
NV	**Drilled Shafts**	23" ± 5"	NS	≤ 1	Δ slump flow J-Ring flow <2.0in	Special provisio
OR	Not allowed					
RI	**General**	23" ± 3"”	NS	NS	Δ slump flow J-Ring flow <2.0 in	
SC	No interest from industry or vendors					
SD	**General**	25" ± 3"	NS	≤ 1	Δ slump flow J-Ring flow <2.0 in	
TX	**Precast**	25" ± 2"	2-7	0 or 1	Δ slump flow J-Ring flow ≤ 2 in, Column Segregation<10%, Bleeding < 2.5%	
VA	**General**	25 ± 3"	NS	0 or 1	Δ slump flow J-Ring flow <2.0 in	
WA	**Precast**	NS	< 6	≤ 1	Δ slump flow J-Ring flow ≤1.5 in, Column segregation <10%	
WV	**Drilled Shafts**	22" ± 1"	2 - 7	< 1.5	Δ slump flow J-Ring flow <1.5 in, Column Segregation <12%	Special provision
	Precast	23" ± 2"	2- 7	≤ 1	Δ slump flow J-Ring flow <1.5 in	Special provision

NS = not specified.
DC = as per design criteria.

Table 3.5 Summary of State DOTs specifications of the hardened performance for SCC Alabama - West Virginia

State	Type	Hardened Performance				Notes
		f´c (psi) 28 day	flexural /tensile	Ec(ksi)	Permeability (coulombs)	
AL	**Precast**	5000	NS	NS	Max 2,000	Permeability requirement for marine environments
AZ	**Precast**	DC	NS	NS	NS	
CA	**General**	DC	NS	NS	NS	
CO	**Caissons**	4000	NS	NS	NS	
	Precast	DC	NS	NS	NS	
FL	**Precast**	3000 - 8500	NS	NS	NS	
ID	**General**	3000-3500	NS	NS	NS	
KY	**Precast**	3500	NS	NS	NS	
ME	**Composite Arch Tube**	6000	NS	NS	NS	Special provision
	General	4350-5075	NS	NS	2000 - 2400	
MD	**Precast**	DC	NS	NS	2500	
MI	Not allowed					
MN	**Bridge**	4300	NS	NS	NS	Special provision
MS	**General**	4000	NS	NS	NS	
	Drilled Shaft		NS	NS	NS	Special provisions
NH	**Precast**	DC	NS	NS	NS	
NJ	**Drilled Shaft**	4600	NS	NS	NS	Special provision
	Precast	5400 min	NS	NS	max 1000	
NC	**Precast**	NS	NS	NS	NS	Special provision
NV	**Drilled Shaft**	4000	NS	NS	NS	Special provision
OR	Not allowed					
RI	**General**	3000 - 5000	NS	NS	1500 -3000	
SC	No interest from industry or vendors					
SD	**General**	4500 min	NS	NS	NS	
TX	**Precast**	DC	NS	NS	<1500	
VA	**General**	DC	NS	NS	NS	
WA	**Precast**	DC	NS	NS	NS	
WV	**Drilled Shaft**	4500 min	NS	NS	NS	Special provision
	Precast	8000	NS	NS	1500	Special provision

NS = not specified.
DC = as per design criteria.

Chapter 4 EXPERIMENTAL PLAN

4.1 Introduction

Throughout this chapter, the mixtures proportions, materials and suppliers, and the fresh tests used in the experimental program are discussed.

During this project, the survey of state Departments of Transportation (DOTs) was conducted to gather specifications related to SCC use for general and precast elements in other states. The findings of the survey were used to develop and select the mixture proportions and components, and selecting the appropriate methods to evaluate the fresh and hardened characteristics of SCC mixtures. In accordance with the requirements of this project, the materials used in the study were procured from local suppliers within the state of Tennessee and were TDOT approved materials.

4.2 Mix Designs

Class P Mixture proportions were developed based on the information obtained from the DOT survey conducted by The University of Tennessee at Chattanooga in cooperation with the TDOT Materials and Tests Division. Two sets of mixtures were developed to assess the effect of VSI on both hardened and fresh properties of Class P-SCC. Each set consists of four Trial mixtures groups. Portland cement was only used as cementitious materials on the first batch, whereas portland cement and Class F fly ash is utilized in the second set. Fly ash was designed to replace 20% of the cement materials in the second batch. TDOT specifications sets a minimum of 658 lbs. of cementitious materials to be used in their mixtures; however, this value did not achieve the strength requirement of 4000 psi in 18 hours, the cement content was increased by 20 lbs in the first 12 batches to 678 lbs, and increased on the second 12 batches containing fly ash to 777 lbs.

The groups in each set were divided on the basis (ASTM C 33) coarse aggregate sizes and fine aggregates used. The first group in each set was using #67 stone and natural sand while the second group was designed to have #67 stone and manufactured sand. The third and fourth group had the same fine aggregates which were natural sand; however the difference was #7 stone used as a coarse aggregate in the third group while #89 stone was used in the fourth group. A total of 12 mixtures were in each set result in 24 mixtures to be tested. Each group consisted of three mixtures; two of them were SCC mixtures with varying VSI value while the third mix was a conventional concrete mix used as a control.

SCC mixtures were designed with 50% fine aggregates of the total volume to provide the necessary filling, passing, and flowability characteristics and a 44% fine aggregate was used for conventional concrete mixtures. Typically, all the mixtures were designed with 0.45 water-cementitious materials ratio. In addition, the TDOT Class P mixtures were developed to have no air entertained in the concrete. Only 2% of entrapped air was allowed in the mixtures. Mixture proportions are provided in Tables 4.1 and 4.2. The aggregate weights are provided for the saturated-surface dry condition. HRWRA values in the Table were estimated in the design, but the actual values were obtained during the mixing process to produce the required VSI.

Class A mixture parameters used by other states were analyzed, and the mix designs for Class A concrete (general use) were then established according to the other states specifications, and TDOT Class A requirements. A total of 24 mixtures were developed which represent two Class A-SCC mixtures and conventional concrete as controls.

The Class A mixtures were designed with 20% cement replacement using Class C fly ash, and Class F for the other. Each Class A mixture was duplicated 12 times with varying visual stability index values of 1 and 2, different aggregate sizes (ASTM C 33 #57,#67, and # 7), and with natural and manufactured sand as shown in Tables 4.3 and 4.4. Different HRWR dosages were used to provide varying fresh properties and to achieve the high flowability of the SCC without increasing the w/cm. Typically, the mixes were designed with HRWR dosages of 7 oz/cwt and 9 oz/cwt to provide a VSI of 1 and 2 respectively, and dosage of 4 oz/cwt of mid-range water reducer to provide conventional concrete mixtures with a slump of 3 to 5.5 in. HRWR doses were later adjusted and corrected during the mixing process to attain the desirable fresh properties. SCC mixtures were designed with 50% sand to total volume to provide the necessary filling, passing, and flowability characteristics and a 44% sand ratio was used for conventional concrete mixtures. Typically, all the mixtures were designed with 0.45 water cementation materials ratio. Also, the TDOT Class A mixes were developed to have a 6% air entertained using Air entrained admixtures (AEA) to provide the necessary durability of SCC. Mixture proportions of the experiential mixtures are presented in Tables 4.3 and 4.4. The aggregate weights are provided for the saturated-surface dry condition.

Table 4.1TDOT Class P Mixtures with Portland Cement

Mixture No	1	2	3	4	5	6	7	8	9	10	11	12
VSI	1	2	Conv.	1	2	Conv.	1	2	Conv.	1	2	Conv.
Cement	678	678	678	678	678	678	678	678	678	678	678	678
Class F-Ash	0	0	0	0	0	0	0	0	0	0	0	0
# 67 stone	1551	1551	1735	1550	1550	1735	0	0	0	0	0	0
# 7 stone	0	0	0	0	0	0	1551	1551	1735	0	0	0
# 89 stone	0	0	0	0	0	0	0	0	0	1551	1551	1735
Natural sand	1470	1470	1295	0	0	0	1470	1470	1295	1470	1470	1295
Manufactured sand	0	0	0	1550	1550	1364	0	0	0	0	0	0
Design Air	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Water	304	304	304	304	304	304	304	304	304	304	304	304
AEA (oz. /yd.)	0	0	0	0	0	0	0	0	0	0	0	0
H/MRWR (oz./cwt)	7	9	4	7	9	4	7	9	4	7	9	4
w/cm ratio	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Sand ratio by volume	0.5	0.5	0.44	0.5	0.5	0.44	0.5	0.5	0.440	0.5	0.5	0.44

All weights in lbs. /yd^3.
HRWR dosages are design values, the actual values are shown in Chapter 5.
Admixture demands are dependent on aggregates.
Con.: Conventional concrete.

Table 4.2 TDOT Class P Mixtures with 20% Cement Replacement of Class F fly Ash

Mixture No	13	14	15	16	17	18	19	20	21	22	23	24
VSI	1	2	Conv.	1	2	Conv.	1	2	Conv.	1	2	Conv.
Cement	622	622	622	622	622	622	622	622	622	622	622	622
F-Ash	155	155	155	155	155	155	155	155	155	155	155	155
# 67 stone	1480	1480	1658	1480	1480	1658	0	0	0	0	0	0
# 7 stone	0	0	0	0	0	0	1480	1480	1658	0	0	0
# 89 stone	0	0	0	0	0	0	0	0	0	1480	1480	1658
Natural sand	1405	1405	1237	0	0	0	1405	1405	1237	1405	1405	1237
Manufactured sand	0	0	0	1480	1480	1304	0	0	0	0	0	0
Design Air	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Water	311.13	311.13	310.71	311.13	311.13	310.71	311.13	311.13	310.71	311.13	311.13	310.71
AEA (oz. /yd.)	0	0	0	0	0	0	0	0	0	0	0	0
H/M-RWR (oz./cwt)	7	9	4	7	9	4	7	9	4	7	9	4
w/cm ratio	0.400	0.400	0.400	0.400	0.400	0.400	0.400	0.400	0.400	0.400	0.400	0.400
Sand ratio by volume	0.500	0.500	0.440	0.500	0.500	0.440	0.500	0.500	0.440	0.500	0.500	0.440

All Weights in lbs. /yd^3.

HRWR dosages are design values, the actual values are shown in Chapter 5.

Admixture demands are dependent on aggregates.

Con.: Conventional concret

Table 4.3 TDOT Class A mixtures with 20% cement replacement of Class C fly ash

Mixture No	25	26	27	28	29	30	31	32	33	34	35	36
VSI	1	2	Con.	1	2	Con.	1	2	Con.	1	2	Con.
Cement	496	496	496	496	496	496	496	496	496	496	496	496
Class F-Ash	0	0	0	0	0	0	0	0	0	0	0	0
Class C-Ash	124	124	124	124	124	124	124	124	124	124	124	124
# 57 stone	1504	1504	1684	0	0	0	0	0	0	0	0	0
# 67 stone	0	0	0	1504	1504	1684	1504	1504	1684	0	0	0
# 7 stone	0	0	0	0	0	0	0	0	0	1504	1504	1684
Natural sand	1426	1426	1256	1426	1426	1256	0	0	0	1426	1426	1256
Manufactured sand	0	0	0	0	0	0	1504	1504	1324	0	0	0
Design Air	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%
Water	279.1	279.1	279.1	279.1	279.1	279.1	279.1	279.1	279.1	279.1	279.1	279.1
AEA (oz/yd)	2	2	2	2	2	2	2	2	2	2	2	2
H/MRWR (oz/cwt)	7	9	4	7	9	4	7	9	4	7	9	4
w/cm ratio	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Sand ratio by volume	0.50	0.50	0.44	0.50	0.50	0.44	0.50	0.50	0.44	0.50	0.50	0.44

All weights in lbs./yd³.
HRWR and AEA dosages are design values, the actual values are shown in Chapter 5.
Admixture demands are dependent on aggregates.
Con.: Conventional concrete.

Table 4.4 TDOT Class A mixtures with 20% cement replacement of Class F fly ash

Mixture No	37	38	39	40	41	42	43	44	45	46	47	48
VSI	1	2	Con.	1	2	Con.	1	2	Con.	1	2	Con.
Cement	496	496	496	496	496	496	496	496	496	496	496	496
F-Ash	124	124	124	124	124	124	124	124	124	124	124	124
C-Ash	0	0	0	0	0	0	0	0	0	0	0	0
# 57 stone	1504	1504	1684	0	0	0	0	0	0	0	0	0
# 67 stone	0	0	0	1504	1504	1684	1504	1504	1684	0	0	0
# 7 stone	0	0	0	0	0	0	0	0	0	1504	1504	1684
Natural sand	1426	1426	1256	1426	1426	1256	0	0	0	1426	1426	1256
Manufactured sand	0	0	0	0	0	0	1504	1504	1324	0	0	0
Design Air	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%
Water	279.1	279.1	279.1	279.1	279.1	279.1	279.1	279.1	279.1	279.1	279.1	279.1
AEA (oz/yd)	2	2	2	2	2	2	2	2	2	2	2	2
H/M-RWR (oz/cwt)	7	9	4	7	9	4	7	9	4	7	9	4
w/cm ratio	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Sand ratio by volume	0.50	0.50	0.44	0.50	0.50	0.44	0.50	0.50	0.44	0.50	0.50	0.44

All Weights in lbs. /yd^3.

HRWR and AEA dosages are design values, the actual values are shown in Chapter 5.

Admixture demands are dependent on aggregates.

Con.: Conventional concrete

4.3 Materials Used in The Experimental Plan

4.3.1 Cementitious materials

Portland cement ASTM C 150 Type I and ASTM C 618 Class C & F fly ash are the cementitious materials used in the project. All cement that was utilized in the project was acquired locally from Buzzi Unicem USA- Chattanooga. The stock was stored in the laboratory during the study period. The chemical composition of the cement is shown in Table 4.5. Class F Fly ash was used to replace 20 % of Portland cement in the mixtures. All Class F fly ash used in the project was acquired locally from The SEFA Group Cumberland City, TN, and was kept in the laboratory during the study period. The chemical composition of Class F is shown in Table 4.6.

Table 4.5 The chemical composition of the cement.

Component	Weight %	Component	Weight %
SiO_2	19.8	C_3S	64.1
Al_2O_3	4.6	C_2S	8.3
Fe_2O_3	3.5	C_3A	6.2
CaO	63.3	C_4AF	10.7
MgO	3	$C_3S+4.75C_3A$	93.3
SO_3	2.7	CO_2	1.2
Total alkalis(Na_2O +0.658 K_2O	0.53	Limestone	3.1
Ignition Loss	1.7	$CACO_3$ in Limestone	89.2
Insoluble Residue	0.3	-	-

Table 4.6 The chemical composition of Class F & C fly ash.

Component	Class F Weight %	Class C Weight %
SiO_2	44.29	35.4
Al_2O_3	18.39	17.3
Fe_2O_3	19.23	5.3
Sum of Constituents	81.9	58.1
CaO	8.87	26.1
MgO	0.86	4.6
SO_3	2.72	2.8
Loss on Ignition	1.65	0.4
Moisture Content	0.16	0.1
Alkalis as Na_2O	0.84	0.84

4.3.2 Coarse Aggregates

The coarse aggregates employed in this study were crushed stone type, sourced locally from Vulcan Materials, Chattanooga, TN. Different aggregate sizes were used during this study which includes ASTM C 33 #57 Stone, #67 Stone, #7 Stone, and #89 Stone, that all met TDOT standards. All the coarse aggregates had bulk specific gravity of 2.74 and absorption of 0.62 %.

Tables 4.7, 4.8, 4.9 and 4.10 shows the coarse aggregate grading for #57 Stone, #67 Stone, and #7 Stone respectively, and the combined aggregate graduation is shown in Figure 4.1.

Table 4.7 #57 Stone gradation

Sieve Opening	**Cumulative Percent Passing**
1.25 in.	100%
1 in.	95%
¾ in.	76%
½ in.	42%
3/8 in.	26%
NO. 4	6%
Pan	0%

Table 4.8 #67 Stone gradation

Sieve Opening	**Cumulative Percent Passing**
1 in.	100%
¾ in.	90%
½ in.	51%
3/8 in.	35%
NO. 4	8%
Pan	0%

Table 4.9 #7 Stone gradation

Sieve Opening, inch	**Cumulative Percent Passing**
¾ in.	100%
½ in.	99%
3/8 in.	80%
NO. 4	11%
NO. 8	1%
Pan	0%

Table 4.9 #89 Stone gradation

Sieve Opening, inch	**Cumulative Percent Passing**
1 in.	100%
¾ in.	100%
½ in.	100%
3/8 in.	98%
NO. 4	39%
NO. 8	6%
NO. 100	0.5%
Pan	0%

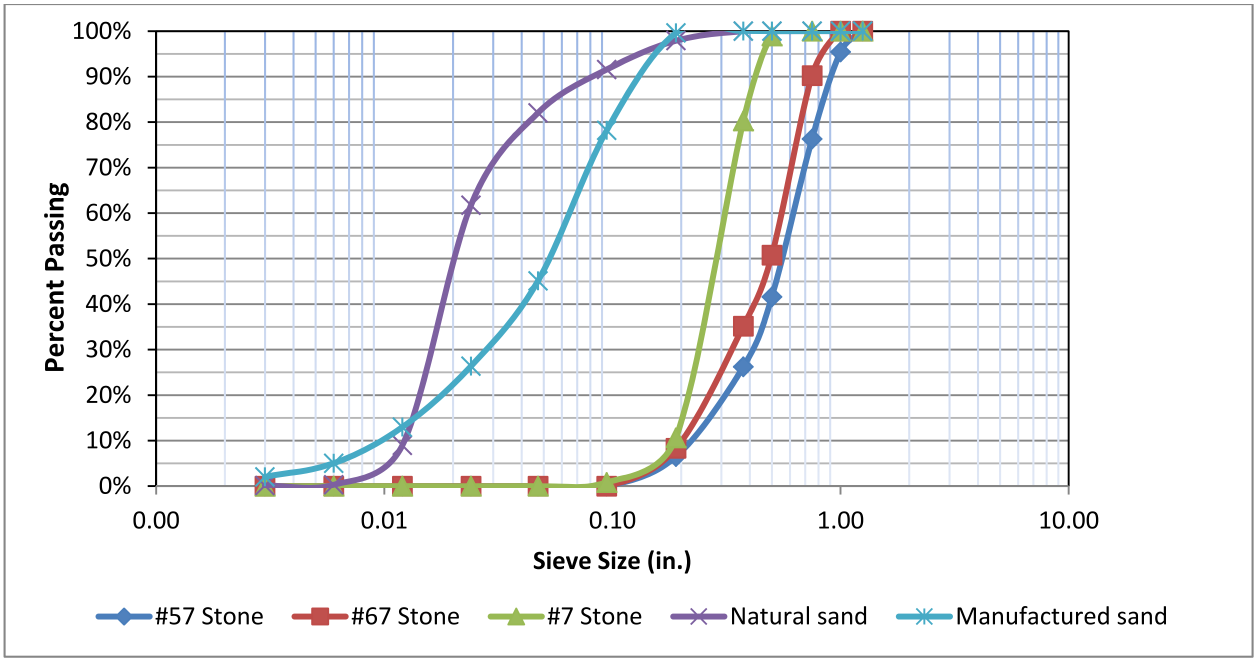


Figure 4.1 The combined aggregate gradation

4.3.3 Fine Aggregates

Two types of fine aggregate were used in this study; natural and manufactured sand, the both meet the TDOT standards. The natural sand (River sand) was sourced locally from Pine Bluff Materials, Nashville, TN**.** The bulk specific gravity of the natural sand was 2.6, and the absorption was 1.30 %. The manufactured sand was also sourced locally from Vulcan Materials, Chattanooga, TN, which has a bulk specific gravity of 2.74 and absorption of 0.64 %. The natural and manufactured sand gradations are shown in Tables 4.11 and 4.12 respectively, and their graduations are illustrated in figure 4.1.

Table 4.10 Natural sand gradation

Sieve Opening	Cumulative Percent Passing
3/8 in.	100.0%
NO. 4	97.9%
NO. 8	91.6%
NO. 16	82.0%
NO. 30	61.8%
NO. 50	9.0%
NO. 100	0.3%
NO. 200	0.1%
Pan	0.0%

Table 4.11Manufactured sand gradation

Sieve Opening	Cumulative Percent Passing
3/8 in.	100.0%
NO. 4	99.6%
NO. 8	78.2%
NO. 16	45.1%
NO. 30	26.4%
NO. 50	13.0%
NO. 100	5.0%
NO. 200	2.0%
Pan	0.0%

4.3.4 Chemical Admixtures

4.3.4.1 Mid-Range Water-Reducing Admixture

MasterPolyheed 900 is a Mid-Range Water-Reducing Admixture that was used to improve the workability of conventional concrete mixtures, to attain a 4 in. slump without increasing the water-cement ratio. MasterPolyheed 900 admixture meets ASTM C 494/C 494M requirements for Type A, water-reducing admixtures. It was sourced from the BASF Corporation. Its technical data sheet was obtained from the supplier and is summarized in Table 4.13.

Table 4.12 Technical Data of MasterPolyheed 900

Data	Specification
Initial Set time (hr:min)	5:18
Water reduction	9 - 10 %
Storage Temperature	35 to 105 °F
Minimum shelf life	18 months
Recommended dosage range	3 to 15 fl oz/cwt of cementitious materials

4.3.4.2 High -Range Water-Reducing Admixture

Two types of HRWRAs were used in the project. ADVA® Cast 575 was used as High range water reducing admixture for Class P-SCC mixtures. ADVA® Cast 575 is a high efficiency, low addition rate polycarboxylate-based high range water reducer designed for the production of a broad range of concrete mixtures, from conventional to Self-Consolidating Concrete. It is designed to impart extreme workability without segregation to the concrete. ADVA Cast 575 meets the requirements of ASTM C494 as a Type A and F, and ASTM C1017 Type I plasticizing agent. ADVA Cast 575 is supplied as a ready-to-use liquid that weighs approximately 8.9 lbs. /gal (1.1 kg/L). ADVA Cast 575 does not contain intentionally added chlorides.

MasterGlenium 7500 is a Full -Range Water-Reducing Admixture that was used to produce Class A-SCC mixtures with different levels of flowability, without increasing the water cement ratio. MasterGlenium 7500 admixture meets ASTM C 494C/ 494M compliance requirements for Type A, water-reducing, and Type F, high-range water-reducing admixtures. It was also sourced from the BASF Corporation. Its technical data sheet obtained from the supplier is summarized in Table 4.14.

Table 4.13 Technical Data of MasterGlenium 7500

Data	Specification
Water reduction	5 - 40%
Storage Temperature	above 40 °F
Minimum shelf life	9 months
Recommended dosage range	2 to 15 fl oz/cwt of cementitious materials

4.3.4.3 Air-Entraining Admixture

MasterAir AE 90 is an air-entraining admixture that was used to provide a uniform structure of voids in concrete mixtures that improves its resistance to damage from cyclic freezing and thawing. MasterAir AE 90 meets the requirements of ASTM C 260, AASHTO M 154 and CRD-C 13. It was sourced from the BASF Corporation. The exact dosage of air-entraining admixture needed for the 6% air content of concrete varied between the mixtures, and it was adjusted during the trial batching process. MasterAir AE 90 technical data sheet obtained from the supplier and summarized in Table 4.15.

Table 4.14 Technical Data of MasterAir AE 90

Data	Specification
Water reduction	5 - 40%
Storage Temperature	31 °F (-0.5 °C) or higher
Minimum shelf life	18 months
Trial mixture recommended dosage range	0.25 to 4 fl oz/cwt of cementitious materials

4.3.5 Mixing water

Municipal tap water was used throughout the experimental mixtures. The average water temperature was 70 +/- 2 °F.

4.4 Preparation of The Experimental Mixes

A total of 48 mixtures were performed during the study period. Thirty two of the mixtures were SCC, and 16 mixtures were conventional (normal slump) mixtures. Typically, a batch of four and a half cubic feet was prepared to provide concrete for the fresh and hardened property test samples of the SCC, and only three and quarter cubic feet of conventional concrete was required. Conventional concrete required a smaller batch due to the fewer fresh tests than the SCC.

Coarse and fine aggregate were stockpiled in the courtyard of the EMCS building. Since the mixing process was performed during the winter, coarse and fine aggregates for one batch were brought into the laboratory a day before to gain the room temperature. Aggregate moisture corrections were used to adjust the batch components (water and aggregates) before mixing to account for moisture condition of the aggregates. The moisture content of aggregate was calculated after weighing a representative sample from the aggregate pile before and after drying it using an electric heater. Appropriate weights of components according to the mix design were measured, adjusted, and then added together inside the nine cubic foot electric drum-type mixer. First, the coarse and fine aggregates were added together and mixed for one minute with 75% of the required water. The water contained the AEA if needed. The cement and fly ash were then added to the stopped mixer and mixed for three minutes with the remaining mixing water which was added gradually while the mixer was running, followed by three minutes rest, and followed by two minutes final mixing. The high range water reducing admixture was added gradually while the mixer was running right after adding the cementitious materials. After thorough mixing, the mixture was ready for taking the samples for fresh and hardened property tests of SCC and conventional concrete, as outlined in the testing protocol in Tables 4.15 and 4.16. Each Class A-SCC mixture was tested at 7, 28, and 56 days. Class P-SCC mixtures underwent accelerated curing using TDOT specification 615-11, and was tested at 18 hrs., 28 days, and 56 days.

Table 4.15 Testing Protocol of SCC mixtures

Fresh Concrete Testing	
Slump Flow and Visual Stability Index (ASTM C 1611)	1 per batch
Consolidating ability by J-Ring (ASTM C 1621)	1 per batch
Static Segregation by Column Test (ASTM C 1610)	1 per batch
Unit Weight and Gravimetric Air Content (ASTM C 138)	1 per batch
Air Content by Pressure Method (ASTM C 231)	1 per batch
Hardened Concrete Testing	
Compressive Strength [1] (ASTM C 39)	2-6x12 inch cylinders per test time
Static Modulus of Elasticity[1] (ASTM C 469)	The 2-6x12 compressive strength cylinders will also be used for modulus per test time
Splitting Tensile Strength [1](ASTM C 496)	2-6x12 inch cylinders per test time
Rapid Chloride Permeability (AASHTO T 277)	3 samples cut from separate 4x8 cylinders per batch
Hardened Concrete Segregation by Ultra-Sonic Pulse Velocity	1- 4x4x24 inch column per batch

Table 4.16 Testing Protocol of conventional concrete mixtures

Fresh Concrete Testing	
Slump Flow (ASTM C 143)	1 per batch
Unit Weight and Gravimetric Air Content (ASTM C 138)	1 per batch
Air Content by Pressure Method (ASTM C 231)	1 per batch
Time of setting of Concrete Mixtures by Penetration Resistance (ASTM C 403)	1-6.5*6.5 inch cylinder per batch
Hardened Concrete Testing	
Compressive Strength [1] (ASTM C 39)	2-6x12 inch cylinders per test time
Static Modulus of Elasticity[1] (ASTM C 469)	The 2-6x12 compressive strength cylinders will also be used for modulus per test time
Splitting Tensile Strength [1](ASTM C 496)	2-6x12 inch cylinders per test time

4.5 Fresh Property Tests on The Experimental Mixes

One of the main objectives of this study is to investigate the fresh characteristics and the fresh segregation potential of SCC mixtures. Several methods were used to test the fresh properties and characteristics of SCC, which are briefly described below:4.5.1 Slump Flow Test

The apparatus for this test was the conventional cone which has 8 in base diameter, 4 in top diameter, and 12 in height. The cone was filled with fresh SCC, while firmly holding the cone in the center of dampened base plate, with the smaller opening facing down. The top of the cone was stuck off using the strike-off bar to remove any excess materials. The cone was gently raised vertically in about four seconds, forming a patty. After the concrete stopped flowing the largest diameter of the patty was measured in two perpendicular directions. The average value of the two diameters was recorded as the slump flow diameter. The range of slump flow was kept between 18 to 30 inches (450 to 760 mm) for SCC as recommended by ACI Committee 237. Figure 4.2 shows the slump flow test.

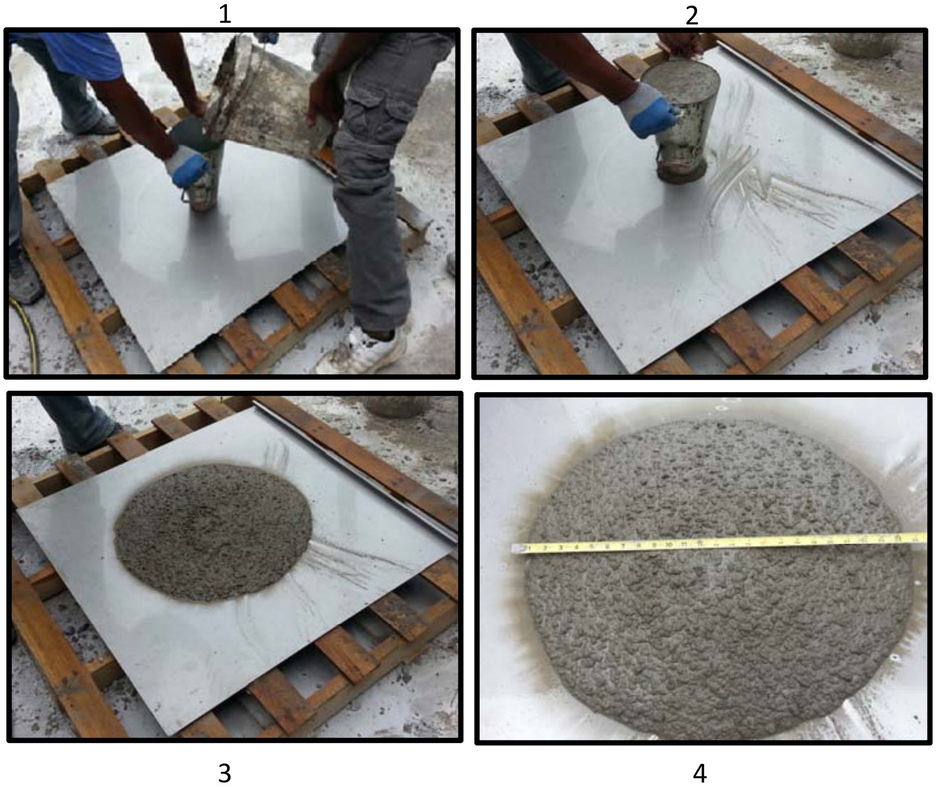
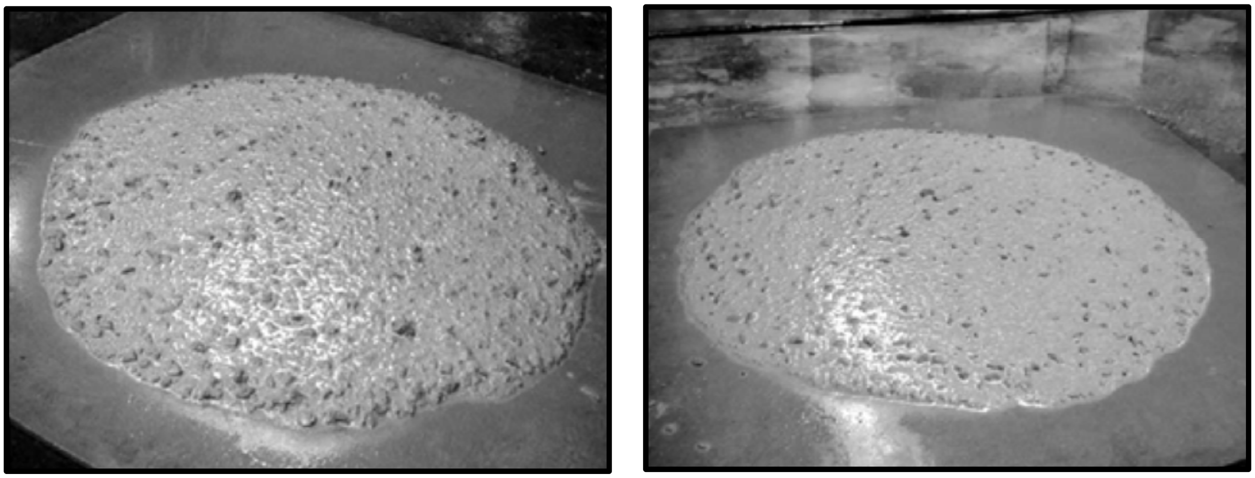


Figure 4.2 The slump flow test

4.5.2 Visual Stability Index

The VSI was determined through visually rating the apparent stability of the slump flow patty based on specific visual properties of the spread patty. The SCC mixtures were designed with a VSI of 1 and 2 which illustrates a stabilized and segregated mixtures respectively. The desirable VSI values were achieved while mixing by HRWR dosages. Assigning the VSI values (1 or 2) to the concrete spread was conducted using the criteria shown in Figure 4.3 (ASTM C1611C1611M).



VSI = 1 – No evidence of segregation and slight bleeding observed as a sheen on the concrete mass

VSI = 2 – A slight mortar halo # 0.5 in.(# 10 mm) and/or aggregatepile in the of the concrete mass

Figure 4.3 Visual stability index criteria

4.5.3 T50

The T50 value was measured during the slump flow test to quantify the flowing ability of SCC, and to provide a relative index of the viscosity. During the slump flow test, the time for the concrete paddy to reach a diameter of 20 in (50 cm) from the time the cone was first lifted was measured in seconds using a stopwatch, as shown in Figure 4.4.

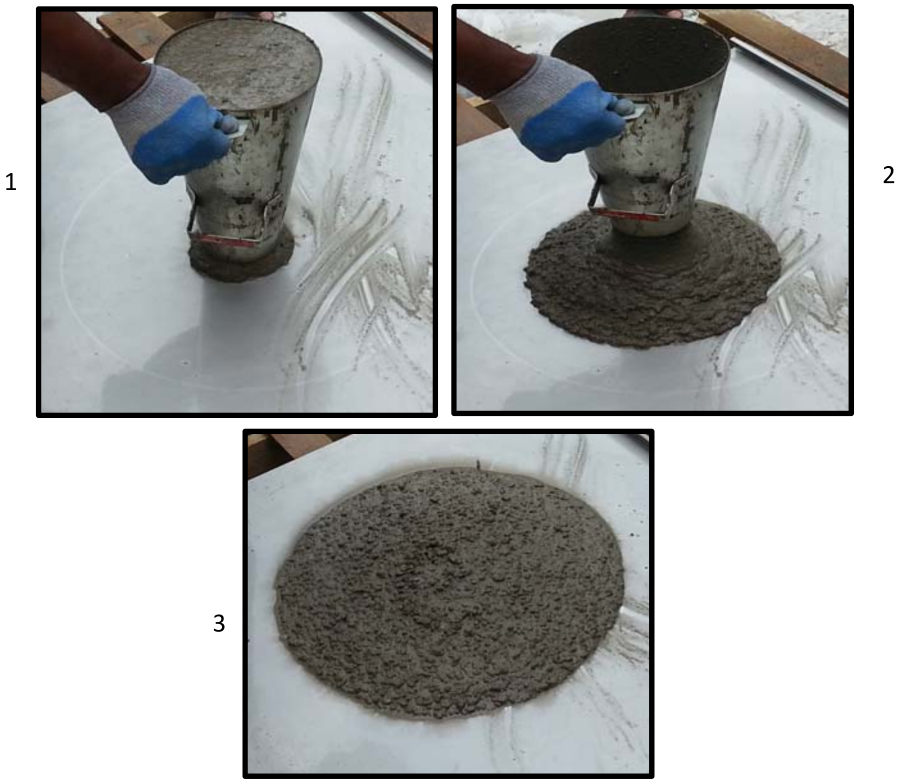


Figure 4.4 T50 measurement

4.5.4 J-ring test

A sample of fresh SCC was poured into a moistened standard slump cone with the J-ring base which contains steel bars. The cone was firmly held in the center of dampened base plate with the smaller opening facing down. Then the top of the cone was stuck off using the strike-off bar to remove the excess materials. The mold was then raised, the SCC passed through J-ring, and the average of diameters measured in two perpendicular directions was recorded as the J-ring flow diameter. An example of a J-Ring test is shown in Figure 4.5.

Figure 4.5 J-ring Test

4.5.5 L-box test

L-Box test was used to evaluate the passing ability of the SCC mixtures. The SCC was poured in the vertical section to its full height; the top of the section was struck off using the strike-off bar, to remove any excess materials. The gate was then lifted to allow the concrete to flow into the horizontal section. When the flow stopped, the heights of the concrete were measured at the end of the horizontal section and in the vertical section. The ratio of the height of concrete in the horizontal section to remaining in the vertical section was recorded. An example of L-Box testing is shown in Figure 4.6.

Figure 4.6 L-box test

4.5.6 Column Segregation

Column Segregation was used to assess the fresh segregation resistance of SCC. A sample of freshly SCC was poured in one lift in the cylindrical column without tapping or vibration. After 15 minutes the column sections were separated using a cutting plate. The SCC from the top and bottom sections was collected and washed through a No.4 (4.75 mm) sieve, leaving the coarse aggregate on it. The coarse aggregate from the top and the bottom levels of the column were brought to the surface-dry condition by rolling them in a dry towel. The weights of the aggregates were determined in order to calculate the percentage of segregation using equation 4.1. An example of the column segregation test apparatus is shown in Figure 4.7.

$$S = 2\left[\frac{(CA_B - CA_T)}{(CA_B + CA_T)}\right] * 100\, , if\ CA_B > CA_T \ldots \quad \text{Equation 4.1}$$

$$S = 0, if CA_B \leq CA_T$$

Where:

S = static segregation, percent.

CA_T = mass of coarse aggregate in the top section of the column.

CA_B = mass of coarse aggregate in the bottom section of the column.


1 2

Figure 4.7 The static column segregation

4.5.7 Unit Weight of fresh concrete

This test was conducted to determine the density of freshly mixed concrete, in accordance with the ASTM C 138 standard. The main apparatus is a cylindrical container made of steel with 8 in diameter and 8.5 in height. The conventional concrete was placed in three layers using a scoop. Each layer was rodded 25 times with a tamping rod, and then the sides of the measure were tapped about 10 times using a rubber mallet. The top of the mold was then stuck off using the strike-off bar, to remove excess materials. The mass of the mold and concrete were then determined, and the density was calculated using the equation 4.2. The same method was used for the SCC mixtures, but the concrete was poured in one layer without rodding or tapping.

$$D = \frac{M_c - M_m}{V_m} \text{ ……..Equation 4.2}$$

Where:
D = density (unit weight) of concrete, lb/ft^3
M_c = mass of the measure filled with concrete, lb
M_m = mass of the measure, lb

4.6 Curing of Concrete

In order to achieve the strength requirements for Class-P concrete of attaining 4000 psi in eighteen hours accelerated curing was used. After completing the fresh concrete tests, a batch with twelve plastic molds of concrete was placed inside the SURE CURE curing cylinders for six hours. The SURE CURE molds were attached to the mini controller which worked as a median between the computer and the molds as shown in plate 1, 2 of Figure 4.9. The mini controller provided the SURE CURE cylinder molds with an electrical current which was input by the computer as shown in plate 3 of Figure 4.9. The SURE CURE molds transform the current transmitted from the mini controller to heat using the coils embedded in the molds. After six hours the system was switched on to apply a temperature of between 80°F and 155 °F for twelve hours. The rate of temperature increments was set to be less than 50 °F per hour to avoid cracking as shown in Figure 4.10. Plant Manager Software developed by SURE CURE systems was used to track the molds temperature during the curing cycle. A temperature profile was entered using Set Cure Cycle Software. The SURE CURE equipment was acquired from Products Engineering based in Evergreen, CO. At the end of the cycle, the concrete cylinders were removed from their molds. Four of the concrete cylinders removed were used for the 18 hours hardened properties tests, and the other eight cylinders were stocked in a basin filled with standard water to cure at temperature 70 +/- 2 °F. An example of the SURE CURE system is shown in Figure 4.9.

Figure 4.8 SURE CURE System Equipment

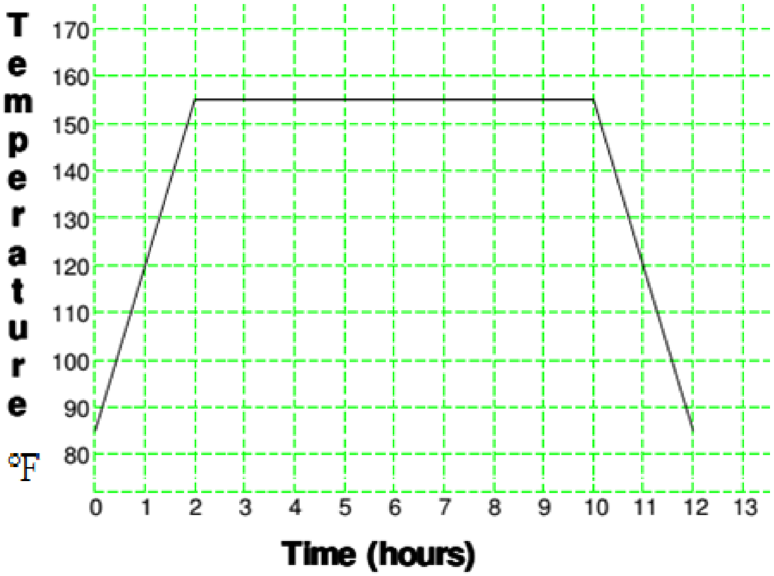


Figure 4.9 Temperature Profile of the Curing Cycle

4.7 Hardened Properties Tests

A number of tests were conducted to assess the hardened properties of conventional concrete and SCC mixtures. The same tests were performed for the both types of mixtures as follows.

4.7.1 Compressive Strength (ASTM C 39)

Compressive strength tests were performed for both SCC and conventional concrete. Each batch was tested after 18 hours, 28 days and 56 days. Two samples were used to conduct the compressive strength test using a Humboldt compression Machine. The sample was properly aligned inside the machine. A load increment of 5000 lbs. /sec was subjected to the sample until failure. This failure point was recorded as the compressive strength of the sample. The same procedure was repeated for all the tested samples. An example of compression test was shown in Figure 4.11.

Figure 4.10Compressive Strength Test

4.7.2 Static Modulus of Elasticity (ASTM C 469)

The test was performed for both SCC and conventional concrete. Two samples were selected for the test. The samples were tested using a Humboldt compressometer and a Forney calibrated load frame. The samples were loaded to approximately 40% of the ultimate concrete strength obtained from the compressive strength test. Two readings were required to get the Modulus of Elasticity using Equation 4.3. An example of this test sample was shown in Figure 4.12.

$$E=\frac{(\sigma_2-\sigma_1)}{(\varepsilon_2-0.00005)} \text{ ………..Equation 4.3}$$

Where:

E=chord modulus of elasticity (in psi)

σ_2 =stress corresponding to 40% of the ultimate load of the concrete (in psi)

σ_1 =stress corresponding to a longitudinal strain of ε_1 at 50 millionths (in psi)

ε_2 =longitudinal strain produced by σ_2

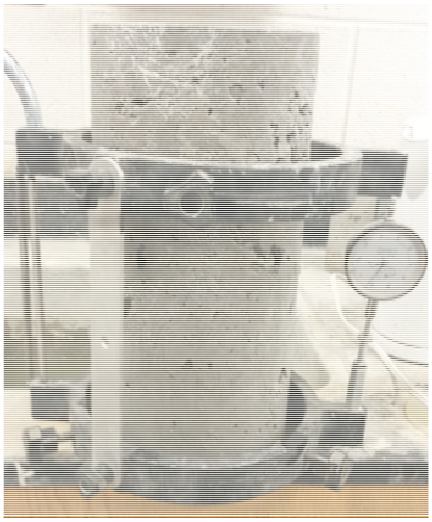


Figure 4.11 Modulus of Elasticity Setup

4.7.3 Splitting Tensile Strength (ASTM C 496)

The Splitting Tensile strength test was used to determine the tensile strength of SCC and conventional concrete. The sample was placed horizontally between the compressive strength machine and the loading surface with wood furring strips to distribute the load as shown in Figure 4.13. The compression was applied diametrically and uniformly along the length of the cylinder until failure. The failure was indicated by a longitudinal crack in the sample. The load increment rate was 300 lbs. /sec. The failing point was recorded. An example of the test is shown in Figure 4.13.

Figure 4.12 Splitting Tensile Strength Test

4.7.4 Ultra-Sonic Pulse Velocity (ASTM C 597)

The Ultra-Sonic Pulse Velocity test was used in this project to assess the hardened segregation of SCC mixtures. The pulse velocity, V, of longitudinal stress waves in a concrete mass is related to its elastic properties and density according to the following relationship:

$$E_d = \rho V^2 \frac{(1+\mu)(1-2\mu)}{(1-\mu)} \quad \text{…………Equation 4.4}$$

Where:
E_d = Dynamic Elastic Modulus (in psi)
ρ = Density (lbs./ft^3)
V = Compressional Pulse Velocity (ft./sec^2)
μ = Dynamic Poison's Ratio

This test method is used to assess the uniformity and relative quality of concrete, to indicate the presence of voids and cracks, and to evaluate the effectiveness of crack repairs. It is also applicable to show changes in the properties of concrete, and in the survey of structures, to estimate the severity of deterioration or cracking. When used to monitor changes in condition over time, test locations are to be marked on the sample to ensure that tests are repeated at the same positions. The degree of saturation of the concrete affects the pulse velocity, and this factor must be considered when evaluating test results. In addition, the pulse velocity in saturated concrete is less sensitive to changes in its relative quality.

Concrete columns measuring 4' x 4' x 26' were tested after 56 days for the pulse velocity for each SCC mixture. Three measurements were taken from the column to assess the hardened segregation of SCC (on the top, the middle of the column and at the bottom). The instrument used is shown in Figure 4.14. In the project, the James Instruments V-Meter Mark IV was used to measure pulse velocity. The system uses bursts of ultrasonic waves to determine the velocity of propagating sound waves through the medium under test to find non-homogeneous conditions. The V-Meter incorporates an advanced microprocessor and state of the art electronics, making it a durable and convenient instrument that captures reliable data, both in a laboratory environment and on site. Also, this system is equipped to analyze S-wave response (shear wave transducers are optional) with relation to P-wave response, thereby calculating Poisson's Ratio to a high level of accuracy. Powered by a rechargeable battery, the V-Meter has been designed with on-site testing particularly in mind. It is fully portable, easy to operate and accurate. It generates low-frequency ultrasonic pulses and measures the time taken for them to travel from one transducer to the other through the material tested. Time is measured by a 10 megahertz clock, yielding a measurement capacity from 0 to 6.5 milliseconds with a resolution of 100 nanoseconds.

Figure 4.13 Ultra-Sonic Pulse Velocity Instrument

4.7.5 Rapid Chloride Permeability Test (ASTM C1202 / AASHTO T277)

A Giatec Perma2 ™ obtained from Giatec scientific was the test equipment used to measure the permeability. The test method involves obtaining a 100 mm (4 in.) diameter core or cylinder sample from the tested concrete. A 50 mm (2 in.) specimen is cut from the sample. The side of the cylindrical specimen is coated with epoxy, and after the epoxy is dried, it is put in a vacuum chamber for 3 hours. The specimen is vacuum saturated for 1 hour and allowed to soak for 18 hours. It is then placed in the test device (see test method for schematic of the device). The left-hand side (–) of the test cell is filled with a 3% NaCl solution. The right-hand side (+) of the test cell is filled with 0.3N NaOH solution. The system is then connected, and a 60-volt potential is applied for 6 hours. Readings are taken every 30 minutes. At the end of 6 hours, the sample is removed from the cell and the amount of coulombs passed through the specimen is calculated. The setup configuration of the test is shown in Figure 4.15.

Figure 4.14 Rapid Chloride Permeability Test Setup

Chapter 5 RESULTS AND DISCUSSION

5.1 Introduction

Throughout this chapter, the results of the fresh and hardened properties tests are presented, for the 48 mixtures conducted during this study. The correlations between these mixtures using different aggregate sizes (#57 stone, #67 stone, #7 stone, and #89 stone, natural and manufactured sand) and fly ash classes (C and F) are presented and discussed.

5.2 Mixture Properties

A total of 48 mixtures were produced as designed in chapter 4. The mixtures were comprised of 32 SCC mixtures and 16 conventional mixtures. The conventional mixtures were included to serve as controls. A number of fresh and hardened properties were tested to assess the performance of the mixtures. The fresh property test performed on the conventional concrete was the Slump test. While SCC was tested for Slump flow, T-50, L-box ratio, J-ring test, and the Fresh Column segregation test. The initial and final setting times and Air entrained values were recorded for both SCC and conventional concrete. The results of the fresh properties of test Class P-SCC mixtures are presented in Table 5.1. The hardened properties tests performed were compressive strength test, tensile strength test and the modulus of elasticity. The hardened properties tests were recorded for 18 hours, 28 days and 56 days tests. The results of the hardened properties tests for Class P-SCC mixtures are shown in Table 5.2. Compressive strength results highlighted with red color in Table 5.2 means that the value is less than 4000 psi which is the TDOT requirements for the compressive strength to be in the 18 hours test. The fresh properties tests results for Class A-SCC are shown in Table 5.3 and the hardened properties are shown in Table 5.4. Later in the chapter, the values obtained from the experiments are compared to VSI 1 and VSI 2 to study the effect of VSI on the fresh and hardened properties which correlate to Fly ash used.

The results of Ultrasonic pulse velocity and surface resistivity are shown in Table 5.5 for Class P-SCC and Table 5.6 for Class A-SCC mixtures. The results obtained from rapid chloride permeability test are shown in Table 5.7 for Class P-SCC and Table 5.8 for Class A-SCC mixtures.

Table 5.1 The Results of Fresh Properties Tests for Class P-SCC

Mix	Cement	Agg. Used	VSI	Slump (in)	J-ring (in)	Dif. (in)	HRWR oz/cwt	Unit. Wt (lb/ft^3)	Temp (F)	Air (%)	T50 sec	L-box ratio	Col. Seg (%)	Time of Set (hr:min)	
														Intial	Final
1	Cement only	#67+Nat. Sand	1	19	17	2	2.99	143.0	75	3.6%	1.5	0.000	9.2%	6:00	8:50
2			2	25	21	4	3.89	141.4	75	4.7%	0.57	0.462	23.3%	7:15	8:30
3			Conv.	5			0.00	146.2	77	3.4%				4:58	6:25
4		#67+Mfg. Sand	1	22.5	17.5	5	3.44	144.2	76	5.3%	3.09	0.000	15.0%	6:30	7:55
5			2	24.75	19.75	5	6.58	148.0	76	1.5%	3.07	0.000	7.7%	5:15	6:57
6			Conv.	3.25			6.21	148.4	75	3.9%				5:30	7:15
7		#7+Nat. Sand	1	23	18.75	4.25	4.49	143.4	76.4	3.1%	4	0.000	12.3%	6:37	8:15
8			2	25.5	24	1.5	6.88	145.4	75.4	1.8%	2.9	0.043	18.2%	7:52	9:50
9			Conv.	3			10.36	143.8	76	3.6%				6:25	8:45
10		#89+Nat. Sand	1	20.5	16	4.5	4.19	139.1	71	6.2%	4.46	0.000	10.1%	7:05	8:53
11			2	22.5	18.25	4.25	5.09	139.9	73	5.6%	3	0.000	8.3%	6:30	8:12
12			Conv.	3.5			4.14	144.8	75	3.0%				6:05	7:57
13	Fly ash-F + Cement	#67+Nat. Sand	1	27.5	26.5	1	6.27	144.0	80	2.1%	1.69	0.625	8.4%	6:20	7:45
14			2	29	28.75	0.25	7.05	149.0	78	0.6%	0.44	0.706	16.4%	6:45	8:10
15			Conv.	3.875			0.00	151.1	78	2.6%				4:50	6:10
16		#67+Mfg. Sand	1	30	30	0	7.83	144.2	84	0.5%	2.3	0.000	37.5%	6:15	8:00
17			2	31.5	31.5	0	10.97	151.5	84	0.4%	2	0.000	25.4%	7:00	8:40
18			Conv.	2.5			14.46	153.1	82	2.9%				6:50	8:30
19		#7+Nat. Sand	1	21.5	19.5	2	3.39	147.0	84	4.0%	1.84	0.500	4.4%	5:35	7:00
20			2	28.5	28	0.5	5.22	145.4	70	3.0%	2.06	0.600	14.7%	5:55	7:08
21			Conv.	4			0.00	149.2	87	3.0%				4:50	6:10
22		#89+Nat. Sand	1	26	24	2	3.92	147.2	78	4.3%	2.13	0.444	0.0%	6:10	7:30
23			2	27.25	26.5	0.75	4.70	145.4	81	5.7%	1.97	0.533	2.0%	7:20	7:27
24			Conv.	2.5			0.00	149.0	86	3.4%				4:55	6:15

Table 5.2 The Results of Hardened Properties Tests for Class P-SCC

		18 hours			**28 days**			**56 days**		
Mix	**VSI**	**Comp. Psi**	**Tensile Psi**	**E. ksi**	**Comp. Psi**	**Tensile Psi**	**E. ksi**	**Comp. Psi**	**Tensile Psi**	**E. ksi**
1	1	3538	360	4850	5577	460	5222	6703	332	6135
2	2	3830	255	5740	6309	351	4940	5494	411	4830
3	Conv.	3252	276	4972	5702	310	6063	6428	292	6584
4	1	4381	272	5093	6306	452	4827	7453	615	4630
5	2	5142	390	5618	7081	477	4757	8150	404	5224
6	Conv.	4405	338	4981	7013	457	8046	7304	533	5123
7	1	5004	254	4163	7282	386	6467	8311	485	5675
8	2	5183	289	4850	7751	398	6548	8292	319	6508
9	Conv.	4455	391	5174	7184	406	6467	8019	403	5695
10	1	4615	359	6871	6611	428	4975	6934	346	4769
11	2	4707	356	4293	7105	370	6007	7737	455	5463
12	Conv.	4250	341	4238	6232	298	5337	7147	376	4972
13	1	5056	506	4756	8506	335	5402	8974	531	7111
14	2	4855	468	4347	5926	442	5270	6845	280	5187
15	Conv.	3495	286	4514	6526	357	5705	6657	327	5635
16	1	4040	342	4540	6750	419	5693	7295	540	5389
17	2	3970	314	4645	6355	441	5309	7070	513	5443
18	Conv.	4897	366	4903	8063	496	6535	8116	514	5905
19	1	4458	267	3965	7299	437	4972	8435	434	4829
20	2	4222	313	4306	7049	467	4872	8274	275	5323
21	Conv.	3486	267	3112	6750	373	5889	6961	437	5346
22	1	4112	319	3826	6622	445	4356	7916	573	6050
23	2	4425	321	4267	6990	500	4466	7719	512	4914
24	Conv.	3408	230	4694	5825	399	6520	7127	475	5489

Conv. is a representation for conventional concrete

Table 5.3 The Results of Fresh Properties Tests for Class A-SCC

Mix	Cement	Agg. Used	VSI	Slump (in)	J-ring (in)	Dif. (in)	AEA (oz/yd^3)	HRW (oz/cwt)	Temp. (F)	Air (%)	T50 (sec.)	L-box ratio	Col. Seg (%)	Time of Set (hr:min)	
														Intial	Final
25	Fly ash-C + Cement	#57+Nat. Sand	1	26.25	23	3.25	1.8	5.8	74	6.50%	0.9	0.000	8.1%	5:30	7:10
26			2	29.25	28.25	1	1.4	6.5	76	6.00%	0.43	0.750	19.4%	6:00	7:45
27			Conv.	4			7.5		67	6.70%				5:15	7:00
28		#67+Nat. Sand	1	24.5	23.5	1	1.6	4.2	82	7.20%	1:47	0.000	5.0%	6:00	7:51
29			2	29.5	27.75	1.75	1.6	5.8	79	6.00%	1:44	0.590	7.0%	6:42	8:08
30			Conv.	4.25			3		75	5.40%				4:50	6:45
31		#67+Mfg. Sand	1	22	19	3	0.8	5.3	73	5.10%	2:25	0.000	12.3%	4:54	6:36
32			2	28.5	26.5	2	1.6	5.8	75	5.40%	1:50	0.000	14.1%	5:20	3:36
33			Conv.	5.5			3	0	72	5.70%				5:18	7:15
34		#7+Nat. Sand	1	23.5	22	1.5	1.2	5.8	71	5.70%	1.12	0.650	7.5%	6:20	8:15
35			2	28.75	28.5	0.25	1	9	77	6.40%	0.66	0.860	8.6%	6:25	8:30
36			Conv.	4.75			2.7	0	73	5.60%				5:30	7:10
37	Fly ash-F + Cement	#57+Nat. Sand	2	26	25.5	0.5	2.2	5.8	80	5.20%	0.75	0.750	16.7%	7:00	8:42
38			1	24.5	22.75	1.75	2	4.8	82	6.00%	2.25	0.000	11.3%	6:00	7:43
39			Conv.	5.5			7.5		0	5.60%				5:36	7:35
40		#67+Nat. Sand	1	27.5	26.75	0.75	2	6.5	81	6.00%	1:09	0.890	10.5%	6:12	7:53
41			2	28.4	27	1.4	3.2	7.4	78	5.20%	0:40	0.760	14.1%	6:55	8:36
42			Conv.	3			7.5	0	76	6.00%				5:30	7:30
43		#67+Mfg. Sand	1	24.5	21.75	2.75	2	6.8	78	6.20%	2.91	0.000	9.0%	4:30	6:06
44			2	27.38	26	1.38	0.8	8.9	73	5.70%	1.81	0.100	10.3%	5:40	7:12
45			Conv.	3			3	4.1	76	6.00%				5:00	6:30
46		#7+Nat. Sand	1	24.5	21.25	3.25	0	7.4	76	6.00%	1.09	0.360	6.9%	6:06	8:00
47			2	29	28	1	0	10.7	74	6.00%	0.47	0.750	18.4%	7:51	9:48
48			Conv.	3.2			6	0	78	5.50%	-			4:30	5:51

Table 5.4 The Results of Hardened Properties Tests for Class A-SCC

		7 days			**28 days**			**56 days**		
Mix	**VSI**	**Comp. Psi**	**Tensile Psi**	**E. ksi**	**Comp. Psi**	**Tensile Psi**	**E. ksi**	**Comp. Psi**	**Tensile Psi**	**E. ksi**
25	1	5000	380	4550	6260	470	5170	6940	400	5300
26	2	5370	405	5050	5880	510	5380	7470	405	5460
27	Conv.	4540	370	4500	5330	390	5580	6030	425	5750
28	1	4800	340	4400	5840	480	5170	6480	410	5400
29	2	4500	395	4350	5150	430	5020	5510	425	4870
30	Conv.	5280	430	5150	7000	450	5700	7550	490	5800
31	1	5180	435	4500	6910	360	5320	7475	625	5225
32	2	4180	440	4100	5060	570	4850	5360	610	4760
33	Conv.	4660	335	4600	6040	490	5080	7050	475	5920
34	1	4430	330	4100	5700	480	4300	5900	430	5260
35	2	5200	435	4850	6410	420	5015	7060	410	5490
36	Conv.	5090	325	5100	6880	510	5230	7200	515	5780
37	2	3870	330	4850	4820	400	4910	5330	490	4940
38	1	4150	345	4250	4980	465	4690	5670	495	5360
39	Conv.	4360	325	4900	5325	385	5415	5980	465	5690
40	1	4450	365	4500	5470	405	5115	6025	540	5360
41	2	3580	250	4350	4625	380	4770	5240	500	5050
42	Conv.	4190	355	3350	5000	465	5230	5500	355	5240
43	1	4280	440	4350	5120	480	5000	5440	550	5420
44	2	4580	395	4450	5940	425	5290	4750	470	5120
45	Conv.	4560	400	3750	560	450	5070	6120	485	5450
46	1	5260	310	5050	6160	425	5110	6200	480	5260
47	2	2230	170	3900	3150	270	4615	3355	350	4940
48	Conv.	4090	360	3750	4890	380	4810	5470	440	5380

Conv. is a representation for conventional concrete

Table 5.5 The Results of Pulse Velocity and Surface Resistivity for Class P-SCC

Mix No.	Length (in)	Pulse Velocity (ft/sec)				Surface resistance (k OM)			
		Top	Middle	Bottom	Average	Top	Middle	Bottom	Average
1	26.5	14,520	14,815	15,083	14,806	19.8	14	12	15.3
2	27.25	15,728	16,181	15,950	15,953	15	13.9	12.8	13.9
4	28	16,340	15,649	15,222	15,737	12	11.1	10.8	11.3
5	28	15,798	15,873	15,798	15,823	10.6	11.3	11.7	11.2
7	26.5	15,150	15,210	15,360	15,240	12	9.9	9.3	10.4
8	26	15,720	15,015	15,504	15,413	14	11.5	12.8	12.8
10	28.75	14,620	14,948	15,649	15,072	12.4	11.7	10.9	11.7
11	28	15,723	15,562	15,065	15,450	12	10.2	9.3	10.5
13	27	14,948	14,749	13,774	14,490	17.7	16.2	19.7	17.9
14	26.5	14,184	13,889	13,441	13,838	16.3	12.7	16.1	15.0
16	25.5	15,221	15,221	15,541	15,328	20.9	21.5	24	22.1
17	26	16,584	14,948	13,661	15,064	9.8	12.5	16.4	12.9
19	28.5	15,083	15,291	15,085	15,153	15	13.5	13	13.8
20	27.75	15,221	15,015	15,432	15,223	19	15.7	22.5	19.1
22	28	15,015	15,083	15,291	15,049	17.9	15.3	14.8	16.0
23	26.5	15,221	15,221	15,432	15,291	16.1	14.3	18.8	16.4

Table 5.6 The Results of Pulse Velocity and Surface Resistivity for Class A-SCC

Mix No.	Length (in)	Pulse Velocity (ft/sec)				Surface resistance (k OM)			
		Top	Middle	Bottom	Average	Top	Middle	Bottom	Average
25	26.75	15,723	15,723	16,181	15,876	29.4	27.1	26.3	27.6
26	26.875	15,015	15,723	14,881	15,206	28.5	26.2	19.4	24.7
28	25.75	15,649	15,873	15,432	15,651	28.8	28.1	26.5	27.8
29	24.125	16,025	15,575	14,949	15,516	19.9	16	15.6	17.2
31	26.25	15,423	15,798	15,504	15,575	39.6	33.2	32	34.9
32	25.25	16,103	17,007	15,723	16,278	28.9	28.1	27.2	28.1
34	26.25	14,368	15,088	15,152	14,869	16.2	16.4	17	16.5
35	26.165	14,368	14,749	14,749	14,622	28.3	22.5	21.9	24.2
37	28.25	15,291	14,493	15,576	15,120	36.7	36.5	32.8	35.3
38	25	14,493	15,949	15,291	15,244	33.3	29.7	27.8	30.3
40	26.25	14,948	15,949	15,576	15,491	37	33.9	32.4	34.4
41	26.75	14,556	15,504	15,221	15,094	26.3	33.5	27.5	29.1
43	21	16,750	16,920	16,750	16,807	38.5	37	34.4	36.6
44	26.5	16,584	15,873	15,576	16,011	36	33.4	30.4	33.3
46	26	15,873	15,949	15,723	15,848	34.4	29.1	28.2	30.6
47	25.875	15,803	15,152	14,620	15,192	41.6	40.5	36.5	39.5

Table 5.7 The Results of Rapid Chloride Permeability Test for Class P-SCC

Mix No.	**Cast date**	**Test Date**	**coulomb**			
			1	2	3	Average
1	7/11/2015	9/5/2015	2549	2855	2973	2792
2	7/12/2015	9/6/2015	2750	2870	2980	2867
3	7/1/2015	8/26/2015	2611	2677	2645	2644
4	7/13/2015	9/7/2015	3201	2822	3031	3018
5	7/14/2015	9/8/2015	2582	2346	2400	2443
6	7/15/2015	9/9/2015	4441	6100	4520	5020
7	7/16/2015	9/10/2015	3165	3200	3110	3158
8	7/17/2015	9/11/2015	3552	3350	3700	3534
9	7/18/2015	9/12/2015	2250	3210	2935	2798
10	7/19/2015	9/13/2015	2490	2614	2470	2525
11	7/20/2015	9/14/2015	2649	2600	2710	2653
12	7/21/2015	9/15/2015	2546	1453	2100	2033
13	6/4/2105	7/30/2105	1955	1772	2143	1957
14	6/2/2015	7/28/2015	7706	6116	5561	6461
15	6/8/2015	8/3/2015	1919	1784	1640	1781
16	5/30/2015	7/25/2015	3552	2989	2399	2980
17	5/28/2015	7/23/2015	2178	4349	3320	3282
18	5/31/2015	7/26/2015	7740	2309	9622	6557
19	5/20/2015	7/15/2015	2957	2334	2269	2520
20	5/21/2015	7/16/2015	3744	3302	2983	3343
21	6/12/2015	8/7/2015	1304	2462	1888	1885
22	5/23/2015	7/18/2015	3071	2977	3009	3019
23	5/24/2015	7/19/2015	1601	2557	3923	2694
24	6/14/2015	8/9/2015	5837	2452	361	2883

The gray boxes means one or more of the interval values went more than 500 mA, and the device is showing error (fully permeable) and the value was replaced with 500 mA

Table 5.8 The Results of Rapid Chloride Permeability Test for Class A-SCC

Mix No.	**Cast date**	**Test Date**	**coulomb**			
			1	2	3	Average
25	8/18/2015	10/13/2015	4782	6340	4800	5307
26	8/20/2015	10/15/2015	9716	10359	10315	10130
27	8/22/2015	10/17/2015	4036	6622	5113	5257
28	7/22/2015	9/16/2015	2144	2050	2075	2090
29	7/23/2015	9/17/2015	10684	10682	10738	10701
30	7/24/2015	9/18/2015	5918	6100	5898	5972
31	7/26/2015	9/20/2015	2382	2338	2481	2400
32	7/27/2015	9/21/2015	2450	2890	2440	2593
33	7/28/2015	9/22/2015	4212	3036	3625	3624
34	7/29/2015	9/23/2015	1816	1561	1730	1702
35	7/30/2015	9/24/2015	1700	2265	2110	2025
36	7/31/2015	9/25/2015	1550	1827	1642	1673
37	8/24/2015	10/19/2015	6965	6450	6901	6772
38	8/25/2015	10/20/2015	2996	3131	3215	3114
39	8/26/2015	10/21/2015	3965	3829	4071	3955
40	8/5/2015	9/30/2015	4370	4600	4203	4391
41	8/6/2015	10/1/2015	2525	1261	2124	1970
42	8/7/2015	10/2/2015	2306	2165	2200	2224
43	8/8/2015	10/3/2015	2279	2285	2441	2335
44	8/9/2015	10/4/2015	1910	1832	2111	1951
45	8/10/2015	10/5/2015	1850	1760	1811	1807
46	8/11/2015	10/6/2015	3224	2570	3005	2933
47	8/12/2015	10/7/2015	3941	3050	3500	3497
48	8/13/2015	10/8/2015	3580	2351	3432	3121

The gray boxes means one or more of the interval values went more than 500 mA, and the device is showing error (fully permeable) and the value was replaced with 500 mA

5.3 Discussion of Fresh Properties of Class A-SCC Concrete Mixtures

5.3.1 Filling Ability and Visual Stability of Class A-SCC Mixtures

As mentioned earlier in Chapter 4, the slump flow test was conducted to measure the filling ability (deformability) of the studied mixtures. Different HRWR dosages were used to produce SCC mixtures with VSI of 1 and 2. The VSI values were determined by a visual rating of the slump flow patty. The T50 value is also another fresh property that was measured to quantify the flowing ability of SCC, and to provide a relative index of the viscosity. The results of slump flow, VSI, and T50 tests were obtained for different aggregate sizes as shown in Section 5.2 and summarized in Figures 5.1, 5.2, and 5.3. Each aggregate size is discussed below in more details.

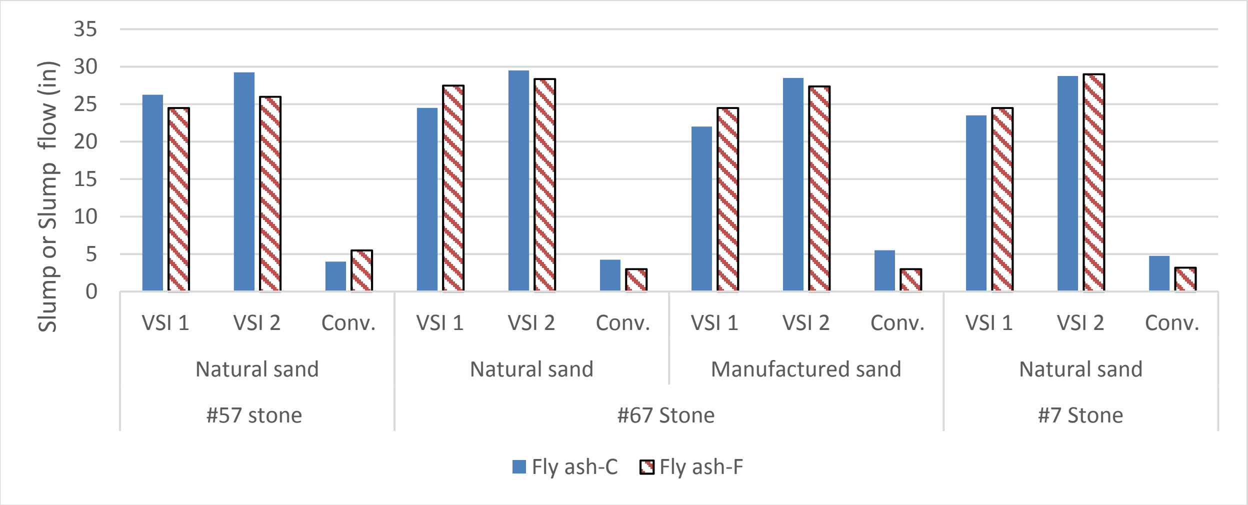


Figure 5.1 Slump and slump flow of the studied stones

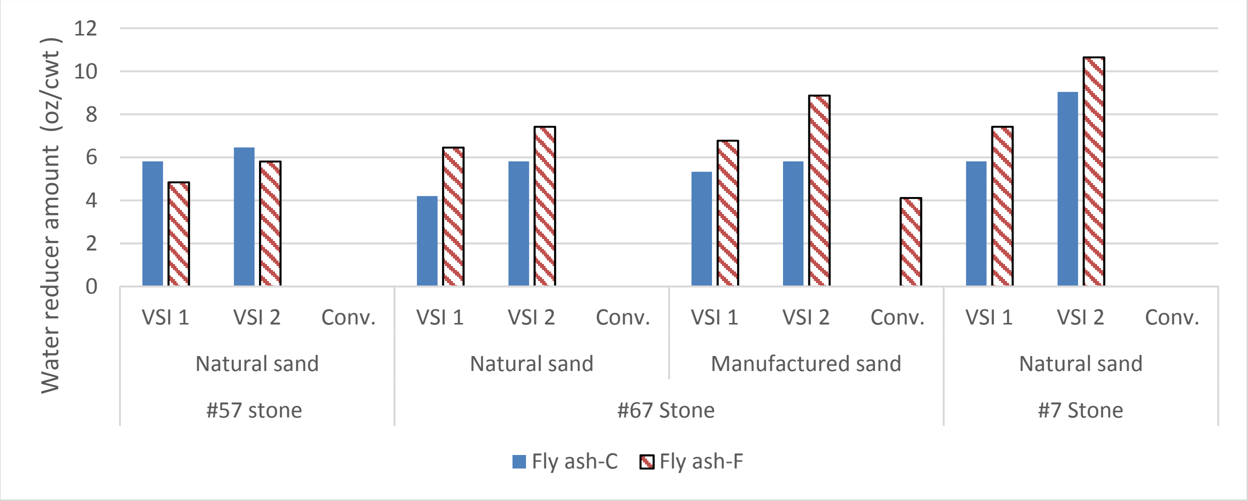


Figure 5.2 Water reducer admixture requirements for the studied stones

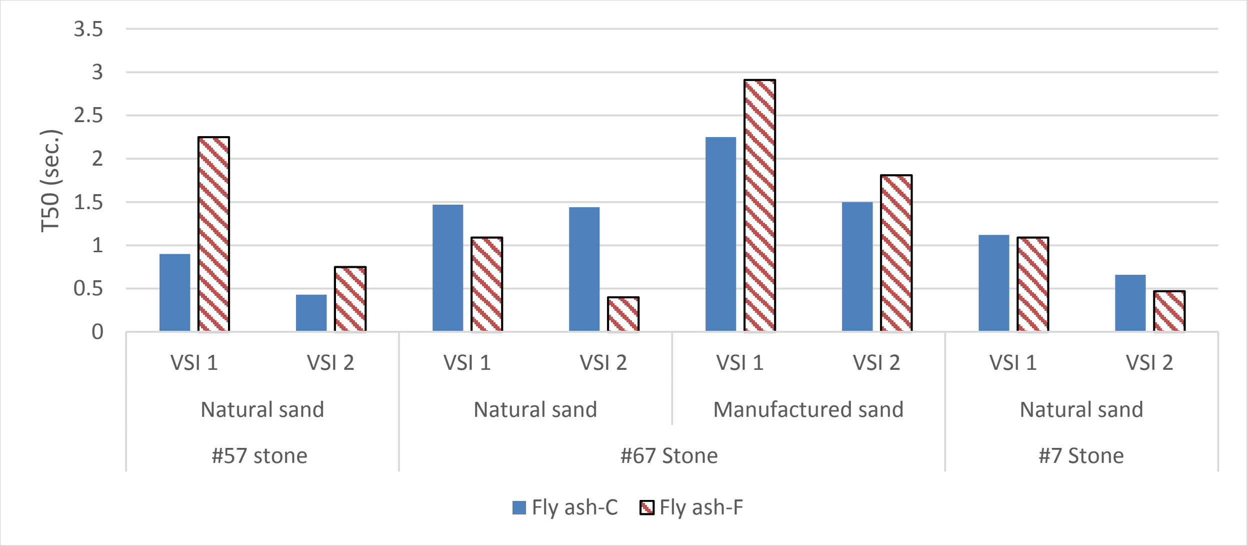


Figure 5.3 T50 values of the studied stones

Mixtures Containing #57 coarse aggregate with Natural Sand

Number 57 coarse aggregate has a maximum size of 1.0 inches and was the largest aggregate size used in this study. A total of six mixtures, four SCC and two conventional, were produced using natural sand. Two classes of fly ash were used to replace 20% of the cement content; three mixtures (Mix No 25, 26, and 27) contained fly ash Class C and the other three contained fly ash Class F (Mix No 37, 38, and 39). The slump flow, VSI, and T50 results are represented in Tables 5.1 and 5.2, for #57 stone, and then summarized in the Figures 5.4 to 5.6.

Figure 5.4 shows the slump flow results for #57 stone, and it is anticipated that the mixtures with the VSI of 2 show higher slump flow compared with the VSI of 1, which is due to the higher flowability of VSI of 2 mixes and the higher HRWR dosages. As can be seen from Figure 5.4, all SCC mixes have slump flow within the range of 20 - 30 in, which is in agreement with the recommended slump flow range by most of the State DOTs specifications reported in Chapter 3. It may also be noticed from Figure 5.4 that the conventional concrete mixture produced using fly ash Class F shows higher slump than that made with Class C fly ash, without adding any water reducer admixtures.

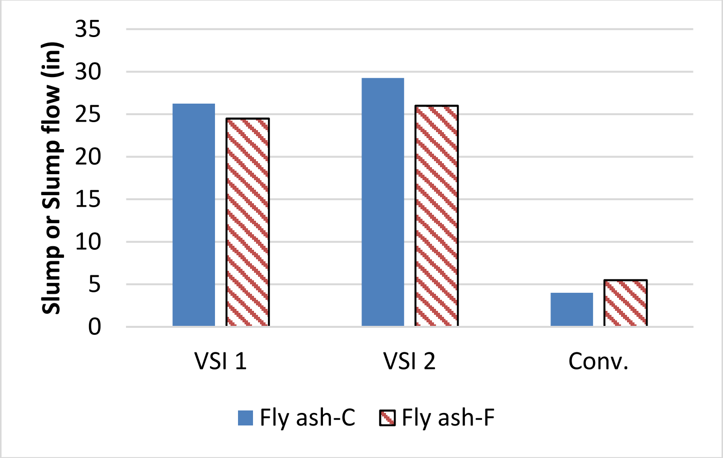


Figure 5.4 Slump and slump flow of #57 stone mixtures

Figure 5.5 summarizes the water reducer admixture requirements for #57 stone; it indicates that the fly ash Class C needs more WRA, to attain the VSI of 1 and 2, than that needed for Class F fly ash mixtures. Therefore, it can be concluded that Class F fly improves the flowability of #57 stone SCC mixes with a lesser amount of WRA than Class C fly ash mixtures. This is in agreement with ACI committee report 237 and FANG et al. (1999); they mentioned a replacement between 20 and 40% Class F fly ash in an SCC mixture could lead to good workability. So the only reason for having higher slump flow in the mixtures containing Class C fly ash, as shown in Figure 5.4, is because of adding more HRWR to these mixtures to attain the desirable VSI values. For the same reason and as illustrated in figure 5.6, the Class C fly ash mixes show shorter T50 time than that of the Class F fly ash mixtures. Following the ACI Committee 237 report, an SCC mixture can be characterized as a lower viscosity mixture when the T50 time is 2 seconds or less, and as a higher viscosity mixture with T50 time greater than 5 seconds. Thus, the #57 stone mixes can be considered as lower viscosity mixtures.

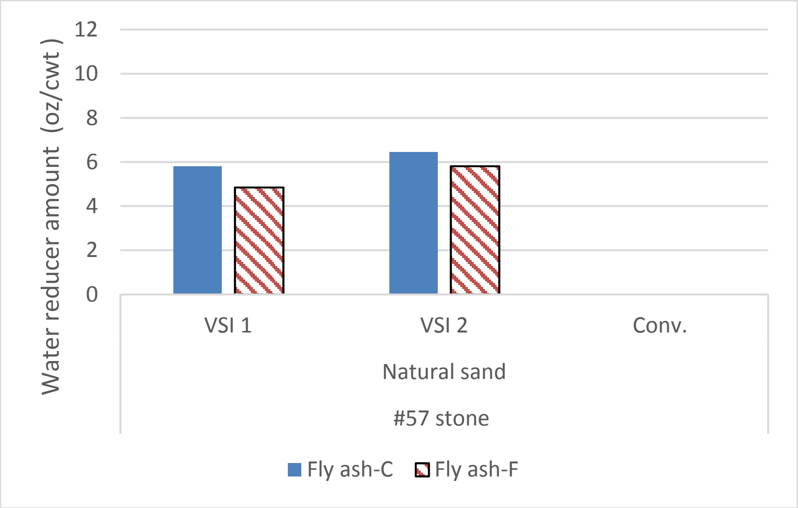


Figure 5.5 Water reducer admixture requirements for #57 stone mixtures.

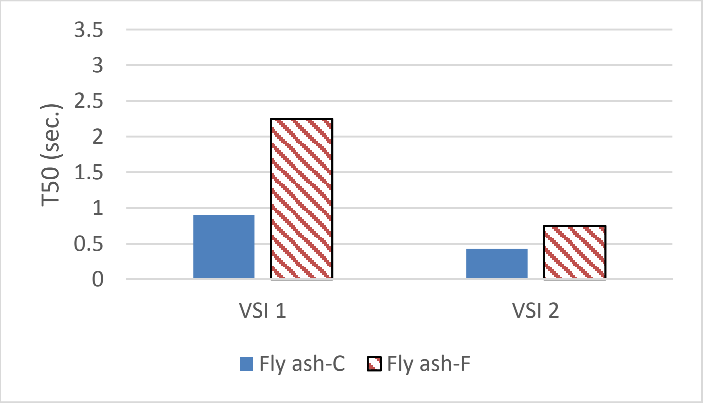


Figure 5.6 T50 values of #57 stone mixtures

Mixtures Containing #67 coarse aggregate with Natural and Manufactured Sand

Number 67 coarse aggregate was recommended by many of the State DOTs specifications as described in Chapter 3. Coarse aggregate #67 has a nominal maximum aggregate size of 3/4 in. A total of 12 mixtures, eight SCC and four conventional concrete, were produced using 67 stone. Six out of the 12 mixtures were devolved using natural sand. Three of them (Mix No 28,29, and 30) were produced with 20% cement replacement using Class C fly ash, and the other three (Mix No 40, 41, and 42) were produced using 20% cement replacement using Class F fly ash, as shown in Tables 5.3 and 5.4. The same six mixtures repeated using manufactured sand instead of the natural sand (Mix No 31, 32, 33, 43, 44, and 45) as shown in Tables 5.5 and 5.6.

The slump flow values and water reducer admixture requirements that are shown in Tables 5.3 to 5.6 were summarized in Figures 5.7 and 5.8. As can be seen from Figure 5.7, all SCC mixes have slump flow within the range of 20 - 30 in, and the mixtures with the VSI of 2 show higher slump flow than that of the VSI of 1, as same as #57 coarse aggregate.

From Figure 5.7, the mixtures made with the natural sand show slightly higher slump flow than that made with the manufactured sand, despite the higher amount of HRWR that was added to the manufactured sand as shown in Figure 5.8. This behavior could be attributed to the particle gradation and shape difference between the natural and manufactured sand. It should be noted that the Class C fly ash mixtures exhibit greater slump flow in both conventional and SCC with a VSI of 2 than Class F fly ash mixes. This performance was demonstrated despite Class F fly ash mixtures having greater water reducer dosages, as shown in Figure 5.8. The above performance exists in the #67 stone mixtures, but the opposite is true in the #57 stone mixtures, as discussed in Section 5.3.1.1.

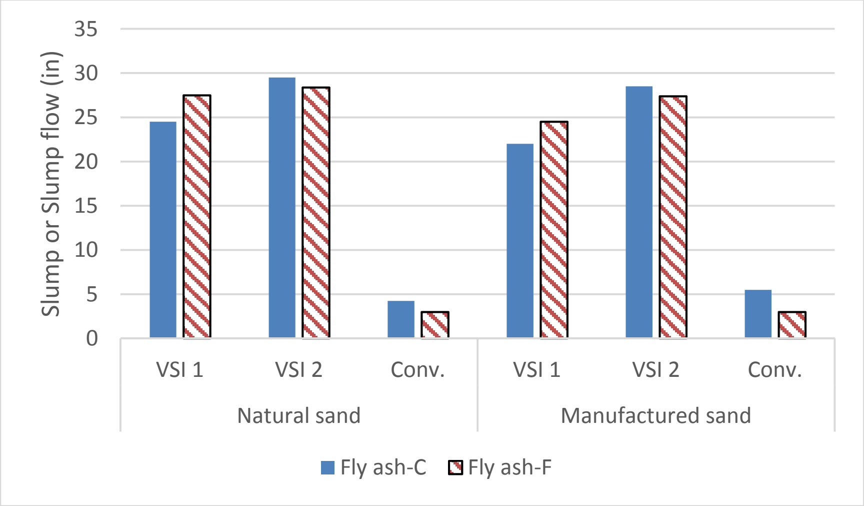


Figure 5.7 Slump and slump flow of #67 stone mixtures

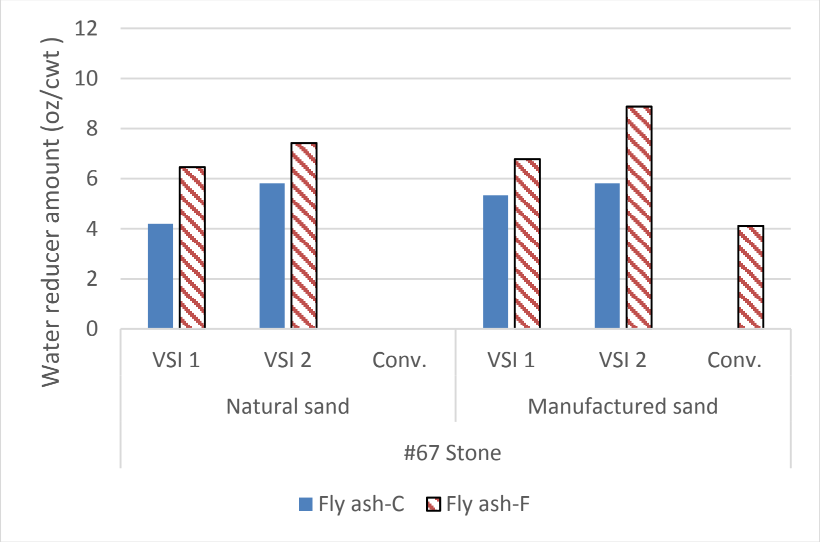


Figure 5.8 Water reducer admixture requirements for #67 stone mixtures

Figure 5.9 shows the T50 values for the #67 stone mixtures. The mixtures containing natural sand show lower viscosity (T50 less than 2 sec.) than that containing manufactured sand. It is also notable; the natural sand mixed with the Class F fly ash is showing less viscosity, contrary to the manufactured sand; which is showing less relative viscosity with Class C fly ash. This behavior could be attributed to the particle gradation and shape difference between the natural and manufactured sand; the natural sands tend to be rounded shape whereas manufactured sands tend to be angular (Kandhal, Motter, & Khatri, 1991).

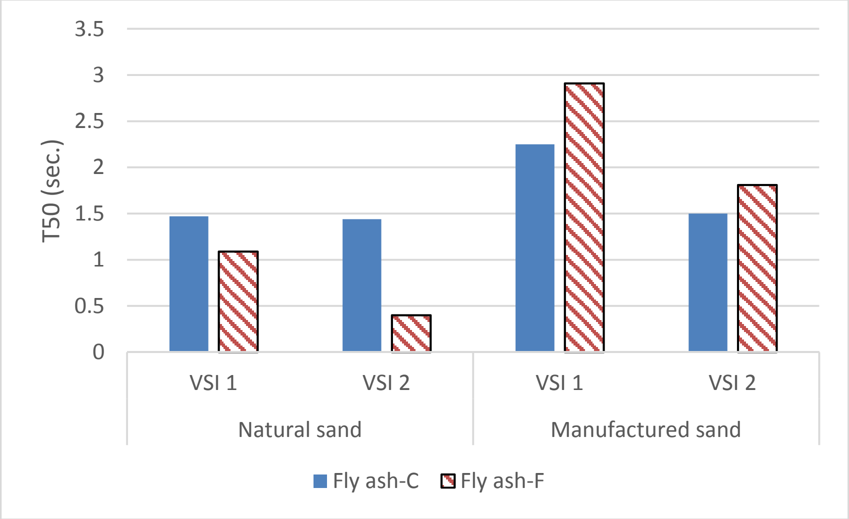


Figure 5.9 The T50 values of #67 stone mixtures

Mixtures Containing #7 coarse aggregate with Natural Sand

Number 7 coarse aggregate was the smallest aggregate size used in this study, which has a maximum aggregate size of 0.5 in. Similar to #57 stone and #67 stone, a total of six mixtures (Mix No 34, 35, 36, 46, 47, and 48) four SCC and two conventional, were produced using natural sand, and Class F and Class C fly ash. The slump flow values, water reducer admixture requirements, and the T50 values that are shown in Tables 5.7 and 5.8 are summarized in Figures 5.10, 5.11, and 5.12, respectively. In Figure 5.10, all SCC mixes have a slump flow within the range of 20 - 30 in. Figure 5.11 demonstrates that using Class C Fly ash mixes had higher slump flow, in conventional and SCC with VSI of 2, than the mixtures made with Class F fly ash. Despite the fact that greater amount of HRWR was added to the Class F fly ash mixtures to attain the desirable VSI values. Therefore, we can conclude that the fly ash Class C improves the flowability of #67 & #7 stone mixes with less amount of WRA than Class F fly ash mixtures, which is inverse to the case of #57 stone, as discussed in Section 5.3.1.1. This phenomenon could be attributed to the large aggregate size of #57 stone, 1 in. as maximum aggregate size, besides the chemical composition difference between fly ash Class F and C which could be the main reasons for having different fly ash effects in the flowability of #57 stone and the other #7 and #67 stones.

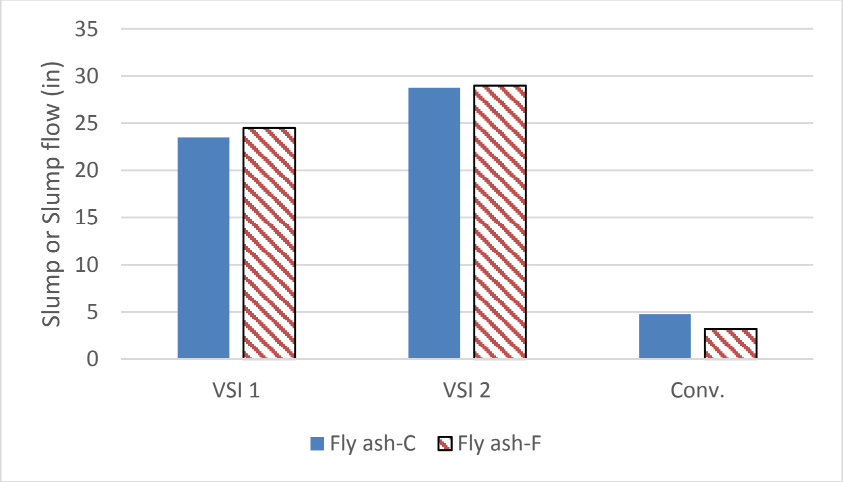


Figure 5.10 Slump and slump flow of #7 stone mixtures

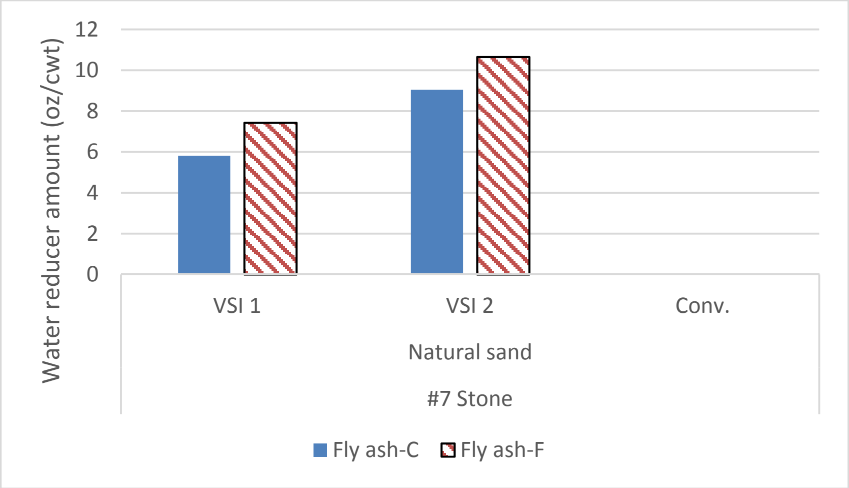


Figure 5.11 Water reducer admixture requirements for #7 stone mixtures

Figure 5.12 demonstrates similar behavior to #67 stone with natural sand; the fly ash Class F mixtures show shorter T50 time than that of the fly ash Class C mixtures. This result is due to the high dosage of WRA that was added to Class F fly ash mixtures to attain the desirable VSI values.

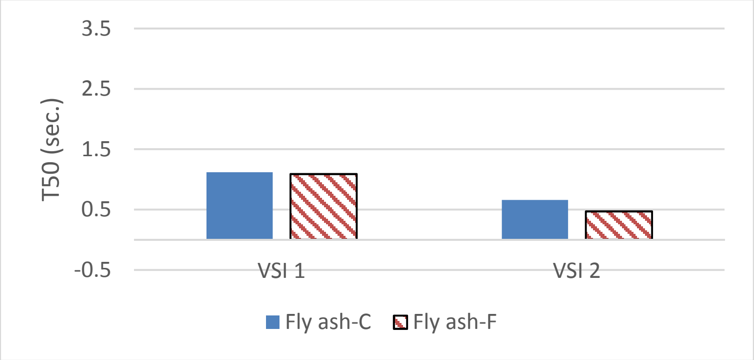


Figure 5.12 The T50 values of #7 stone mixtures

5.3.2 Passing Ability of Class A-SCC Mixtures

The J-ring and L-box tests were conducted to measure the passing ability of the studied mixtures. The mixes' passing ability and their blocking tendency could be identified according to the ASTM C1621 standard classification shown in Table 2.1. The ACI committee report 237 recommends the L-box ratio be near to the 1.0 as an indication of good passing ability. The results of J-ring and L-box tests were obtained for different aggregate sizes as described in Section 5.2 and summarized in Figures 5.13 and 5.14. The results of each aggregate size are discussed in the following section.

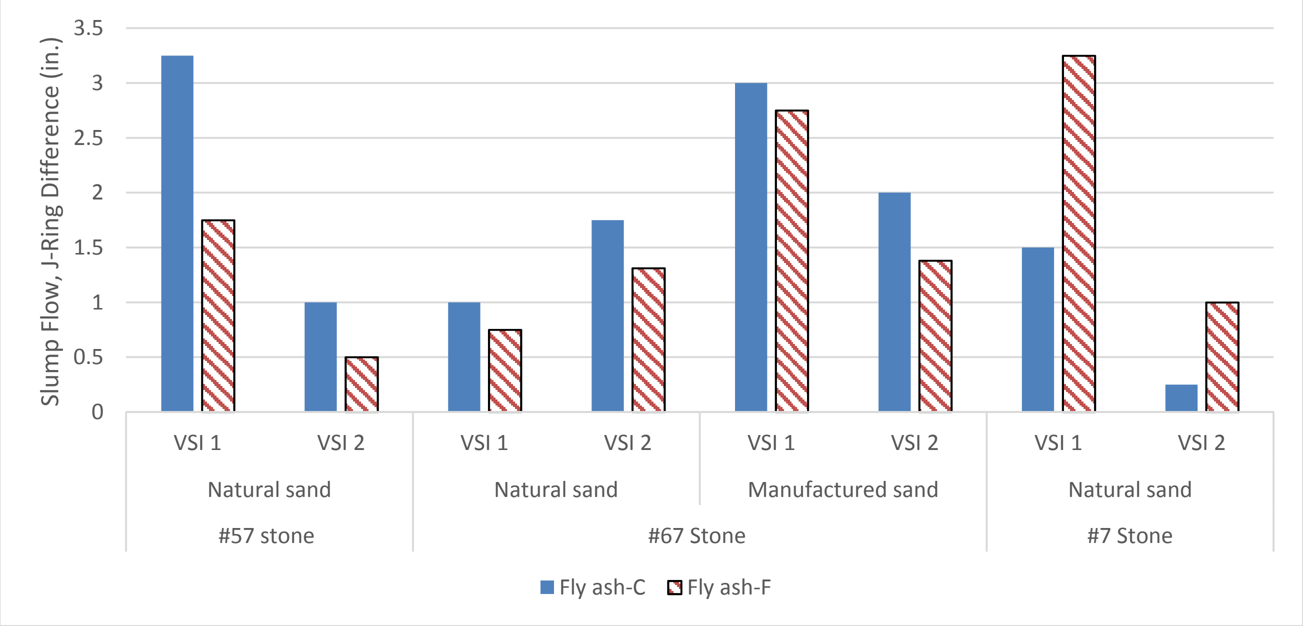


Figure 5.13 Slump flow and J-ring difference for the studied stones

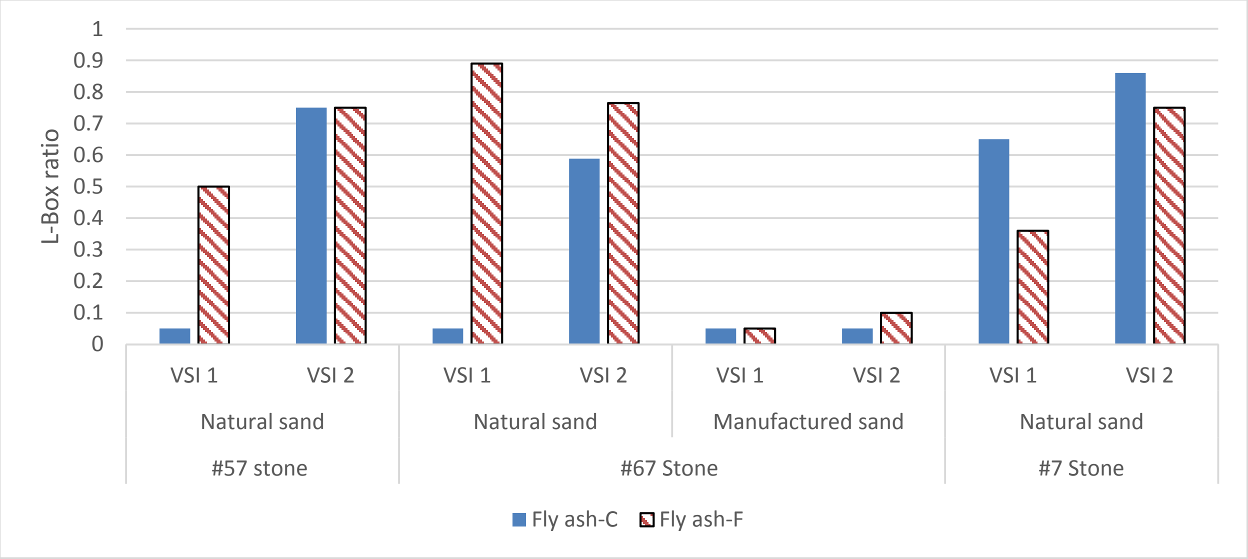


Figure 5.14 The L-Box Ratio for the studied stones

Mixtures Containing #57 coarse aggregate with Natural Sand

Figure 5.15 below shows the difference between the slump flow and J-ring values, which are shown in Tables 5.1 and 5.2 for #57 stone mixtures. As can be seen from Figure 5.15, the mixtures with VSI of 2 showed better passing ability than that of VSI of 1 mixture, which is anticipated and attributed to the high flowability of VSI 2 mixtures. It may also be observed that the mixtures containing Class F fly ash show better passing ability than that of Class C mixtures, about half the difference. Also, most of the State DOTs specifications require that the difference between the conventional slump flow and the J-ring slump flow to be less than 2 inches (minimal to noticeable blocking), which is in agreement with the results of the mixtures containing fly ash F, as shown in Figure 5.15.

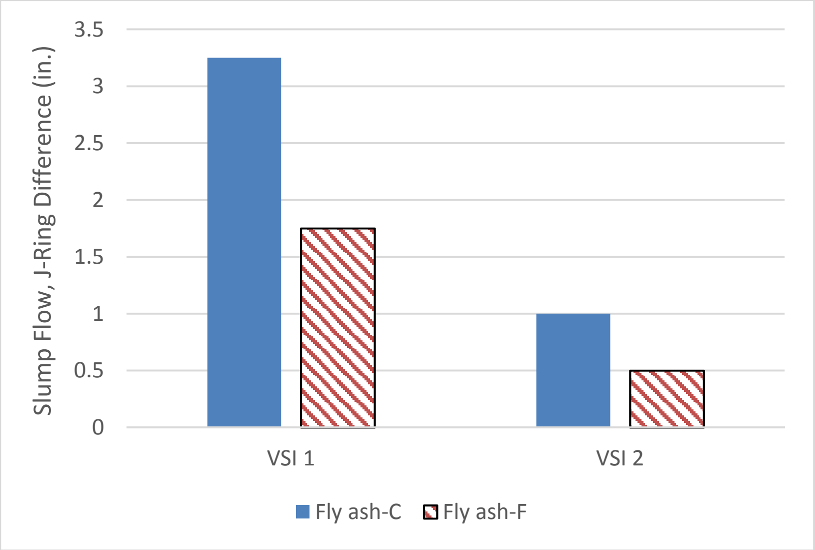


Figure 5.15 Slump flow and J-ring difference for #57 stone mixtures

As can be seen from Figure 5.16, which is showing the L-box ratio for #57 stone, using Class F fly ash produced L-box ratio of 0.5, in the VSI of 1 mixture, compared to the zero L- box ratio (Blocking) resulted from using Class C fly ash. The large aggregate size of #57 stone and the weak flowability of VSI of 1 mixture could be the main reason of having blocking in L- box test. On the other hand, the VSI of 2 showed higher passing ability compared to that of VSI of 1, which is in agreement with the results of J-ring test shown in Figure 5.15. The part where the gate is to be lifted, had always been difficult because the gate will stick and will need an excess force to lift it, which will result in an inaccurate measurements of the ratio.

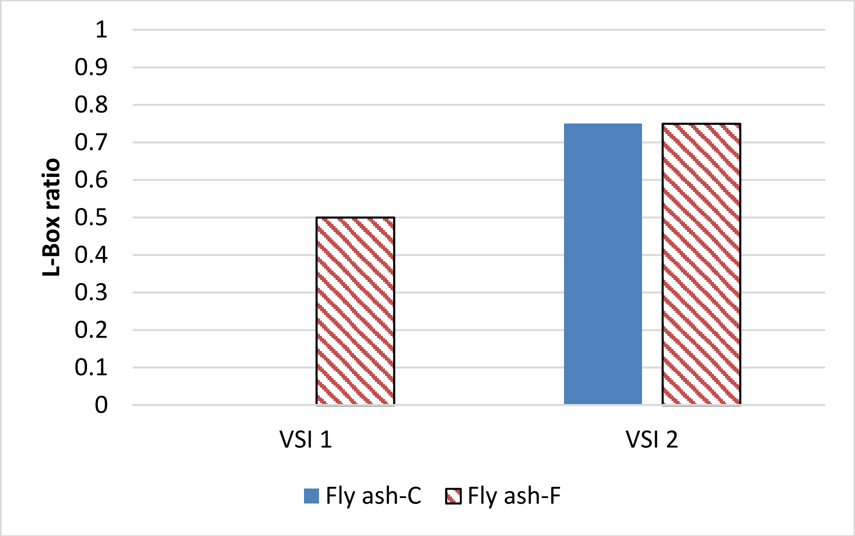


Figure 5.16 The L-Box Ratio for #57 stone mixtures

Mixtures Containing #67 coarse aggregate with Natural and Manufactured Sand

As shown in Figure 5.17, the manufactured sand shows very little passing ability (noticeable to extreme blocking) than that of the natural sand, especially in the VSI of 1 mixture. Similar to #57 stone, the fly ash Class F improves the passing ability of the #67 stone mixtures, which is clear in Figure 5.17 that all the fly ash Class F mixtures show less slump flow and J-ring difference (high passing ability, No visible blocking) than that of fly ash Class C. It can be observed from Figure 5.12, all #67 stone mixtures are in agreement with the State DOTs specifications (less than 2 in. difference), except the manufactured sand with the VSI of 1 shows more than 2 in. difference between the slump flow and J-ring. Another sign of the poor passing ability of the manufactured sand can be seen clear in the L-box results as shown in figure 5.18, which is showing blocking (zero L-box ratio) in the VSI of 1 mixture and only 0.1 L-box ratio in the VSI of 2.

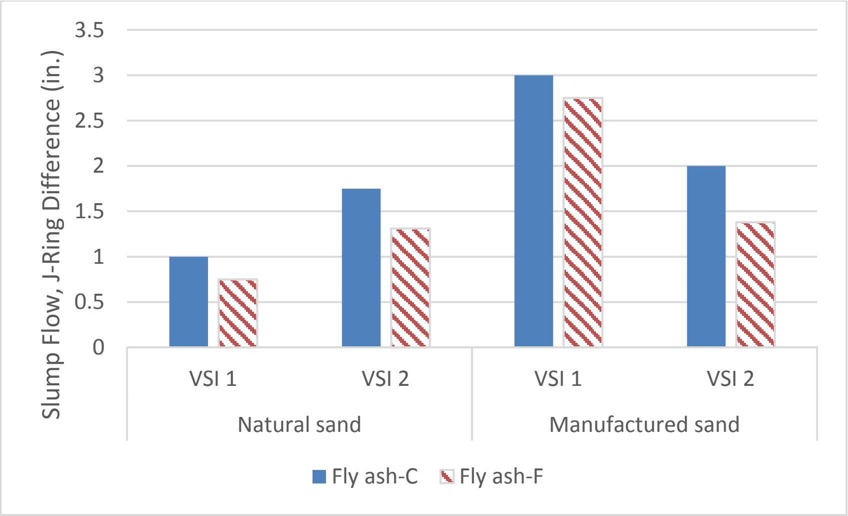


Figure 5.17 Slump flow and J-ring difference for #67 stone mixtures

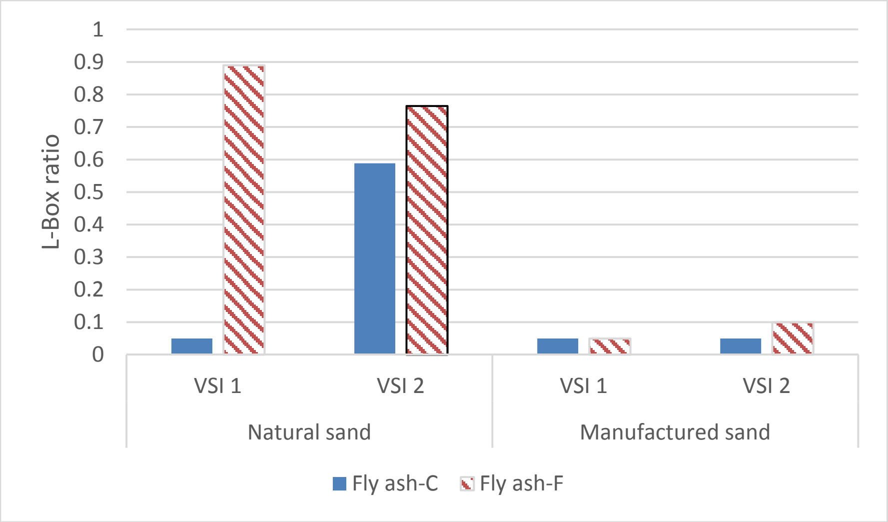


Figure 5.18 The L-Box Ratio for #67 stone mixtures

Mixtures Containing #7 coarse aggregate with Natural Sand

As shown in Figure 5.19, the coarse aggregate #7 has a good passing ability (no visible blocking) in the VSI 2 mixtures, and a noticeable to extreme blocking in the VSI 1 mixture. Similar to #57 and #67 stone mixture results, the Class F fly ash shows good passing ability compared to that of Class C fly ash. That could be attributed to the difference in calcium oxide content between the two classes of fly ash which causes different effects on the fresh properties of SCC, as mentioned by S. Keske 2011.

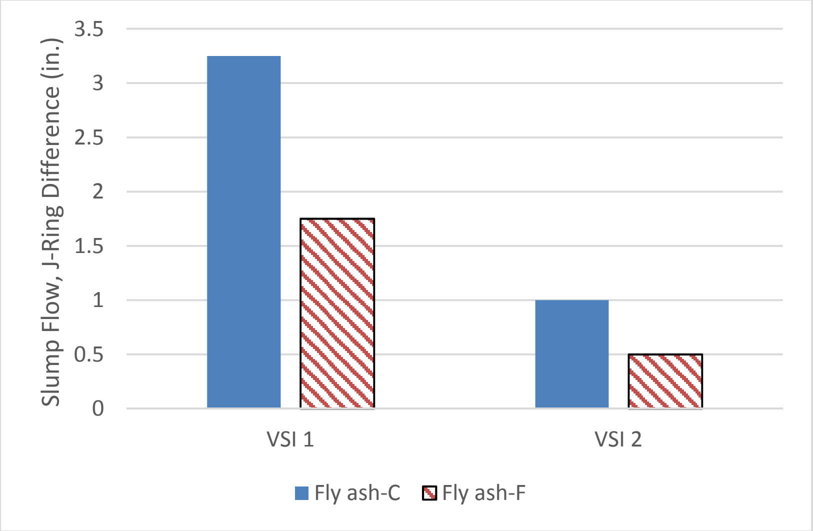


Figure 5.19 Slump flow and J-ring difference for #7 stone mixtures

Figure 5.20 summarizes the L-box results for #7 stone that shown in Tables 5.7 and 5.8. There is a different effect of Class F fly ash in # 7 stone than that in the #57 and #67 stones. As was noted in the L- box results for #57 and #67 stone, shown in Figure 5.16 and 5.18 respectively, the Class f fly ash concrete shows more passing ability (high L-Box ratio) than that of Class C fly ash. This is not the case in the Figure 5.20; the Class C fly ash shows more passing ability than that of Class F fly ash. This phenomenon could be attributed to the small size of aggregate #7 stone, which could be the main reason for having different fly ash effects in the L-box test for #7 stone and the other #57 and #67 stones. In general L-box test showed some difficulties; high force accompanied by some vibrations was applied while lifting the gate which affected the test accuracy and precision.

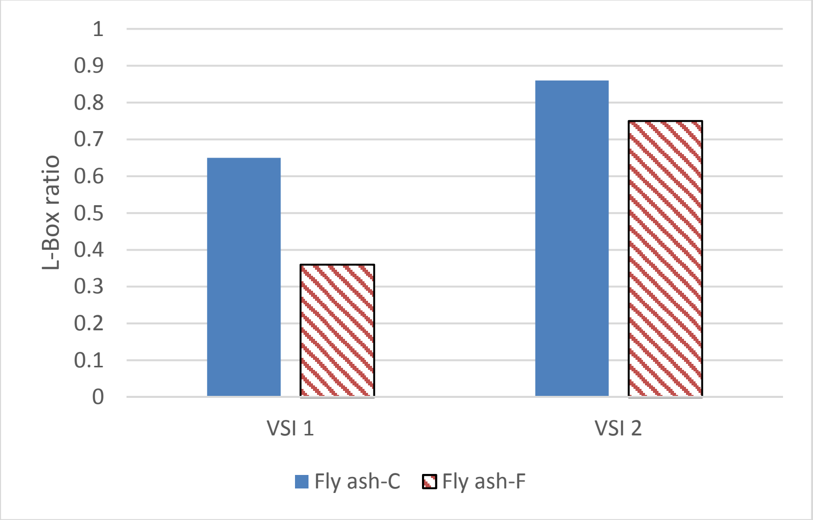


Figure 5.20 The L-Box Ratio for #7 stone mixtures

5.3.3 Stability of Class A-SCC Mixtures

The Column Segregation test was used to assess the segregation resistance of Class A-SCC mixtures. The SCC is generally considered to be accepted if the percent-segregation is less than 10% (ACI, 2007). However, some of the State DOTs specifications specify 15% as a maximum column segregation limit. The results of the Column Segregation test were obtained for different aggregate sizes as described in Section 5.2 and summarized in Figure 5.21. Most the VSI 1 mixtures meet the 10% limit, and all meet the 15% requirements as shown in Figure 5.21. Each aggregate size is discussed proceeding sections.

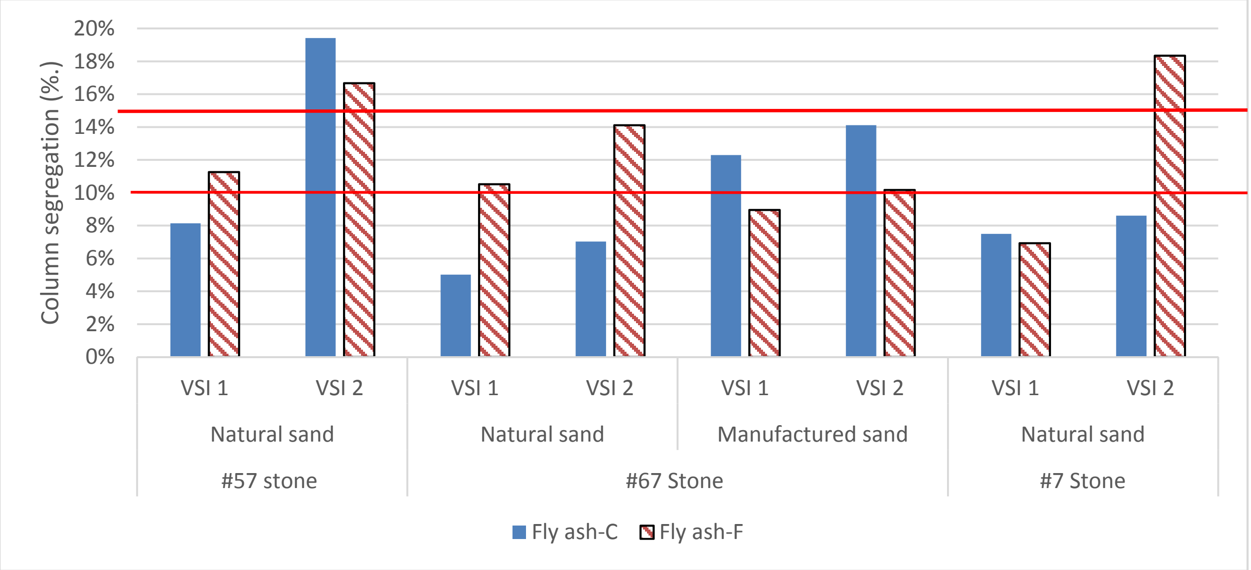


Figure 5.21 The column segregation for the SCC mixtures

Mixtures Containing #57 coarse aggregate with Natural Sand

As mentioned earlier in this Chapter, the #57 coarse aggregate is the largest aggregate size used in this study. Thus, it was anticipated to see high segregation potential for #57 stone mixtures due to the gap gradation of #57 stone shown in Figure 4.1. So it can be seen clearly in Figure 5.22 the VSI of 2 mixtures possess high segregation values (between15% to 20%) which are incompatible with the ACI recommendations (greater than 10%). Conversely, the VSI of 1 shows reasonable segregation, especially in the mixtures containing Class C fly ash and it is in agreement with the ACI recommendations.

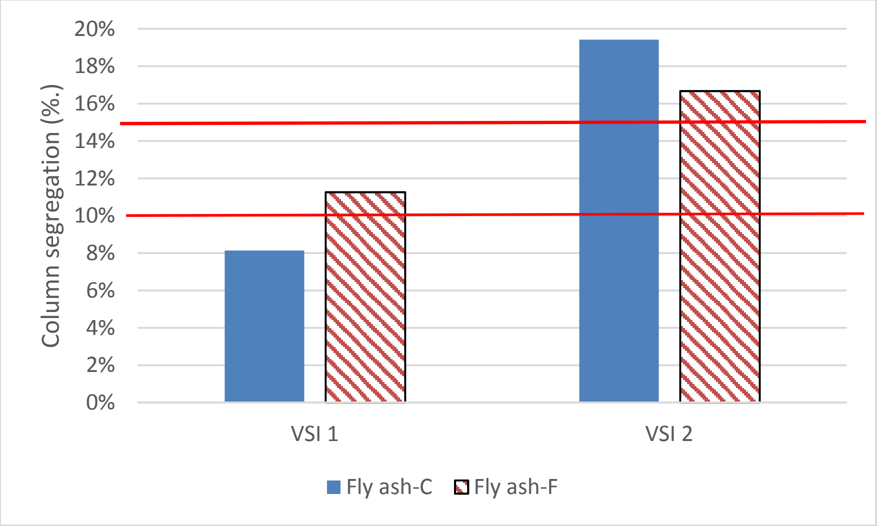


Figure 5.22 The column segregation for #57 stone mixtures

5.3.3.2 Mixtures Containing #67 coarse aggregate with Natural and Manufactured Sand

It may be noticed from Figure 5.23; the natural sand shows a little less segregation potential than that of the manufactured sand. Also, it can be seen clearly, the VSI of 2 for the mixtures containing the manufactured sand show high segregation values (greater than 10%) which are incompatible with the ACI requirements. It is also notable, and in agreement with #57 stone, the Class C fly ash shows lower segregation potential, in the natural sand mixtures with VSI of 1, than that of Class F fly ash mixture. While the manufacture sand adversely shows lower relative segregation potential with Class F fly ash rather than Class C. This contradiction in the fly ash effects could be attributed to the difference in natural and manufactured sand gradation and particles shape.

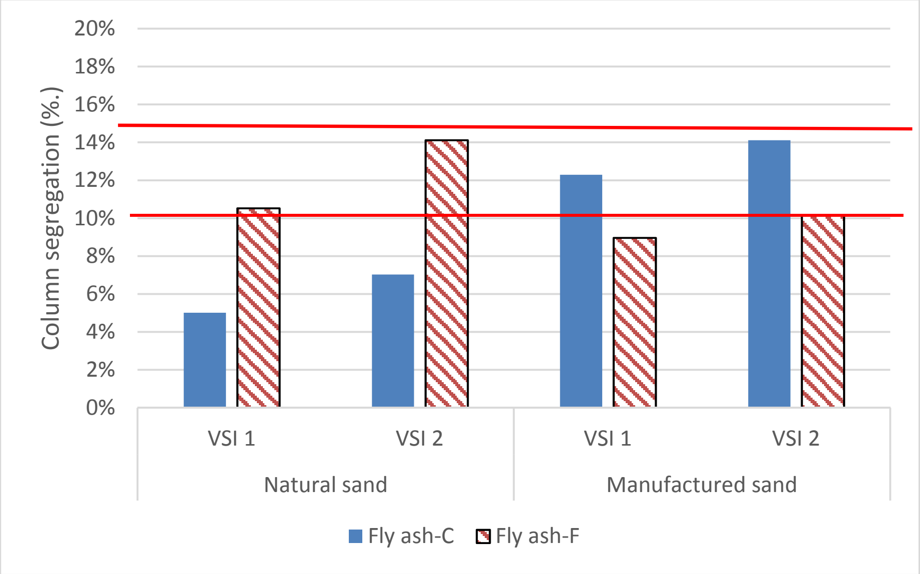


Figure 5.23 The column segregation for #67 stone mixtures

Mixtures Containing #7 coarse aggregate with Natural Sand

The #7 coarse aggregate was the smallest size used in this study. Therefore, it was anticipated to show less segregation potential than that of the other aggregate sizes. This trend could also be attributed to the well-graded #7 stone mixtures as shown in Figure 4.1. Studies show that the well-graded mixtures tend not to have as many problems as gap-graded mixes concerning workability and segregation during vibration (Richardson, 2005). As observed from Figure 5.24, all the mixtures show acceptable segregation potential except Mix No. 20 with 18.35 % segregation. This high segregation value could be attributed to the large amount of HRWR that was added to this mixture as shown in Figure 5.11.

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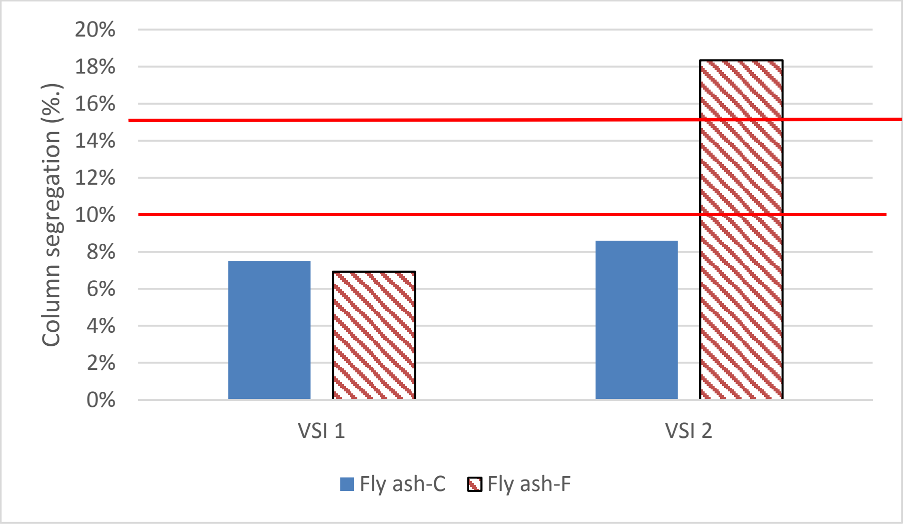

Figure 5.24 The Colum Segregation for #7 stone mixtures

5.3.4 Initial and Final Time of Setting for SCC and Conventional Concrete Mixtures

The Time of setting of concrete mixtures by penetration resistance was conducted for the both SCC and conventional concrete mixtures. The test was performed on a mortar sample that was obtained by sieving a representative sample of fresh concrete through a 4.75-mm sieve. Thus, it was not anticipated to notice much variation between the different aggregate sizes. The results of the various aggregate sizes are discussed below in details.

Mixtures Containing #57 coarse aggregate with Natural Sand

Figure 5.25 shows the initial and final time of setting for #57 stone, which ranged from 5 to 8.5 hours, and it was anticipated to notice such variation between the setting time between VSI of 1 and 2 and the conventional mixtures. This variation in the time of setting can be attributed to the different HRWR dosages among the mixtures; the VSI of 2 possessed the highest HRWR dosage, and it showed longer time. Also, it is noticeable that Class F fly ash is showing longer setting time than that of Class C fly ash, which due to the chemical composition difference between C and F fly ash; Class C fly ash contains a higher amount of calcium oxide than Class F fly ash.

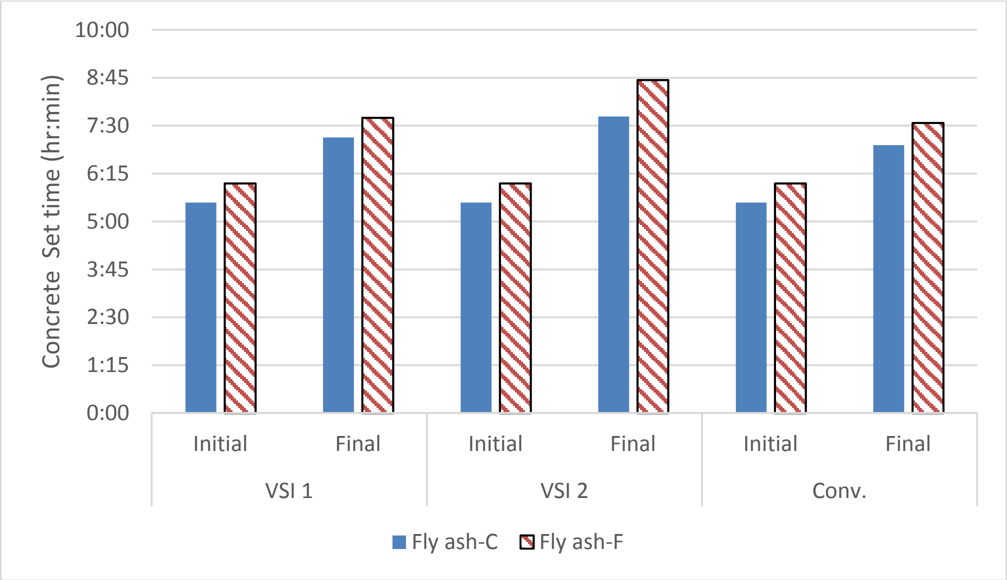

Figure 5.25 The initial and final time of setting for #57 stone mixtures

Mixtures Containing #67 coarse aggregate with Natural and Manufactured Sand

As shown in Figure 5.26, the manufactured sand concrete mixes set more quickly than the natural sand mixes. This difference in set time could be due to the different particle sizes of the manufactured sand; it is quite larger than natural sand and, therefore, would have less surface area for cementitious materials to coat. The chemical makeup of the manufactured sand could also potentially contribute to the shorter set times exhibited, since the manufactured sand used is a calcium-bearing material. Also, it can be seen, similar to #57 stone, the Class C fly ash shortened the initial and final time of setting more than that of Class F fly ash.

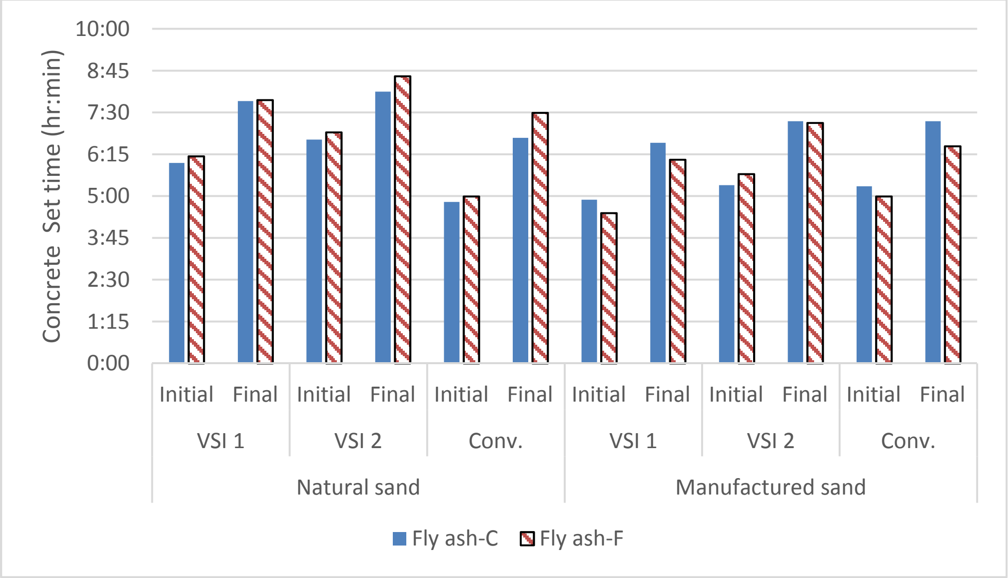

Figure 5.26 The initial and final time of setting for #67 stone mixtures

Mixtures Containing #7 coarse aggregate with Natural Sand

The same observations that were noticed in Figures 5.25 and 5.26 could be confirmed in Figure 5.27 for #7 stone.

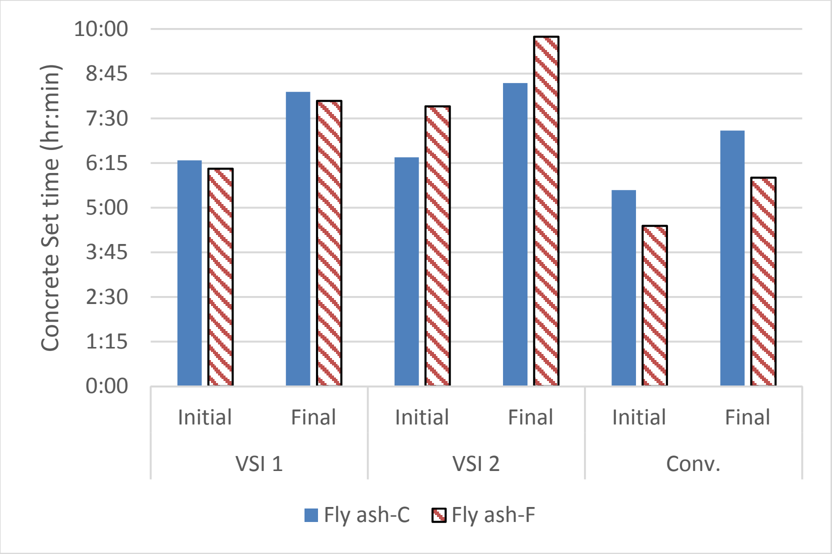

Figure 5.27 The initial and final time of setting for #7 stone mixtures

5.3.5 Air Entrained Admixture Requirements for Class A-SCC Concrete Mixtures

The AEA was used to provide 5.5 % to 7.5 % air content within the concrete mixes. The dosages of AEA for the different aggregate sizes are discussed below.

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Mixtures Containing #57 coarse aggregate with Natural Sand

As can be seen in Figure 5.28, the SCC mixtures (VSI 1 and 2) require less AEA dosages than that for the conventional concrete mixture. This could be attributed to the HRWR effect which reduces the amount of air-entraining admixture necessary to achieve a given air content, as mentioned by S. Keske 2011.

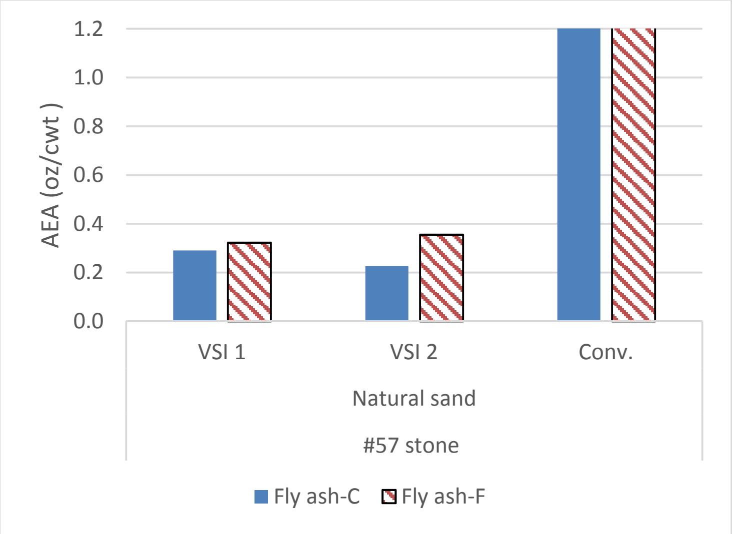

Figure 5.28 The AEA requirements for #57 stone mixtures

Mixtures Containing #67 coarse aggregate with Natural and Manufactured Sand

The same observations that have noticed in Figures 5.28 can be confirmed in Figure 5.29 for #67 stone mixtures. It can also be observed; the natural sand requires more AEA dosages to attain the desirable air contents than that for the manufactured sand, which can be attributed to the effect of different gradation between the natural and manufactured sand.

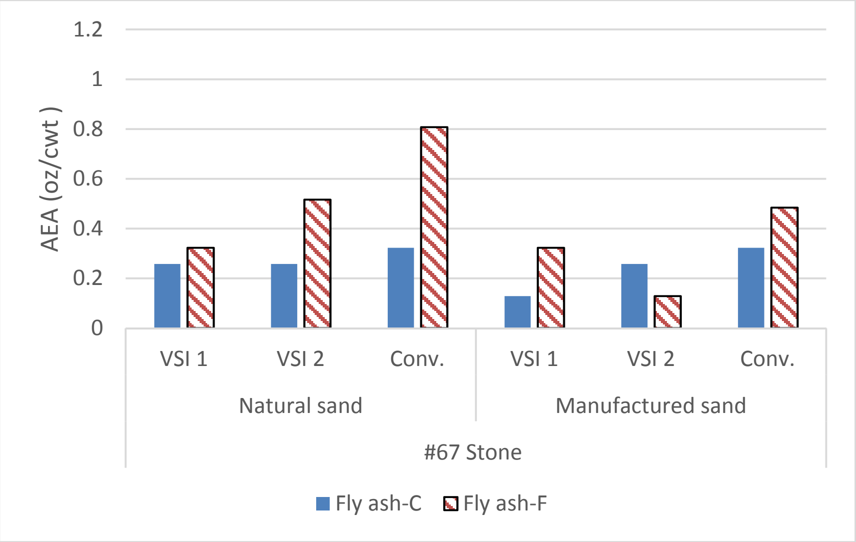

Figure 5.29 The AEA requirements for #67 stone mixtures

Mixtures Containing #7 coarse aggregate with Natural Sand

It can be seen clearly in Figure 5.30, the #7 coarse aggregate needed less AEA dosages than that for #57 and #67 aggregate, as shown in Figures 5.28 and 5.29 respectively. The small aggregate size of #7 could be the main reason behind the AEA reduction.

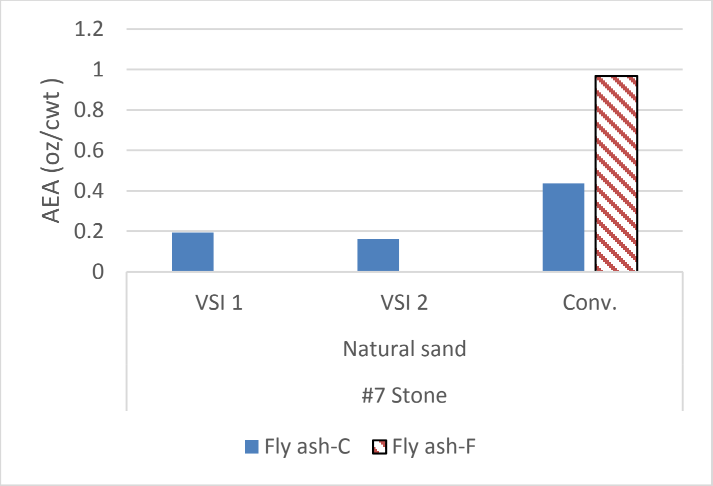

Figure 5.30 The AEA requirements for #7 stone mixtures

5.4 Discussion of Fresh Properties of Class P-SCC Concrete Mixtures

5.4.1 Filling Ability of Class P-SCC Mixtures

The filling ability of the Class P-SCC was assessed with the Slump flow test and T-50 values. Slump flow values vary proportionally with VSI value as shown in Figure 5.31. VSI 1 and VSI 2 were achieved by using different HRWR dosages as illustrated in figure 5.32, and determined by a visual rating of the slump flow patty as mentioned in chapter 4. T-50 values were measured to provide a relative index of the viscosity. Slump flow and Slump values are shown in Figure 5.31, while T-50 values are illustrated in figure 5.33.

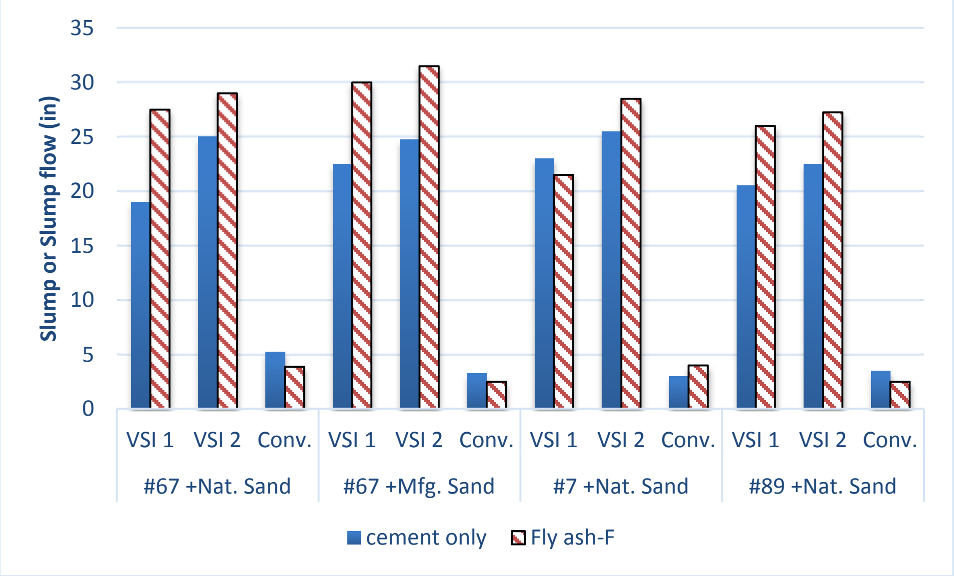

Figure 5.31 Slump and Slump Flow of the Studied Mixtures

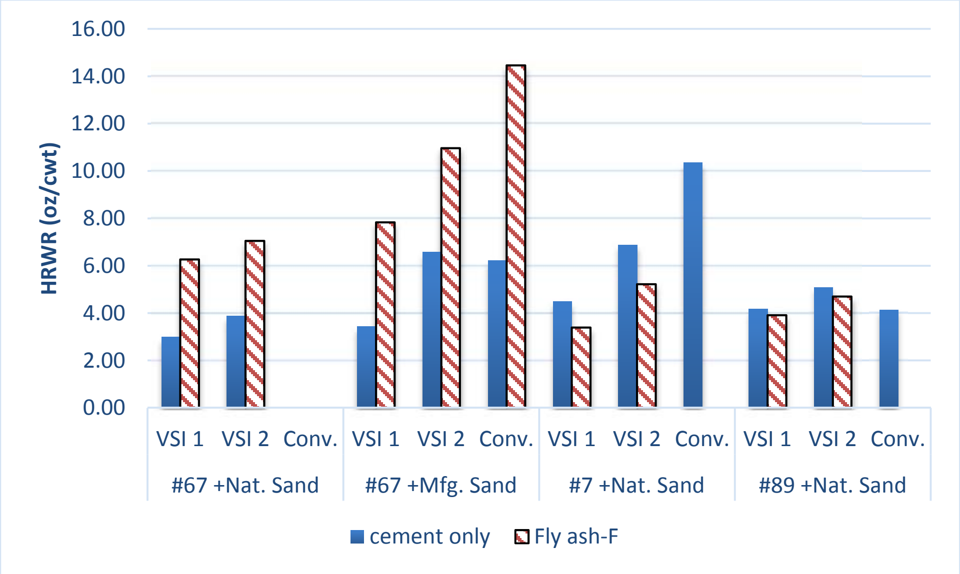

Figure 5.32 Water Reducer Admixture Requirements for the Studied Mixtures

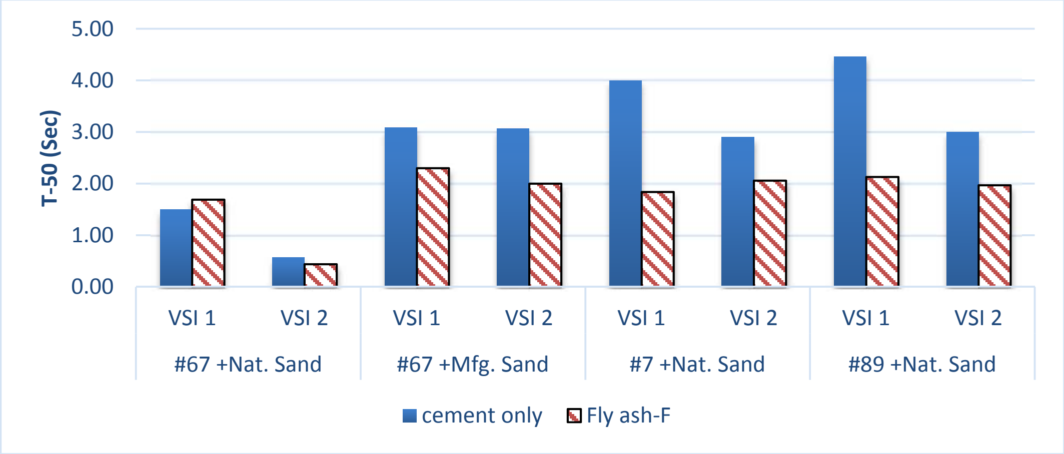

Figure 5.33 T-50 Results of the Studied Mixtures

Mixtures Containing #67 coarse aggregate with Natural and Manufactured Sand

Number 67 coarse aggregate was used to a total of 12 mixtures, eight SCC and four conventional concrete. Half of the mixtures were developed using natural sand, three of them (Mix No 1, 2, and 3) were produced only with portland cement, and the other three (Mix No 13, 14, and 15) were produced using 20% cement replacement with Class F fly ash. Manufactured sand was used with the same criteria of the natural sand on the other half of the mixtures (Mixtures No 4, 5, 6, 16, 17 and 18).

The slump flow values and water reducer admixture requirements were summarized in Figures 5.34 and 5.35. As can be seen from Figure 5.34, all SCC mixtures have slump flow range between 19 to 26.5 inches, and the mixtures with the VSI of 2 show higher slump flow than that of the VSI of 1. Mixtures made with natural sand has a higher slump flow values compared to the ones made with manufactured sand as shown in Figure 4.4, and at the same time the amount of HRWR added to the manufactured sand is higher than the one added to the natural sand as shown in Figure 5.35.

This behavior could be attributed to the particle gradation and shape difference between the natural and manufactured sand. It should be noted that the OPC mixtures exhibit a slightly higher slump flow in both conventional and SCC with a VSI of 2 than Class F fly ash mixtures, however that class F fly ash mixtures have a greater HRWR dosages.

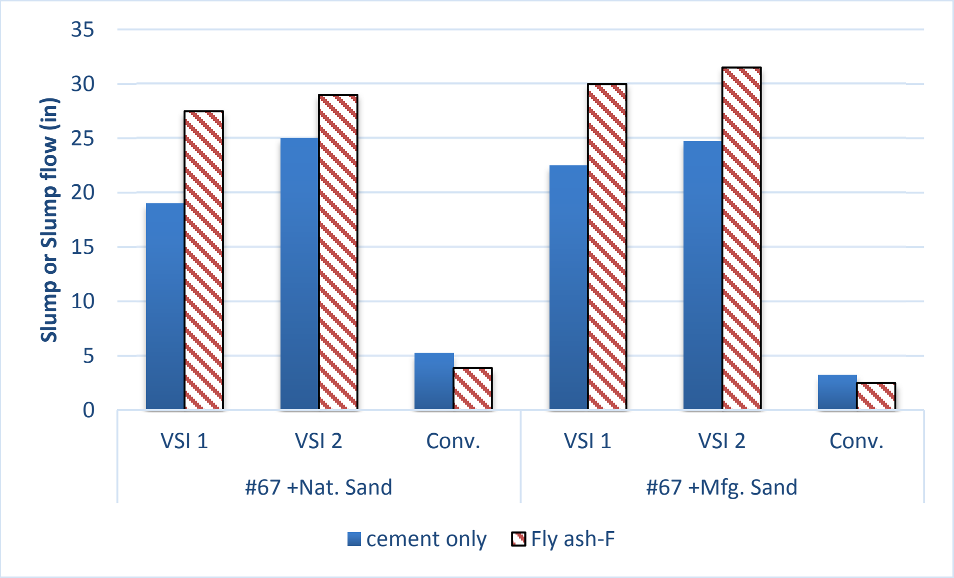

Figure 5.34 Slump and Slump flow of #67 Stone Mixtures

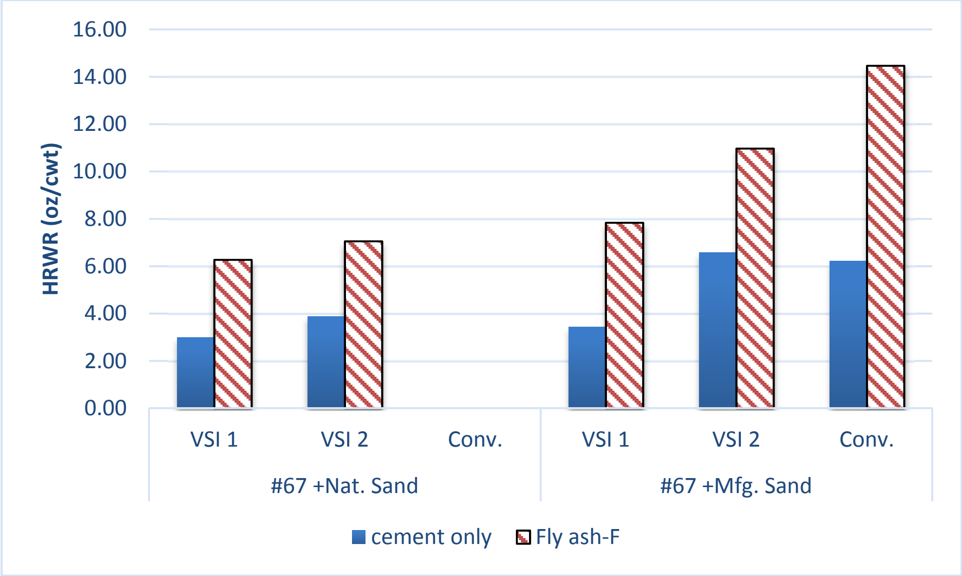

Figure 5.35 Water Reducer Admixture Requirements for #67 Stone Mixtures.

As shown in Figure 5.36 that the mixtures containing natural sand show lower viscosity than that containing manufactured sand. This behavior could be attributed to the particle gradation and shape difference between the natural and manufactured sand; the natural sands tend to be rounded shape whereas manufactured sands tend to be angular. It is also shown that the mixtures with the Class F fly ash is showing higher viscosity (higher T-50) compared to the OPC mixtures.

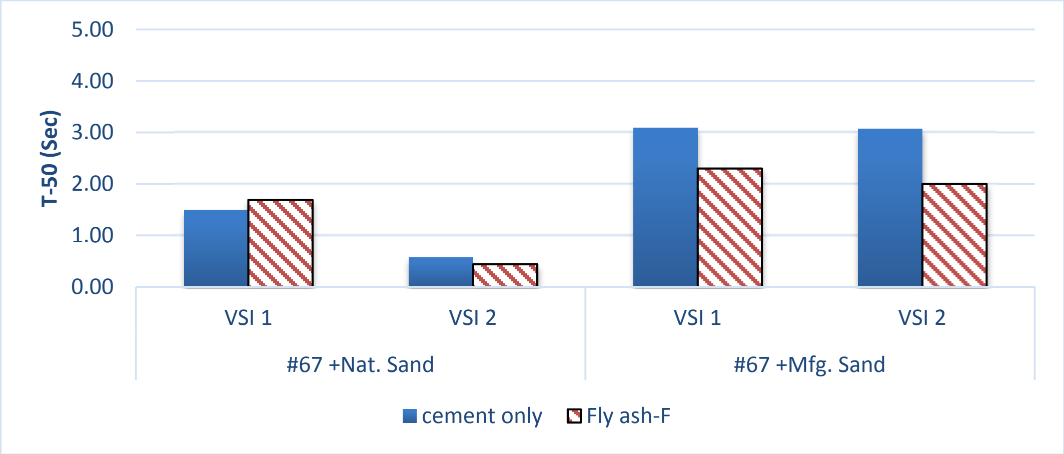

Figure 5.36 T-50 Values of #67 Stone Mixtures

Mixtures Containing #7 coarse aggregate with Natural Sand

Number 7 coarse aggregate has a maximum aggregate size of 0.5 in. A total of six mixtures (Mix No 7, 8, 9, 19, 20, and 21) two SCC with VSI 1, two SCC with VSI 2 and two conventional, were produced using natural sand. The slump flow values, water reducer admixture requirements, and the T50 values are summarized in Figures 5.37, 5.38, and 5.39 respectively. From Figure 5.37 it is shown that all SCC mixtures have slump flow within the range of 20 - 30 in. Slump flow results seem to be higher for VSI 1 using OPC than fly ash mixtures while the opposite is true when producing VSI 2 as shown in Figure 5.37. Also, it is evident in Figure 5.37, Class F fly ash mixtures show a higher slump compared to OPC in the conventional mixes, although the amount of WRA used in the OPC mixtures is higher than used in the fly ash mixtures. HRWR dosages used with #7 stone are generally lower than with #67 stone mixes.

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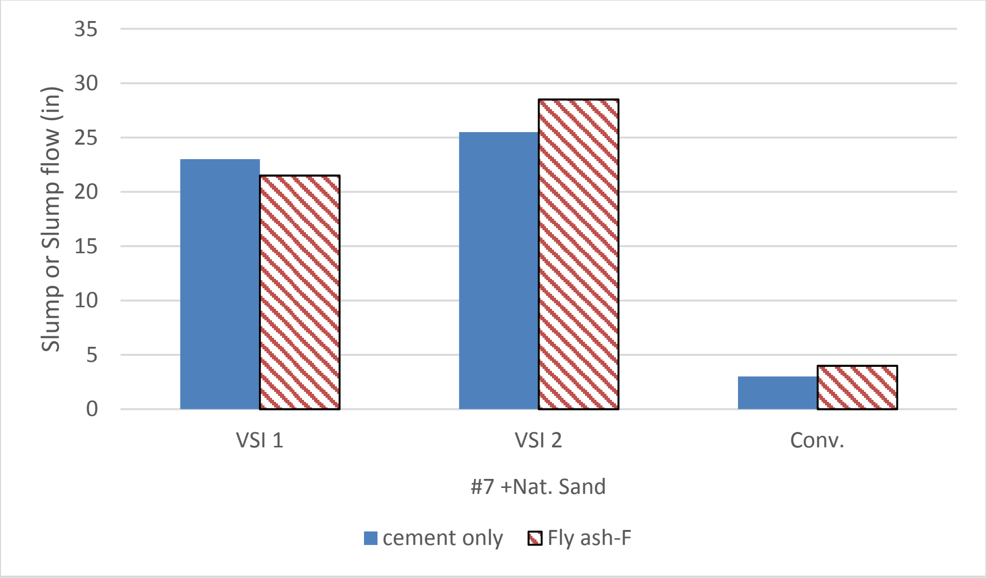

Figure 5.37 Slump and Slump Flow of #7 Stone Mixtures

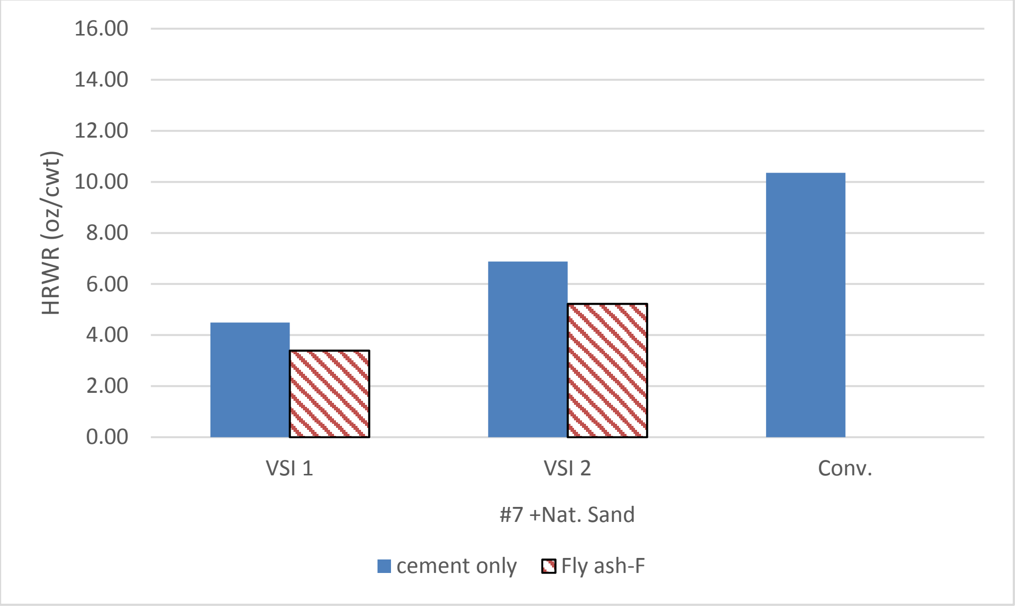

Figure 5.38 Water Reducer Admixture Requirements for #7 Stone Mixtures

The same phenomena of #67 stone with the natural sand, the Class F fly ash mixtures show shorter T-50 time than that of the OPC mixtures as shown in Figure 5.39, which is due to the high dosages of HRWR that was added to Class F fly ash mixtures to attain the desirable VSI values.

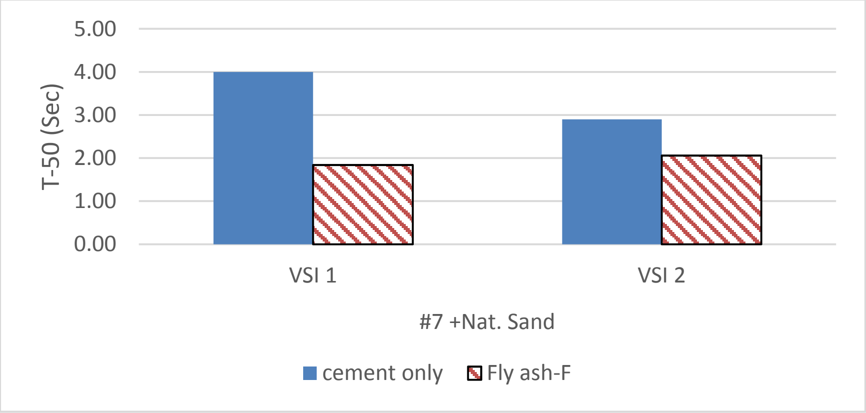

Figure 5.39 The T-50 Values of #7 Stone Mixtures

Mixtures Containing #89 coarse aggregate with Natural Sand

The #89 coarse aggregate was used in this study with natural sand only. Also, it was the smallest aggregate size employed in this study. A total of six mixtures (Mix No 10, 11, 12, 22, 23, and 24) two SCC with VSI 1, two SCC with VSI 2 and two conventional, were produced using natural sand. The slump flow values, water reducer admixture requirements, and the T50 values are summarized in Figures 5.40, 5.41, and 5.42 respectively. From Figure 5.40 it is shown that all SCC mixtures have slump flow within the range of 20 - 30 in. The same phenomena with #7 stone that Slump flow results seems to be higher for VSI 1 using OPC than fly ash mixtures while it is the opposite that is true when producing VSI 2 as shown in Figure 5.40. Also, it is evident in Figure 5.40, using Class F fly ash shows a higher slump in the conventional than the mixtures made with OPC, although the amount of WRA used in the OPC mixtures are higher than used in fly ash mixture. HRWR dosages used with #89 stone are generally lower than the ones used with #67 stone and #7 stone.

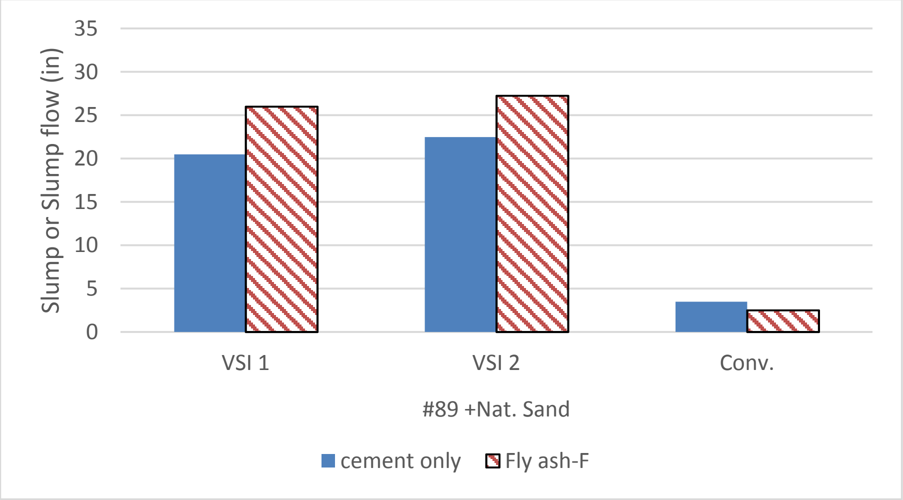

Figure 5.40 Slump and Slump Flow of #89 Stone Mixtures

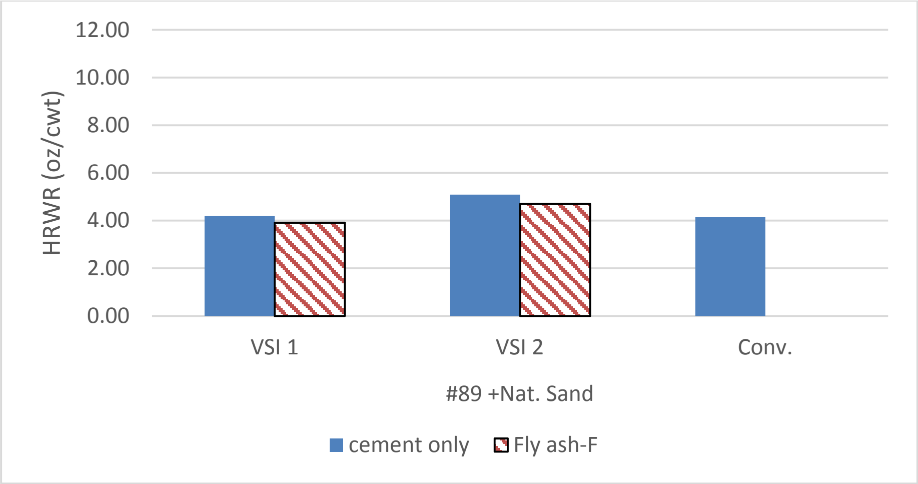

Figure 5.41 Water Reducer Admixture Requirements for #89 Stone Mixtures

The Class F fly ash mixtures show shorter T-50 time than that of the OPC mixtures as shown in Figure 5.42, which is due to the high dosages of HRWR that was added to Class F fly ash mixtures to attain the desirable VSI values.

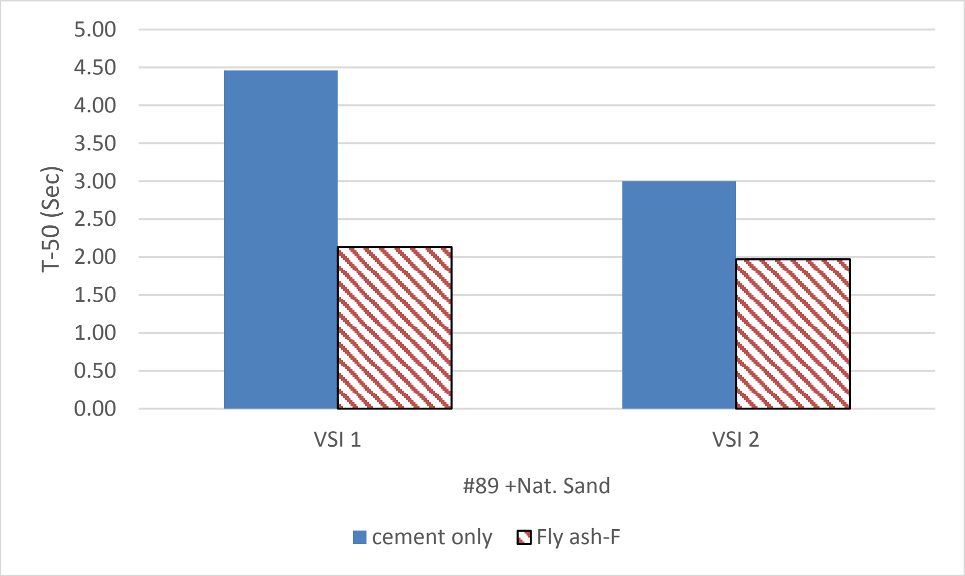

Figure 5.42The T-50 Results of #89 Stone Mixtures

5.4.2 Passing Ability of SCC Mixtures

The passing ability property was assessed as mentioned earlier by conducting the J-ring and L-box tests on the studied mixtures. ASTM C1621 standards classify the blocking tendency for J-ring results as shown in Table 5.9, while The ACI 237 committee report recommends the L-box ratio close to the 1.0 as better passing ability. The results of J-ring and L-box tests were obtained for different aggregate sizes are summarized in Figures 5.43 and 5.44.

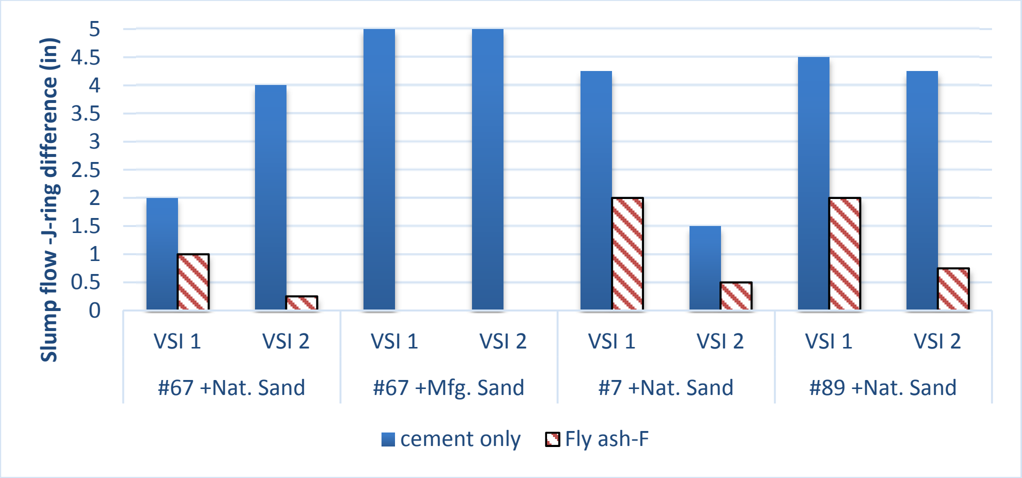

Figure 5.43 Slump Flow and J-ring Difference for the Studied SCC by Aggregate Type

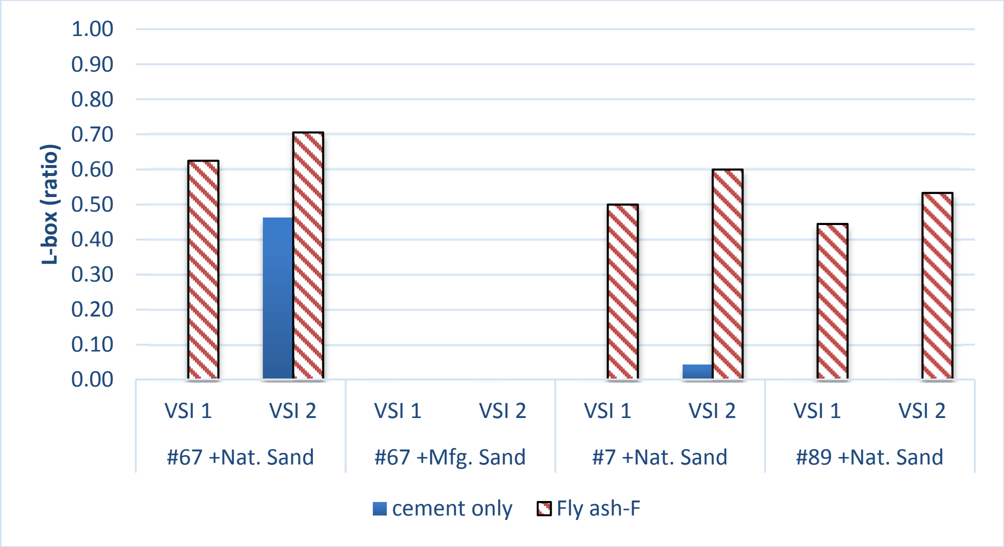

Figure 5.44 The L-Box Ratio for the Studied Mixtures

Mixtures Containing #67 coarse aggregate with Natural and Manufactured Sand

The passing ability of the manufactured sand is very poor compared to the natural sand as shown in Figure 5.45, especially in the VSI of 1 mixture. Mixtures with Class F fly ash has a better passing ability than OPC mixtures when producing VSI of 1 mixture while OPC mixtures have a better passing ability with VSI of 2. From Figure 5.45, all #67 stone and manufactured sand mixtures have a difference of more than 2 inches which is not favorable. OPC and natural sand mixtures of VSI 1 and Fly ash mixture with VSI 2 are the only mixtures within the favorable limits of TDOT (the difference is less than 2 in).

All manufactured sand mixtures showed a zero L-box ratio as illustrated in figure 5.46. It is shown that Fly ash mixtures with natural sand have a better L-box ratio that OPC mixtures. Mixtures with VSI 2 showed a better performance than VSI 1.

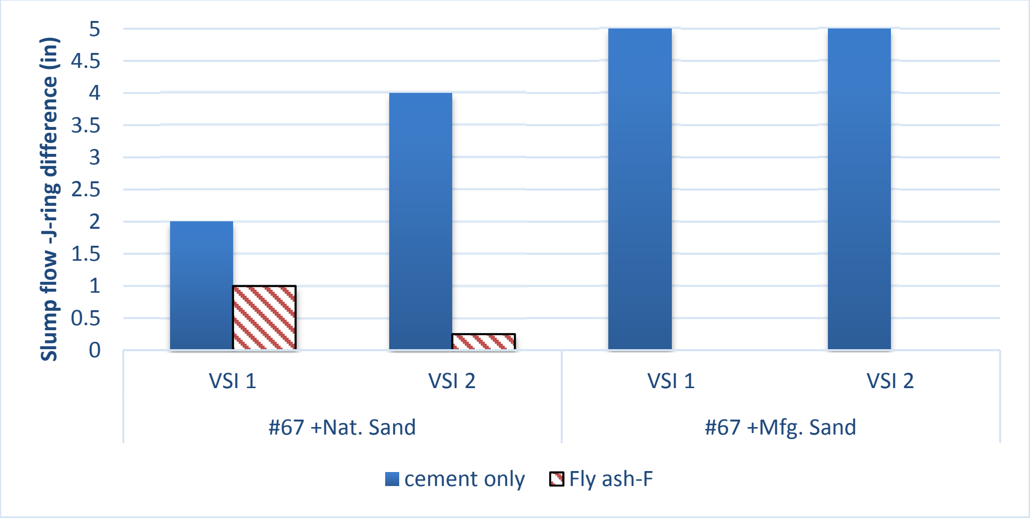

Figure 5.45 Slump Flow and J-Ring Difference for #67 Stone Mixtures

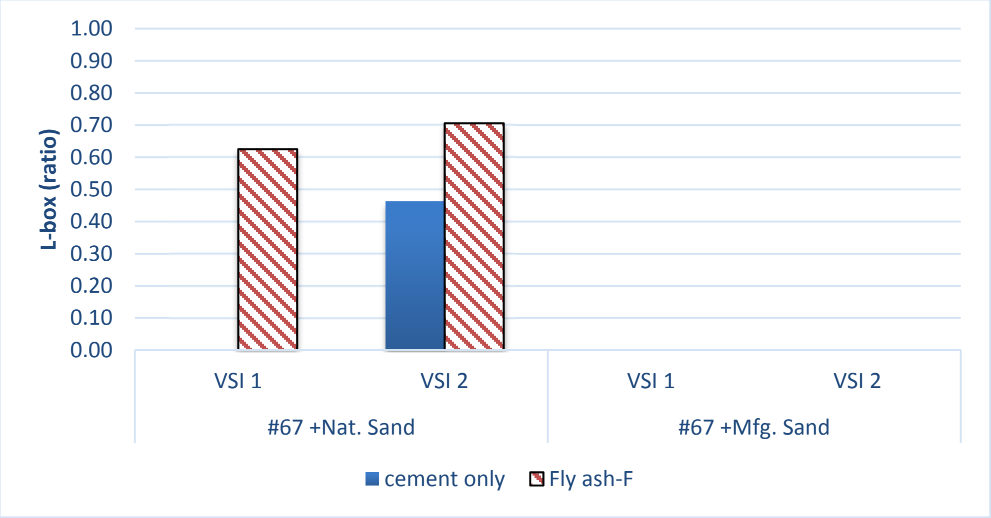

Figure 5.46 The L-Box Ratio for #67 Stone Mixtures

Mixtures Containing #7 coarse aggregate with Natural Sand

As shown in Figure 5.47, the #7 coarse aggregate with VSI of 2 has a good passing ability compared to VSI of 1 mixture. Fly ash mixtures demonstrated a better performance than OPC mixtures. As shown in Figure 5.48, it is shown that Fly ash mixtures have a better L- box ratio that OPC mixtures. Mixtures with VSI 2 showed a better performance than VSI 1.

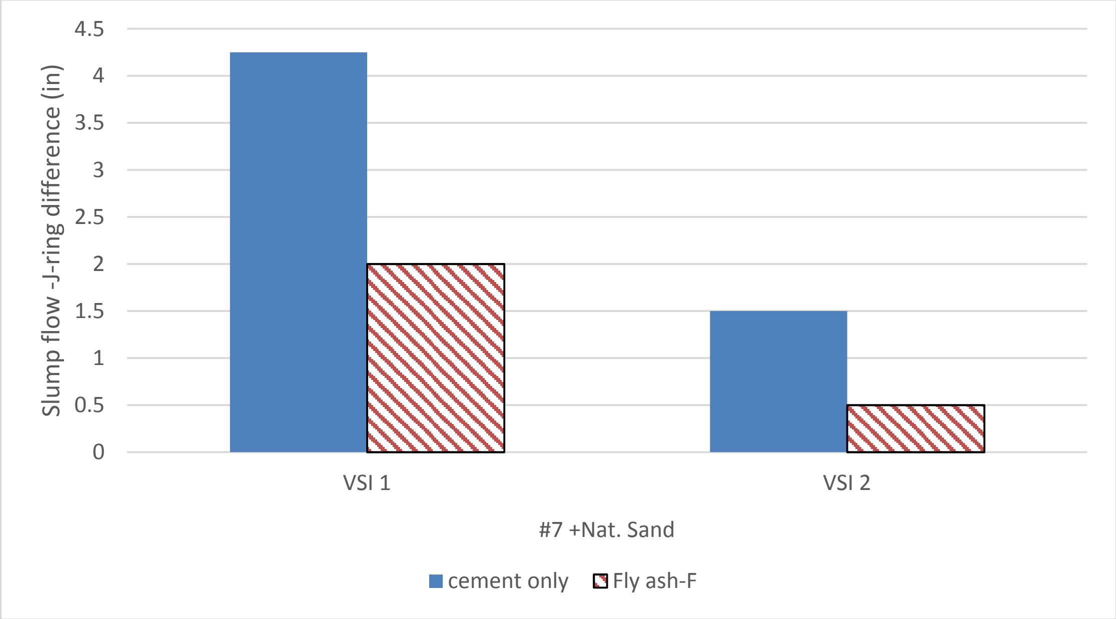

Figure 5.47 Slump Flow and J-Ring Difference for #7 Stone Mixtures

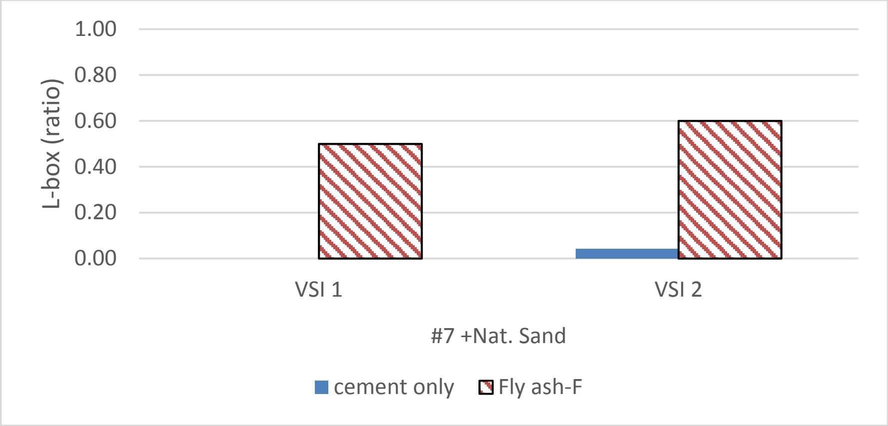

Figure 5.48 The L-Box Ratio for #7 Stone Mixtures

Mixtures Containing #89 coarse aggregate with Natural Sand

As shown in Figure 5.49, the #7 coarse aggregate with VSI of 2 has a good passing ability compared to VSI of 1 mixtures. Fly ash mixtures demonstrated a better performance than OPC mixtures. As shown in Figure 5.50, it is shown that Fly ash mixtures have a better L- box ratio that OPC mixtures. Mixtures with VSI 2 showed a better performance than VSI 1 (L-box ratio of zero).

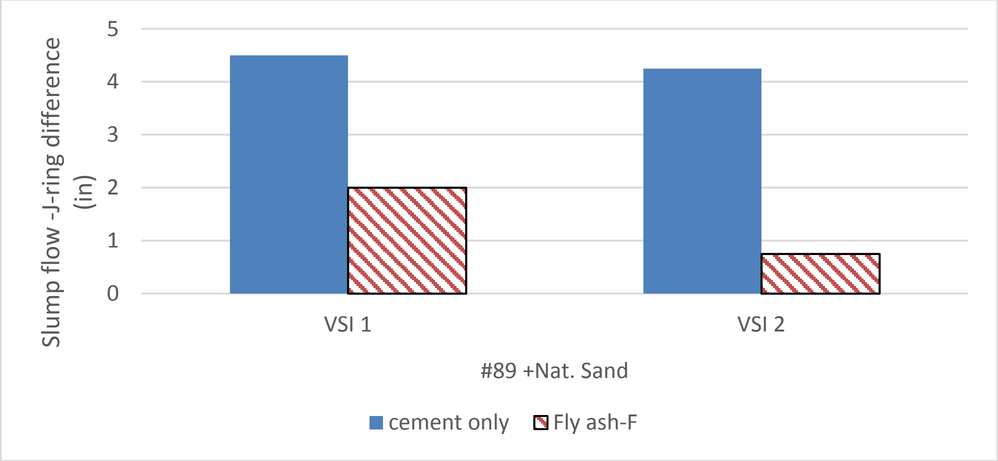

Figure 5.49 Slump flow and J-ring Difference for #89 Stone Mixtures

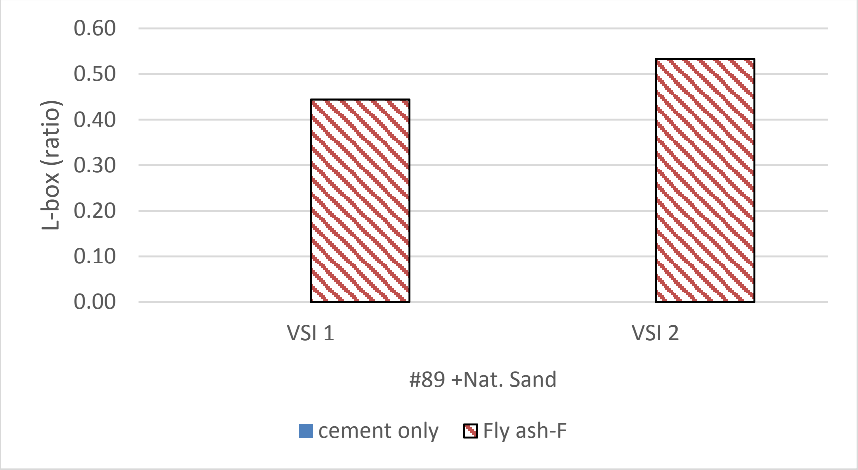

Figure 5.50The L-Box Ratio for #89 Stone Mixtures

5.4.3 Stability of Class P-SCC Mixtures

Stability of the SCC was measured with the Column Segregation test. The acceptance limit of percent segregation recommended by ACI is less than 10% (ACI, 2007). However, some of the State DOTs specifications specify 15% as a maximum column segregation limit. The results of the Column Segregation test were obtained for different aggregate sizes as described in Section 5.2 and summarized in Figure 5.51. The stability property evaluated by column segregation ratio for each stone size are discussed separately later in this section.

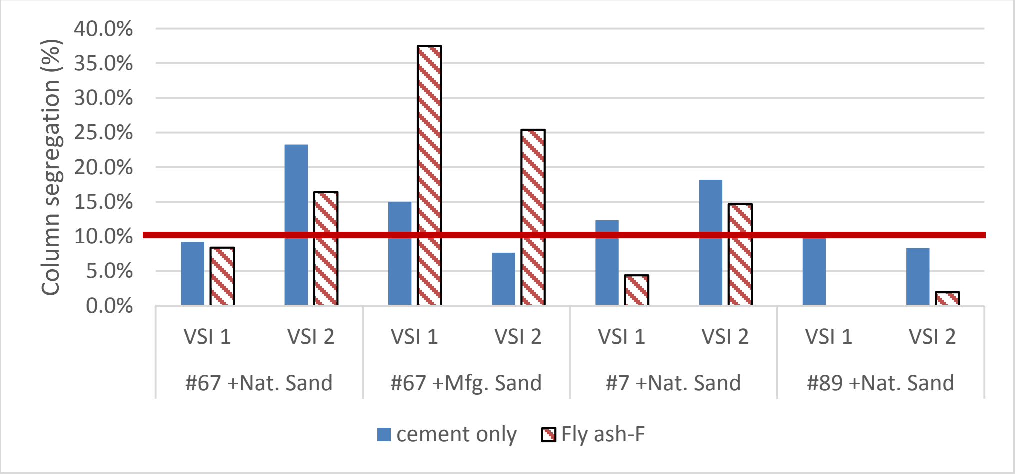

Figure 5.51 The Column Segregation for the SCC Mixtures

Mixtures Containing #67 coarse aggregate with Natural and Manufactured Sand

It may be noticed from Figure 5.52; the natural sand shows a less segregation potential compared to the manufactured sand with VSI of 1, and the opposite is true. Also, it can be seen clearly; Fly ash mixtures have less column segregation percentages compared to OPC mixtures when used with natural sand, and the opposite is true when using the manufactured sand. The mixtures that have segregation less than 10% were mixtures of natural sand with VSI of 1 and mixtures of manufactured sand with VSI of 2.

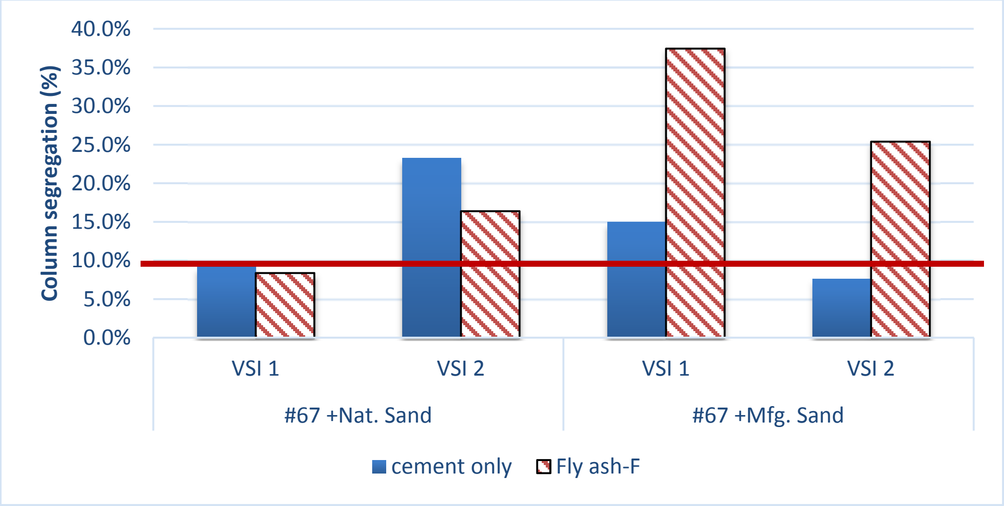

Figure 5.52 The Column Segregation for #67 Stone Mixtures

Mixtures Containing #7 coarse aggregate with Natural

The #7 coarse aggregate is a relatively small size aggregate. Therefore, it was anticipated to show less segregation potential than #67 stone size but this was not the case. As observed from Figure 5.53, only the mixtures of fly ash and VSI of 1 has acceptable value (less than 10%).

These high segregation values could be attributed to the high amount of HRWR that was added in these mixtures as shown in Figure 5.38.

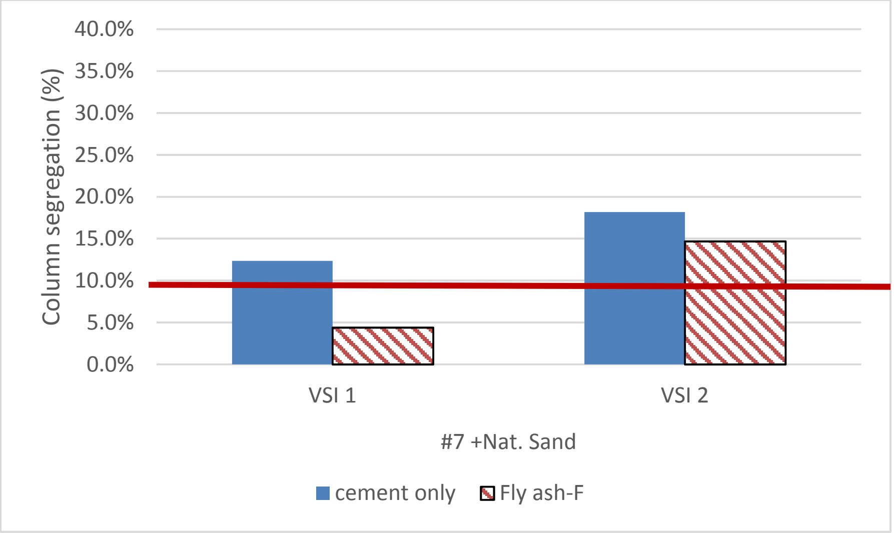

Figure 5.53 The Column Segregation for #7 Stone Mixtures

Mixtures Containing #89 coarse aggregate with Natural Sand

The #89 coarse aggregate was the smallest size used in this study. Studies show that the well-graded mixtures tend not to have as many problems as gap-graded mixtures regarding workability and segregation during vibration (Richardson, 2005). As observed from Figure 5.54, all the mixes show a relatively acceptable segregation potential.

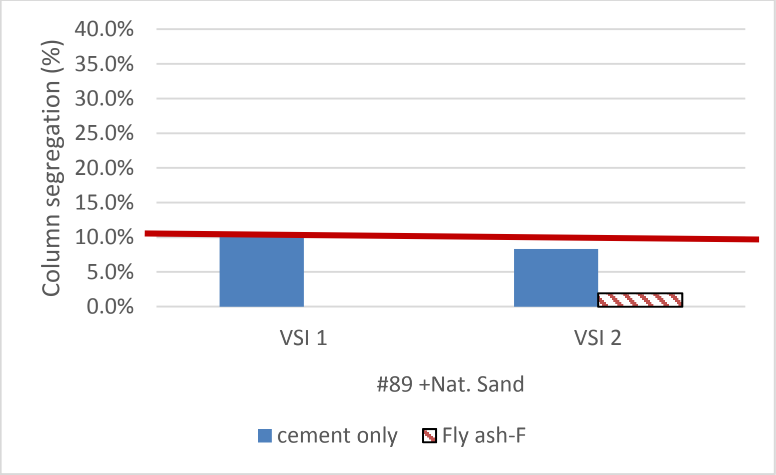

Figure 5.54 The Colum Segregation for #89 Stone Mixtures

5.4.4 Initial and Final Setting Time for SCC and Conventional Concrete Mixtures

The Time of setting of concrete mixtures was conducted for the both SCC and conventional concrete mixtures. The test used penetration resistance on a mortar sample that was obtained by sieving a representative sample of fresh concrete through sieve #4 (4.75 mm). The initial setting time is when the concrete resistance reaches 500 psi, while the final setting time is when it achieved 4000 psi. The time is measured from the point cement is added to the aggregates. Conventional concrete usually has a setting time less than SCC as shown in Figure 5.55. It was not anticipated to notice much variation between the different aggregate sizes. The results of the various aggregate sizes are shown in Figure 5.55 and discussed later in details for each aggregate size.

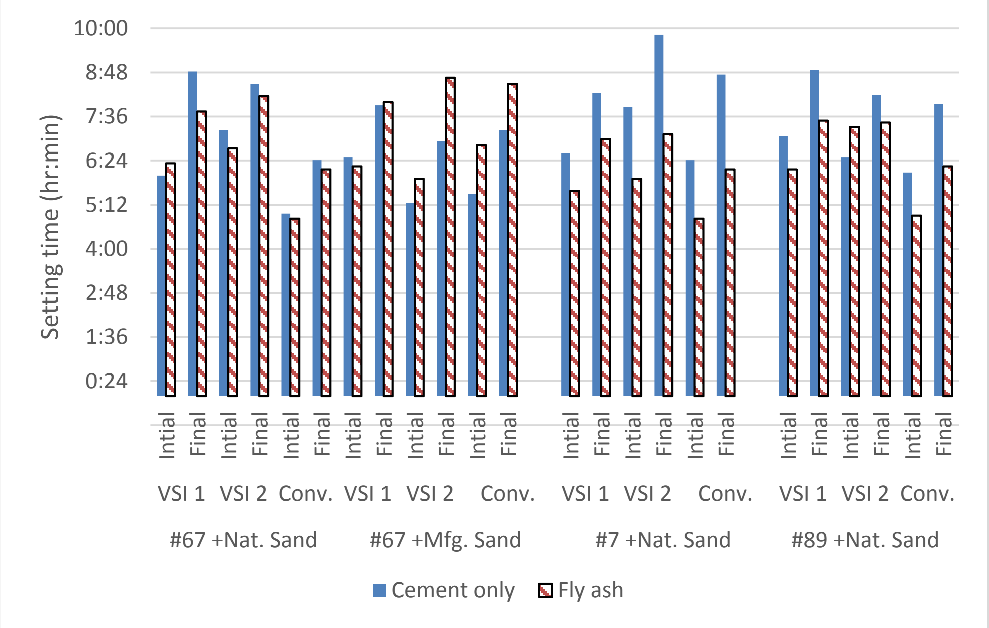

Figure 5.55 The Initial and Final Time of Setting for SCC & Conventional Mixtures

Mixtures Containing #67 coarse aggregate with Natural and Manufactured Sand

As illustrated in Figure 5.56, the manufactured sand has a faster setting time than that of the natural sand. Which could be due to the different particles gradation of the manufactured sand; which was contained larger particles than that of the natural sand. Also, it can be seen; the fly ash mixtures have longer setting time compared to the OPC mixtures. This could be attributed to fly ash acting as a retarding agent in the concrete. Since the project concerns about early age strength shorter setting time is favorable. Also, it is clear from Figure 5.56 that mixtures with VSI of 2 have a longer setting time than mixtures with VSI of 1 as a result of the higher HRWR dosages.

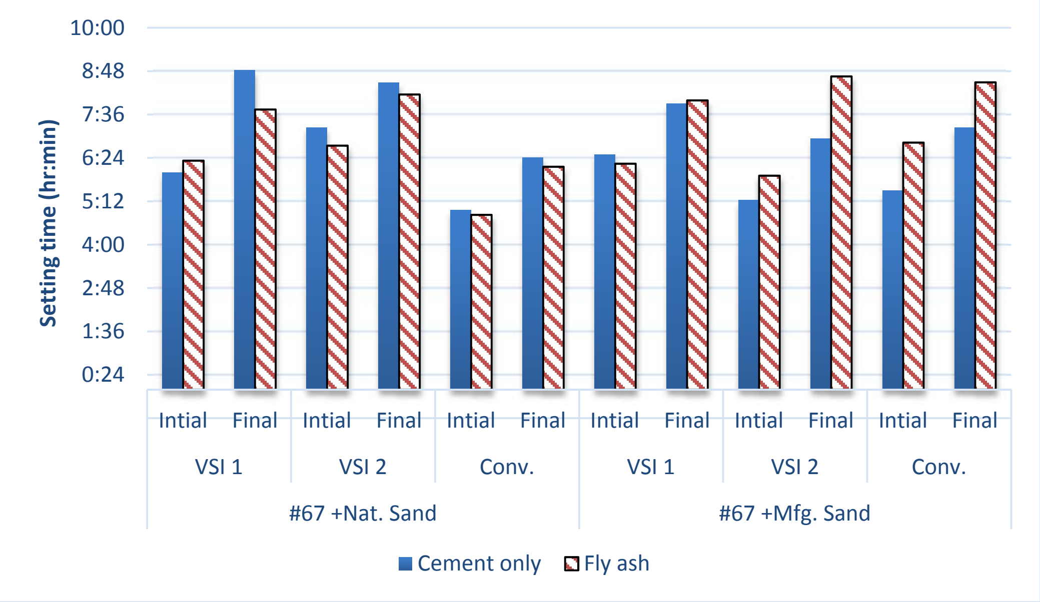

Figure 5.56 The Initial and Final Time of Setting for #67 Stone Mixtures

Mixtures Containing #7 coarse aggregate with Natural Sand

Figure 5.57 shows the initial and final time of setting for #7 stone, which ranged from 6 to 9.5 hours, and it was anticipated to notice such variation between the setting time between VSI of 1 and 2 and the conventional mixtures. This variation in the time of setting can be attributed to the different HRWR dosages among the mixtures; the VSI of 2 possessed the highest HRWR dosage, and it showed greater time of setting. Also, that Class F fly ash is showing a slightly longer setting time than OPC mixtures.

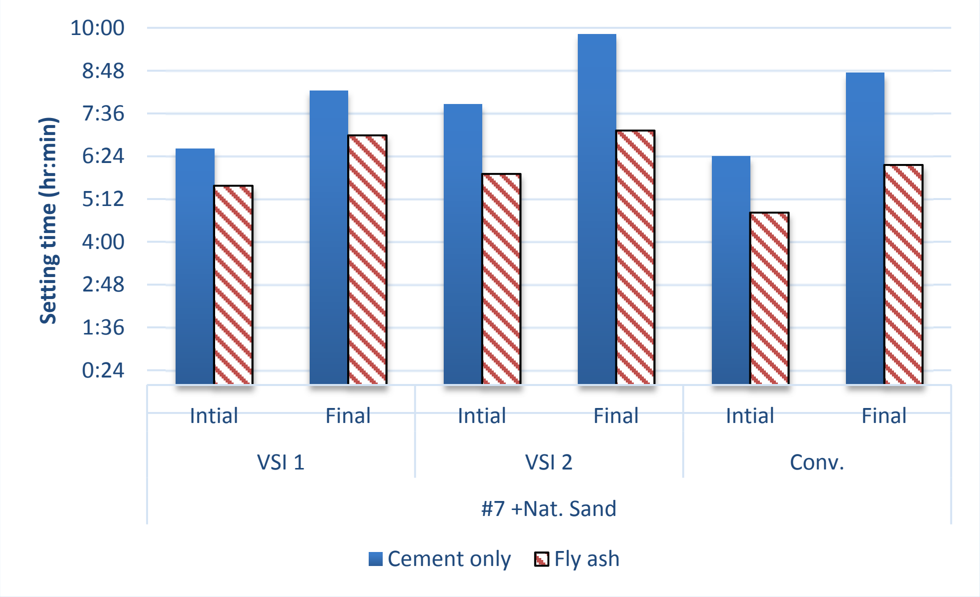

Figure 5.57 The Initial and Final Time of Setting for #7 Stone Mixtures

Mixtures Containing #89 coarse aggregate with Natural Sand

As shown in Figure 5.58, Fly ash mixtures of VSI 1 has shorter setting time than OPC mixtures and opposite to #67 and #7 stones mixtures. Apart from the above, the same observations that were noticed in Figures 5.56 and 5.57 could be confirmed in Figure 5.58.

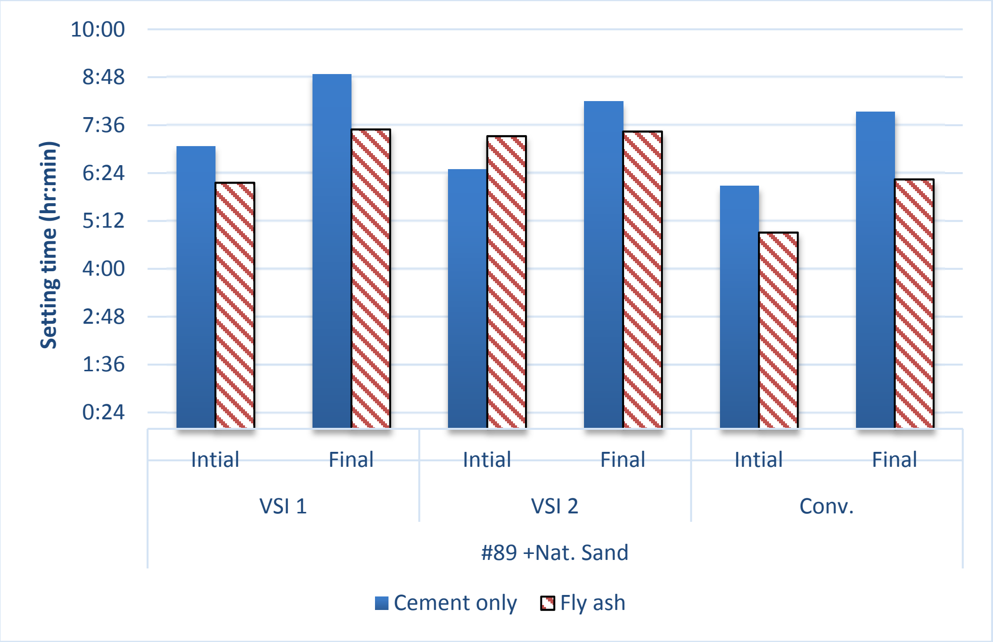

Figure 5.58 The Initial and Final Time of Setting for #89 Stone Mixtures

5.5 Discussion of Hardened Properties of Class A-SCC Mixtures

A number of tests were conducted to evaluate the hardened properties of the SCC and conventional concrete mixtures. The tests were carried out to evaluate Strength, Tension, Elasticity, Permeability and Segregation. The hardened properties tests are discussed with correlate to aggregates sizes in details in the following section.

5.5.1 The Compressive Strength for the Studied Mixtures

The compressive strength results that were shown in Table 5.4 are summarized in Figures 5.59, 5.60 and 5.61 for 7, 28 and 56 day results.

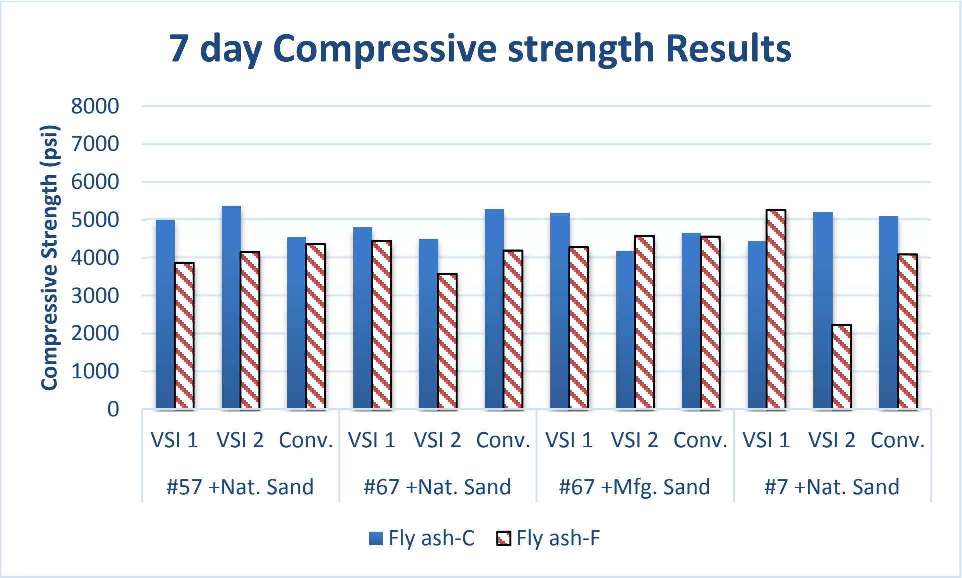

Figure 5.59 The 7 day Compressive Strength of the Class A Mixtures

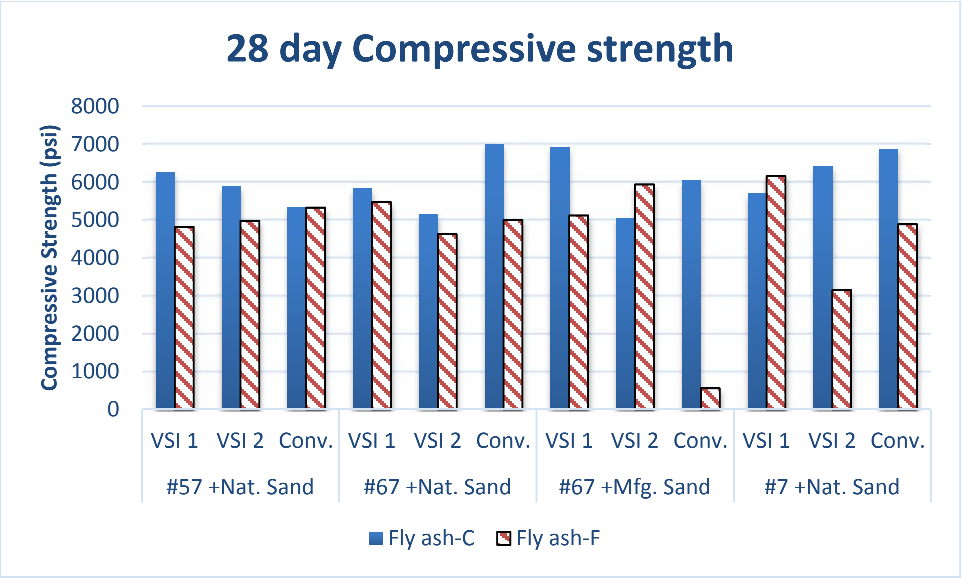

Figure 5.60 The 28 Day Compressive Strength of the Class A Mixtures

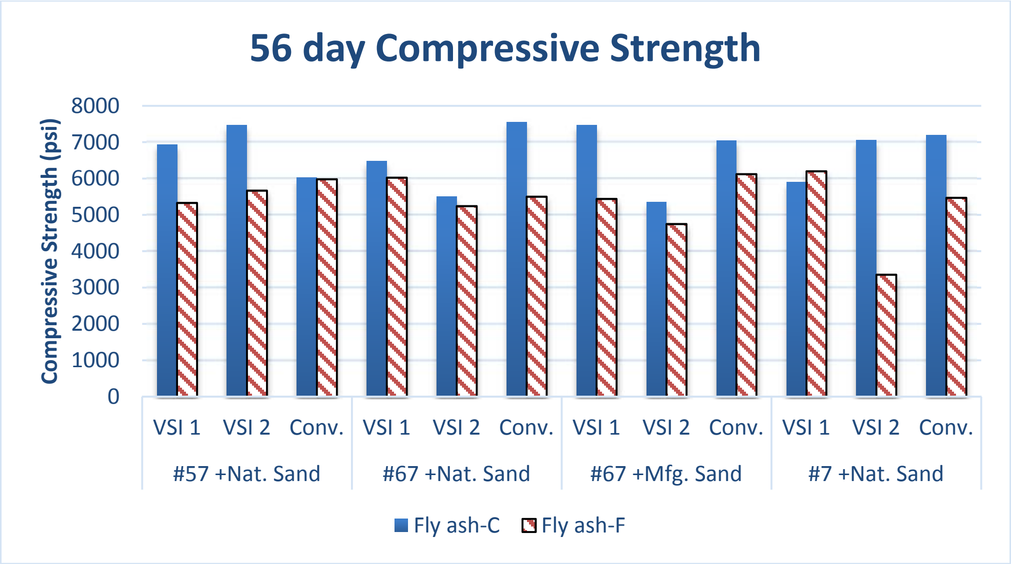

Figure 5.61 The 56 Day Compressive Strength of the Class A Mixtures

Mixtures Containing Coarse Aggregates #57 with Natural Sand

As shown in Figure 5.62, Class C Fly ash mixtures exhibited more compressive strength than Class F fly ash mixtures. This is in agreement with Mehta and (Monteiro 2006); early strength gains at three and seven days are reduced when using Class F fly ash than when using Class C, as mentioned by (Keske, 2011). This is because Class C fly ash is partly cementitious in nature due to its higher Calcium Oxide content, whereas Class F fly ash is almost entirely pozzolanic in nature and is much slower to hydrate. And the same phenomenon continues in 28 days and 56-day results as shown in Figures 5.63 and 5.64.

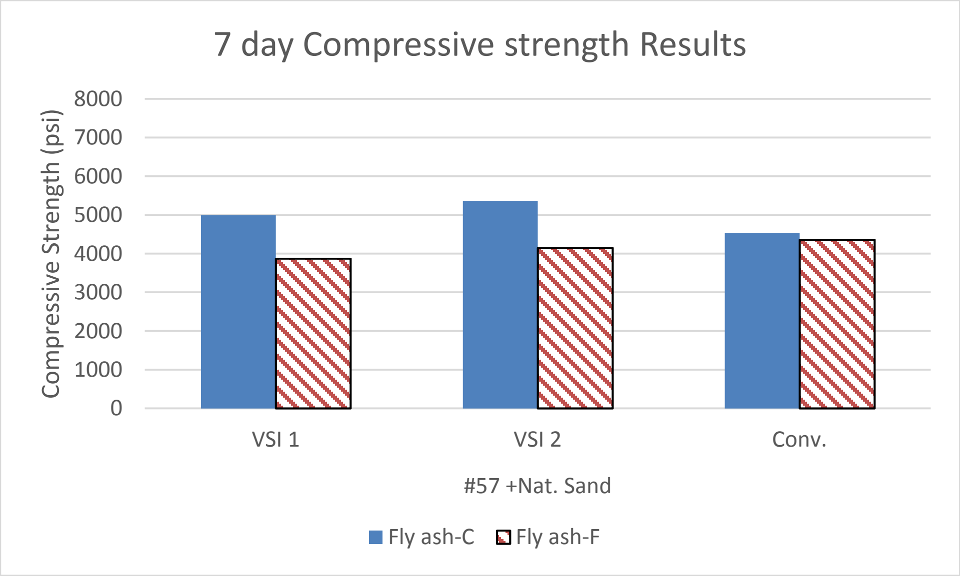

Figure 5.62 The 7 day Compressive Strength of #57 Stone Class A Mixtures

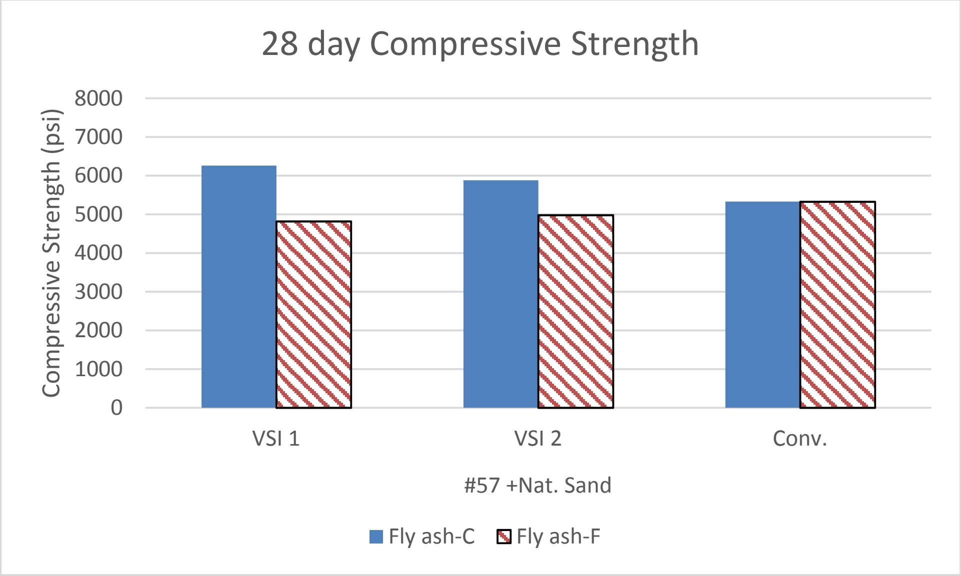

Figure 5.63 The 28 Day Compressive Strength of #57 Stone Class A Mixtures

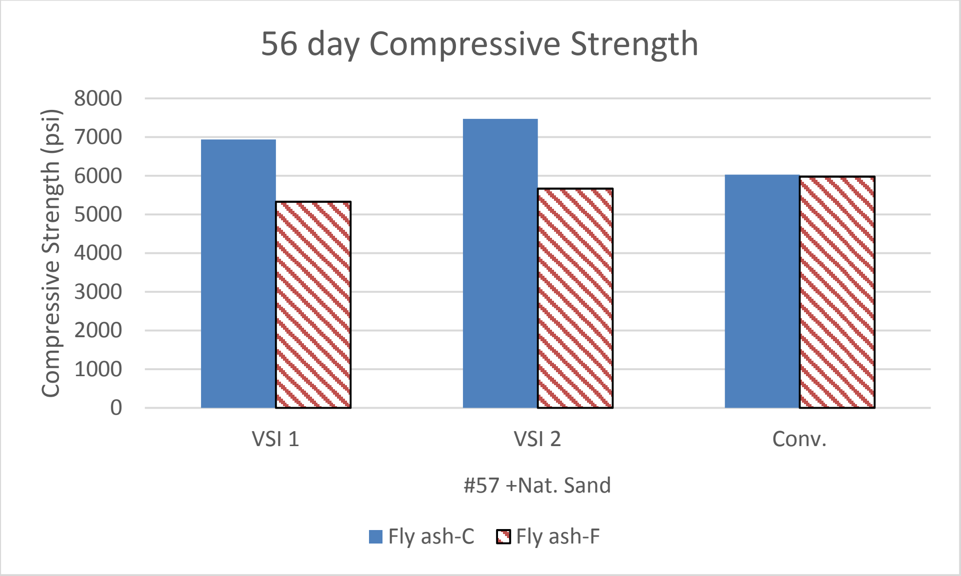

Figure 5.64 The 56 Day Compressive Strength of #57 Stone Class A Mixtures

Mixtures Containing Coarse Aggregates #67 with Natural and Manufactured Sand

Class C fly ash mixtures showed a higher compressive strength at all ages compared with Class F fly ash mixtures except on VSI 2 and mixed with manufactured sand at 7 and 28 days as shown in Figures 5.65, 5.66 and 5.67. All VSI 1 had higher compressive strength compared to VSI of 2.

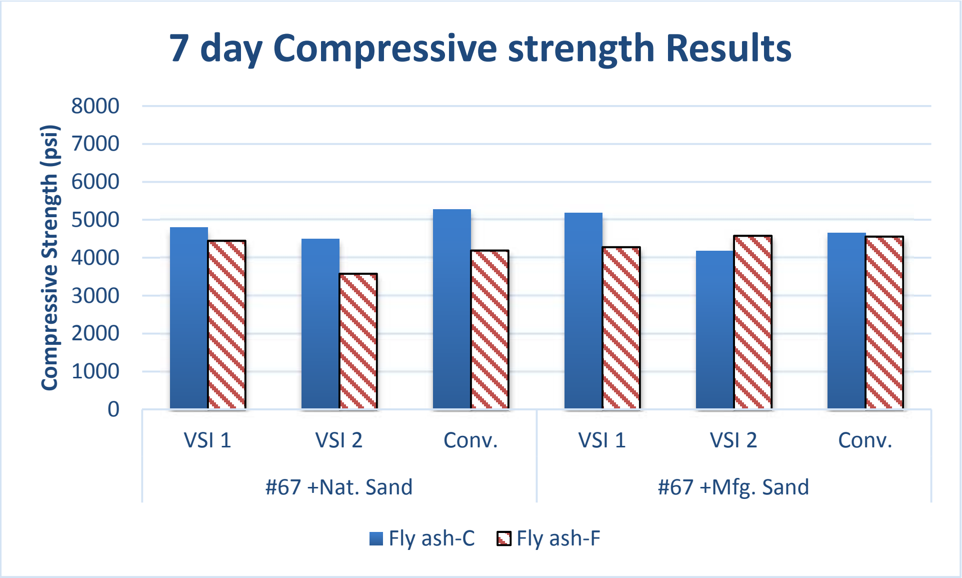

Figure 5.65 The 7 day Compressive Strength of #67 Stone Class A Mixtures

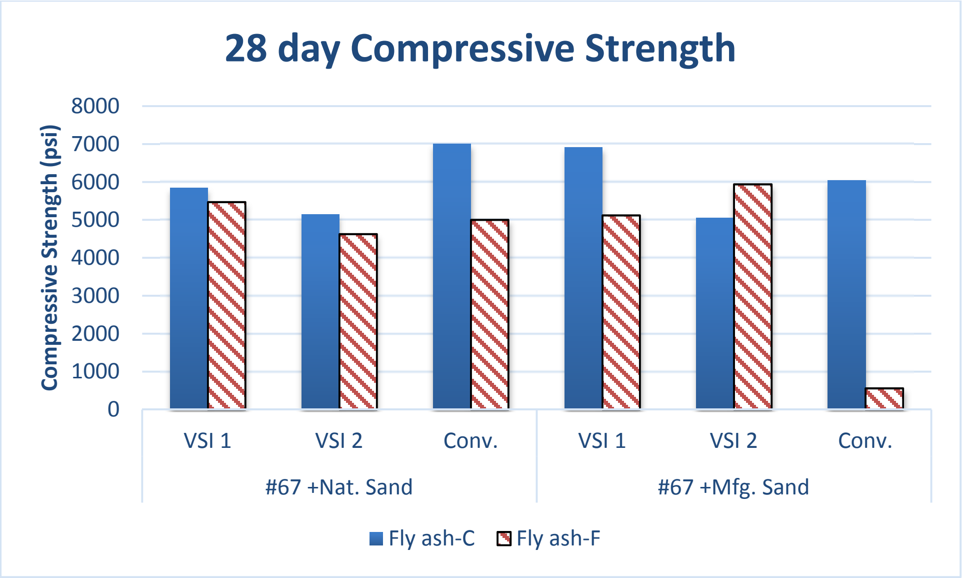

Figure 5.66 The 28 Day Compressive Strength of #67 Stone Class A Mixtures

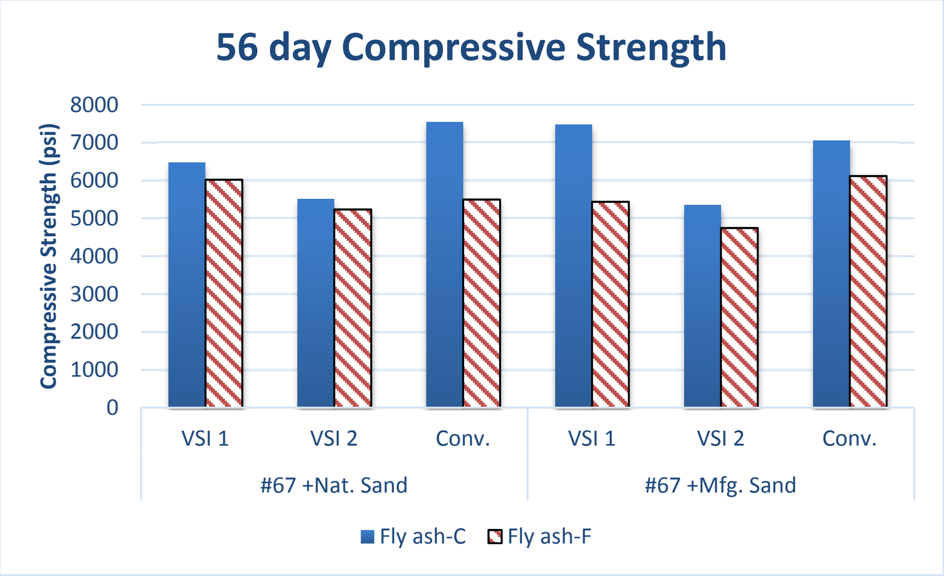

Figure 5.67 The 56 Day Compressive Strength of #67 Stone Class A Mixtures

Mixtures Containing Coarse Aggregates #7 with Natural Sand

As illustrated in Figure 5.68, OPC mixtures have a compressive strength above 4000 psi, while fly ash mixtures have a compressive strength less than 4000 psi. This phenomenon could be attributed to the fly ash slow reaction compared to the cement. The #7 stone and #89 stone are smaller size aggregates, having more surface area than larger aggregates. This, in effect, spreads out cementitious materials, leading to longer setting times as shown in Figure 4.27 and Figure 4.28. With the reasons mentioned above, it makes it more difficult to achieve higher early age strengths when using fly ash with smaller size aggregates. The same results happened with 28 days results as shown in Figure 4.36.

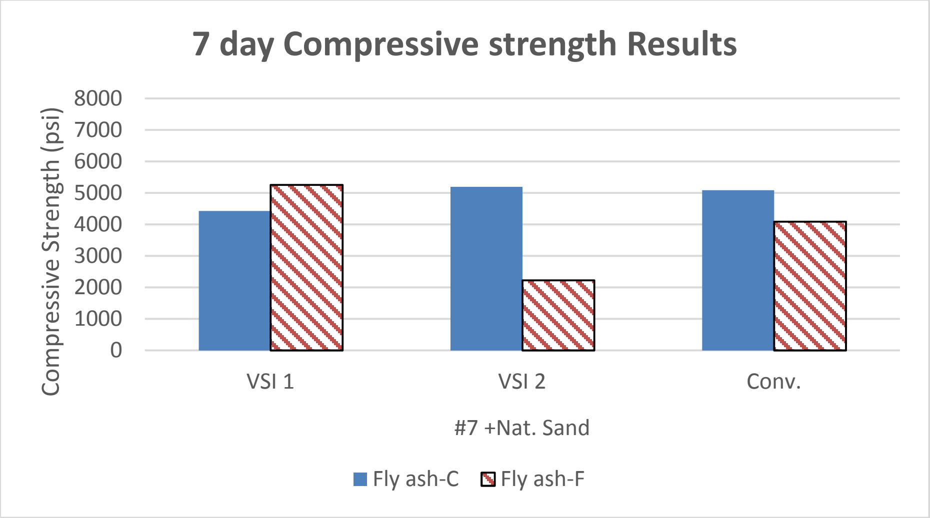

Figure 5.68 The 7 day Compressive Strength of #7 Stone Class A Mixtures

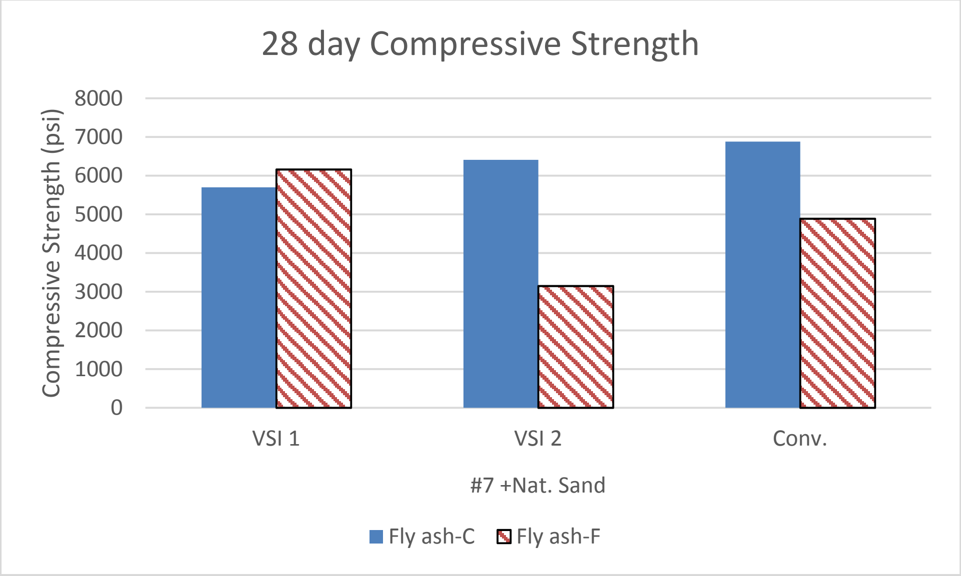

Figure 5.69 The 28 Day Compressive Strength of #7 Stone Class A Mixtures

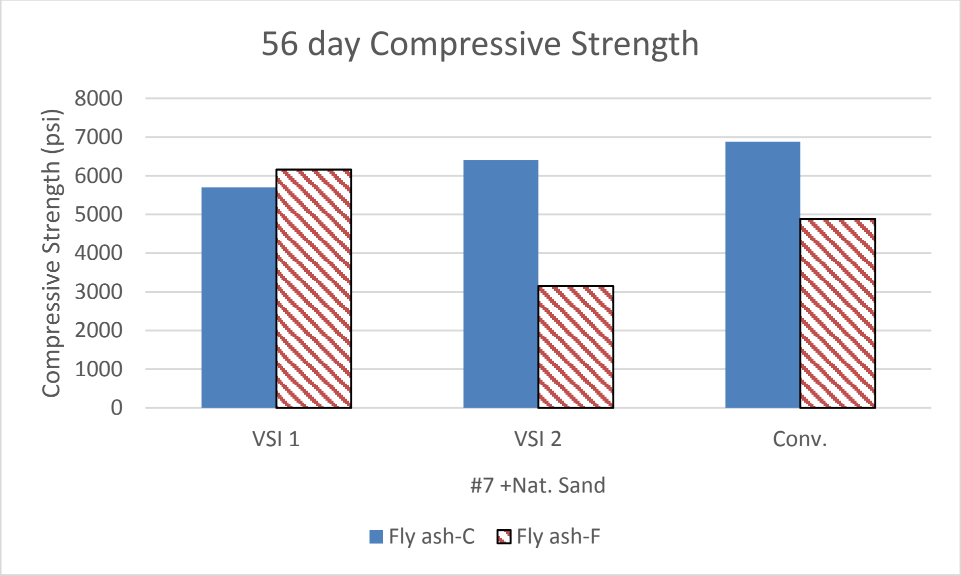

Figure 5.70 The 56 Day Compressive Strength of #7 Stone Class A Mixtures

5.5.2 The Tensile Strength of the Class A Mixtures

The modulus of elasticity test was performed for all SCC and conventional mixtures. The results of the test shown in Table 5.4 and summarized in Figures 5.71 for 7 days results and Figure 5.72 for 28 days and 56 days in Figure 5.73 according to aggregate size.

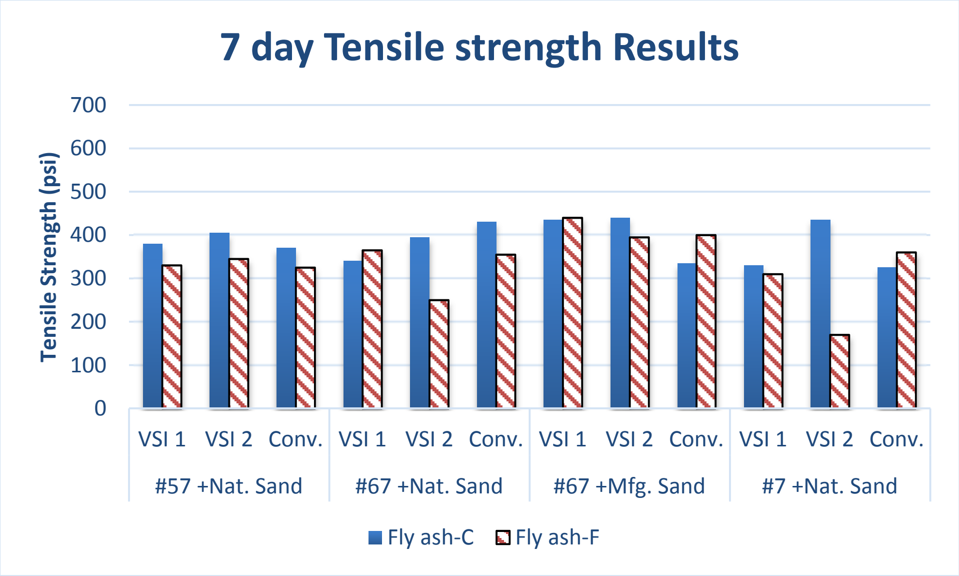

Figure 5.71 The 7 day Tensile Strength Results for the Class A Mixtures

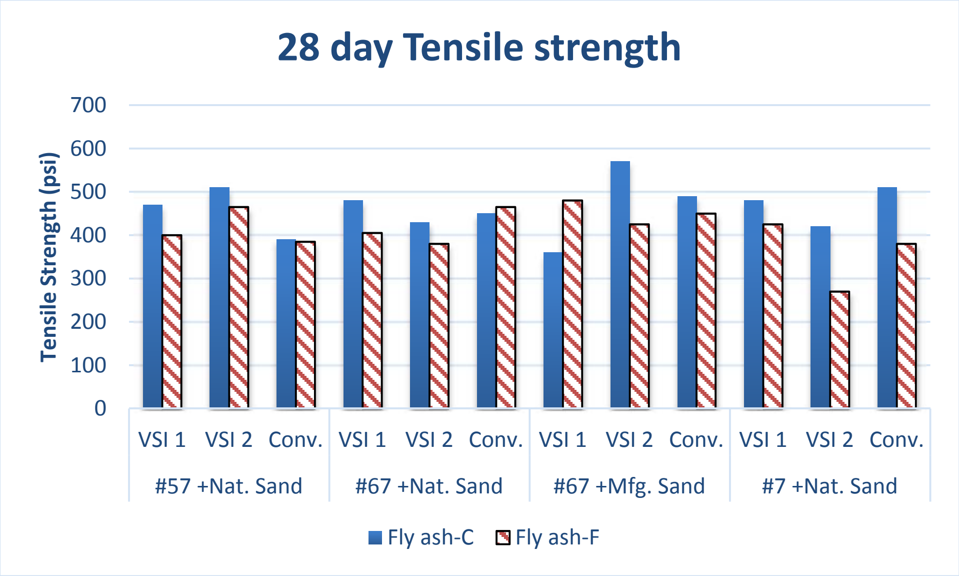

Figure 5.72 The 28 Day Tensile Strength Results for the Class A Mixtures

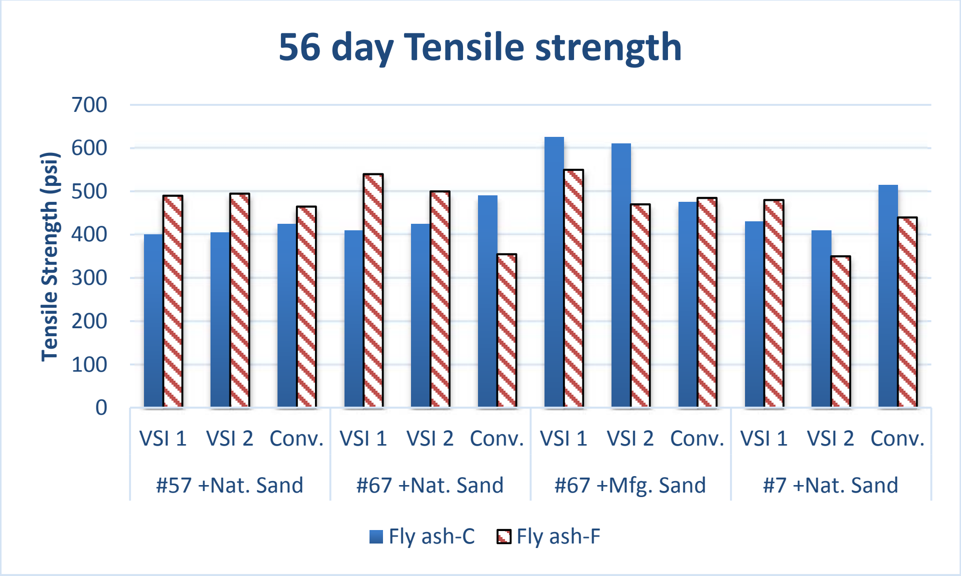

Figure 5.73 The 56 Day Tensile Strength Results for the Class A Mixtures

Mixtures Containing Coarse Aggregates #57 with Natural Sand

As shown in Figures 5.74, 5.75 and 5.76, the tensile strength was higher with class C fly ash at 7 and 28 days, and the opposite is observed at the 56 days result. This could be attributed to the slow reaction with Class F fly ash mixtures. VSI of 1 and 2 showed nearly the same values for both fly ash types.

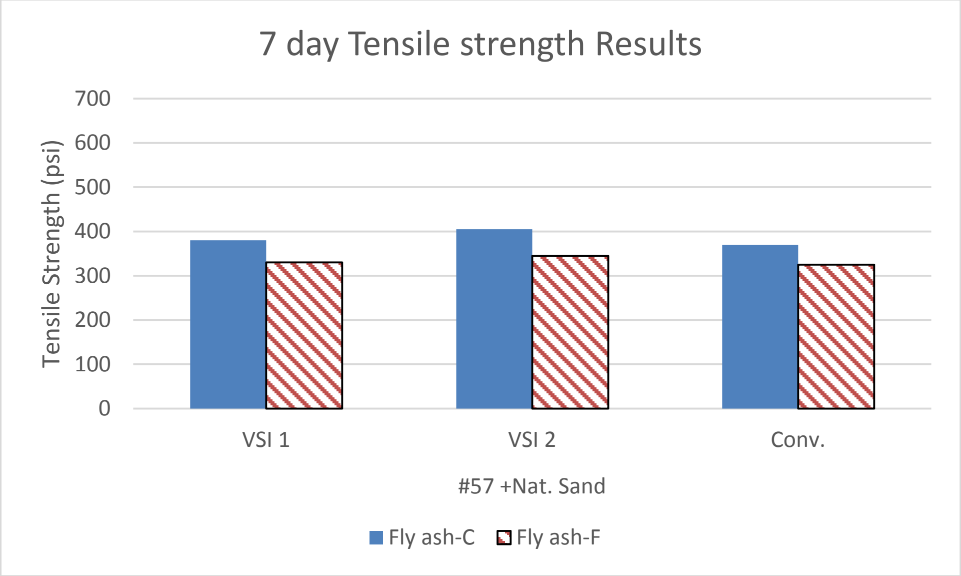

Figure 5.74 The 7 Day Tensile Strength of #57 Stone Class A Mixtures

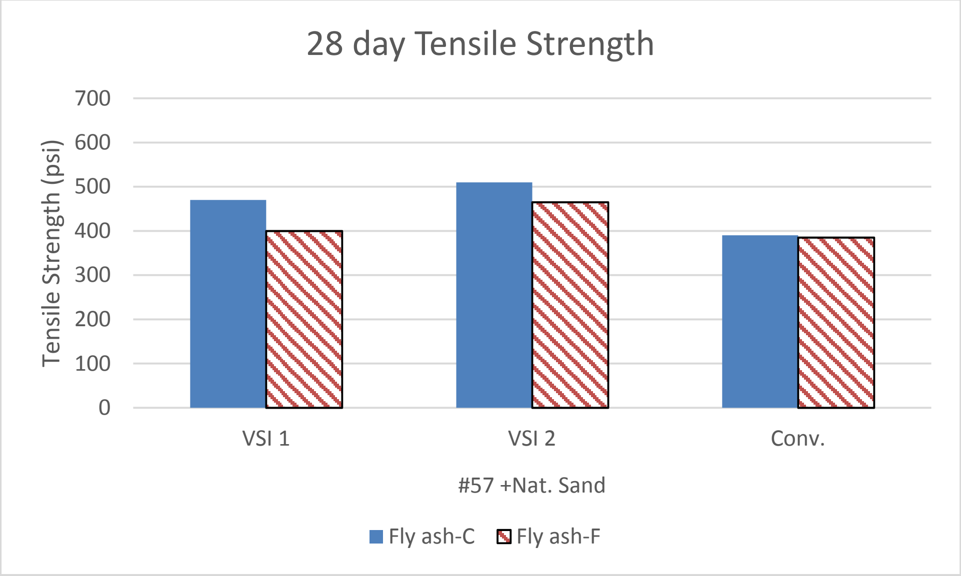

Figure 5.75 The 28 Day Tensile Strength of #57 Stone Class A Mixtures

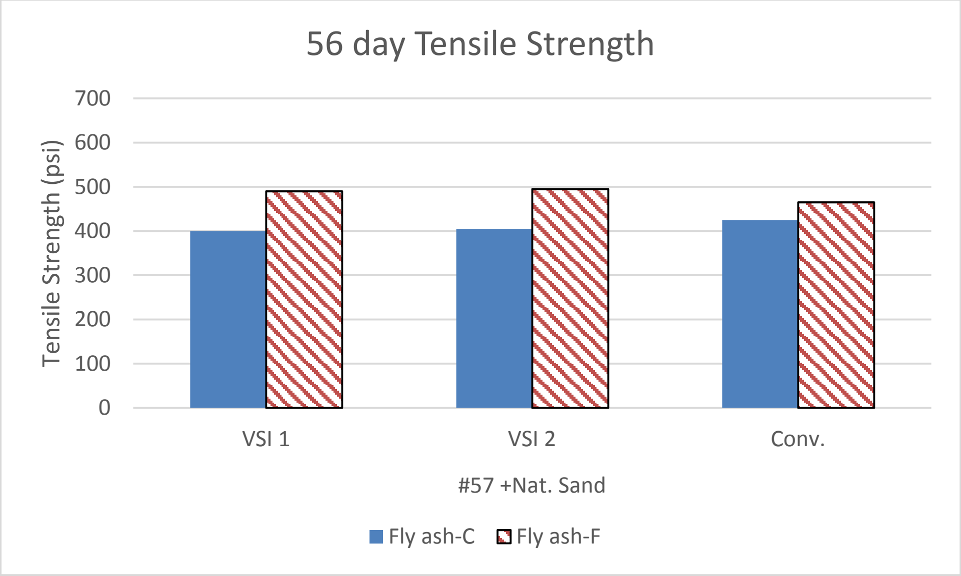

Figure 5.76 The 56 Day Tensile Strength of #57 Stone Class A Mixtures

Mixtures Containing Coarse Aggregates #67 with Natural and manufactured Sand

As illustrated in Figures 5.77, 5.78 and 5.79, class C fly ash mixtures had higher tensile strength in 7 and 56 days and lower at 28 days when mixed with manufactured sand. VSI of 1 was slightly higher than VSI of 2 at natural sand mixtures. Manufactured sand mixtures showed fluctuating results.

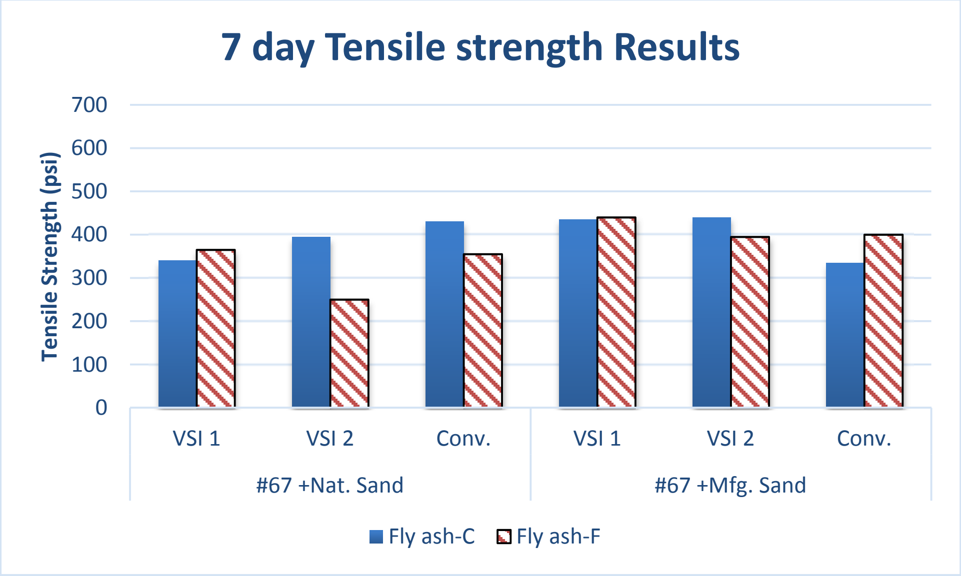

Figure 5.77 The 7 Day Tensile Strength of #67 Stone Class A Mixtures

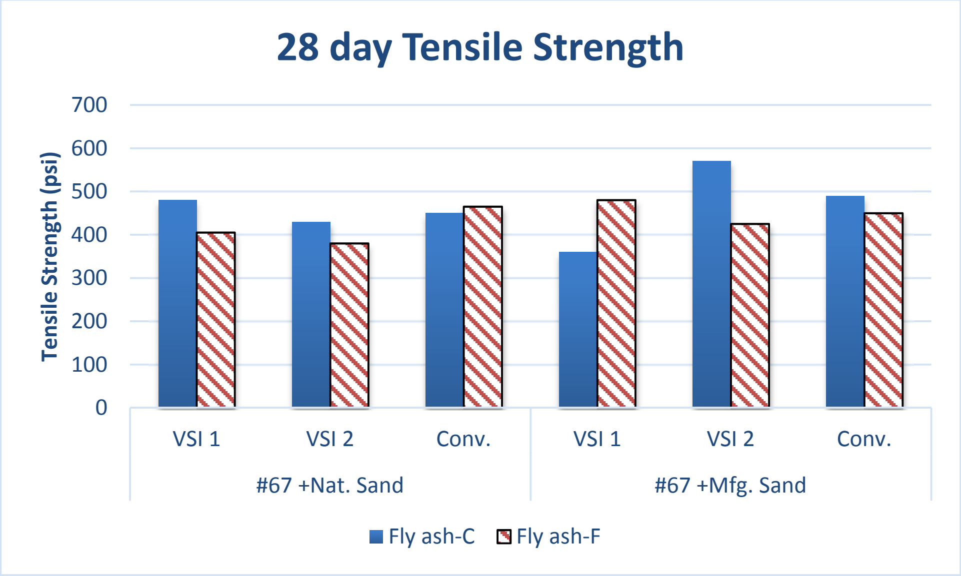

Figure 5.78 The 28 Day Tensile Strength of #67 Stone Class A Mixtures

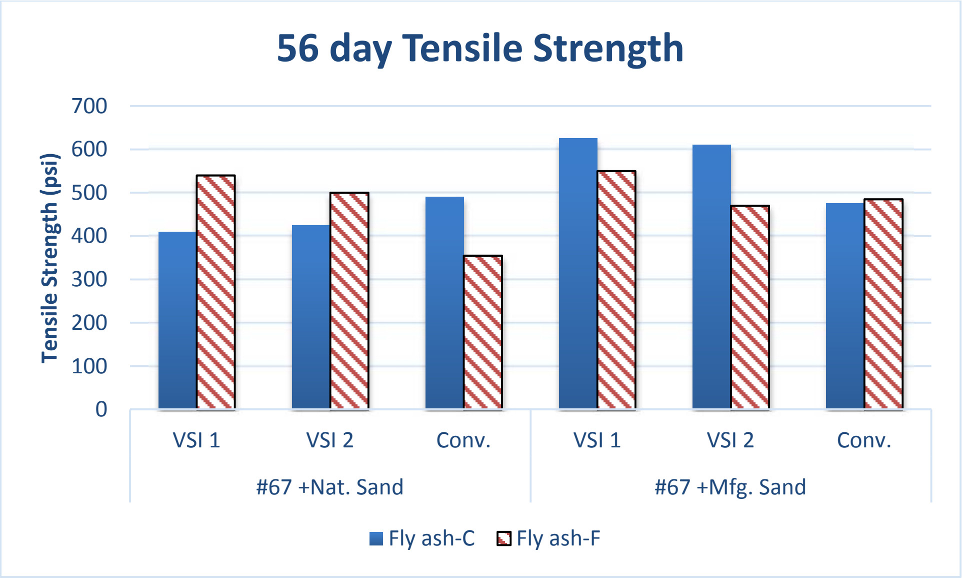

Figure 5.79 The 56 Day Tensile Strength of #67 Stone Class A Mixtures

Mixtures Containing Coarse Aggregates #7 with Natural Sand

As shown in Figures 5.80, 5.81 and 5.82, the tensile strength was higher with class C fly ash at 7 and 28 days, except for VSI of 1 at 56 days result. This could be attributed to the slow reaction with Class F fly ash mixtures. VSI of 1 and 2 showed nearly the same values for both fly ash types.

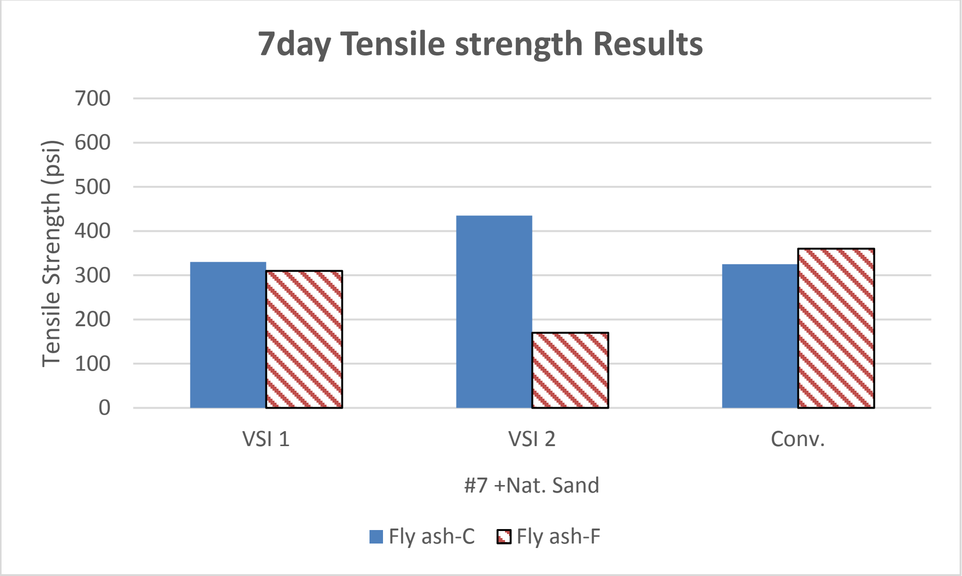

Figure 5.80 The 7 Day Tensile Strength of #7 Stone Class A Mixtures

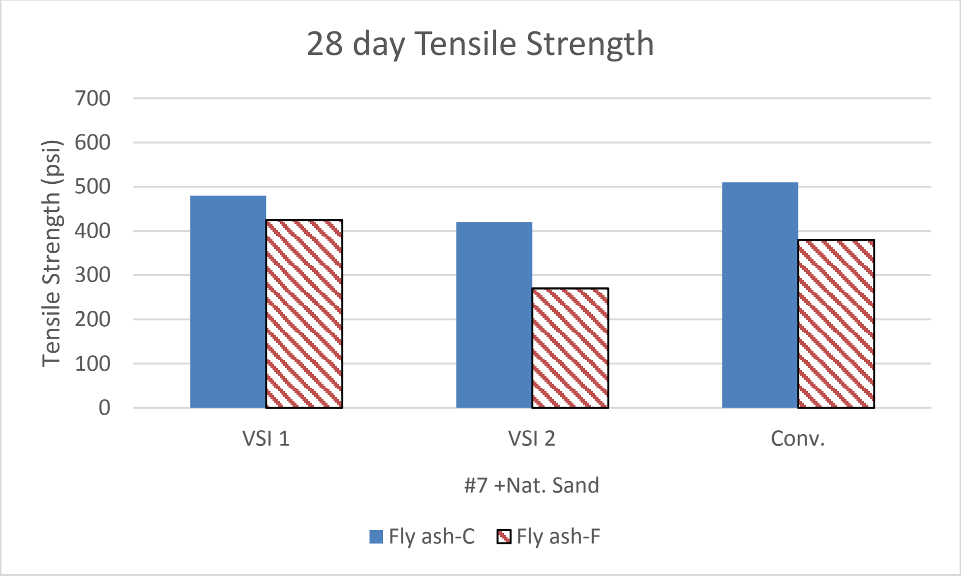

Figure 5.81 The 28 Day Tensile Strength of #7 Stone Class A Mixtures

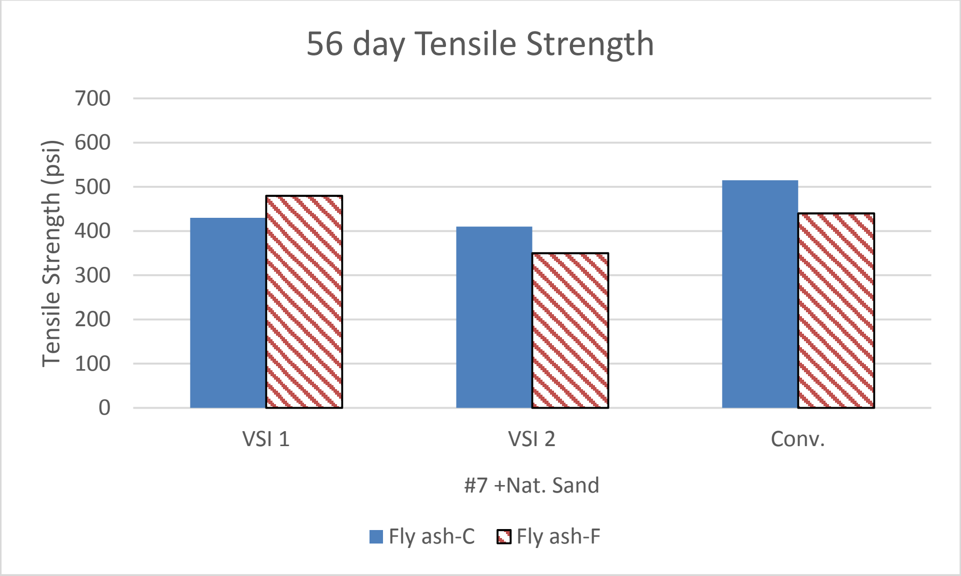

Figure 5.82 The 56 Day Tensile Strength of #7 Stone Class A Mixtures

5.5.3 Modulus Elasticity of the Class A Mixtures

The Modulus of Elasticity test was performed on the studied mixtures as described in chapter 2. The results of the tests are shown in Table 5.4 and summarized in Figure 5.83 for the 7 days tests and Figure 5.84, 5.85 for the 28, 56 days tests. Results for each aggregate size areis discussed in detail in this section.

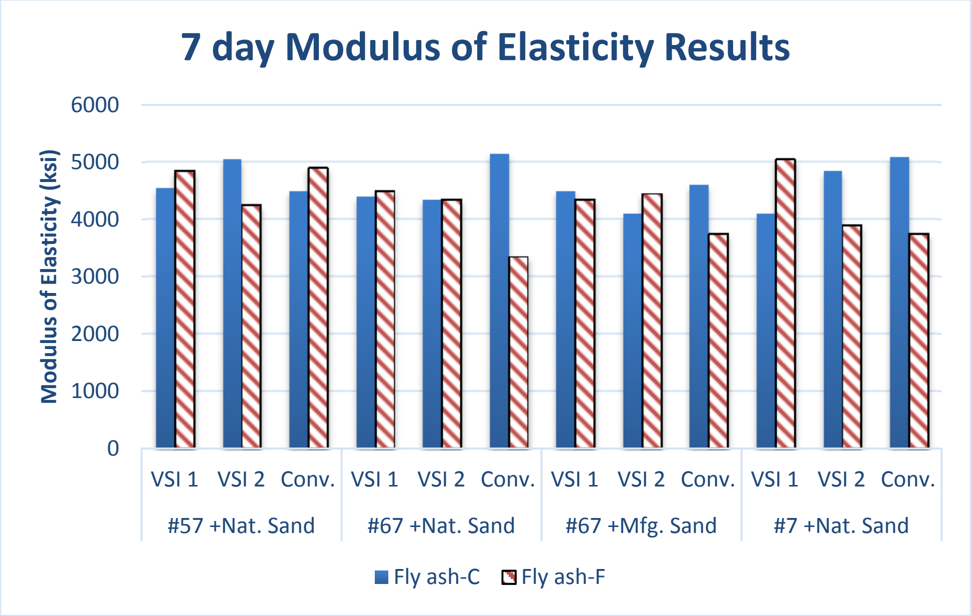

Figure 5.83 The 7 Day Modulus of Elasticity Results for the Class A Mixtures

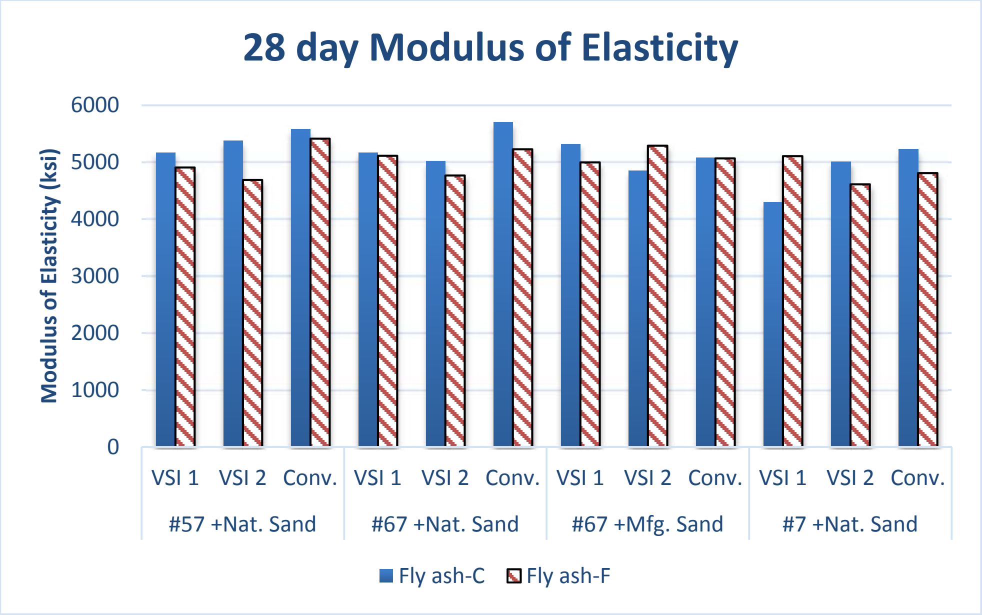

Figure 5.84 The 28 Day Modulus of Elasticity Results for the Class A Mixtures

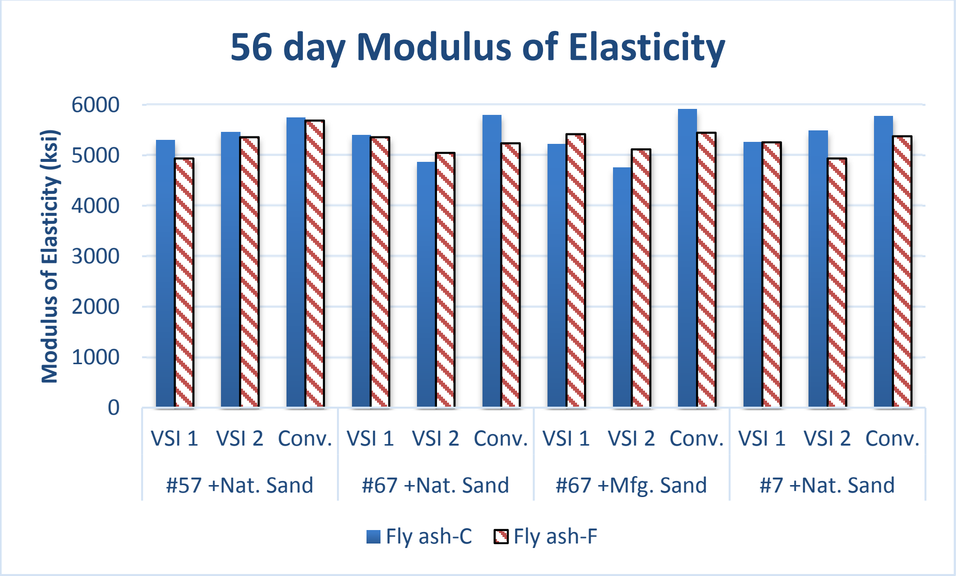

Figure 5.85 The 56 Day Modulus of Elasticity Results for the Class A Mixtures

Mixtures Containing Coarse Aggregates #57 with Natural Sand

As shown in Figure 5.86 that the modulus of elasticity is higher in Class C fly ash mixtures than fly ash f mixtures, except for VSI of 1 and conventional concrete at 7 days. While after 28 and 56 days, it is clear that all with fly ash C have more modulus of elasticity than Class F fly ash mixtures. Also mixtures with VSI of 2 had a higher value in Modulus of elasticity than mixtures of VSI of 1.

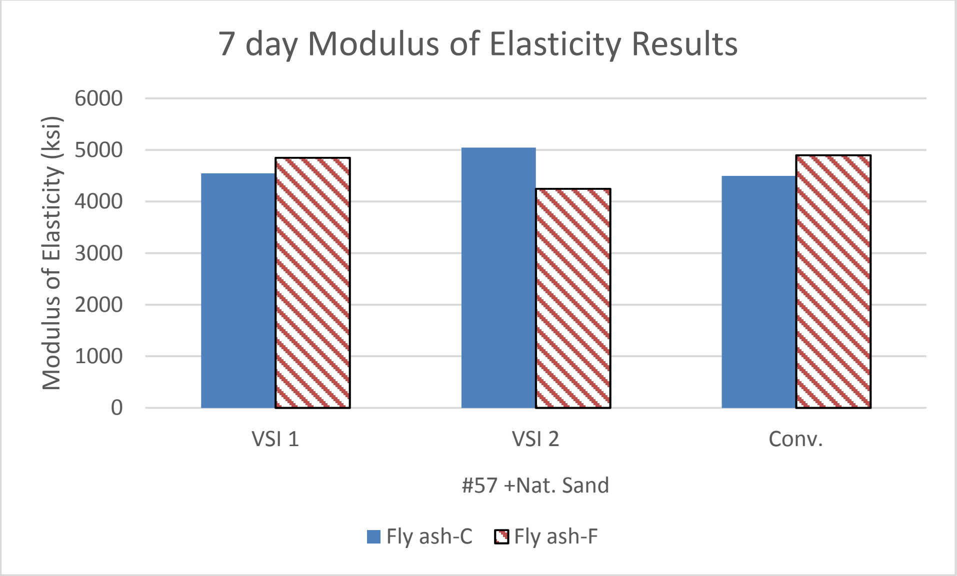

Figure 5.86 The 7 Day Modulus of Elasticity for #57 Stone Class A Mixtures

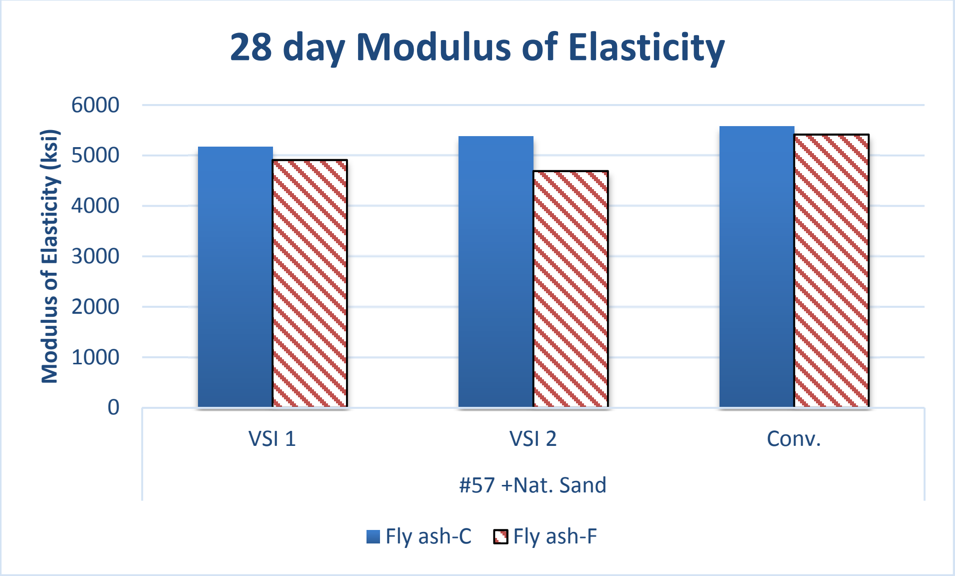

Figure 5.87 The 28 Day Modulus of Elasticity for #57 Stone Class A Mixtures

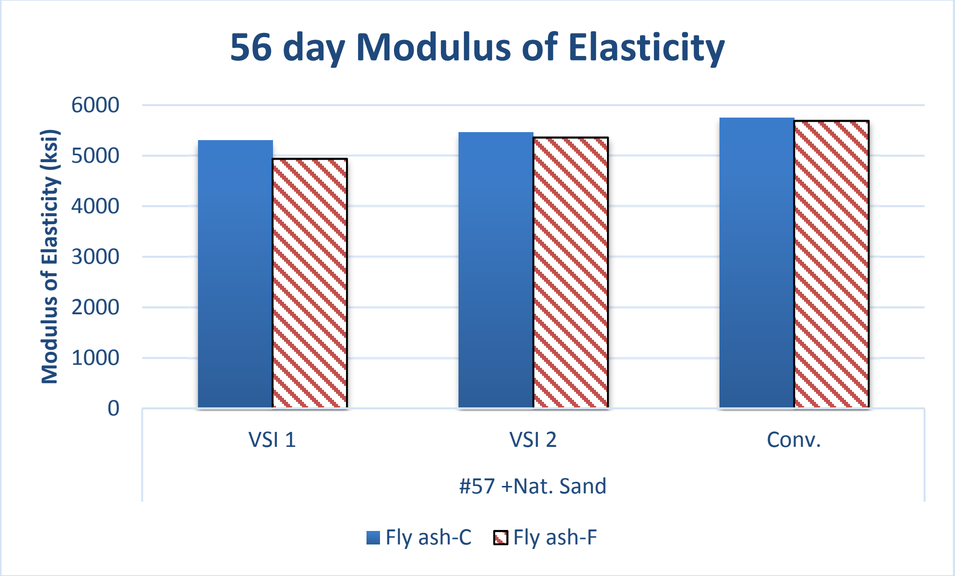

Figure 5.88 The 56 Day Modulus of Elasticity for #57 Stone Class A Mixtures

Mixtures Containing Coarse Aggregates #67 with Natural and Manufactured Sand

Both Class F and C fly ash mixtures had approximately the same values of elasticity modulus except for conventional concrete mixtures with natural sand. VSI values fluctuate between the mixtures and no pattern could be detected.

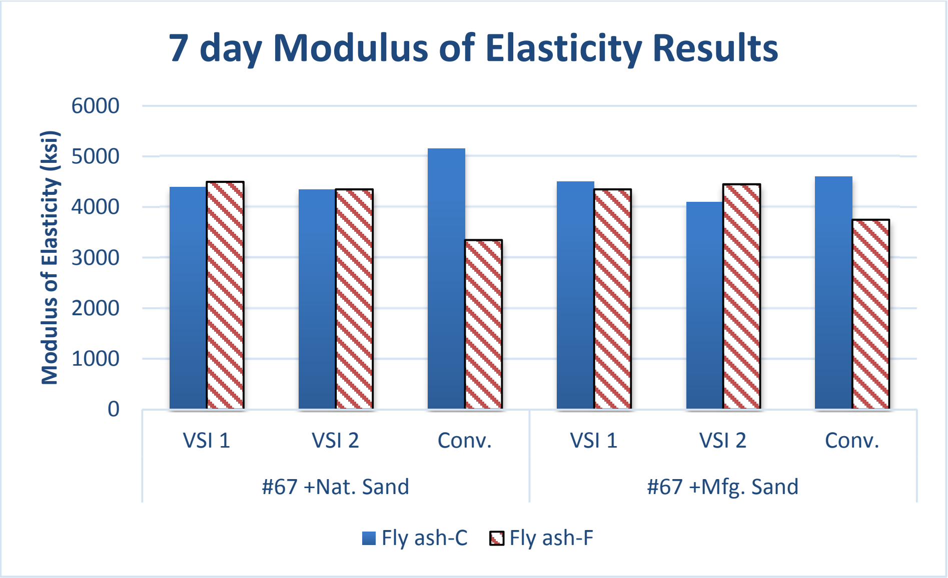

Figure 5.89 The 7 Day Modulus of Elasticity for #67 Stone Class A Mixtures

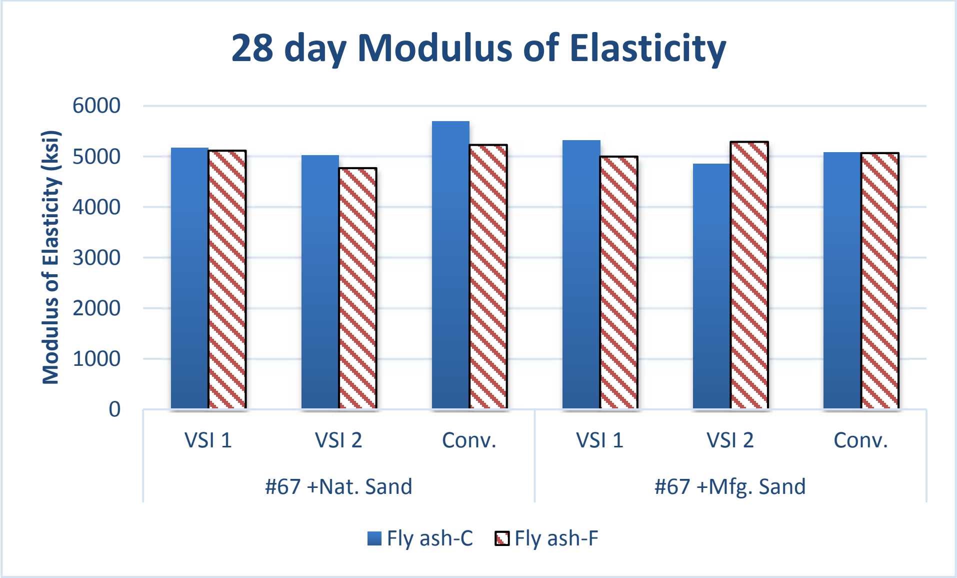

Figure 5.90 The 28 Day Modulus of Elasticity for #67 Stone Class A Mixtures

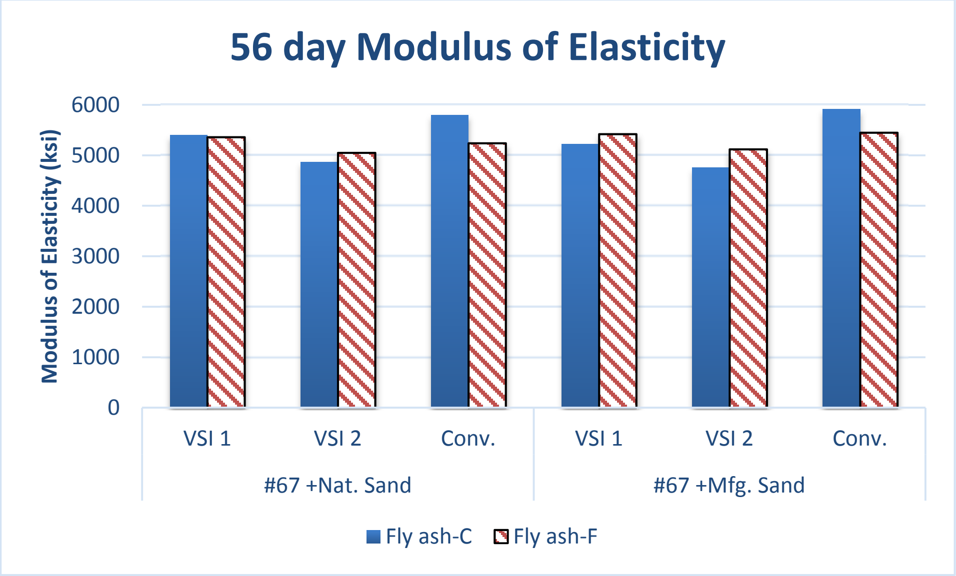

Figure 5.91 The 56 Day Modulus of Elasticity for #67 Stone Class A Mixtures

Mixtures Containing Coarse Aggregates #7 with Natural Sand

As shown in Figures below the modulus of elasticity of Class C fly ash mixtures is higher than Class F fly ash mixtures for VSI of 2 and the opposite is true for VSI of 1.

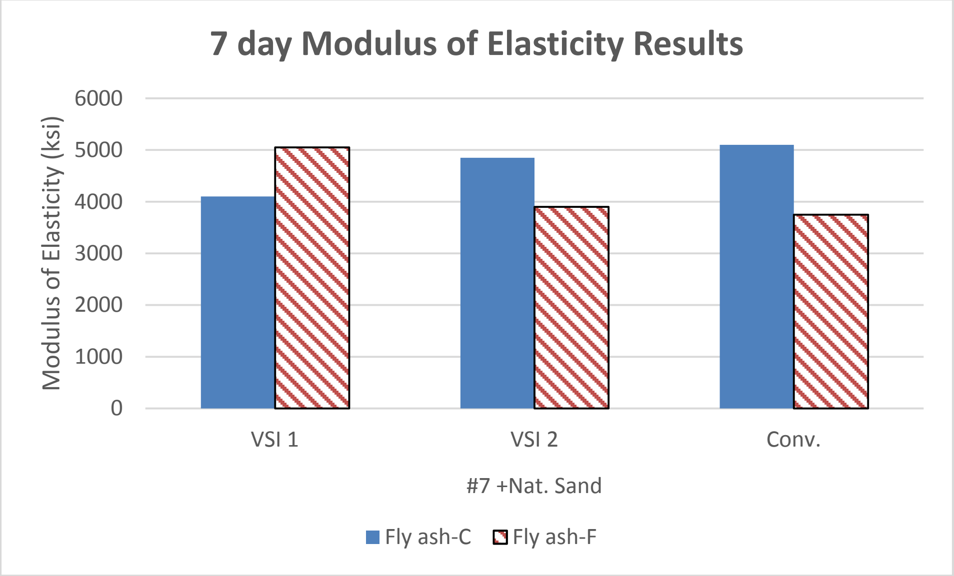

Figure 5.92 The 7 Day Modulus of Elasticity for #7 Stone Class A Mixtures

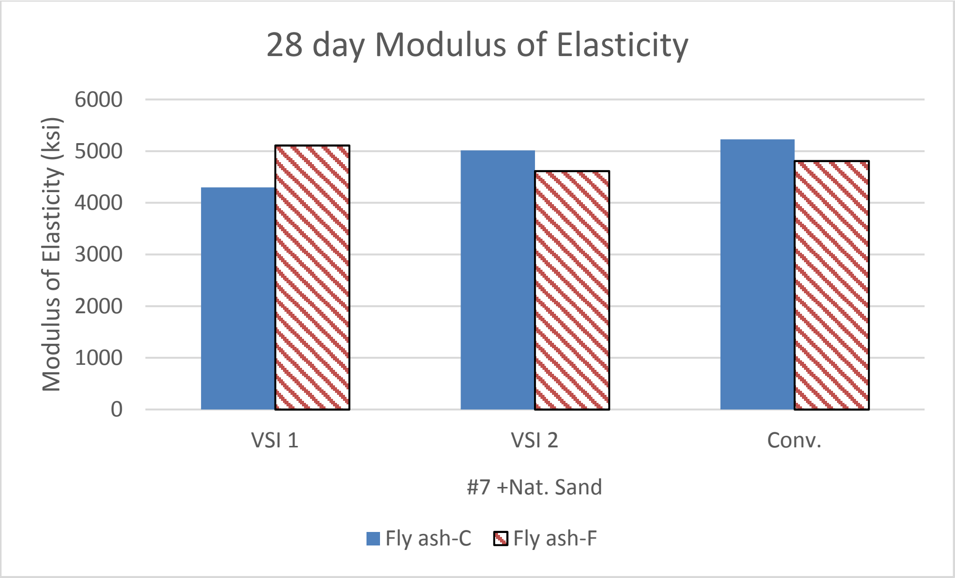

Figure 5.93 The 28 Day Modulus of Elasticity for #7 Stone Class A Mixtures

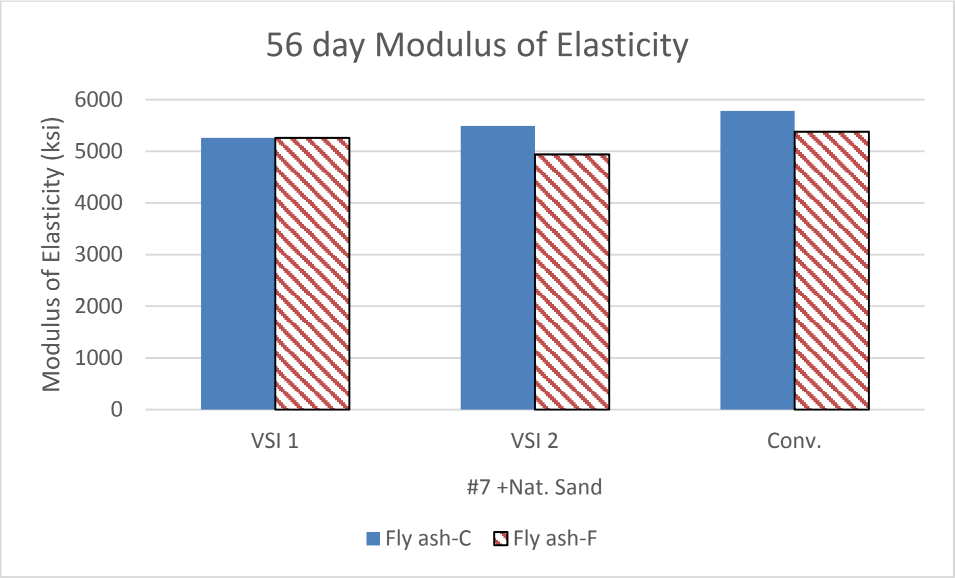

Figure 5.94 The 56 Day Modulus of Elasticity for #7 Stone Class A Mixtures

5.5.4 Rapid chloride Permeability Test

The results of RCPT were used to assess the permeability of the concrete. The results are shown in Table 5.8, are being discussed in this section. Table 5.10 describes how the values of RCPT are assessed and categorized. Figure 5.95 displays the results of the RCPT. RCPT values are being discussed based on the stone size later in this section.

Table 5.10 Chloride iron Penetrability based on charge passed (ASTM C1202)

Chloride Penetration	**56 days RCPT Charge Passed (coulomb)**
High	> 4,000
Moderate	2,000 – 4,000
Low	1,000 – 2,000
Very Low	100 – 1,000
Negligible	<100

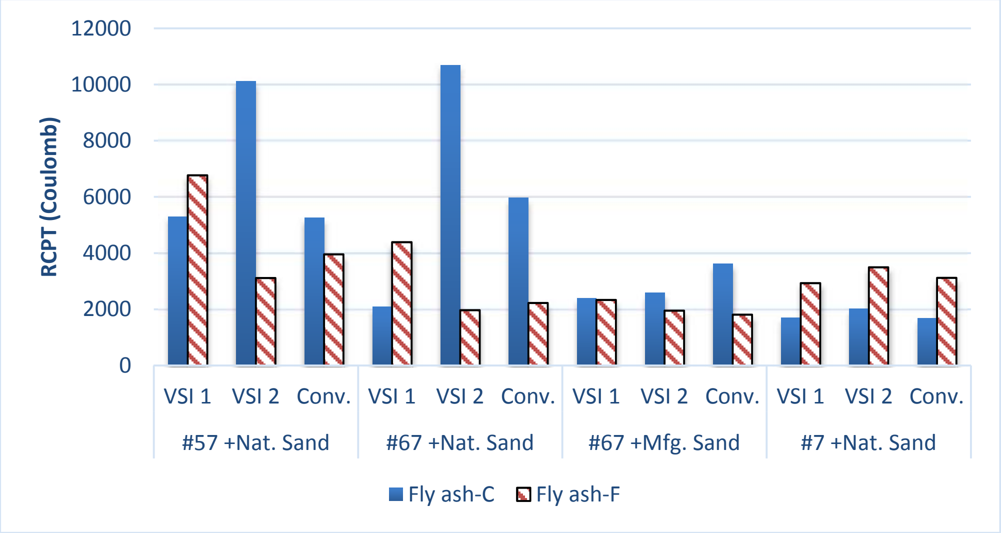

Figure 5.95 RCPT Values of the studied Class A Mixtures

Mixtures Containing Coarse Aggregates #57 with Natural Sand

As shown in Figure 5.96, all the values had high chloride penetration except with VSI of 2 when mixed with Class F fly ash has a moderate chloride penetration. This could be attributed to the bigger size of the aggregate that has creates more voids inside the mixtures.

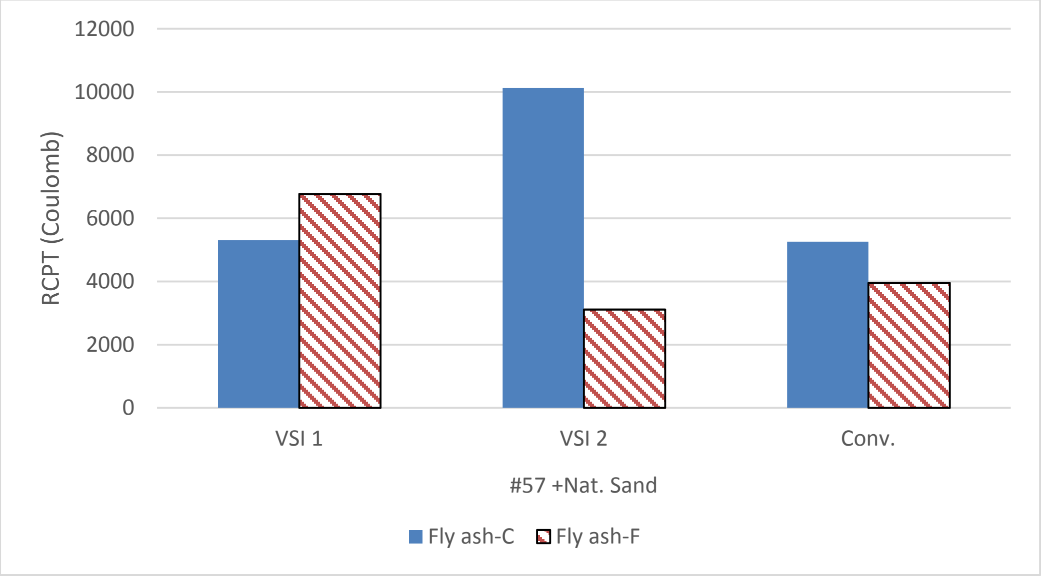

Figure 5.96 RCPT Values of #57 Stone Class A Mixtures

Mixtures Containing Coarse Aggregates #67 with Natural and Manufactured Sand

RCPT values were higher in natural sand mixture for VSI of 1 for Class F fly ash mixture than Class C and the opposite is true for VSI of 2. Manufactured sand mixtures had approximately the same values for VSI 1 & 2. The results of RCPT for #67 mixtures are shown in Figure 5.97.

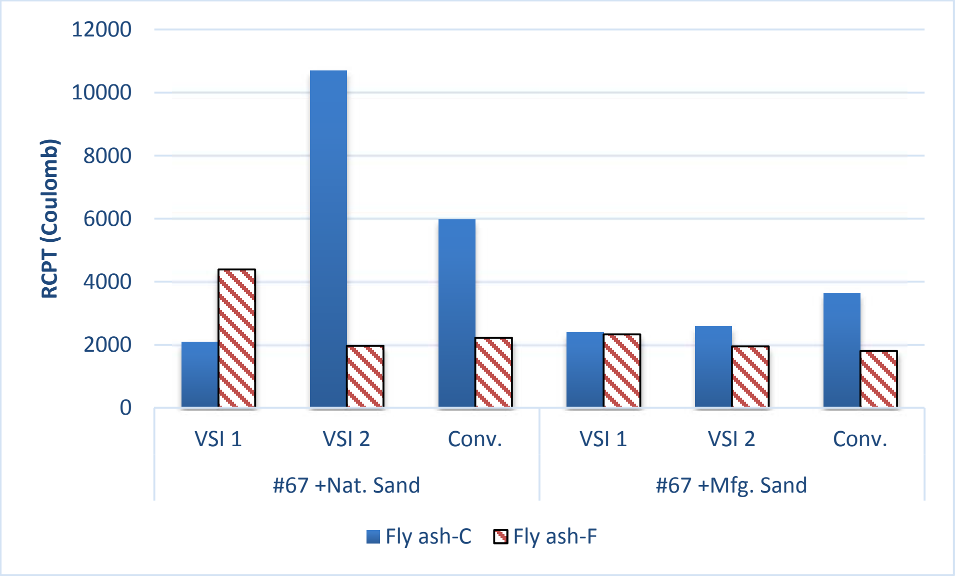

Figure 5.97 RCPT Values of #67 Stone Class A Mixtures

Mixtures Containing Coarse Aggregates #7 with Natural Sand

As shown in Figure 5.98 Class C fly ash mixtures had low chloride penetration compared to class F fly ash mixtures which had moderate chloride penetration, as Shown in Figure 5.98.

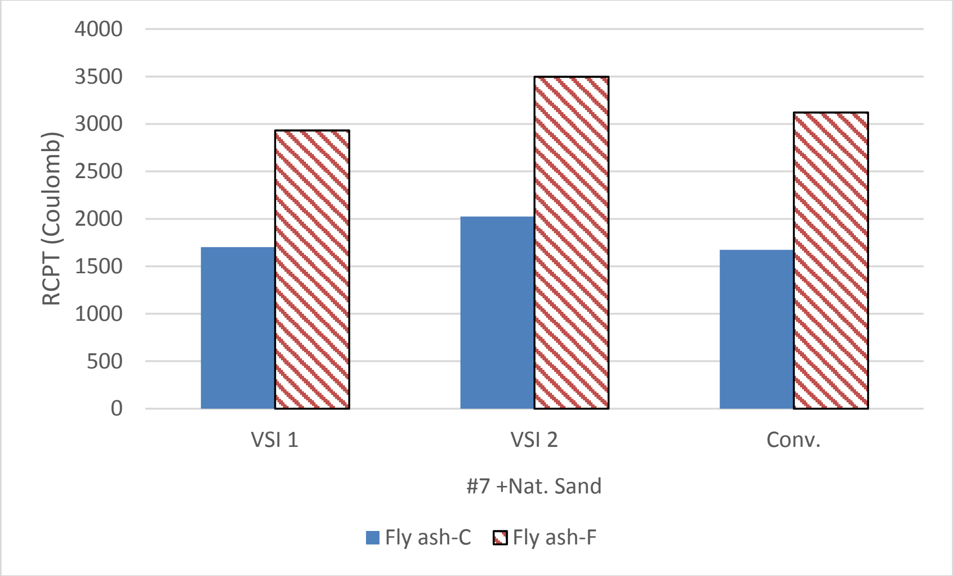

Figure 5.98 RCPT Values of #7 Stone Class A Mixtures

5.6 Discussion of Hardened Properties of Class P-SCC Mixtures

A number of tests were conducted to evaluate the hardened properties of the SCC and conventional concrete mixtures. The primary tests are Compressive strength, Tensile strength and Modulus of Elasticity. The tests intervals used in this study are 18 hours, 28 and 56 days tests results. TDOT requires 18 hours compressive strength to be not less than 4000 psi. The hardened properties tests are discussed with correlate to aggregates sizes in details in the following section.

5.6.1 The Compressive Strength for the Class P Mixtures

The compressive strength results that shown in Table 5.2 are summarized in Figure 5.99, which is 18 hours results and Figure 5.100 which is 28 days results and Figure 5.101 for 56 days results.

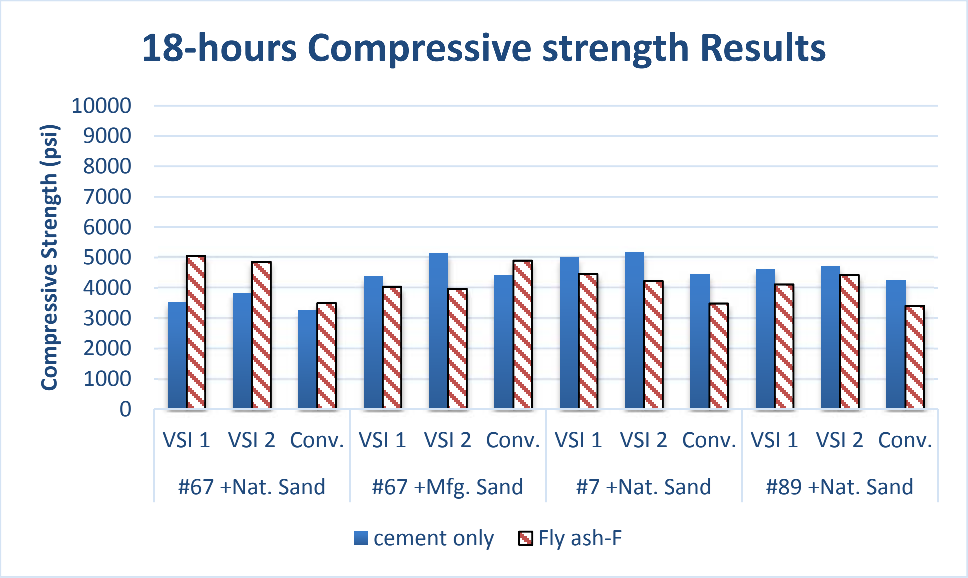

Figure 5.99 The 18-hours Compressive Strength of the Class P Mixtures

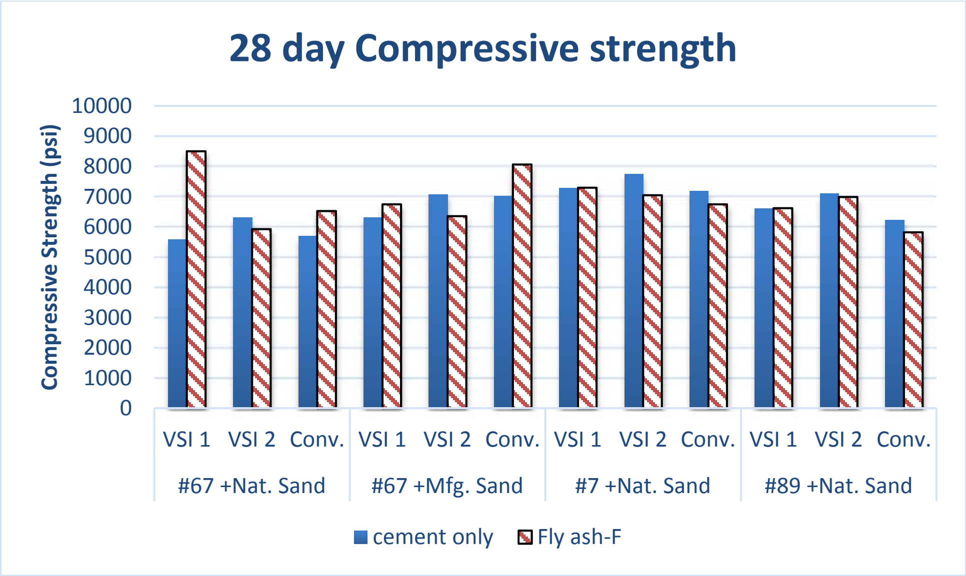

Figure 5.100 The 28 Day Compressive Strength of the Class P Mixtures

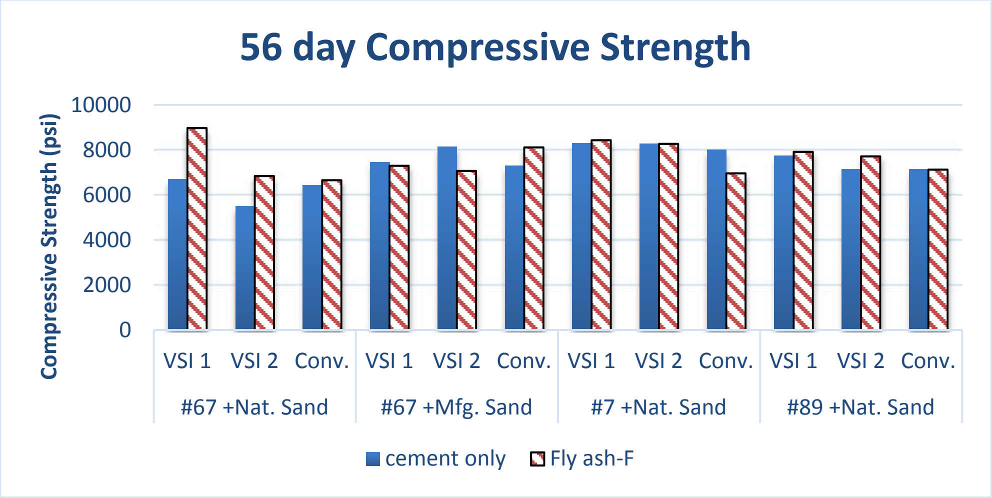

Figure 5.101 The 56 Day Compressive Strength of the Class P Mixtures

Mixtures Containing Coarse Aggregates #67 with Natural and Manufactured Sand

As shown in Figure 5.102 that manufactured sand mixtures has an early age compressive strength above 4000 psi when mixed with OPC and lower than 4000 psi when mixed with fly ash. Natural sand mixtures have the opposite behavior of the manufactured sand. Natural sand mixture with OPC has a higher compressive strength when using VSI of 1 than VSI of 2. It is apparent that in the case of Class-P Concrete it is better to use manufactured sand with plain cement mixes or use natural sand with fly ash. All the mixtures showed a good compressive strength after 28 days as shown in Figure 5.103.

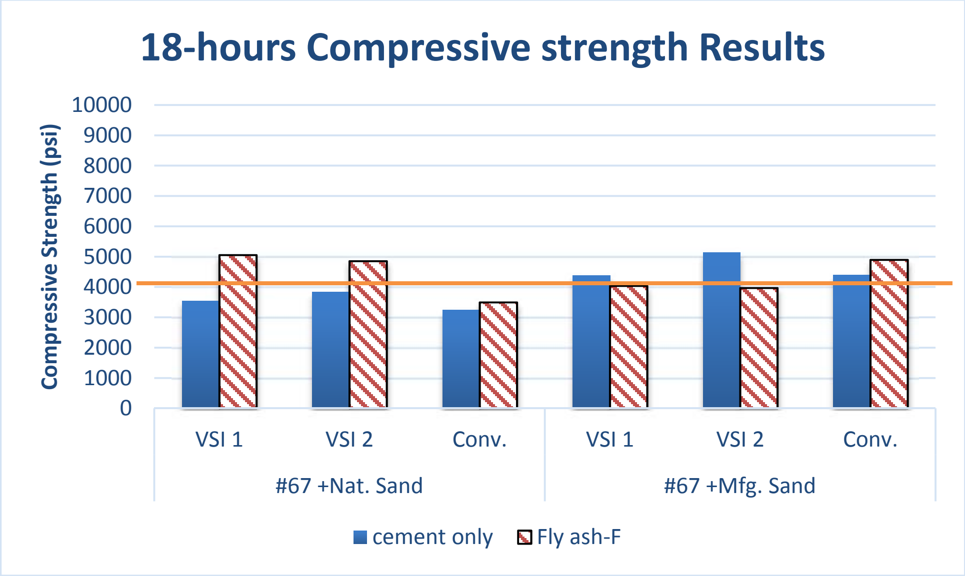

Figure 5.102 The 18-hours Compressive Strength of #67 Stone Class P Mixtures

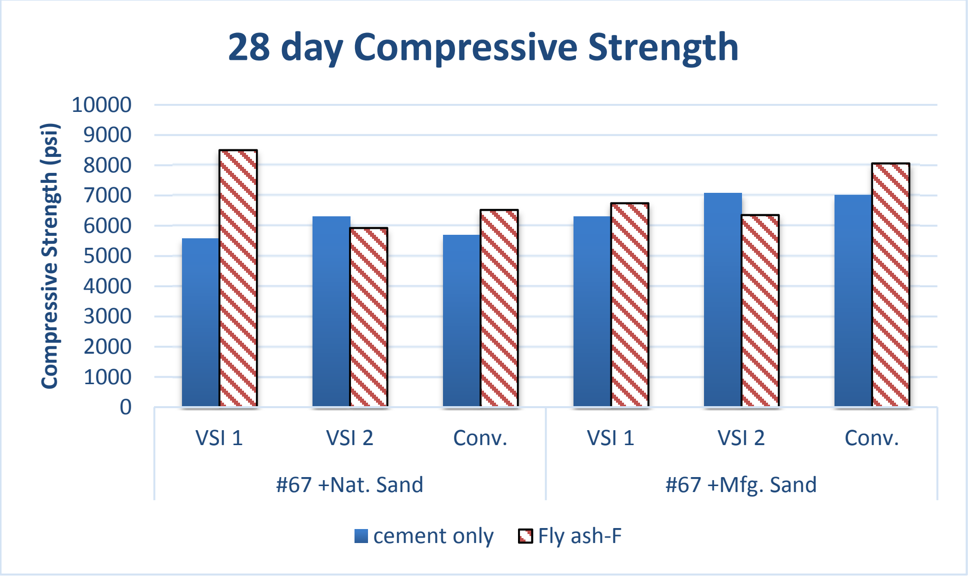

Figure 5.103 The 28 Day Compressive Strength of #67 Stone Class P Mixtures

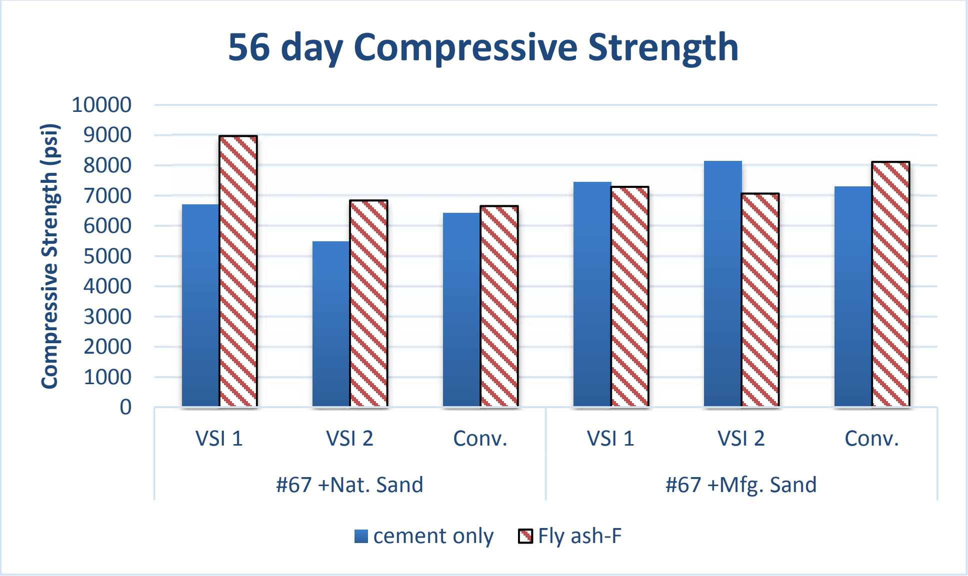

Figure 5.104 The 56 Day Compressive Strength of #67 Stone Class P Mixtures

Mixtures Containing Coarse Aggregates #7 with Natural Sand

As shown in Figure 5.105, that OPC mixture has an early age compressive strength above 4000 psi, and higher than Class F fly ash mixtures. This phenomenon could be attributed to the fly ash slow reaction compared to the cement. Also, it was not the case with #67 stone because #7 stone because of the previously mentioned surface area phenomenon that exhibits itself in the form of longer set times. With the reasons mentioned above, it makes harder to achieve higher early age strength. The same results happened with 28; 56 days results as shown in Figure 5.106, 5.107.

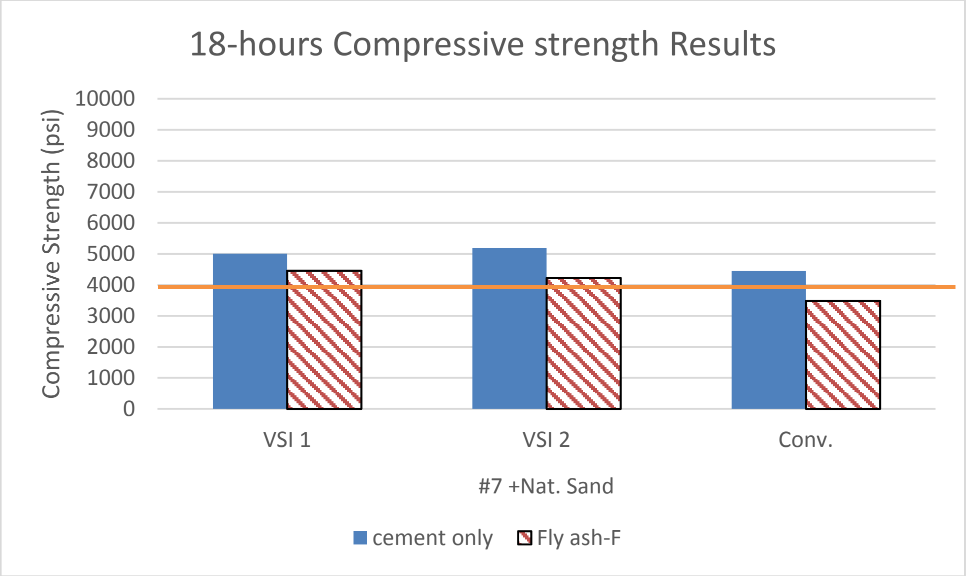

Figure 5.105 The 18-hours Compressive Strength of #7 Stone Class P Mixtures

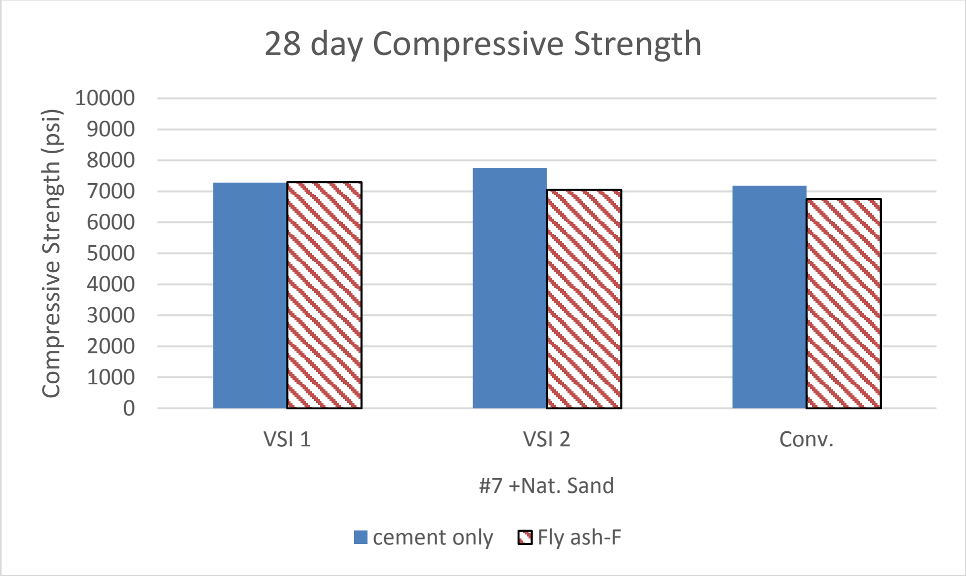

Figure 5.106 The 28 Day Compressive Strength of #7 Stone Class P Mixtures

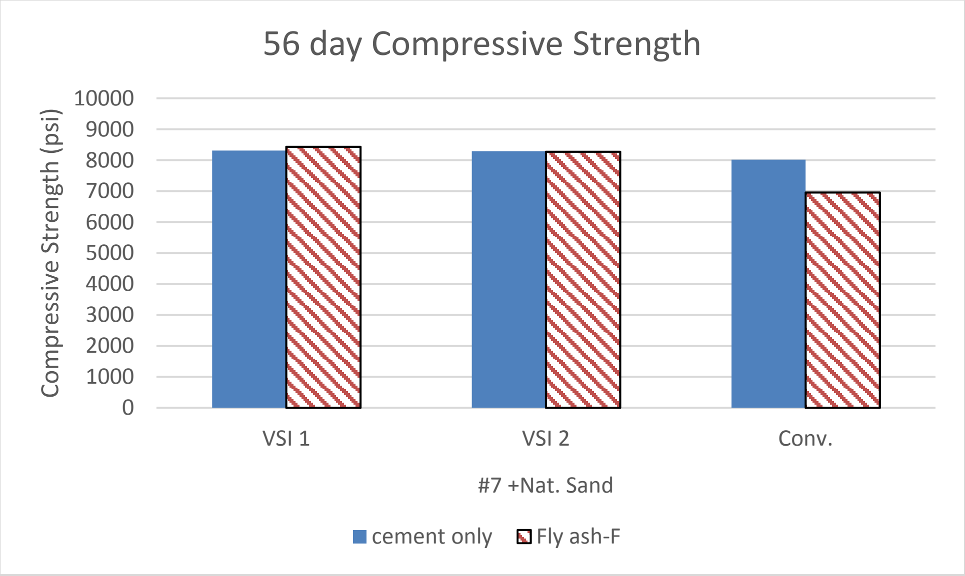

Figure 5.107 The 56 Day Compressive Strength of #7 Stone Class P Mixtures

Mixtures Containing Coarse Aggregates #89 with Natural Sand

Similar observations as #7 stone mixtures were observed for #89 stone mixtures. The results of 18 hours, 28 and 56 days are shown in Figures 5.108, 5.109 and 5.110.

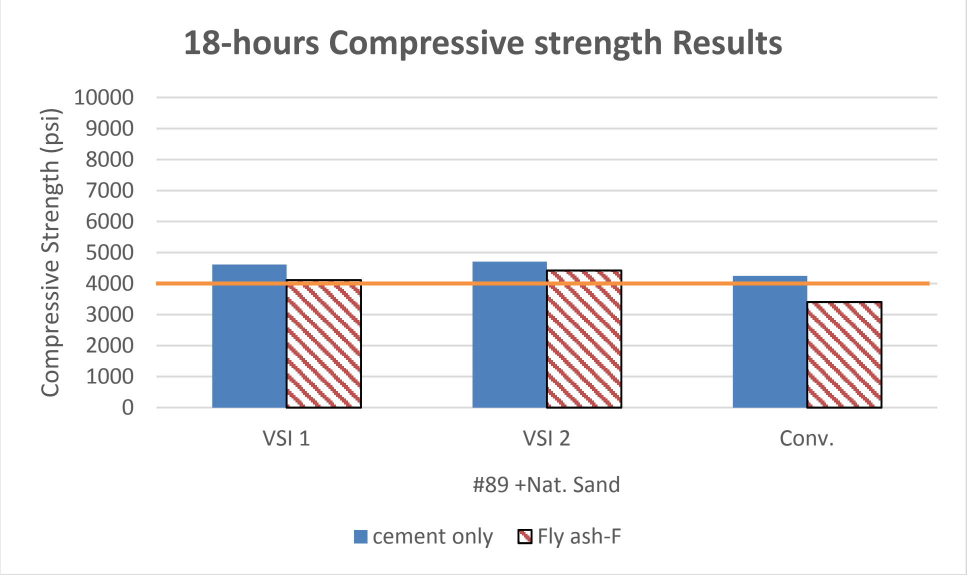

Figure 5.108 The 18-hours Compressive Strength of #89 Stone Class P Mixtures

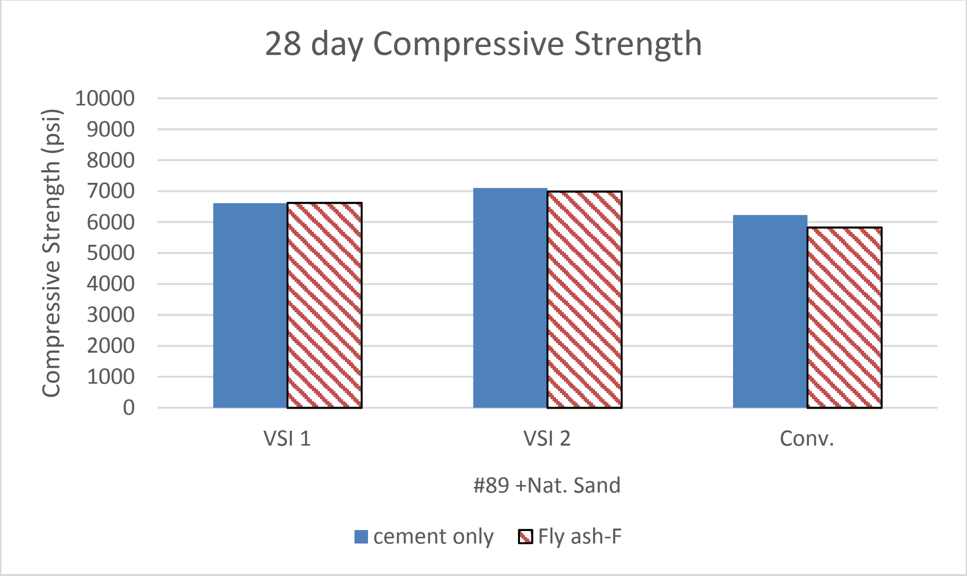

Figure 5.109 The 28 Day Compressive Strength of #89 Stone Class P Mixtures

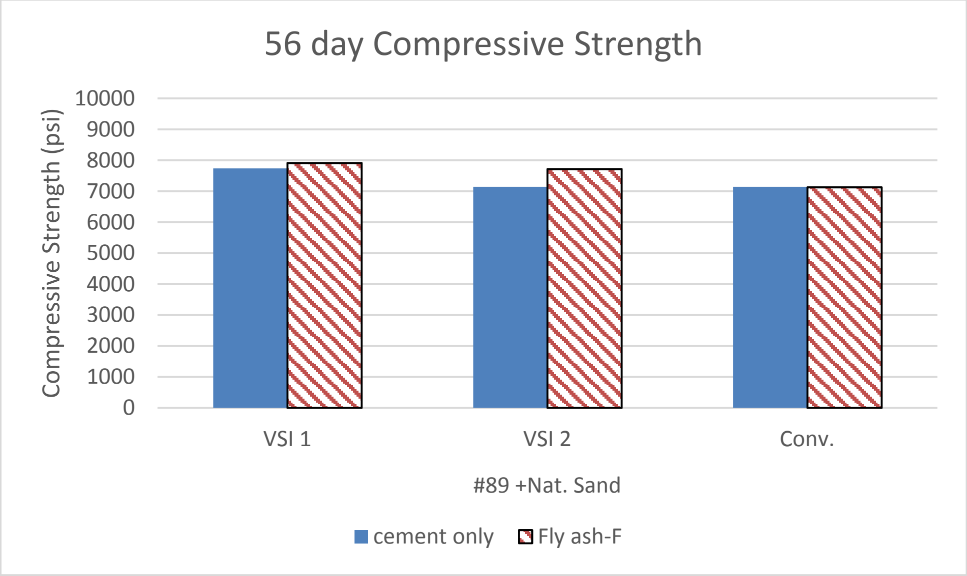

Figure 5.110 The 56 Day Compressive Strength of #89 Stone Class P Mixtures

5.6.2 The Tensile Strength of the Class P Mixtures

The modulus of elasticity test was performed for all SCC and conventional mixtures. The results of the test shown in Table 5.2 and summarized in Figures 5.111 for 18-hours results and Figures 5.112, 5.113 for 28, 56 days. Each aggregate size results are discussed in detail in this section.

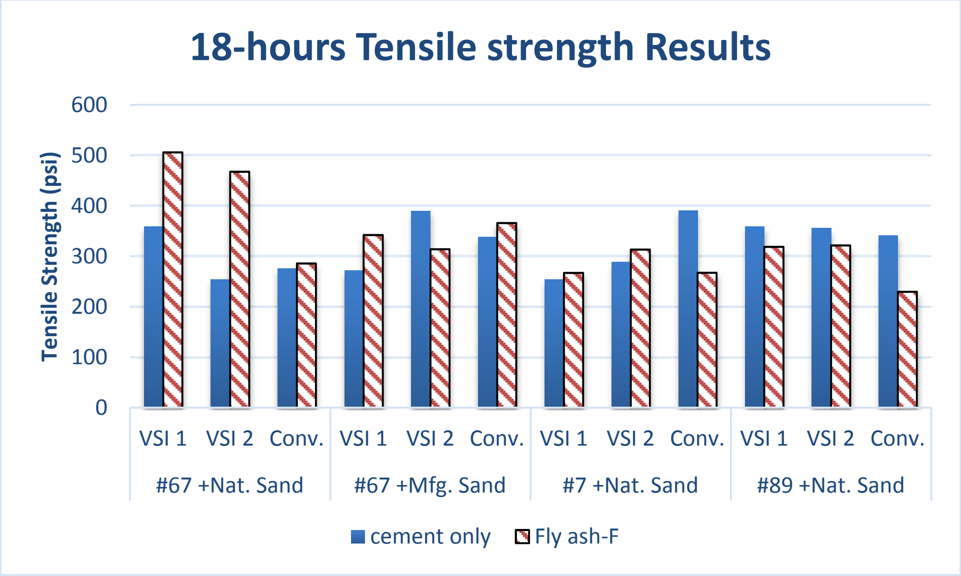

Figure 5.111 The 18-hours Tensile Strength Results for the Class P Mixtures

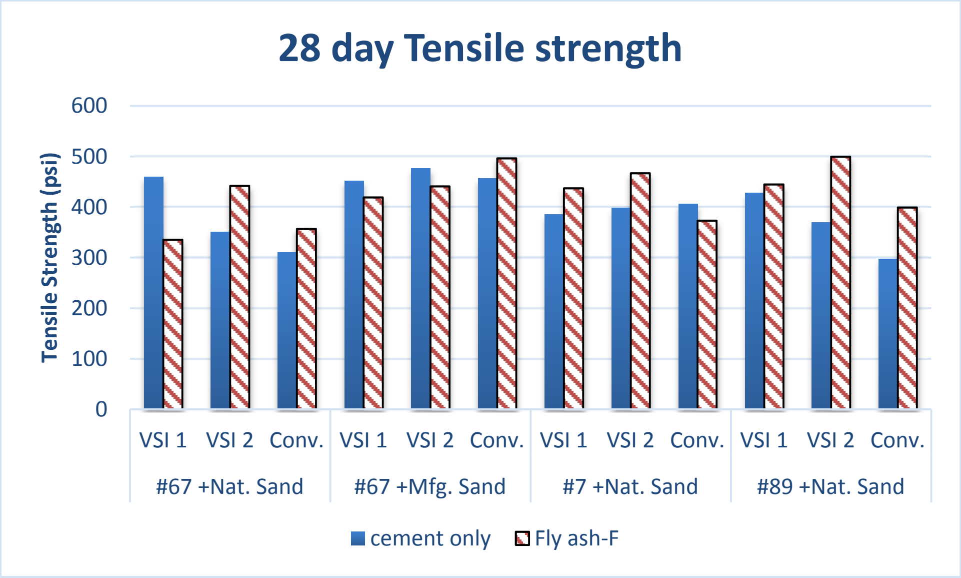

Figure 5.112 The 28 Day Tensile Strength Results for the Class P Mixtures

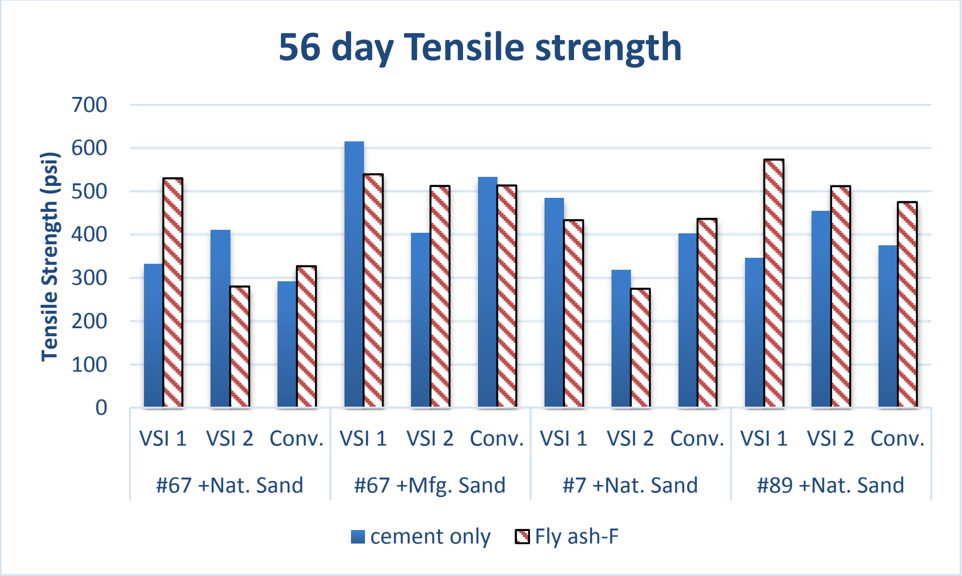

Figure 5.113 The 56 Day Tensile Strength Results for the Class P Mixtures

Mixtures Containing Coarse Aggregates #67 with Natural and Manufactured Sand

As shown in Figure 5.114, that fly ash with natural sand mixture showed a slightly higher 18 hours tensile strength than OPC mixture with VSI of 2, but apart from that OPC mixtures have a relatively higher tensile strength values than fly ash mixtures for SCC and conventional mixtures. While for the 28 and 56 days tests fly ash mixtures have higher tensile strength than OPC mixtures when using natural sand and lower strength with manufactured sand as shown in Figures 5.115 and 5.116. This could be attributed to the slower reaction of the fly ash in the early age of the concrete.

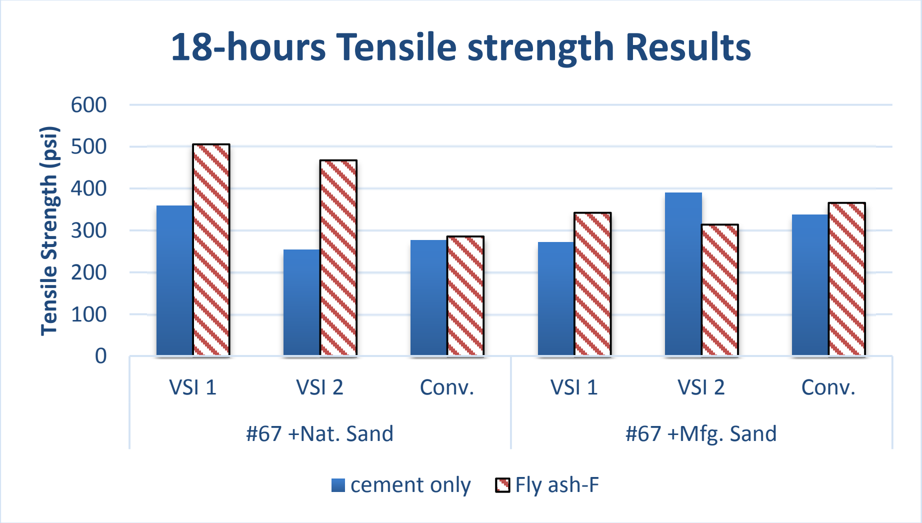

Figure 5.114 The 18-hours Tensile Strength of #67 Stone Class P Mixtures

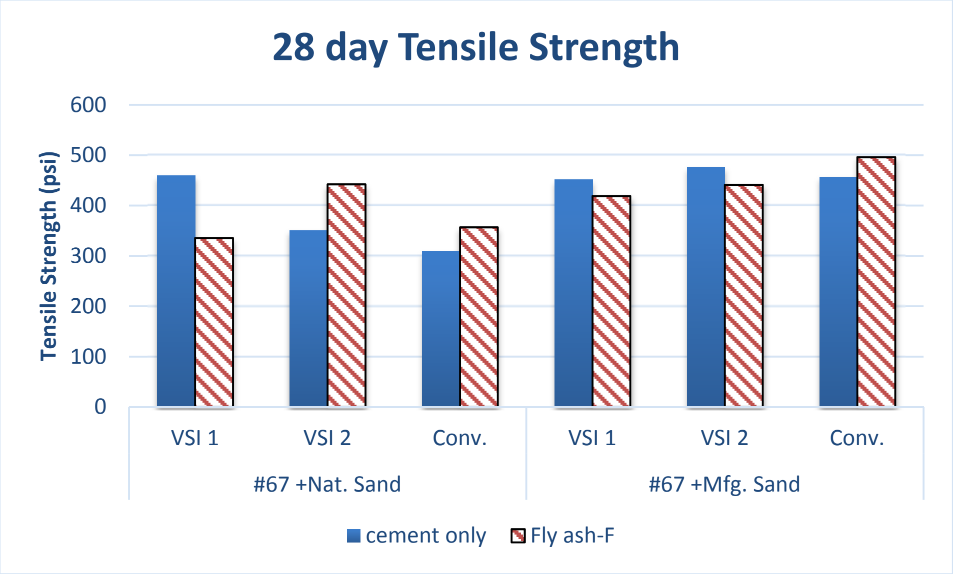

Figure 5.115 The 28 Day Tensile Strength of #67 Stone Class P Mixtures

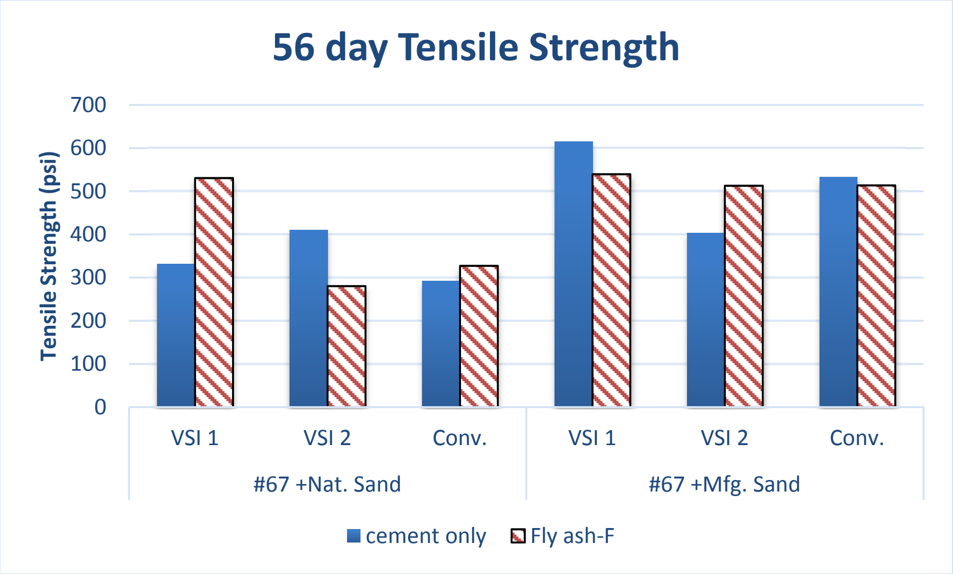

Figure 5.116 The 56 Day Tensile Strength of #67 Stone Class P Mixtures

Mixtures Containing Coarse Aggregates #7 with Natural Sand

As shown in Figure 5.117, that OPC mixtures have higher early age tensile strength than fly ash mixtures, while the values are very much equal in 28, 56 days as shown in Figures 5.118 and 5.119. This could be attributed to the slower reaction of the fly ash in the early age of the concrete.

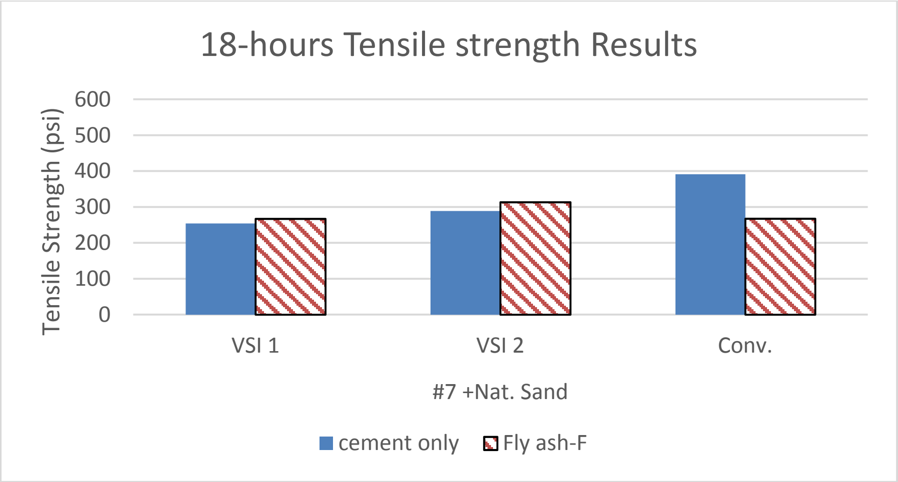

Figure 5.117 The 18-hours Tensile Strength of #7 Stone Class P Mixtures

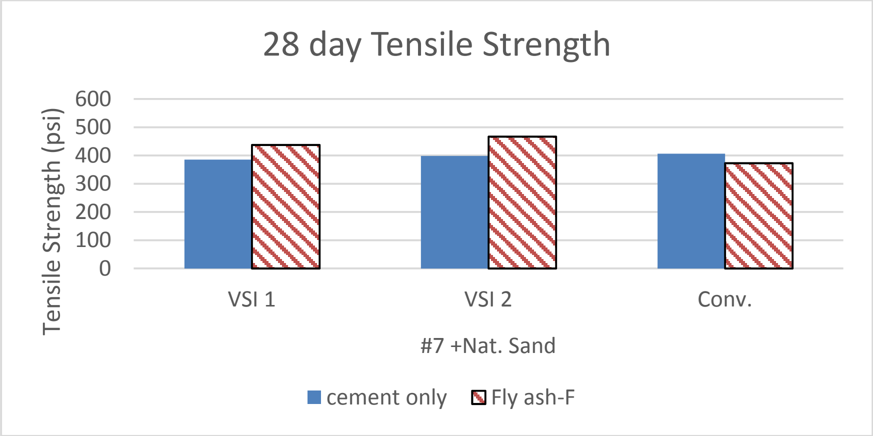

Figure 5.118 The 28 Day Tensile Strength of #7 Stone Class P Mixtures

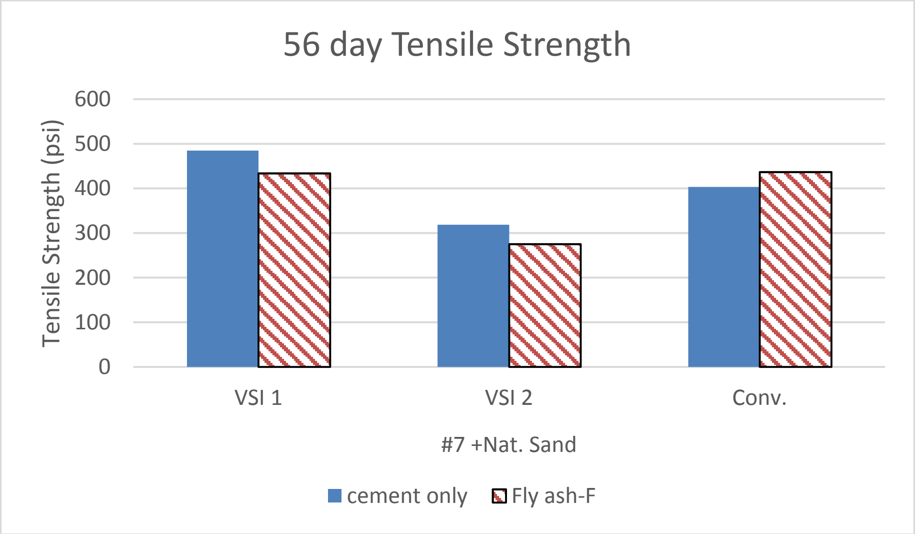

Figure 5.119 The 56 Day Tensile Strength of #7 Stone Class P Mixtures

Mixtures Containing Coarse Aggregates #89 with Natural Sand

As shown in Figure 5.120, and the same as #7 stone mixtures that OPC mixtures have higher early age tensile strength than fly ash mixtures, while the values are close in 28, 56 days as shown in Figures 5.121 and 5.122. This could be attributed to the slower reaction of the fly ash in the early age of the concrete.

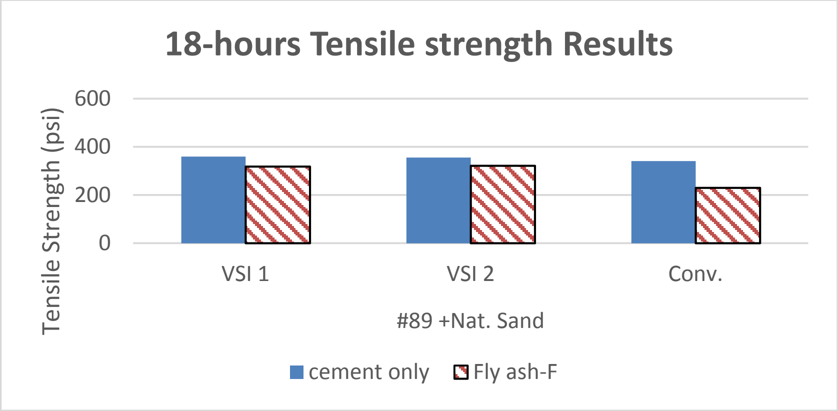

Figure 5.120 The 18-hours Tensile Strength of #89 Stone Class P Mixtures

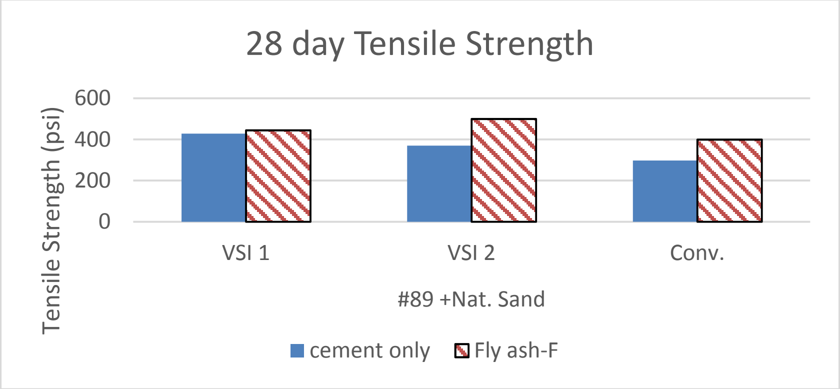

Figure 5.121 The 28 Day Tensile Strength of #89 Stone Class P Mixtures

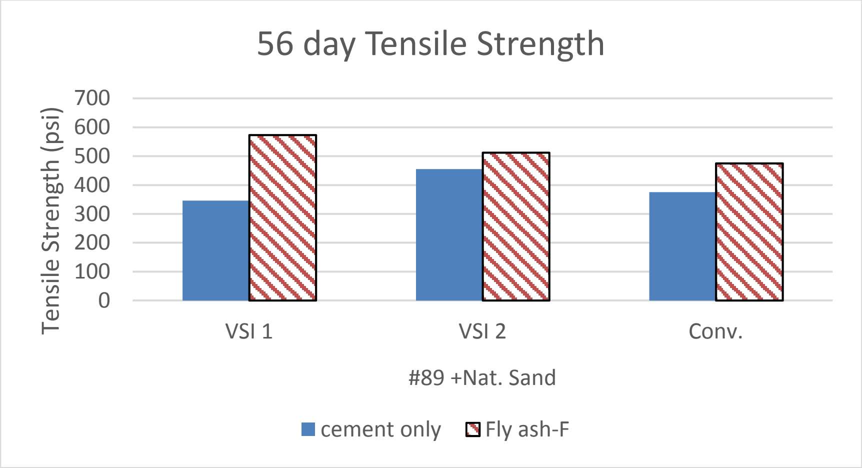

Figure 5.122 The 56 Day Tensile Strength of #89 Stone Class P Mixtures

5.6.3 Modulus Elasticity of the Class P Mixtures

The Modulus of Elasticity test was performed on the studied mixtures as described in chapter 2. The results of the test are shown in Table 5.2 and summarized in Figure 5.123 for the 18 hours tests and Figures 5.124, 5.125 for the 28, 56 days tests. Each aggregate size results are discussed in detail in this section.

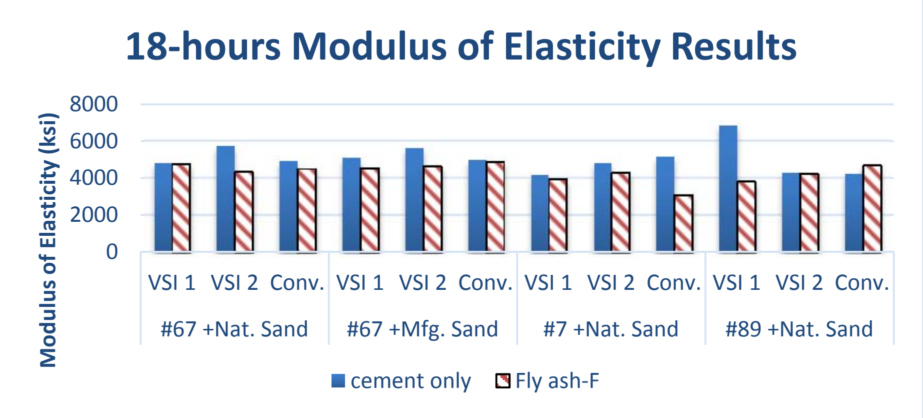

Figure 5.123 The 18-hours Modulus of Elasticity Results for the Studied Class P Mixtures

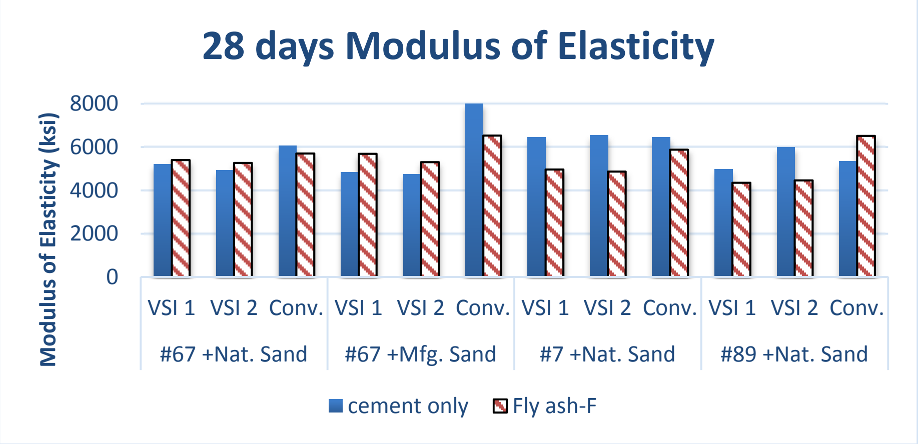

Figure 5.124 The 28 Day Modulus of Elasticity Results for the Studied Class P Mixtures

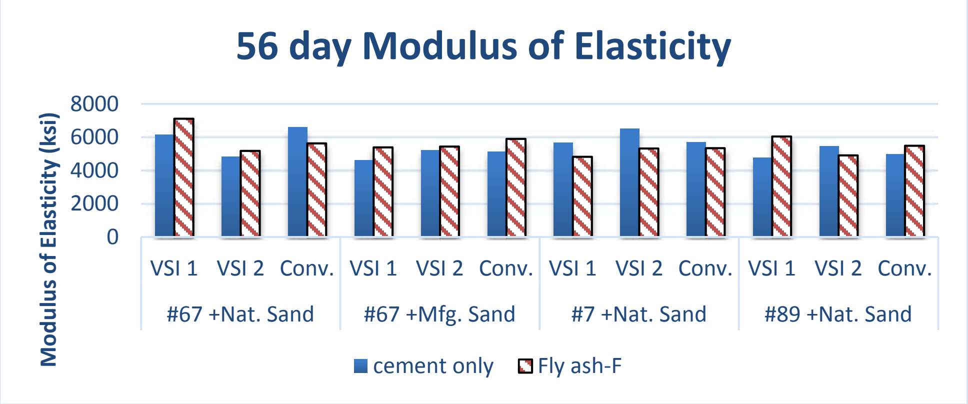

Figure 5.125 The 28 Day Modulus of Elasticity Results for the Studied Class P Mixtures

Mixtures Containing Coarse Aggregates #67 with Natural and Manufactured Sand

As shown in Figure 5.126, which the early age modulus of elasticity is relatively higher in OPC mixtures than fly ash mixtures. While after 28, 56 days, it is clear that all natural sand mixtures with Class F fly ash have more modulus of elasticity than OPC mixtures when mixed with natural sand and the opposite is true for manufactured sand as shown in Figure 5.127 and 5.128. This could be attributed to the slower reaction of the fly ash in the early age of the concrete.

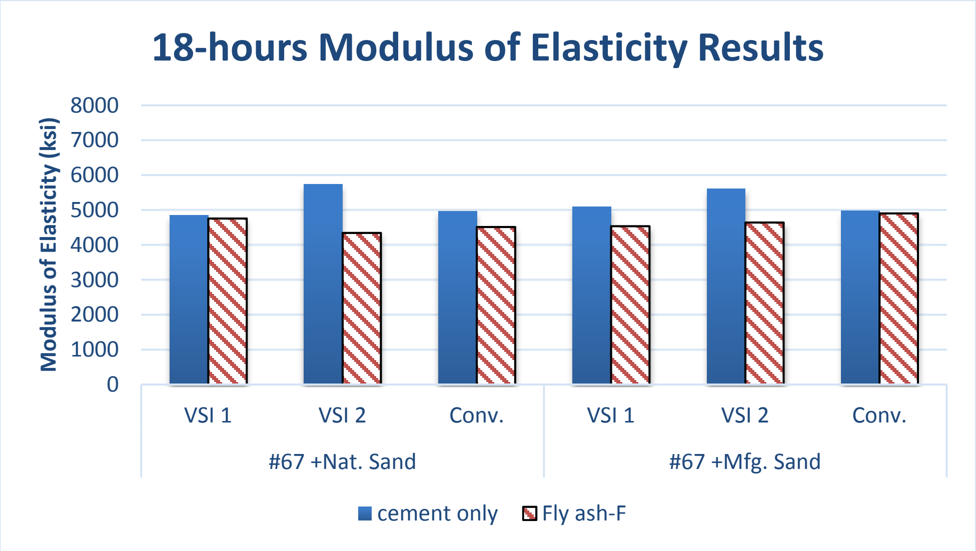

Figure 5.126 The 18-hours Modulus of Elasticity for #67 Stone Class P Mixtures

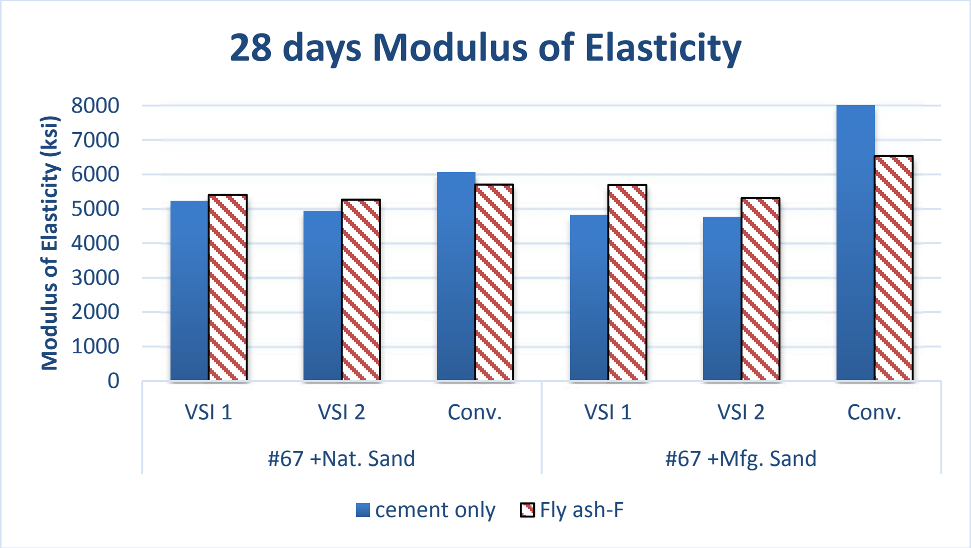

Figure 5.127 The 28 Day Modulus of Elasticity for #67 Stone Class P Mixtures

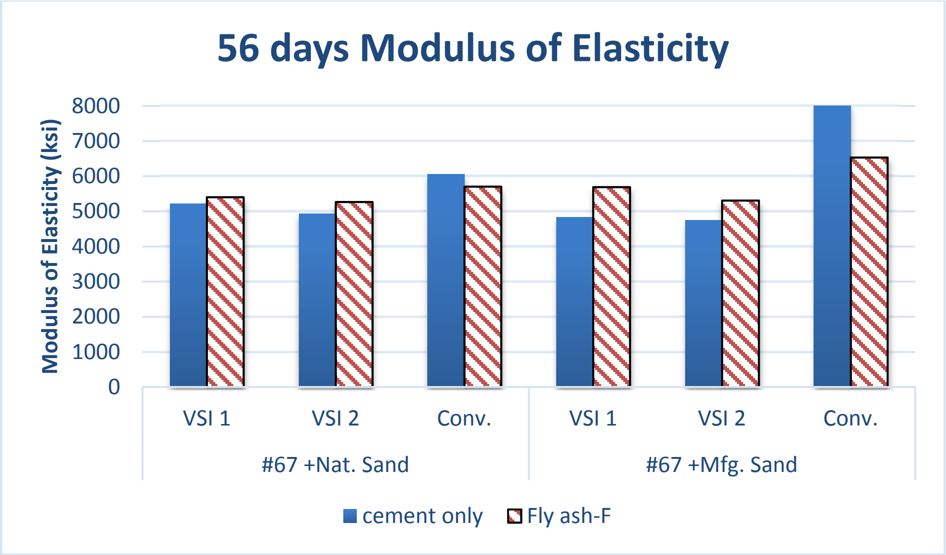

Figure 5.128 The 28 Day Modulus of Elasticity for #67 Stone Class P Mixtures

Mixtures Containing Coarse Aggregates #7 with Natural Sand

As shown in Figure 5.129 that #7 stone mixtures have a relatively higher early age modulus of elasticity when mixed only with OPC than Class F mixtures, and it continues to increase at 28, 56 days as shown in Figure 5.130 and 5.131.

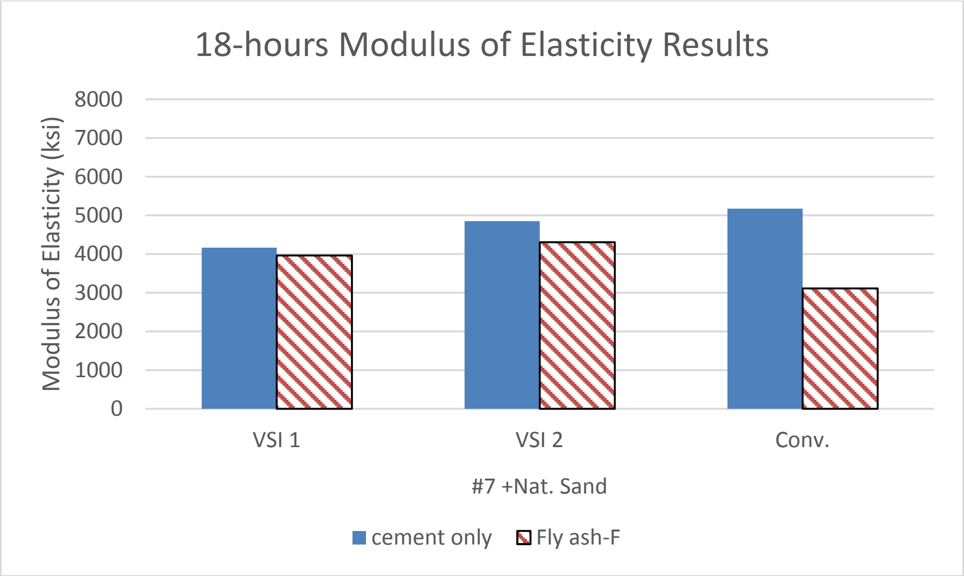

Figure 5.129 The 18-hours Modulus of Elasticity for #7 Stone Class P Mixtures

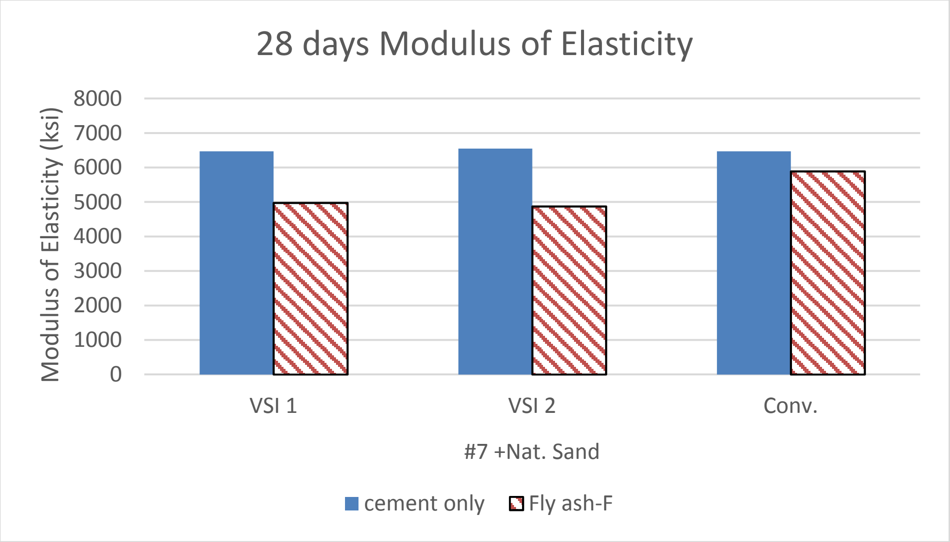

Figure 5.130 The 28 Day Modulus of Elasticity for #7 Stone Class P Mixtures

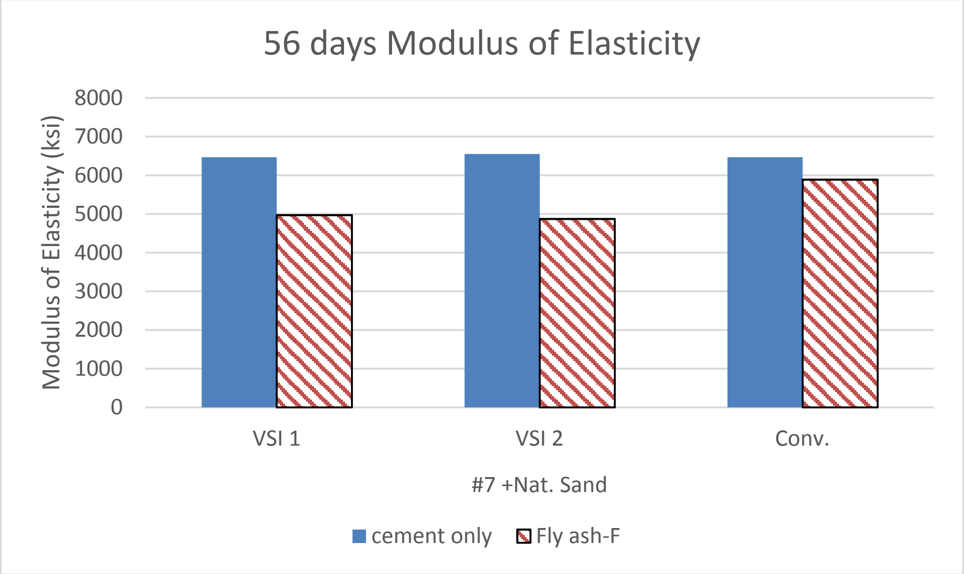

Figure 5.131 The 56 Day Modulus of Elasticity for #7 Stone Class P Mixtures

Mixtures Containing Coarse Aggregates #89 with Natural Sand

Similar observations could be seen in #89 stone mixtures as #7 mixtures from Figure 5.132, 5.133 and 5.134, except in the case of conventional concrete where Class F fly ash mixtures showed a higher Modulus of elasticity in all ages of testing.

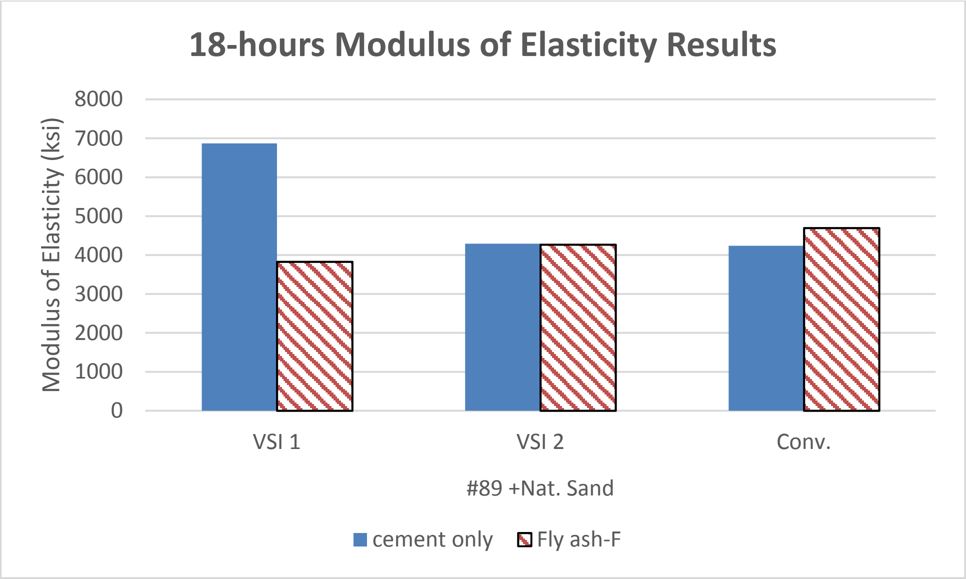

Figure 5.132 The 18-hours Modulus of Elasticity for #89 Stone Class P Mixtures

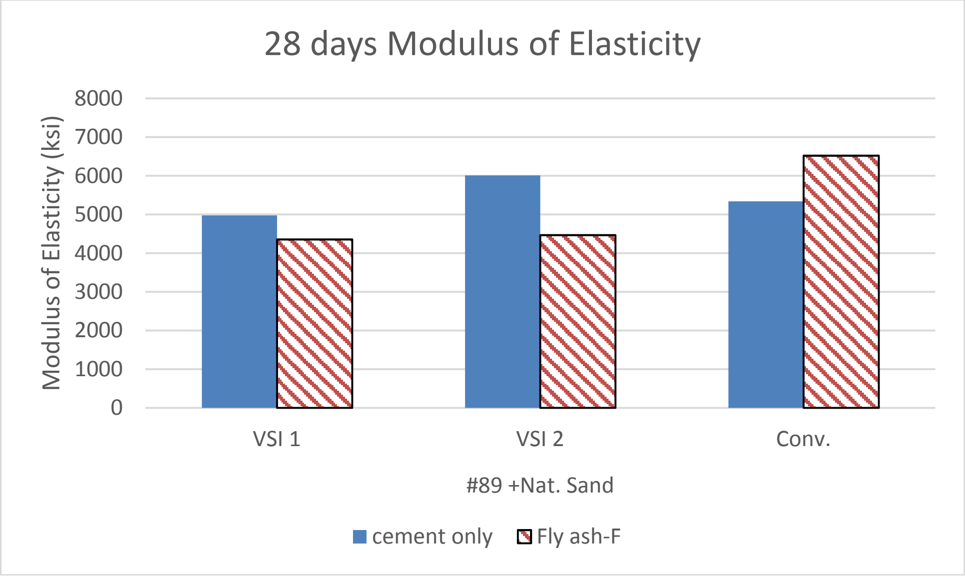

Figure 5.133The 28 Day Modulus of Elasticity for #89 Stone Class P Mixtures

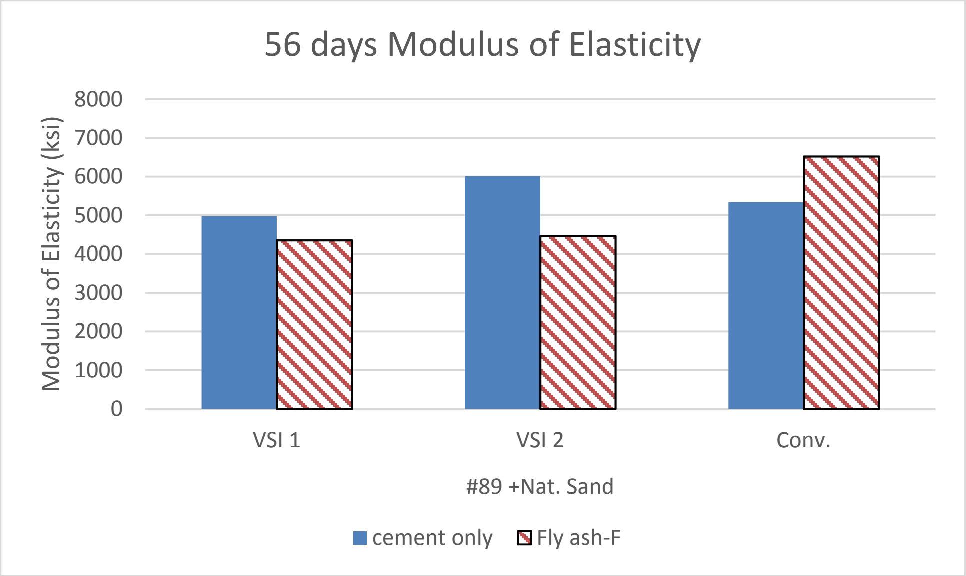

Figure 5.134 The 28 Day Modulus of Elasticity for #89 Stone Class P Mixtures

5.6.4 Rapid chloride Permeability Test Results for Class P Mixtures

The results of RCPT were used to assess the permeability of the concrete. The results were shown in Table 5.7, are being discussed in this section. Table 5.10 describes how the values of RCPT are assessed and categorized. Figure 5.134 shows the results of the RCPT. RCPT values are being discussed based on the stone size later in this section.

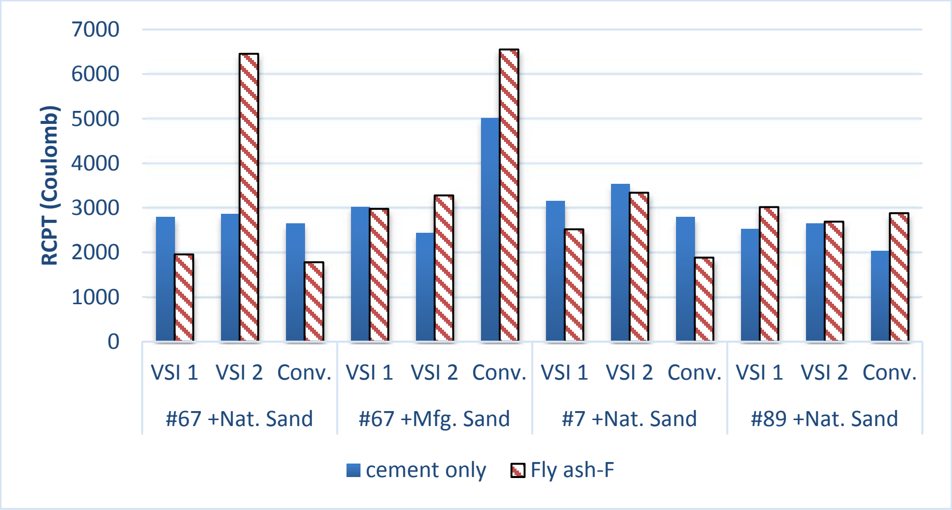

Figure 5.135 RCPT Values of the Class P Mixtures

Mixtures Containing Coarse Aggregates #67 with Natural and Manufactured Sand

RCPT values were higher in natural sand mixture for VSI of 1 for OPC mixture than Class F and the opposite is true for VSI of 2. Manufactured sand mixtures had approximately the same values for VSI 1 & 2. The results of RCPT for #67 mixtures are shown in Figure 5.135.

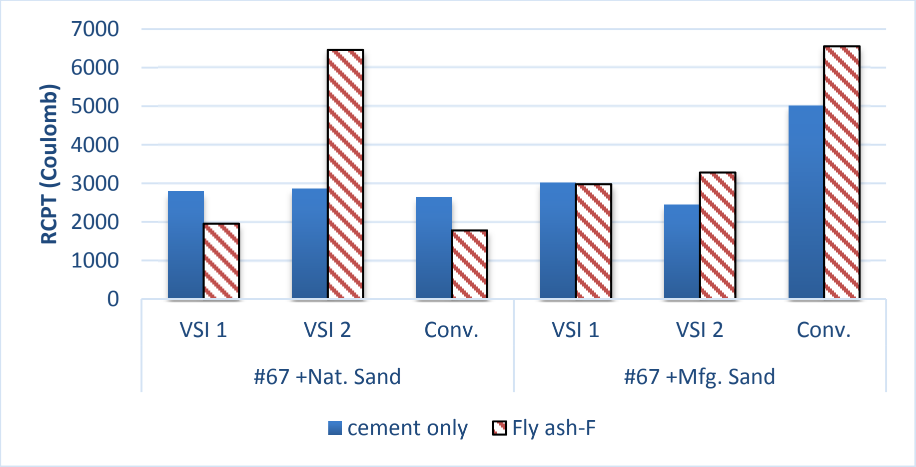

Figure 5.136 RCPT Values of #67 Stone Class P Mixtures

Mixtures Containing Coarse Aggregates #7 with Natural Sand

As shown in Figure 5.136, all the mixtures had a moderate chloride penetration. Class F fly ash mixtures had relatively lower chloride penetration compared to OPC mixtures.

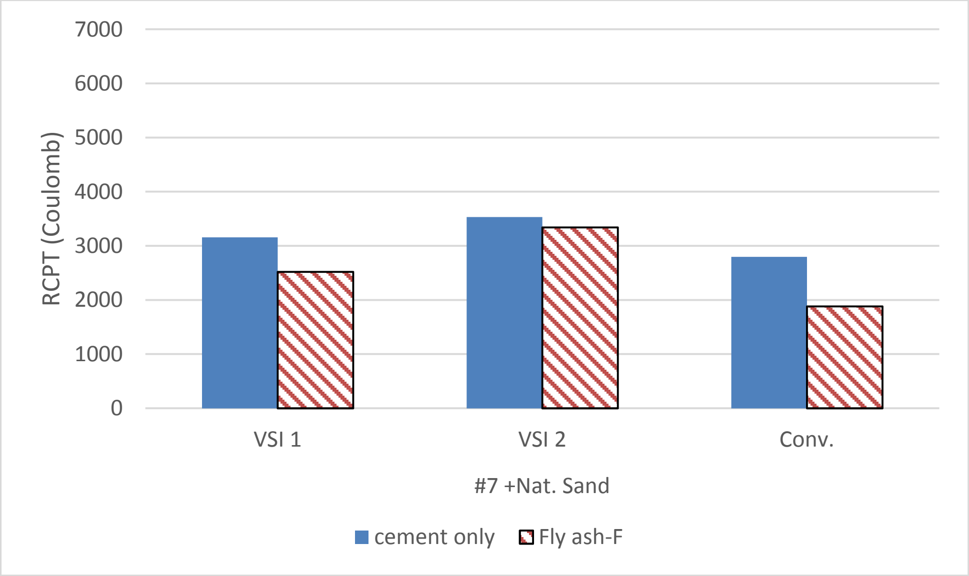

Figure 5.137 RCPT Values of #7 Stone Class P Mixtures

5.6.4.3 Mixtures Containing Coarse Aggregates #89 with Natural Sand

As shown in Figure 5.137, all the mixtures had a moderate chloride penetration. Class F fly ash mixtures had relatively higher chloride penetration compared to OPC mixtures.

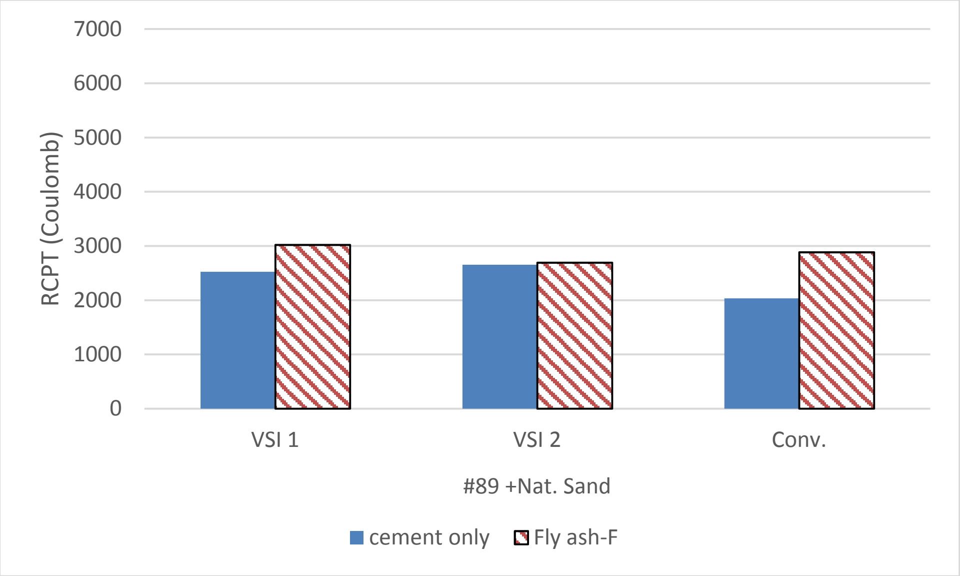

Figure 5.138 RCPT Values of #89 Stone Class P Mixtures

Chapter 6 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1 Summary

This study was funded by the Tennessee Department of Transportation (TDOT) carried out by University of Tennessee at Chattanooga (UTC) to develop four SCC mixtures two precast and two general use, and ensure they meet the minimum strength and durability requirement for TDOT Class P (precast) and Class A (general use) mixtures. The primary aims of this study were to investigate the fresh and hardened properties of Class A-SCC and Class P-SCC using different aggregate sizes (ASTM C 33 #57, #67, #7, and #89 stone), natural and manufactured sand, and using two classes of fly ash (C and F). In addition, it aimed to investigate the effects of Visual stability index (VSI) on fresh segregation of SCC mixtures.

Before developing the trial mixtures, a survey of state Departments of Transportation (DOTs) was conducted to gather specifications related to SCC use for general and precast elements in other states. The survey addressed the mixture parameters, fresh performance requirements, and the hardened performance requirements. The findings of the survey were summarized in Chapter 3 and then used to develop and select the mixture proportions and components; and choose the appropriate methods to evaluate the fresh and hardened characteristics of SCC mixtures.

Two Class A and two Class P mixtures were designed in this project. One Class P mixture designed with only portland cement and the other mixture was developed with 20% cement replacement with Class F fly ash. Two Class A mixtures were developed. The first was developed with 20% cement replacement using Class C fly ash, and with Class F for the second. Each Class P mixtures duplicated 12 times with visual stability index values of 1 and 2, different aggregate sizes (#67, # 7, and # 89), natural and manufactured sand as discussed in Chapter 4. Each Class A mixtures duplicated 12 times with visual stability index values of 1 and 2, different aggregate sizes (#57, #67, and # 7), and with natural and manufactured sand as discussed in Chapter 4.

Many methods were conducted to evaluate the fresh properties and characteristics of SCC mixtures which are described in Chapter 4 and summarized below:

- Slump flow test, Visual Stability Index, and T50 time were conducted to assess the filling ability and relative viscosity of the SCC mixtures,
- J-ring and L-box tests were carried out to assess the passing ability of SCC mixtures, and
- Column Segregation test was used to determine the fresh stability of SCC mixtures.

Several methods were used to evaluate the hardened properties and characteristics of SCC mixtures which are described in Chapter 4 and summarized below:

- Compressive strength test
- Tensile Strength test
- Modulus of Elasticity test
- Ultrasonic Pulse Velocity Test
- Surface Resistivity
- Rapid Chloride Permeability Test

The fresh and hardened property test results from the 48 mixtures were collected based on the VSI values of 1 and 2 and then compared with each other and with the results of conventional concrete mixtures. Then, the observations, conclusions, and the recommendation made during the collection and analysis of these findings are discussed below.

6.2 Conclusions

The results of this study support the following conclusions:

6.2.1 Observations and Conclusions from #57 Stone Concrete Mixtures

- The #57 stone in combination with natural sand exhibited acceptable filling ability. The Class F fly ash improves the flowability of #57 stone SCC mixtures with less amount of WRA than Class C fly ash mixtures.
- The #57 mixtures, containing natural sand and Class C fly ash, exhibited acceptable passing ability with the VSI of 2, and relatively poorer passing ability with the VSI of 1. While using Class F fly ash provides acceptable passing ability in the both VSI of 1 and 2.
- A higher segregation tendency is expected in the #57 stone mixtures with VSI of 2. Using Class C fly ash in the #57 stone mixtures showed promise in reducing the segregation potential.
- The VSI of 2 mixtures generally had longer setting time than that of VSI of 1 mixture this is probably due to the higher amounts of WRA required to achieve the VSI 2. Using Class F fly ash can increase the setting time more than that of Class C fly ash.
- The #57 mixtures showed an acceptable compressive strength in all testing ages. Also, VSI of 1 and 2 had relatively similar numbers to each other in compressive strength, modulus of elasticity and tensile strength.
- The #57 mixtures showed a high chloride penetration with both VSI 1 and 2; this could be attributed to the relatively large size of aggregates of #57 stone.

6.2.2 Observations and Conclusions from #67 Stone Concrete Mixtures

- The mixtures that contained #67 stone coarse aggregate and natural sand had higher slump flow and better filling ability compared to that of the manufactured sand.
- The manufactured sand mixtures generally had poor passing ability and higher segregation potential (greater than 10% Column Segregation) compared to the mixtures containing natural sand.
- Using Class C fly ash improved the flowability of #67 stone mixtures with less amount of WRA than that with using Class F fly ash. Also, using Class C fly ash reduced the segregation potential of mixtures containing #67 stone.
- The mixtures containing natural sand had lower relative viscosity (T50 less than 2 sec.) and longer setting time than that containing manufactured sand.
- The Class F fly ash improves the natural sand viscosity and passing ability while the Class C fly ash improves the manufactured sand viscosity and reduces its segregation potential.
- The mixtures containing #67 stone showed better fresh properties than that of #57 stone mixtures.
- Using Class F fly ash improves the compressive strength of #67 stone mixtures with natural sand (compressive strength more than 4000 psi) and lower the compressive strength when mixed with manufactured sand.

- Generally, #67 stone mixtures show better fresh properties with natural sand than manufactured sand, and better hardened properties when mixed with fly ash. Manufactured sand mixtures showed acceptable hardened properties in combination with portland cement only mixtures.

6.2.3 Observations and Conclusions from #7 Stone Concrete Mixtures

- In general, the mixtures containing #7 stone mixtures have better fresh properties than #67 stone mixtures and have good hardened properties when combined with portland cement only.
- The test results indicated that Class F fly ash mixtures had a difficulty reaching the required early-age compressive strength for class P mixtures. Also fly ash mixtures has more setting time than OPC mixtures this could be attributed to the slow reaction process of the fly ash.
- The #7 coarse aggregate mixtures are more convenient for making Class-P SCC mixtures when cement was used as the sole cementitious materials.

6.2.4 Observations and Conclusions from #89 Stone Concrete Mixtures

- The #89 stone mixtures have better fresh properties than #67 stone mixtures have. Also, they have good hardened properties when mixed with only OPC.
- The test results indicated that the Class F fly ash mixtures have poor hardened properties, this could be attributed to the slower pozzolanic reaction process of the Class F fly ash
- The #89 coarse aggregate mixtures are more convenient for making Class-P SCC mixtures when only cement was used.

6.3 Recommendations

The results of this study support the following recommendations:

- The results of this study indicated that Class- P SCC made with #67 stone VSI 1 mixtures have good results when mixed with Class-F fly ash and natural sand.
- The combination of #67 stone and manufactured sand is not recommended because it shows high segregation potential and low passing ability.
- The #7 and #89 aggregates with OPC are highly recommended to produce Class-P SCC mixtures with high flowability, high passing ability, and with less segregation potential and a good early age compressive strength.
- Class F fly ash is recommended with large size aggregates like #67.
- It is recommended for future work to investigate the use a blended fine aggregate of natural and manufactured sand and study their effect on the fresh characteristics of SCC. Also, investigate the impact of using manufactured sand with smaller size aggregates like #7 and #89 stone sizes on the early-age compressive strength.
- The results of this study indicate that SCC mixes made with the #57 stone, #67 stone, or manufactured sand, with the VSI value of 2, show high segregation potential. Therefore, VSI value of 2 is not recommended with these aggregates.
- The #7 aggregate is recommended to produce SCC mixtures with high flowability, high passing ability, and with less segregation potential.

- It is not recommended to use the manufactured sand as sole fine aggregate in the SCC mixtures; it shows high segregation potential and poor passing ability.
- Using fly ash classes C and F can improve the fresh characteristics of SCC mixtures.
- It is also recommended for future work to investigate the fresh properties of using a blended fine aggregate with natural and manufactured sand and study their effect on the fresh characteristics of SCC. Also, the #7 stone mixtures with HRWR show low or no air entraining agent dosages to provide their design air contents, so it is recommended for future work to study the air voids produced by the HRWR alone to make sure they provide resistance to the damage caused by freeze/thaw cycles.

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