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The Behavior and Durability of Self-Consolidating Concrete

May 2015

Nevada Department of Transportation
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FINAL REPORT

THE BEHAVIOR AND DURABILITY OF SELF-CONSOLIDATING CONCRETE

Prepared for:
Nevada Department of Transportation (NDOT)
Carson City, Nevada

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We wish to extend gratitude and appreciation to the Nevada Department of Transportation for the funding of the research that is presented in this report. In particular, we wish to acknowledge Mr. Manjunathan Kumar, Research Coordinator; Mr. Darin Tedford, Engineer, Material Division; Mr. Abid Sulahria, and Angela Alter, Planner/Analyst for NDOT's Research Division for assistance during research proposal selection, data collection, and development of this report. We also appreciate the Technical Writer of UNLV's Howard R. Hughes College of Engineering, Mrs. Julie Longo, for editing and formatting the report. It should be noted that we greatly appreciate Mr. Mark Bliss, Director of Quality, Calportland Materials Group for feedback from his self-consolidating concrete experience.

ABSTRACT

This report focuses on the production of self-consolidating concrete using local materials from Las Vegas, Nevada. Tests were conducted on eight self-consolidating concrete mixtures having two different percentages of fly-ash replacement (25% and 35%) as well as the inclusion of the superplasticizer ADVA 195 and the viscosity modifying admixture V-MAR 3. The fresh properties tested were flowability, passing ability, and stability. Mechanical properties evaluated were compressive strength, splitting tensile strength, and the modulus of elasticity. The durability of specimens produced from the mixtures was tested for chloride ion resistance, sulfate resistance, and salt scaling.

A key outcome of these tests for both fresh and hardened properties was that the mix design of self-consolidating concrete should be tailored according to the planned application (drilled shafts, precast products, repair concrete, etc…). Another key outcome was the importance mix design to accommodate the hauling time while maintaining consistent fresh properties of self-consolidating concrete at the delivery site.

Recommendations for applications for self-consolidating concrete include using additional parameters to assess the suitability of the mixture to the designated application such as (T50, J-ring), especially in critical applications where complications occur. And while additional testing may become a burden on the overall operation, it can be performed in trial batches and selectively during delivery. Another recommendation is to further investigate the use of techniques to control bleeding in large volume self-consolidating concrete casts.

EXECUTIVE SUMMARY

The executive summary (ES), often the most influential part of the report, should be written with the busy transportation administrator in mind. The ES should provide a readable, accurate, condensed description of the research findings and conclusions that evolved from the project. The ES should contain only information essential to understanding the findings and how they relate to the solution of problems–It is NOT an abbreviated version of the full report.

CRP ESs—whether they are stand-alone documents or incorporated into the full final report—follow a standard format. Generally, an ES is about 10% of the length of the full final report. An ES should contain the following items:

1. Introduction. This section summarizes the problem that led to the study, current knowledge used in solving the problem, and the objectives and scope of the assigned research. This section SHOULD NOT contain the details of any state-of-the-art survey made, forms used in soliciting information, or details on test procedures or mathematical analyses that may have been used—such details should be provided in the final report and appendixes.
2. Findings. This section presents what was found and how the resulting findings clarify the problem. Details, design charts, spreadsheets, software, and other items of immediate use to practicing engineers or other users should be in the final report and appendixes.
3. Conclusions. The conclusions discuss what the findings mean beyond project-specific conditions.
4. Recommendations. The recommendations discuss what should be done on the basis of the findings and conclusions.

1. INTRODUCTION

Self-consolidating concrete (SCC) is a specially engineered concrete that is highly stable, thus less prone to segregation; capable of flowing under its own weight through highly congested spaces; and does not require any external and/or mechanical vibration (ACI 201, ACI 211, ACI 237, ACI 301, and ASTM C1621/C1621M). SCC has gained a great deal of popularity in recent years because of some the desired attributes it embodies, and this has led to a significant amount of research to ascertain its practicality. Due to the extensive specifications that have been developed and use of SCC by engineering professionals in North America, SCC has been tagged as an Industry Critical Technology by the Strategic Development Council. As a result, there is an initiative to ensure that 15% of all ready mix to be SCC by the year 2015 (ACI 211).

SCC usage in the construction industry has provided quite a number advantages and benefits to the clients, consultants, and contractors. Even though it can be debated that the short-term cost of producing SCC is higher than that of normal vibrated concrete (NVC), the overall cuts in the cost of operation and construction has been undeniably meaningful. Further, there has been significant reduction in man-hours because of the elimination of the need for personnel to vibrate concrete during placement. Additionally, there has been a significant reduction in noise pollution, enabling the neighbors of the construction project to enjoy low levels of disturbances. Structurally, this has ensured flexibility for designers with regard to producing greater detail in their designs. They have the liberty of producing designs in which highly congested reinforcement is required in keeping with the expected demand of the structure. Due to this flexibility, as well as the self-consolidating and stable characteristics of the concrete mass, few restraints and little work has been required to ensure concrete placement and realization of the concrete structure.

The difference in the composition and properties of local materials and the different admixtures producers use, are warranting factors to determine the properties of the SCC designed for use in a particular project location. This research seeks to investigate the effect of local materials and the admixtures ADVA 195 and V-MAR 3 on properties of SCC to be used in Nevada Department of Transportation (NDOT) projects, such as the bridge construction in Mesquite. All specimen fabrication and testing conducted at the laboratory were in complete compliance with the American Standards for Testing Materials (ASTM).

2. LITERATURE REVIEW

2.1 Properties of Fresh Self-Consolidating Concrete (SCC)

The main reason to selecting SCC as a building material is to utilize the increased workability that SCC provides compared to conventional (vibrated) concrete. This workability has three main properties: (1) filling ability, (2) passing ability and (3) resistance to segregation. Filling ability describes the potential for fresh SCC to fill the formwork and properly surround reinforcement within the form. Passing ability for SCC allows the fresh mixture either to pass through reinforcements without becoming congested or be able to pass through narrow portions of the formwork without aggregate accumulating and causing a blockage. Resistance to segregation prevents suspended particles from settling within the fresh mix and causing a non-homogeneous condition within the fresh or hardened states (ACI 301; ASTM C1621/C1621M).

Rheology, the study of flow and deformation, must be considered and integrated with the workability properties (ACI 237; ASTM C1712). Several models are available to use determining the rheological properties of SCC, and involve the shear and yield stresses, plastic viscosity, and shear strain of fresh mixture concrete (ASTM C1610/C1610M). A basic rheological model is the Bingham Fluid Model, which relates these properties as a straight-line function, including the above-mentioned parameters.

Recently, rheology has been used to compare the flow properties of fresh SCC in order to find correlations among the various parameters. Such properties as stability can be optimized when utilizing rheology properties. Furthermore, such tests as the V-funnel can be used to quantify such rheological parameters as viscosity. While correlations may exist, differences in testing apparatuses can cause different values when using similar SCC mixtures. Interpreting the data that rheology tests provide and being able to apply these tests for various testing apparatuses becomes a challenge. Using standardized equipment by testing organizations would prove useful; however, it is imperative to use one testing device throughout the duration of any laboratory testing.

Filling ability can be measured using the slump flow and T_{20} (T_{50}) tests. These tests are described in detail in ASTM C1611, *Slump Flow of Self-Consolidating Concrete*. These tests employ similar equipment to ASTM C143, *Standard Test Method for Slump of Hydraulic-Cement Concrete*, which is used to measure slump of conventional concrete (ASTM C143/C143M; ASTM C1610/1610M; ASTM C1621/C1621M). Included in ASTM C1611 is the T-20 parameter, which is the time taken for a slump flow disk to reach a diameter or 20 in (50 cm). T20 has an expected time between two and seven seconds (ASTM C1611/C1611M). Filling ability may be increased using several methods, such as higher fine content, reduced aggregate quantity, viscosity-modifying admixtures (VMA), and the appropriate water/cement ratio (ASTM C1610/C1610M). Monitoring water content and high-range water-reducing admixtures also can control slump flow. Additionally, determining the appropriate time to add admixtures to the fresh concrete mixture is vital. On-site adjustments to admixtures and water content should be made in order to obtain the desired slump flow for the project, as the properties of the concrete mixture may have changed during transport or when waiting to be used at the job site. Careful monitoring is required of slump flow and in-line testing of the fresh concrete properties.

Passing ability is quantified using several tests, including the V-funnel, L-box, U-box, and J-ring tests, according to ASTM C1621, *Standard Test Method for Passing Ability of Self-Consolidating Concrete by J-Ring*. Applications of these tests measure the ability of fresh concrete, initially at rest, to pass through congested reinforcement or through narrow openings, where coarse aggregate may accumulate and cause a blockage. Compared to conventional concrete, a much higher passing ability is expected due to the increased workability associated with SCC. To increase the passing ability of SCC, several techniques may be used, including low coarse-aggregate amounts, reduced coarse-aggregate size, use of a VMA, and low water/cement ratio (ASTM C1610/C1610M).

Resistance to segregation, also referred to as stability, is measured by several methods, including:

- The column segregation test, ASTM C1610, Standard Test Method for Static Segregation of Self-Consolidation Using Column Technique and ASTM C1610, Standard Test Method for Static Segregation of Self-Consolidation Using Column Technique;
- The penetration apparatus test, ASTM C1712, Standard Test Method for Rapid Assessment of Resistance of Self-Consolidating Concrete Using Penetration Test; and
- The visual stability index (VSI) test, ASTM C1611, *Standard Test Method for Slump Flow of Self-Consolidating Concrete*.

These tests measure the static stability of fresh SCC by allowing the mixture to segregate under its own weight without mechanical vibration. Static stability is measured by performing a sieve analysis, measuring penetration within the fresh mixture, or by visual analysis. Dynamic stability refers to segregation resistance while the fresh SCC is being transported or placed, and is analyzed using the passing ability tests. As with the other workability properties, segregation resistance is increased by smaller coarse aggregates, low water/cement ratio, and the use of VMA (ASTM C1610/C1610M; Bernabeu and Laborde 2013). These methods achieve segregation resistance by reducing the segregation of solids and reducing bleeding within the fresh mixture.

Furthermore, increasing the cohesiveness of the mixture can minimize segregation. This is done by means of two methods, the addition of fine aggregates to reduce the amount of free water within the mixture or by using a VMA to increase the viscosity of the mixture. A combination of these two methods may be used when there are uncontrolled moisture conditions (ASTM C1610/C1610M). Ultimately, controlling only a few parameters increases the workability of SCC: the amount of coarse and fine aggregate, the water/cement ratio, the use of a VMA, and a proper mixture design.

2.2 Hardened Properties of SCC

For SCC to be a viable alternative, it must exhibit the same or nearly the same hardened characteristics as conventional concrete. Several key properties of cured concrete include compressive strength, modulus of elasticity, creep, and durability.

A key aspect of SCC mixture design is reduction of the water/cement ratio when compared to conventional concrete. Compressive strength of concrete mixtures is inversely proportional to the water/cement ratio, typically giving SCC a higher compressive strength. Moreover, the mixture design of the SCC has a significant effect on the compressive strength as a higher amount of fines is used, whether it is in the form of additional cement, fly ash, or other pozzolanic materials. The addition of fines increases the amount of cementitious material, and therefore increases the compressive strength.

For concrete, the modulus of elasticity (Young's modulus) is affected directly by the amount of coarse aggregate and the modulus of that aggregate. Since SCC typically incorporates a lower amount of coarse aggregate, the modulus of elasticity may be lower than similar conventional concrete mixtures. As well, an increase of fines within the mixture may cause the same effect, resulting in a reduction of the modulus of elasticity. Because of the SCC mixture design varies from a conventional concrete mixture design, using standard equations to calculate the modulus using compressive strength may not accurately represent the actual modulus of elasticity for SCC.

Creep is the deformation of hardened concrete caused by stresses from various sources over time. SCC typically has a reduced water/cement ratio caused by superplasticizers and increased fine aggregates. As the concrete cures, water within the mixture becomes consumed at the core before fully hydrating, causing autogenous shrinkage. Further, drying shrinkage may occur when water trapped within the cement paste becomes lost to evaporation. External forces may be applied to concrete not yet fully cured, such as pre-stress and construction loads, and can cause additional deformation. The onset of creep in SCC comes early because low water/cement ratios produce autogenous shrinkage.

Durability, as defined by the American Concrete Institute (ACI), "is determined by its ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration" (Beygi et al. 2014). Some of these processes include freeze-thaw cycles, alkali-aggregate reactions, reinforcement corrosion, and abrasion. If this is allowed to occur, weakening of concrete occurs in various forms; satisfactory concrete performance will diminish as these processes continue. Proper mixture design, admixture usage, and understanding of these processes are pivotal in preventing long-term damage or extensive maintenance and repair of concrete.

2.3 Mixture Design of SCC

SCC differs from conventional concrete in its fresh state because it must be designed specifically to obtain the desired properties, which are filling ability, passing ability, and stability. These three properties can be developed using similar methods during mixture design. As compared to conventional concrete, in general, SCC has a lower coarse-aggregate content and size, a higher fine/paste content, a reduced water/cement ratio, and the addition of a VMA and/or superplasticizers. The quantities or proportions of each must be calculated carefully and tested to meet job-specific requirements. There are three distinct types of SCC mixtures, 1) a powder mixture, 2) a VMA mixture, and 3) a combination of powder and VMA mixtures. Powder mixtures involve higher amounts of cementitious materials, whereas VMA mixtures use admixtures to achieve the same effect. Combination mixtures utilize a blend of both mixture types.

While there are three types of SCC mixtures, the methodologies for designing these mixtures can vary greatly in approach when determining the amount of material and the proportions. The mixture design is dependent upon the use of the concrete member and the fresh properties that are desired. Proportions as stated by ACI 211.1, *Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete* (Bury and Schemmel 2013), and ACI 301, *Specifications for Structural Concrete* (Daczko 2012), may not be desirable for SCC because fresh concrete characteristics may not be achieved using those standards. An example of this is the maximum allowable aggregate size and the effect this factor has on passing ability. Larger aggregates may cause accumulation within the formwork; while allowed in conventional mixture designs, this may be detrimental to SCC mixtures.

Several sources refer to a method known as the rational mixture design, proposed by Okamura and Ozawa. This procedure fixes the coarse-aggregate and fine-aggregate content, leaving only the water/cement ratio and the amount of admixtures free to be changed. According to this design, 50% of coarse aggregate consists of concrete solids and 40% of fine aggregate consists of mortar. *PCI Interim Guidelines for SCC* uses an adaptation of Okamura and Ozawa's method, which begins with determining the target air content for the hardened concrete. From there, the composition is determined of coarse aggregate, sand, and mortar paste. Afterwards, admixtures are added to the fresh mixture, and the water content is adjusted to fully utilize these admixtures. Finally, tests are completed on the mixture, and adjustments are determined (Domone 2007). ACI 237, *Self-Consolidating Concrete*, provides similar guidance for mixture design, but replaces the desired air content with a desired slump-flow requirement. This method is referenced in *The European Guidelines for Self Compacting Concrete* to determine the appropriate amount of water needed for flow and stability (Bernabeu and Laborde 2013).

Additional methodologies for mixture design include the ‘Chinese Method’ proposed by Su et al. This method determines the aggregate volume and then determines the mixture proportions of the binder. Aggregates are combined and loosely packed, leaving voids within the aggregate structure that need to be filled by the binder. When compared to the method proposed by Okamura and Ozawa, the Chinese Method saves on cost by using a reduced amount of binder and an increased amount of sand. Typically, the mixture design is easier to determine as well (Erdogdu 2005; European Project Group 2005). Moreover, this method follows a standard particle-size distribution for aggregate, the Andreasen and Andersen curve, whereas Okamura and Ozawa's method may not inherently follow such a distribution (European Project Group 2005). Regardless of which methodology is used to create the SCC mixture, nearly all reviewed literature suggests consultation with a professional SCC-mixture designer to obtain the job-specific performance required.

Tables 2.1, 2.2, and 2.3 show examples of mixture designs from three different regions: Japan, Europe and the United States. Comparisons were made for each region of the powder-type SCC mixture (Mixture 1), used in liquefied natural gas tanks; the VMA-type mixture (Mixture 2), used in caisson foundations; and the combination mixture of powder and VMA (Mixture 3), used in structural concrete. HRWR represents high-range water reducing admixtures, and VMA represents viscosity-modifying admixtures (James and Nickerson 2013).

Table 2.1 Self-Consolidating Concrete (SCC) Mixtures in Japan (Hassan and Ahmed 2013)

Ingredient	**Mixture 1 (Powder)**	**Mixture 2 (VMA)**	**Mixture 3 (Combination)**
Water, kg	175	165	175
Portland Cement, kg	530	220	298
Fly Ash, kg	70	0	206
Ground Granulated Blast Furnace Slag, kg	0	220	0
Silica Fume, kg	0	0	0
Fine Aggregate, kg	751	870	702
Coarse Aggregate, kg	789	825	871
High-range water reducing admixtures (HRWR), kg	9.0	4.4	10.6
Viscosity-modifying admixtures (VMA), kg	0	4.1	0.0875

Table 2.2 SCC Mixtures in Europe (Highway IDEA Project 2005)

Ingredient	**Mixture 1 (Powder)**	**Mixture 2 (VMA)**	**Mixture 3 (Combination)**
Water, kg	190	192	200
Portland Cement, kg	280	330	310
Fly Ash, kg	0	0	190
Ground Granulated Blast Furnace Slag, kg	0	200	0
Silica Fume, kg	0	0	0
Fine Aggregate, kg	865	870	700
Coarse Aggregate, kg	750	750	750
HRWR, kg	4.2	5.3	6.5
VMA, kg	0	0	7.5

Table 2.3 SCC Mixtures in the United States (Domone 2007)

Ingredient	Mixture 1 (Powder)	Mixture 2 (VMA)	Mixture 3 (Combination)
Water, kg	174	180	154
Portland Cement, kg	408	357	416
Fly Ash, kg	45	0	0
Ground Granulated Blast Furnace Slag, kg	0	119	0
Silica Fume, kg	0	0	0
Fine Aggregate, kg	1052	936	1015
Coarse Aggregate, kg	616	684	892
HRWR, mL	1602	2500	2616
VMA, kg	0	0	542

2.4 Applications of SCC in the United States

As the benefits of SCC become known within the industry, an increasing amount of states are looking to take advantage of this alternative building material. Several states and various federal organizations have conducted research in adopting SCC and primarily have compared it to conventional concrete under various applications to determine the viability of SCC as a building material.

2.4.1 U.S.-Specific Self-Consolidating Concrete for Bridges

Conventional concrete mixtures were used, designed specifically for bridge slabs in accordance with Michigan DOT. SCC mixture designs were created to be comparable to conventional mixtures and both were tested using standard procedures for several properties. Detailed figures for SCC and conventional concrete were created for compressive strength, freeze-thaw resistance, tensile strength, modulus of elasticity, creep and shrinkage. The SCC concrete showed a high early strength (5ksi at day 1, 7.5 ksi at day 7) which was double conventional concrete. Freeze-thaw resistance was examined and found to be sufficient after 640 cycles of testing. Segregation was tested by slump flow and cutting samples to visually inspect aggregate distribution. The SCC mixture showed excellent distribution of coarse aggregate without significant clustering of material. Finally, cost was evaluated between the two mixture designs. Due to the increased amount of cement material within SCC, a higher cost was determined. However, the paper explained that high material cost was offset by decreased labor cost and increased productivity.

2.4.2 Evaluation of Self-Consolidating Concrete (SCC) for Use in North Dakota Transportation Projects

This report contained similar testing and results compared to the previous publication. SCC mixtures were compared to similar conventional concrete mixtures and had identical proportions, except for the amount of admixture added. Properties tested include strength, stiffness, permeability, shrinkage, durability and freeze-thaw resistance. The results showed that strength and stiffness in SCC was similar or improved compared to conventional concrete. Air voids were higher within the SCC mixture design and increased permeability. In addition to testing of SCC versus conventional concrete, a survey was conducted consisting of all 50 states' department of transportation and their usage of SCC. This report showed that only nine states (of those that responded) had specifications for the usage of SCC, while 29 states either were researching the use of SCC or actively using it within their projects in some form.

2.4.3 Implementation of Self-Consolidating Concrete for Prestressed Concreted Girders

This report investigated the use of SCC for pre-stressed concrete girders in North Carolina. A bridge was actively being constructed during the time this investigation took place and was used to determine hardened concrete requirements. A set of three girders were tested, two made from SCC and one of conventional concrete as control. The SCC mixtures were designed and tested using standard procedures, including slump flow, VSI, and passing ability, among others. Hardened properties of all test girders were tested, such as compressive strength, modulus of elasticity, etc. To test the feasibility of the SCC girders, load was applied to each member to simulate the design service load to determine load versus deformation properties.

Results from testing showed that SCC performed just as well, if not better in some aspects compared to conventional concrete. The hardened properties of the SCC were comparable to the conventional control girder, but the fresh properties were not optimal. A different mixture design incorporating a larger amount of fines was suggested. When loaded to design service load, the SCC girders performed satisfactorily, showing no cracking and similar deformation and during unloading returned to its original provision. The finishes of the SCC mixtures were better than that of conventional concrete, but still contained small holes less than one-eighth of an inch. An improvement of SCC was the casting time; SCC girders took 20 minutes to cast as opposed to 30-45 minutes for conventional concrete. It was suggested that SCC usage be increased in order to take advantage of these benefits.

2.4.4 Underwater Tremie Concrete Mixture Development – Lake Mead Intake #3 Tunnel Project

This paper reviews the use of SCC, with specialized admixtures, to be used in an underwater environment, with long transportation time and delayed setting. 11,000 cubic yards of concrete was poured into a location 350 feet underwater and two miles from shore (Kumar and Dubey 2013). Several requirements were also placed upon the concrete mixture, such as curing temperature and washout. After several different iterations of mixture design in the laboratory was completed, field testing occurred using a tremie system to pump concrete. However, there were complications with the tremie systems that caused a whole new mixture design to be developed. The anti-washout admixture caused the concrete to harden within the tremie pipes and the concrete hopper. Because of this, the anti-washout admixture was replaced with a VMA; this change solved the problems that previously occurred with the tremie system and could then be used for the project. This report specifically shows the need for field testing of SCC mixtures to ensure that the mixture is sufficient for the job intended. By ignoring field conditions and relying only on laboratory testing, unforeseen problems can and will occur and need to be taken properly into consideration.

2.5 Effect of Powder Content on SCC

2.5.1 Shrinkage

Concrete composed of high binder content is very much at risk of plastic shrinkage. Plastic shrinkage is the contraction of fresh concrete before and during setting, leading to the development of negative capillary pressure. The negative pressure causes the aggregates to pull towards each other, resulting in the alteration of the concrete mass, hence shrinkage.

Turcry and Loukili (2006) demonstrated the effect of plastic shrinkage on SCC by observing that with moderate evaporation, SCC mixtures exhibit plastic shrinkage before and after setting. However, SCC under conditions of high wind exhibited little or no difference as compared to test specimens fabricated with ordinary concrete. In addition, this group reported that bleed water, very predominant in ordinary concrete, does not occur with SCC because of its higher binder composition. The presence of bleedwater reduces the evaporation of water from the concrete mass.

Roziere et al. (2007) correlated the relationship between the paste volume and shrinkage strain. Tests that were run on fabricated specimens indicated that strains exhibiting greater shrinkage strains were attained as the mortar content increased. Reduction in paste volume was reported to be inversely proportional with the amount of shrinkage cracks. Reduced generation of internal stress, due to the lower amount of the mortar, resulted in fewer cracks.

Lange et al. (2008) reinforced the idea that SCC having a higher volume of paste tended to exhibit greater shrinkage due to internal drying from hydration. The outcome of this shrinkage was the development of a high amount of internal stresses, leading to the development of cracks.

There are conflicting reports concerning the effect of shrinkage whereby the denser microstructure due to the finer powders did not lead to fabricated specimens undergoing higher strains.

2.5.2 Fracture

The amount of coarse aggregate and the accompanying amount of the powder content is a key factor to the durability of concrete in terms of fracture. Due to a larger amount of the mortar phase in the hardened concrete matrix, SCC is expected to have little resistance to fracture propagation, making it much less durable to meet the expected serviceability requirements.

Nikbin et al. (2014) reported that the amount of coarse aggregate in a concrete mixture had a substantial effect on mechanical properties, most especially with regard to fracture behavior. They concluded that mixtures with more coarse aggregate with correspondingly less mortar content had greater fracture toughness compared to mixtures with less coarse aggregate and more mortar content. Brittle number was also looked into and it came out that it increased greatly with increasing amount of coarse aggregate.

Beygi et al., (2014) corroborated the effect of the volume of powder volume on the fracture property of SCC. Not only does a lesser amount of powder reduce the tendency for fracture, thus less ductile, the size of coarse aggregate in the mixture affects the fracture energies of the mixture. The more varied the aggregate blend is, with the inclusion of a coarser aggregate content, the more durable the concrete is with respect to fracture.

2.5.3 Miscellaneous Effects

Shear capacity is influenced greatly by the duration of the mortar phase and the shapes of the coarse-aggregate content. A greater amount of powder leads to a wider mortar content between the coarse aggregate. Domone (2007) bolsters this theory by asserting that since the coarse aggregates are significantly distant from each other, the development of cracks in the mortar can be allowed to grow further before it is arrested by the closest aggregates in the line of shear.

The fresh properties of SCC are greatly hindered by the increase in the volume of the powder contents in the mixture. Hypothetically, increasing the powder content enhances the stability of the mixture. However, it has detrimental effects on flowability and the kinetic energy of the concrete mass. The more cohesive force there is in the fresh concrete mass, less flow rate occurs of the mass.

3. MATERIALS

The cement used in this research was Type II/V Portland cement, packaged by the American Eagle Ready Mix, LLC, in Las Vegas, Nevada. The supplementary cementitious material employed was Class F Fly Ash, obtained from a local quarry plant in Las Vegas, Nevada, together with the coarse aggregate and sand. Purified portable drinking water with a pH of 7 was used for the design mixtures. Table 3.1 shows the physical properties of the cement, fly ash, coarse aggregate, and sand used for the SCC mixtures.

Table 3.1 Physical Properties of Materials Used in SCC Mixtures

Material	**Properties**
Bulk Specific Gravity	
Portland Cement (Type II/V)	3.15
Fly Ash (Class F)	2.33
Sand	2.77
Coarse Aggregate, Mean Size of Aggregate (MSA): 0.75 in	2.93
Absorption, %	
Sand	0.9
Coarse Aggregate (MSA: 0.75 in.)	0.65

The admixtures used in the mixing process were ADVA 195 and V-MAR 3. The inclusion of these superplasticizers (SP) was essential to attain certain properties typical of SCC. ADVA® 195 is a polycarboxylate-based admixture that is a high-range water reducer (HRWR). Its addition to the SCC mixtures is essential to ensure that mixtures attain the desired fluidity and flowability, thereby reducing the demand of a higher water-to-cement (w/c) ratio in order to achieve the desired properties. V-MAR® 3 is a biopolymer-based admixture injected into SCC-mixture designs ensure their stability and prevent the washout of the mortar component from the coarse aggregate. The result is a cohesive concrete composition that significantly eradicates the likelihood of bleeding and the formation of mortar halos. Table 3.2 shows the densities of the admixtures used in the SCC production.

Table 3.2 Densities of SCC Admixtures

Admixtures	Density (lb/gal)
ADVA® 195	8.80
V-MAR® 3	8.50

A constant w/c ratio of 0.4 and coarse aggregate having maximum-sized aggregates of 0.75 in were used throughout the research. The mixture designs had two different percentage compositions of fly ash as the supplementary cementing material (SCM). The two percentage replacements were 25% and 35% of the cementitious material. The only variables worked on to obtain the desired rheological properties were the percentage composition of the superplasticizer and viscosity-modifying admixtures. For every mixture design, a low-slump and a high-slump SCC were engineered to give a range of the dosages required for a successful mix. Therefore, four mixture designs were developed, having different mixture IDs:

0.75-25-L: A low-slump self-consolidating concrete mixture made with a 0.75-in coarse aggregate size, with 25% fly-ash replacement

0.75-25-H: A high-slump self-consolidating concrete mixture made with a 0.75-in coarse aggregate size, with 25% fly-ash replacement

0.75-35-L: A low-slump self-consolidating concrete mixture made with a 0.75-in coarse aggregate size, with 35% fly-ash replacement

0.75-35-H: A high-slump self-consolidating concrete mixture made with a 0.75-in coarse aggregate size, with 35% fly-ash replacement

0.5-25-L: A low-slump self-consolidating concrete mixture made with a 0.5-in coarse aggregate size, with 25% fly-ash replacement

0.5-25-H: A high-slump self-consolidating concrete mixture made with a 0.5-in coarse aggregate size, with 25% fly-ash replacement

0.5-35-L: A low-slump self-consolidating concrete mixture made with a 0.5-in coarse aggregate size, with 35% fly-ash replacement

0.5-35-H: A high-slump self-consolidating concrete mixture made with a 0.5-in coarse aggregate size, with 35% fly-ash replacement

Tables 3.3 to 3.6 show the batch weights and volumes, respectively, for one cubic yard for each mixture.

Table 3.3 Batch Weights per Cubic Yard of 0.75-in Coarse Aggregate Concrete

	Mixture ID			
Mixture Components	0.75-25-L	0.75-25-H	0.75-35-L	0.75-35-H
Cement, lb/yd^3	495	495	428	428
Fly Ash, lb/yd^3	165	165	225	225
Coarse Aggregate, lb/yd^3	1636	1636	1636	1636
Sand, lb/yd^3	1337	1337	1337	1337
Water, lb/yd^3	272	268	273	267
ADVA® 195, %	0.74	1.07	0.5	0.74
V-MAR® 3, %	0.17	0.74	0.17	0.57

Table 3.4 Batch Volumes per Cubic Yard of 0.75-in Coarse Aggregate Concrete

	Mixture ID			
Mixture Components	0.75-25-L	0.75-25-H	0.75-35-L	0.75-35-H
Cement, ft^3/yd^3	2.5	2.5	2.18	2.18
Fly Ash, ft^3/yd^3	1.13	1.13	1.58	1.58
Coarse Aggregate, ft^3/yd^3	8.92	8.9	8.92	8.92
Sand, ft^3/yd^3	9.8	9.8	9.69	9.69
Water, ft^3/yd^3	4.16	4.1	4.18	4.14
Air Content, %	0.41	0.41	0.41	0.41

Table 3.5 Batch Weight per Cubic Yard of 0.5-in Coarse Aggregate Concrete

	Mixture ID			
Mixture Components	0.5-25-L	0.5-25-H	0.5-35-L	0.5-35-H
Cement, lb/yd^3	493	493	428	428
Fly Ash, lb/yd^3	164	164	225	225
Coarse Aggregate, lb/yd^3	1636	1636	1636	1636
Sand, lb/yd^3	1337	1337	1337	1337
Water, lb/yd^3	272	268	271	269
ADVA® 195, %	0.61	0.92	0.79	1.03
V-MAR® 3, %	0.15	0.68	0.28	0.58

Table 3.6 Batch Volume per Cubic Yard of 0.5-in Coarse Aggregate Concrete

	Mixture ID			
Mixture Components	0.5-25-L	0.5-25-H	0.5-35-L	0.5-35-H
Cement, ft^3/yd^3	2.47	2.47	2.16	2.16
Fly Ash, ft^3/yd^3	1.12	1.12	1.62	1.62
Coarse Aggregate, ft^3/yd^3	8.93	8.93	8.91	8.91
Sand, ft^3/yd^3	9.81	9.81	9.72	9.72
Water, ft^3/yd^3	4.05	4.05	4.10	4.05
Air Content, %	0.41	0.41	0.41	0.41

4. EXPERIMENTAL SETUP

4.1 Testing of Fresh Properties

The constituents of the SCC mixtures were added in a specific sequential order to ensure their homogeneity. First, the coarse aggregate, cementitious materials, and sand were poured into the concrete mixer sequentially, and allowed to mix for approximately 90 sec. Second, three quarters of total amount of water was added, followed by the aqueous solution of superplasticizer (ADVA 195); 60 sec later, the last quarter of the water was added mixed with the viscosity-modifying admixture (V-MAR 3). The mixer was turned off, and the mixture was allowed to sit for approximately 120 sec. After that, the mixer was turned back on, and mixing was allowed to continue for another 180 sec. The effective mixing duration of the SCC mixture in the mixer was approximately 6 min.

The design mixtures were tested to ascertain their fresh properties and to make sure they were acceptable according to ASTM standards. Tests for quantitative and qualitative assessment of fresh properties were the slump flow test (ASTM C1611), the J-ring test (ASTM C1621), the L-Box test, and the Static Column Segregation test (ASTM C1610). The slump flow diameter, the J-ring flow diameter, and L-Box test values indicated the fluidity and the passing ability of the mixture designs. Likewise, the Static Column Segregation test, which computed the aggregate distribution within the mixtures, evaluated the stability of the mixtures.

Procedure A of ASTM C1611 was undertaken to test representative samples of the mixtures in order to assess their flowability and kinetic energies. Procedure A involved dampening and inverting the slump mold such that the smaller circular opening faced downward, touching the working surface, and the bigger opening faced upward. The concrete mixture was poured continuously into an inverted slump mold to slightly overfill the mold. The slump mold then gradually was lifted, and the spread of the concrete was observed and noted. Figure 4.1 illustrates the low and high slump flow for self-consolidating concrete made with three-quarter size coarse aggregate size with 25% fly-ash replacements (0.75-25-L and 0.75-25-H).

Figure 4.1 Low and high diameters of slump flow for 0.75% coarse aggregate and 25% fly ash.

The J-ring test (ASTM C1621) consists of a metallic ring with metallic bar protrusions evenly spaced around the perimeter. For every mixture design, Procedure A of ASTM C1611 was employed along with the metallic ring. Figure 4.2 shows results for ASTM C1621 tests for passing ability for a low-slump self-consolidating concrete with 25% fly-ash replacements (0.75-25-L and 0.75-25-H).

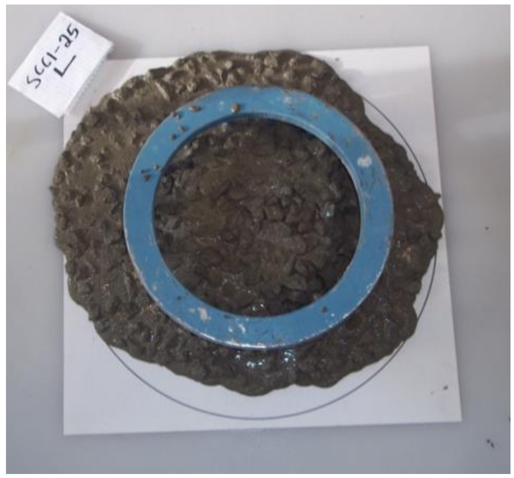

Figure 4.2 J-ring flow diameter for low-slump SCC with 25% fly-ash replacement (0.75-25-L).

Likewise, the Static Column Segregation test (ASTM C1610) was conducted on all the mixture designs. The apparatus used in determining the stability of the SCC included a polyvinyl chloride mold, which consisted of sub-units continuously joined together as it was being filled with concrete. The mold connections were made mortar-tight by the installations of clips. Concrete from the upper and lower molds were collected separately and washed in a No. 4 sieve to extract the coarse aggregates. The extracted coarse aggregates were allowed to dry, and then were weighed to determine their masses. The sole parameter to determine their acceptability was the net weight of the coarse aggregates. Figure 4.3 shows the experimental setup for the ASTM C1610 segregation test for a low-slump self-consolidating concrete made with three-quarter inch coarse aggregate with 25% fly-ash replacements (0.75-25-L).

Figure 4.3 Test setup for Static Column Segregation for 0.75-25-L.

The L-Box test was conducted to test the passing ability of the SCC. The apparatus used consisted of an L-shaped trough with metallic bars evenly spaced at the opening of the junction between the vertical and the horizontal troughs. During filling the vertical mold with concrete, the opening was closed with a metallic plate. This plate was removed to allow the fresh concrete mass to flow through the bars towards the end of the horizontal trough. The parameters needed to assess the acceptability of the mixture with regard to passing ability were the trough-end depths and heights. Figure 4.4 shows the experimental setup for the L-Box test for 0.75-25-L.

Figure 4.3 Experimental setup for the L-Box test (0.75-25-L).

4.2 Testing of Mechanical Properties

Cylindrical molds that had 4-in diameters and 8-in heights were used to cast representative samples of the mixtures. For every SCC mixture design accepted based on the quantitative and qualitative assessment of their fresh properties, SCC cylindrical molds were created. Figure 4.5 shows some of lubricated cylindrical molds used for specimen fabrications.

Figure 4.4 Lubricated cylindrical molds for specimen fabrication.

The cylinders were cured in a convection tank at a constant temperature of 30^{o}C until they attained their testing age. SCC cylinders were created for each mixture, and were used for the compressive strength test (ASTM C109) and the splitting tensile-strength test at appropriate ages. The load application, according to ASTM standards, were 83-166 lb/sec for the splitting tensile test and 351-528 lb/sec for the compressive strength test. Figure 4.6 shows setups for compressive strength tests undertaken on fabricated specimens.

Figure 4.5 Experimental setup for Compressive Strength testing.

The specimens failed at low fracture energy when tested for their compressive strength. The crack development was gradual against the application of compressive stress. Development of alligator cracks was very much a result of the enhanced composition of the concrete. Fly ash with a lower specific gravity, as compared to cement, had the ability of achieving a denser matrix. Percentages of fly ash incorporated resulted in a more voluminous weight yet similar to the required weight.

Failure by tensile-strength application featured a unilateral line of crack along the direction of the applied stress. The development of the crack was gradual, and similar to that of the specimens that underwent compressive strength testing. Figure 4.7 shows a setup for the splitting tensile strength test conducted on fabricated specimens.

Figure 4.6 Experimental setup for the Splitting Tensile Strength test.

The coarse aggregates in the concrete specimens were evenly distributed based upon visual inspection, which indicates the stability of the SCC mixtures. The Static Column segregation test, carried out on the fresh concrete mass, strongly corroborated this assertion. Figure 4.8 shows the coarse aggregate distribution in the hardened concrete mass for 0.75-25.

Figure 4.7 Coarse aggregate distribution for hardened 0.75-25

Figure 4.9 shows the coarse aggregate distribution in the hardened concrete mass for 0.75-35, and Figure 4.10 shows the coarse aggregate distribution in the hardened concrete mass for 0.5-25.

Figure 4.8 Coarse aggregate distribution for hardened 0.75-35.

Figure 4.9 Coarse aggregate distribution for hardened 05-25.

Figure 4.11 shows the coarse aggregate distribution in the hardened concrete mass for 0.5-35.

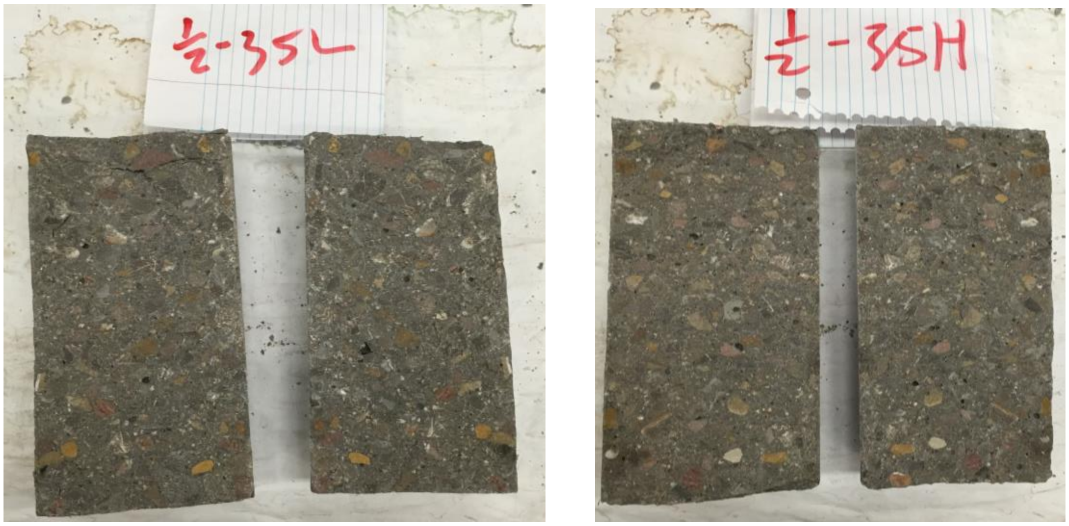

Figure 4.10 Coarse aggregate distribution for hardened 05-35.

The static modulus of elasticity test (ASTM C469) was conducted on specimens fabricated from each mixture design. A compressometer to take strains readings, coupled with the compressive testing step, was used to ascertain the stress-strain relation of the fabricated specimens. Figure 4.12 shows the experimental setup for ASTM C469 testing ran on fabricated specimens.

Figure 4.11 Experimental setup for the Static Modulus of Elasticity test.

4.3 Testing for Durability

Tests conducted to ascertain the durability of the design mixtures were the rapid chloride penetration test (ASTM C1202), sulfate resistance (ASTM C1012), and surface scaling (ASTM C672).

The rapid chloride penetration test (RCPT) was run on specimens fabricated from each mixture design. The goal was to ascertain the permeability of the concrete specimens to chloride ions. The setup included an electrical connection between two embedded ends of a 4-in circular disc-sized specimen. Each end of the concrete disc was embedded in a solution of either sodium hydroxide (NaOH) or sodium chloride (NaCl). The concentration of NaOH was 0.3 N in distilled water, and the concentration for NaCl was 3% by mass in distilled water. The permeability class of the concrete specimen was determined by the amount of current that passed between the two ends of the disc. Figure 4.13 shows the experimental setup for the rapid chloride permeability test carried out on the specimens.

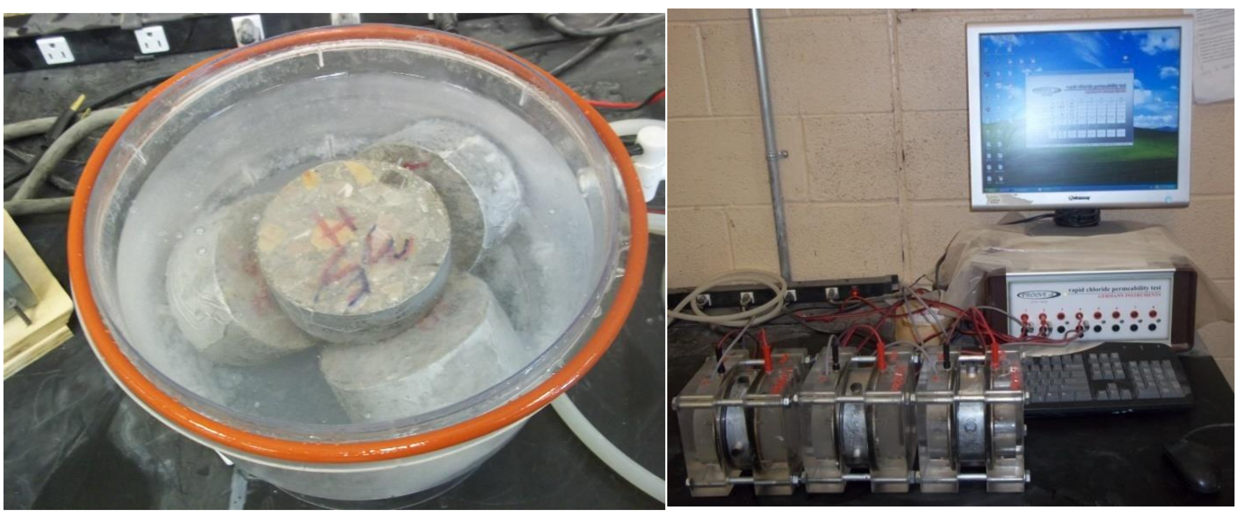

Figure 4.12 Experimental setup for the rapid chloride penetration test (RCPT).

Fabricated specimens of each mixture underwent the test for sulfate resistance. Two groups of specimens were created. The control group was immersed in distilled water, and the second group was immersed in sodium sulfate (Na_2SO_4) solution of 50 g / 1000 mL. This was an attempt to establish – unequivocally and lucidly – the effect deterioration of sulfate attack. The immersion periods were 3, 7, and 14 days. The length and the weight attained by the specimens during each immersion period in the Na_2SO_4 solution was obtained. Figure 4.14 shows the experimental setup for the control immersion solution and the Na_2SO_4 solution for sulfate resistance of the fabricated specimens.

Figure 4.13 Experimental setup for the sulfate attack test.

In addition, this study investigated the effects of deicing chemicals on the surface condition of the fabricated concrete specimens. The fabricated specimens underwent a moist-cure condition for 14 days and open-air cure for 14 days. The surface of the specimen was designed with a depression to hold a brine solution of 4 g of anhydrous calcium chloride ($CaCl_2$) in 100 mL of water. The specimens were subjected to cooling by placing them in a freezing chamber for 18 hrs, and afterwards in the open air 6 hrs. The cycle of freezing and open air was continued for 14 cycles, and the brine pond was replenished at appropriate periods by the addition of water. Figure 4.15 illustrates the fabrication of the specimen molds for the surface scaling test.

Figure 4.14 Fabrication of specimens for the surface scaling test.

5. SCC BEST PRACTICES

5.1 Fresh Properties Test for SCC

Fresh properties are the dominant distinguishing factors that set self-consolidating concrete apart from conventional concrete. Research has shown commonality in the hardened properties between SCC and normally vibrated (NVC). As mentioned earlier, the three primary characteristics used to delineate the performance of SCC are fluidity (filling ability), passing ability, and stability. Fluidity, unlike passing ability and stability, is the sole characteristic that defines SCC without any consideration to application purposes. Even though the criteria for various applications for passing ability may differ, the degree of fluidity (flow ability) remains a constant regardless of the application (Dackzo, 2012).

The slump flow test (ASTM C 1611) is the procedure employed to assess the fluidity of the concrete mass. In this test, an Abram's cone is filled with concrete either by orienting it in the upright or in an inverted position, or then lifted to release the concrete mass onto the flow board. The flow diameter of the spread gives an indication of the flow ability of SCC concrete; in contrast, for conventional concrete, the slump is derived from the drop of the slump. Another parameter derived from the slump flow test is the time it takes for the concrete to reach the 50-cm mark on the working board, known as the T_{50} test. T_{50} provides visual perception of the stability of different concrete mixtures with the same slump flow; the longer it takes the concrete to reach the 50-cm mark, the more viscous the mass will be and, consequentially, more stable. ASTM standards provide ratings to visually assess the stability of the SCC mixture, based on the flow of the mixture on the working board. The value '0' represents a highly stable mixture with no evidence of segregation or bleeding; the value '3' represents an utterly unstable SCC mixture with halo formation and a pile of coarse aggregate concentrated at the center of the concrete mass on the flow board.

The J-ring test (ASTM C 1621), which consists of the slump flow test and a ring with bars arranged equally spaced about its circumference, is a test of the passing ability of the concrete. After released from the Abrams cone, the concrete mass is allowed to flow through the bars until the flow comes to a halt; at that point, the spread is measured. This gives an indication of the ability of the concrete to flow through and around obstructions. The magnitude of the deviation of the J-ring spread from the slump flow spread defines the passing ability of the concrete: the smaller the difference, the better the passing ability of the concrete. ASTM recommends that a difference less than or equal to 1 inch denotes a good mix with no visible blockage; greater than 2 in signifies an extreme degree of blockage with the formation of halo.

Another test, but less popular, used to assess the workability of SCC is the V-funnel test. This test measures the plastic viscosity of the concrete mass by determining the length of time it takes the funnel to empty the concrete fill. The longer the time it takes for the concrete to be emptied, the more viscous the mass is and, consequently, the better its resistance to segregation.

The L-Box test consists of a vertical trough connected to a horizontal trough, with metallic bars vertically spaced at the intersecting opening of the two troughs. Concrete is poured to fill the vertical trough to the brim; then, a containment door at the junction between the vertical and the horizontal trough is lifted to permit concrete to flow to the horizontal trough. The difference in elevation of the concrete at the extremities of the horizontal trough is measured, and their ratio is the blocking ratio, which indicates the passing ability of the concrete mass. However, the sheer size of the apparatus for this test makes field-testing quite cumbersome; it is more conveniently suited for laboratory experiments.

The Static Column Segregation test (ASTM C 1610) is an experimental procedure that was carried out to determine the coarse-aggregate distribution of the fresh concrete mixture. A polyvinyl chloride mold assembled by three circular columns was filled with fresh SCC. The concrete on the top and bottom mold later were washed and weighed separately to determine the respective masses of the coarse aggregate retained in a 4.75-mm sieve. The percentage of segregation was computed empirically from the mass of retained coarse aggregate (ASTM C 1610).

This test is quite cumbersome and time consuming to be carried on site before placement. Therefore, the stability of the SCC mixture could be carried in the batching plant or in the laboratory under the supervision of trusted and appointed personnel to accurately and honestly report the performance of the mixture before placement. There is no specific recommended range of percentage segregation in the standards and the literature; however, experienced practitioners have arrived at a general consensus that segregation up to 10% -- but not more than 20% -- is adequate to ensure the stability of SCC applications (Bury et al. 2013).

5.2 Adjusting Deficiencies in SCC Mixtures

It is important to point out that SCC mixtures from the development of meticulous mixture designs may be inadequate. Therefore, remedial measures to arrive at the desired performance of SCC becomes necessary. Various factors may contribute to the deficiencies in the concrete mixture, including but not limited to the inability to correctly estimate the mixing time, human errors during material and admixture proportioning, inadequate human or other resources to handle the mixing process and mechanical failures of the concrete mixer and in batch plants. Nevertheless, when the deficiencies are diagnosed, it is necessary to revive the workability of the mixture to meet the acceptance criteria set by supervisory bodies and clients. Some commonplace deficiencies are to be expected, and their corrective measures are described as follows.

5.2.1 Fluidity

Increasing the paste volume directly enhances the flow ability of the concrete mass. Ultimately, the paste volume is achieved by the incorporation of the right quantity of powder content. However, it is essential to acknowledge the effect of the powder content on the viscosity of the concrete mass. Increasing the paste volume without a warranted increase in water quantity will result in concrete that is significantly more viscous with less filling ability. Moreover, it is important to consider the effect of the water-to-cement ratio on the hardened strength of the concrete when correcting the flow ability defect.

Given a specific concrete mix design, the compressive strength will decrease with an increase in the water-to-cement ratio. Alternatively, to ensure the fluidity of the concrete mass, superplasticizers can be incorporated; if already a composing element, they can be adjusted to attain the flow ability. However, overdosing the mixture with superplasticizers in the attempt to achieve the required fluidity should be approached with caution so that the stability of the mixture is not broken down, leading to halo formation and excessive bleeding.

5.2.2 Halo

Halo is the aftermath of a highly unstable concrete mass in which the cohesive force and the consequential viscosity is inadequate to support the homogenous dispersion of the aggregates. As result, the aggregates are washed out and separated from the paste volume, causing concrete placement with excessive bleeding. Incorporation and further adjustment of the admixtures that modify the viscosity greatly affect the viscosity and, eventually, the stability of the mixture. In addition, increments in the quantity of fine aggregates and powders enhance the stability of the mixture by partially eradicating, if not completely, the segregation it might incur.

5.2.3 Blockage

Blockage predominately defines the passing ability of the mixture, and allows visual assessment of the homogeneity of the SCC. The passing ability of the SCC mixture partially is determined by the maximum aggregate size used in the design. In order to ensure that the mixture can flow through and around obstructions, the maximum size of the constituent aggregate might have to be reduced when the blockage is insufficient. Moreover, the paste volume as well as the mortar volume will have to be increased to minimize blockage. In order to ensure flow in unison with the entire concrete mass, the presence of the required paste volume ensures the stability of the aggregates and reduces the internal friction. The required paste volume is achieved by the incorporating VMA, finer powders, water, or a combination of two or more of these remediating alternatives.

5.2.4 Segregation

Likewise, ensuring the required amount of paste volume is essential to maintain the stability of the mixture. The paste is an essential factor in containing the suspension and allowing the even dispersion of the aggregate throughout the entire concrete matrix. The settlement of the aggregates can be attained by using finer powders, reducing the water content, and adding the optimum amount of VMA without hindering workability.

5.3 Remediation of Slump Loss

Slump loss is an intricate phenomenon with concrete placed after a prolonged hauling time because the batching plant is not located close to the construction site. Slump loss can be defined as the change in the microstructure of the concrete, resulting in a less fluid, thus less workable, mass over time. In fact, it contributes significantly to the workability of concrete during placement. Therefore, close attention is required either at the batching plant or the place of placement to ensure the desired constituency of the concrete mass.

The hydration reaction, which inconspicuously starts when mixing begins, is a contributing factor to the slump loss that the concrete incurs during hauling. The greater the hauling time, the less fluid the concrete becomes. Continuous mixing by means of using mixing drums during hauling may seem to be a way to arrest slump loss; however, research has shown such continuous mixing over an extended hauling time is detrimental to other fresh properties of the concrete mass. Mehdipour et al. (2012) reported significant bleeding as well as a less stable mixture after 30 min of agitating the concrete mixture, even though a significant increase in fluidity was observed.

Incorporation of certain supplementary cementitious materials have proved to be very helpful in controlling bleeding, which is a very common and usual phenomenon with concrete under constant re-tempering. Metakaolin used in conjunction with fly ash purportedly is capable of pushing the limit of balance between fluidity and stability of a fresh concrete mass (Mehdipour et al., 2012). In order to confidently establish such a design capability when maintaining the consistency of concrete during the desired lapse of time in hauling and remediation, further research is needed, using local materials from Nevada and the admixtures VMA and ADVA 195.

In addition, repeated attempts by continuous mixing to break down the products of hydration before placement can lead to significant loss in the strength of the hardened concrete mass. Erdogdu (2004) gave an account of how the mechanical action of the mixing drum contributes to slump loss by raising the temperature of the concrete mass. This resulted in the loss of water, which reduced the ability of the concrete to retain some of its fresh properties.

Studies focusing on slump loss of concrete due to hauling have proposed either designing mixtures of higher slump than required for placement at the batching plant or retempering later at the construction site before placement. The first approach mostly is achieved by overdosing the concrete mixture with a high-range water reducing admixture (HRWR) to attain a certain amount of fluidity to stand the test of hauling time. Erdogdu (2004) noted the risk involved in this approach because of the difficulty in estimating the amount of time needed for hauling. Factors involved during hauling include traffic congestion, flat tires, and road blockage and rerouting; these pose significant uncertainties to the final performance of the concrete at the time of placement.

The second approach is to either retemper the concrete when it arrives at the construction site with more HRWR, water, or both. Retempering with water is the most damaging because it increases the water-to- cement ratio, resulting in a weaker concrete strength. Retempering with

HRWR has been reported to slightly increase the compressive strength as compared to a reference concrete mixture with no retempering (Erdogdu, 2004). This can be attributed to the fact that reference mixture has more air voids and less packing density as compared to the retempered mixture. Retempering with both water and HRWR simultaneously can be viewed as more of an economic approach than a technical one, where moderate strength can be attained.

The choice of what method of remediation to employ is strongly determined by the hauling time, economic constraints, and the amount of expertise available for the project. With overdosing, the need for trained personnel is reduced, if not eliminated, to assess the workability of the concrete at the construction site before placement. Also, the concrete producers can assure the quality of the concrete at the batching plant before dispatching. While overdosing affords all these advantages, it falls short when the hauling time cannot be accurately projected. In that respect, retempering can guarantee that the final rheological properties needed are attained by stationing trained personnel at the construction site to assess the workability of the concrete before placement. Moreover, wastage due to the inability of concrete to pass the specification criteria is avoided, making retempering economically feasible in this regard.

5.4 Review of Performance Criteria for SCC Applications

The *European Guidelines for Self-Consolidating Concrete* (2005) provides recommendations for the expected performance of fresh SCC. The fresh properties that are considered are slump flow, viscosity, passing ability and segregation. Table 5.1 shows the expected performance of the fresh properties and the types of applications for each classification.

Table 5.1 Expected performance criteria for SCC applications in Europe

European Slump-flow Classes		
SCC Classification	***Slump flow (inch)***	***Application***
SF1	22-25	Open structures with less dense (minimal) reinforcements, such as slabs, and structures requiring less flow distances, such as piles and deep foundations.
SF2	26-30	Applicable to most normal applications.
SF3	30-34	Highly congested reinforcements and structures with complicated shapes; used when a good surface finish is required.
European Viscosity Class		
Class	T_{50}	***Application***
Class 1	≤ 2	High filling ability by means of densely packed reinforcement; a good surface finish with the potential for bleeding.
Class 2	>2	High capacity to resist segregation; a good surface finish may be impaired.
European Passing Ability Class (L-Box Blocking Ratio)		
Class	***Passing Ability***	***Application***
Class 1	≥ 0.8	Structures with a gap of 80 mm to 100 mm.
Class 2	< 0.8	Structures with a gap of 60 mm to 80 mm.
European Segregation Resistance Class		
Class	***Segregation Resistance (%)***	***Application***
Class1	≤ 20	Thin slabs; flow distance is shorter than 5 m.
Class 2	≤ 15	Vertical applications with flow distances greater than 5 m.

Based on the experience from using SCC, there are suggested ranges explicitly stated for different engineering applications. Table 5.2 shows the slump-flow ranges for various applications with respect to European and North American guidelines (Dackzo, 2012).

Table 5.2 Slump flow specifications for SCC applications

Application	**Slump flow (in.)**
European Guidelines	
Ramps	19 - 22
Floors and slabs	19 - 28
Walls and piles	21 - 25
Tall and slender elements	23 - 32
North American Guidelines	
Slab	18 - 28
Architectural section	24 - 28
Wall minimum reinforcement	18 - 26
Structural column or wall densely reinforced	24 - 28

Various state DOTs have committed resources to developing guidelines regarding the use of SCC in the United States. Extensive research has been conducted for various types of applications deemed essential to the DOTs. Even though a couple of DOTs do not have published documents explicitly stating the performance criteria of SCC, a number of them have documents, born out of research, that are specially dedicated to certain engineering applications (Mamaghani et al., 2010). Table 5.3 shows the various DOTs specifications for specific type of applications.

Table 5.3 States' DOT specifications for SCC applications

State DOTs	Application	Specifications
Alabama	Drilled shaft	Reported slump flow is in the range of 24 to 24.5 in. However, the targeted slump flows were in the range of 24 to 28 in. The recorded T_{50} and L-box blocking ratio were less than 1 sec and 0.78 to 1, respectively.
Idaho	General application	Slump flows are categorized with respect to the targeted 28-day compressive strength. Slump flows for concrete strengths 3500 psi or higher and 3000 psi or lower were 20 to 30 in and 18 to 32 in, respectively.
Illinois	Precast products	Slump flows are within 20 to 28 in with the percentage of column static segregation not exceeding 15%. L-Box blocking ratio and visual stability index rating for SCC should exceed 0.6 and 1, respectively.
Georgia	Precast concrete	A minimum spread (slump flow) of 20 in is required, with an L-box blocking ratio in the range of 0.8 to 1.
New Jersey	Precast concrete	Slump flows should be within 24 to 28 in, with a visual stability index rating not exceeding 1.
South Carolina	Drilled shaft	Actual slump flows acquired from a SCC project were within 24 to 26 in, while the targeted slump flows were 23+/-3 in.
South Dakota	Box culverts	Slump flows should be maintained within 22 to 28 in, with the difference between slump flow and J-ring flow not exceeding 2 in.
Virginia	Repairs and restoration	Slump flows: 25 to 28 in.
	Prestressed beams	Slump flow: 23 to 28 in.
Washington	Noise walls and test shafts	Slump flows should be within 22 to 29 in, with their differences with the J-ring flow not exceeding 2 in. T_{50} and percentage static column segregation should not exceed 6 sec and 10%, respectively.

6. RESULTS

6.1 Fresh Properties

The parameters needed to assess the acceptability of the SCC mixtures were slump flow, J-ring flow, T_{50}, L-box, and static column segregation. The results were purely experimental. Performance of the fresh properties for SCC mixtures with 0.75-in coarse aggregate (Table 6.1) and SCC mixtures with 0.5-in coarse aggregate (Table 6.2) were evaluated quantitatively.

Table 6.1 Fresh Properties of three-quarter inch concrete mixtures

	Mixture ID			
Fresh Property	0.75-25-L	0.75-25-H	0.75-35-L	0.75-35-H
Slump, in.	20.8	24.5	21.0	25.5
J-Ring, in	20.3	23.5	20.3	24.5
T_{50}, sec	8	4	4	3
L-Box (Blocking Ratio)	0.17	0.1	0.33	0.14
Static Column Segregation, %	4.5	3.67	9.6	8.4

Table 6.2 Fresh properties of one-half inch concrete mixtures

	Mixture ID			
Fresh Property	0.5-25-L	0.5-25-H	0.5-35-L	0.5-35-H
Slump, in.	20	25.5	23	24.5
J-Ring, in.	19	24.5	22	23.5
T_{50}, sec	11.6	5	4	3
L-Box (Blocking Ratio)	0.3	0.1	0.4	0.2
Static Column Segregation, %	14.8	9.3	9.4	8.1

ASTM limits and guidelines were extensively used to assess the quality and acceptability of each SCC mixture. Qualitatively, all the mixtures were stable with respect to the visual stability indices (VSI), having VSIs of 0. The passing ability of the mixtures was evaluated according to limits set by ASTM. All the mixtures had blocking assessment values less the 1; hence, there were no signs of visible blocking from the mixtures. The stability of the mixtures was tested, and the values were within ASTM-set limits. A qualitative and quantitative outcome of tests for SCC mixtures with 0.75-in coarse aggregate (Table 6.3) and 0.5-in coarse aggregate (Table 5.4) are presented.

Table 6.3 Qualitative and quantitative assessment of three-quarter concrete mixtures

Mixture ID	Visual Stability Index	Blocking Assessment	% Segregation Max = 10% ~15%
0.75-25-L	Stable	No visible blocking (0.5 in)	4.5
0.75-25-H	Stable	No visible blocking (1.0 in)	3.7
0.75-35-L	Stable	No visible blocking (0.7 in)	9.6
0.75-35-H	Stable	No visible blocking (1.0 in)	8.4

Table 6.4 Qualitative and quantitative assessment of one-half inch concrete mixtures

Mixture ID	Visual Stability Index	Blocking Assessment	% Segregation Max = 10% ~15%
0.5-25-L	Stable	No visible blocking (1.0 in)	14.8
0.5-25-H	Stable	No visible blocking (1.0 in)	9.3
0.5-35-L	Stable	No visible blocking (1.0 in)	9.4
0.5-35-H	Stable	No visible blocking (1.0 in)	8.1

6.2 Compressive and Tensile Strengths

The compressive strength and splitting tensile strength were ascertained for SCC mixtures 0.75-25-L, 0.75-25-H, 0.75-35-L, and 0.75-35-H. The results of both strength tests are presented (Table 6.5). Figure 6.1 and 6.2 illustrate their respective 7-day and 28-day compressive strengths.

Table 6.5 Compressive and Splitting Tensile Strength of the mixtures

	Compressive, PSI		**Tensile, PSI**	
Mixture ID	7 Days	28 Days	7 Days	28 Days
0.75-25-L	4,698	5,877	605	658
0.75-25-H	3,737	7,650	512	724
0.75-35-L	3,367	5,699	439	677
0.75-35-H	1,787	4,278	384	559

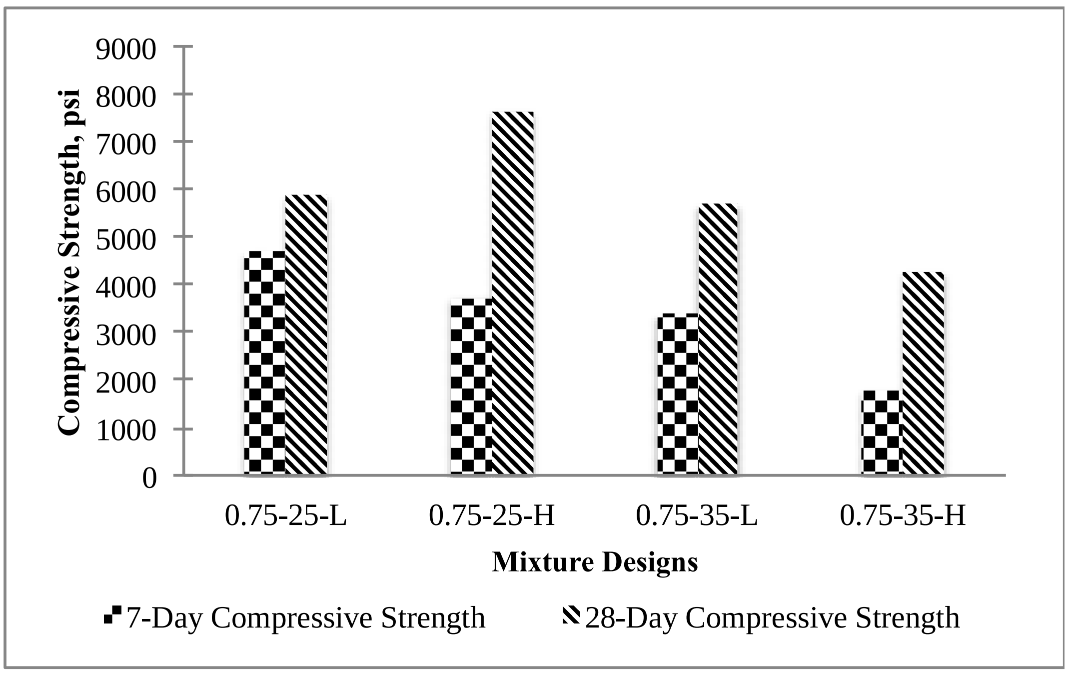

Figure 6.1 Compressive strength for 0.75-in coarse aggregate SCC mixtures.

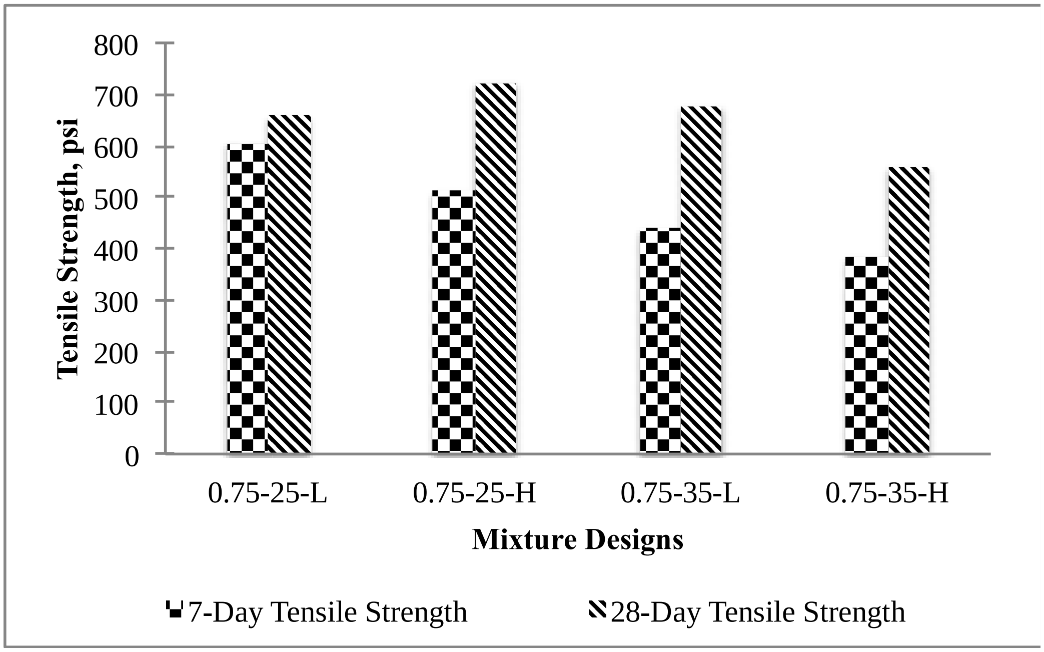

Figure 6.2 Tensile strength for 0.5-in coarse aggregate SCC mixtures.

6.3 Modulus of Elasticity

Table 6.6 presents the results of tests for static modulus of elasticity (ASTM C469). Figure 6.3 shows stress versus strain for SCC mixture designs that had 0.75-in coarse aggregates, and Figure 6.4 for 0.5-in coarse aggregates.

Table 6.6 Static Modulus of Elasticity for SCC Mixture Designs

Mixture ID	ASTM C469
0.75-25-L	924,320
0.75-25-H	1,000,000
0.75-35-L	777,373
0.75-35-H	880,545
0.5-25-L	527,942
0.5-25-H	450,697
0.5-35-L	553,309
0.5-35-H	786,872

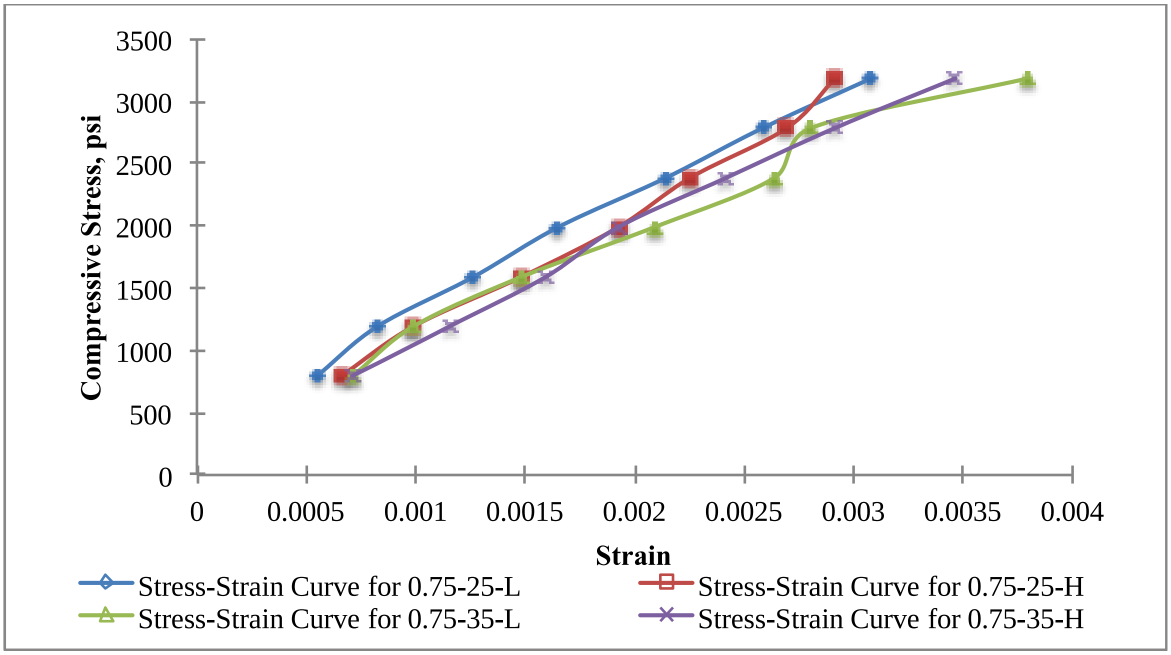

Figure 6.3 Stress-strain curves for 0.75-in self-consolidating concrete mixture designs.

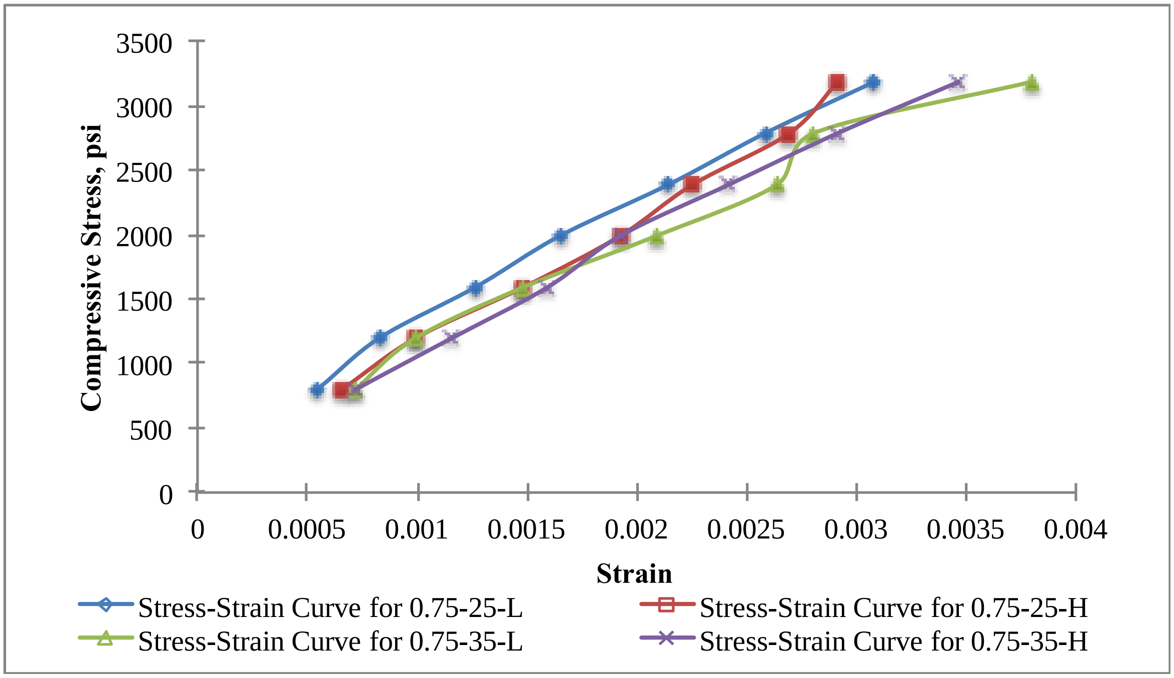

Figure 6.4 Stress-strain curves for 0.5-in self-consolidating concrete mixture designs.

6.4 Rapid Chloride Permeability Test

The charge passed for each of the SCC mixtures that underwent the rapid chloride permeability test (RCPT) is presented in Table 6.7, together with their permeability classes. The permeability class establishes the degree of imperviousness of the concrete to chloride ions. For comparison, Figure 6.5 illustrates the charge passed for each SCC mixture that underwent the RCPT.

Table 6.7 Values of the Rapid Chloride Permeability Test for SCC Mixtures

Mixture ID	Charged Passed (Coulombs)	Permeability Class
0.75-25-L	956	Very Low
0.75-25-H	880	Very Low
0.75-35-L	1,039	Low
0.75-35-H	751	Very Low
0.5-25-L	640	Very Low
0.5-25-H	754	Very Low
0.5-35-L	750	Very Low
0.5-35-H	646	Very Low

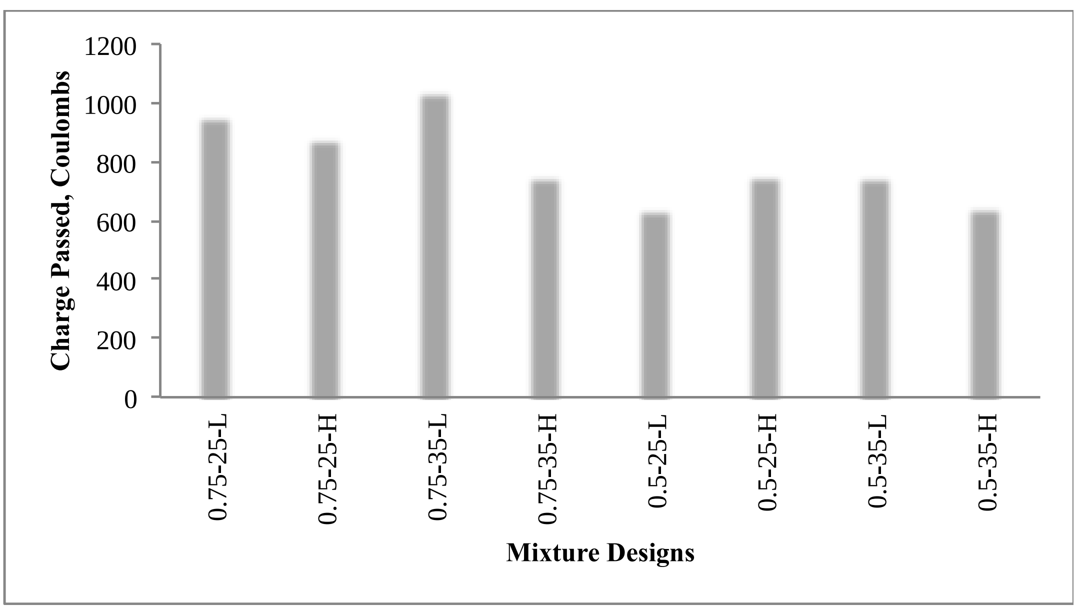

Figure 6.5 Charge passed for self-consolidating concrete mixtures.

6.6 Sulfate Resistance

The effect of sulfate attack was ascertained by measuring the weights for specific immersions periods. Table 6.8 shows the net weights of the fabricated concrete mass at specific immersion periods.

Table 6.8 Fabricated Concrete Mass under Sulfate Attack

Immersion Period (week)	Fabricated Concrete Mass, 1b			
	0.75-25-L	**0.75-25-H**	**0.75-35-L**	**0.75-35-H**
0	8.6635	9.0575	8.6660	8.7295
1	8.6575	9.0540	8.6655	8.7290
2	8.6580	9.0530	8.6655	8.7300

Figure 6.6 shows the fabricated specimens for each 0.75-25 and 0.75-35 mixture before being immersed for the first time in the Na_2SO_4 solution, and Figure 6.7 shows the fabricated specimens for each SCC mixture after one week of immersion in the Na_2SO_4 solution.

Figure 6.6 Fabricated specimen before immersion.

Figure 6.7 Fabricated specimen after one week of immersion.

6.7 Surface Scaling

The specimens were inspected for specific period to assess the impact of the NaCl solution on the depressed surfaces. The effects of the brine solution on the surface were visually rated with respect to ASTM C672 surface ratings.

Table 6.9 Visual Ratings for Surface Conditions of Various Design Specimens

Specimens	Surface Condition	ASTM C672 Visual Rating
5 Cycles		
0.75-25-L	No scaling	0
0.75-25-H	No scaling	0
0.75-35-L	Very slight scaling	1
0.75-35-H	No scaling	0
15 Cycles		
0.75-25-L	Slight to moderate scaling	2
0.75-25-H	Very slight scaling	1
0.75-35-L	Moderate scaling	3
0.75-35-H	No Scaling	0

Figure 6.8 shows the fabricated specimens from each design mix after undergoing 14 days of an air-curing regime.

Figure 6.8 Specimens prior to commencement of the freezing and thawing cycles.

Figure 6.9 shows the specimens for both 0.75-25-L and 0.75-25-H after 15 cycles of freezing and thawing.

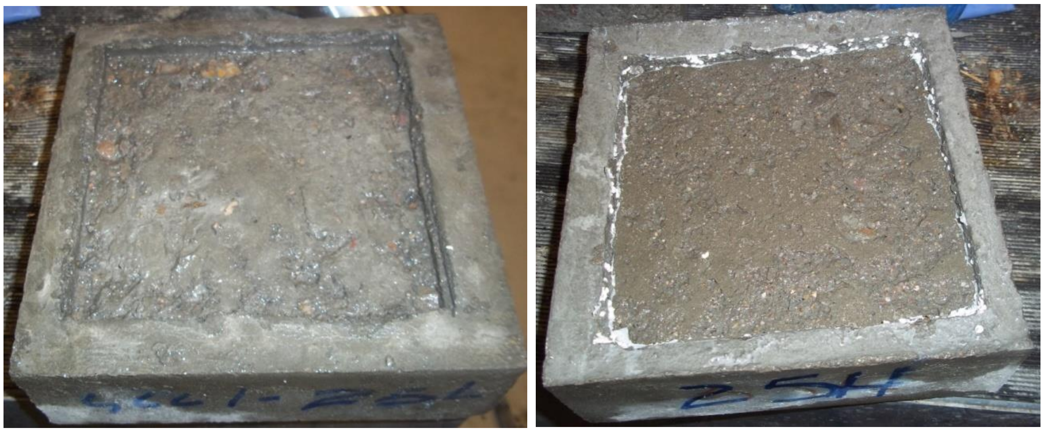

Figure 6.9 (Left) 0.75-25-L and (right) 0.75-25-H specimens after 15 freezing and thawing cycles.

Figure 6.10 shows the specimens for both 0.75-35-L and 0.75-35-H after 15 cycles of freezing and thawing.

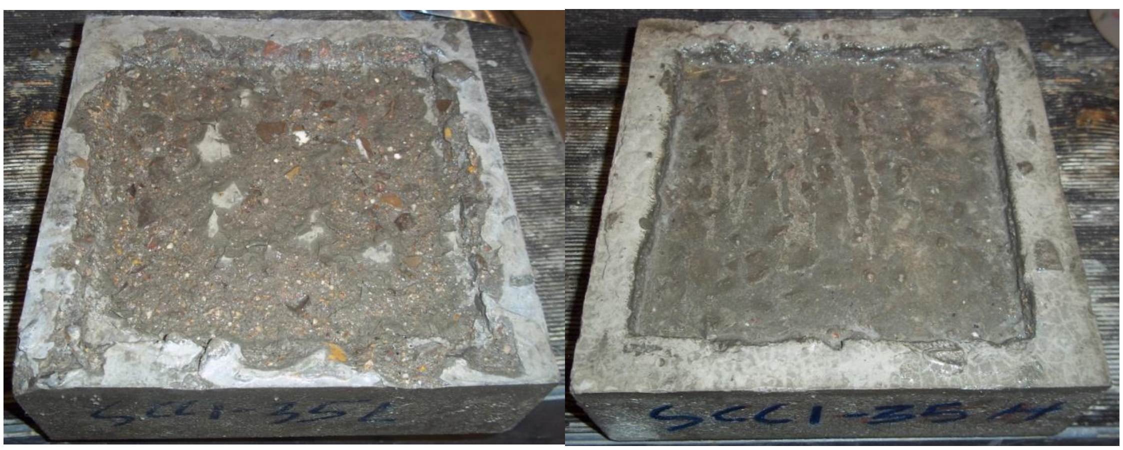

Figure 6.10 (Left) 0.75-35-L and (right) 0.75-35-H after 15 freezing and thawing cycles.

Figure 6.11 shows the specimens for both 0.75-25-L and 0.75-25-H after 20 cycles of freezing and thawing.

Figure 6.11 (Left) 0.75-25-L and (right) 0.75-25-H after 20 freezing and thawing cycles.

Figure 6.12 shows the specimens for both 0.75-35-L and 0.75-35-H after 20 cycles of freezing and thawing.

Figure 6.12 (Left) 0.75-35-L and (right) 0.75-35-H after 20 freezing and thawing cycles.

Figure 6.13 shows the specimens for both 0.75-25-L and 0.75-25-H after 30 cycles of freezing and thawing.

Figure 6.13 (Left) 0.75-25-L and (right) 0.75-25-H after 30 freezing and thawing cycles.

Figure 6.14 shows the specimens for both 0.75-35-L and 0.75-35-H after 30 cycles of freezing and thawing.

Figure 6.14 (Left) 0.75-35-L and (right) 0.75-35-H after 30 freezing and thawing cycles.

Figure 6.15 shows the specimen for 0.5-25-H before the commencement of freezing and thawing cycles after 14 days of wet curing and air-dry conditions, respectively.

Figure 6.15 Specimen 0.5-25-H prior to commencement of freezing and thawing cycles

Figure 6.16 shows the specimens for both 0.5-35-L and 0.5-35-H before commencement of freezing and thawing cycles after wet curing and air-drying, respectively.

Figure 6.16 (Left) 0.5-35-L and (right) 0.5-35-H prior to commencement of freezing and thawing cycles.

Figure 6.17 shows the specimen for 0.5-25-H after 10 cycles of freezing and thawing.

Figure 6.17 0.5-25-H after 10 freezing and thawing cycles.

Figure 6.18 shows the specimens for both 0.75-25-L and 0.75-25-H after 10 cycles of freezing and thawing.

Figure 6.18 0.5-35-L (Left) and 0.5-35-H (right) after 10 freezing and thawing cycles.

Figure 6.19 shows the specimen for 0.5-25-H after 20 cycles of freezing and thawing.

Figure 6.19 0.5-25-H after 20 freezing and thawing cycles.

Figure 6.20 shows the specimen for both 0.75-35-L and 0.75-35-H after 20 cycles of freezing and thawing.

Figure 6.20 (Left) 0.5-35-L and (right) 0.5-35-H after 20 freezing and thawing cycles.

Figure 6.21 shows the specimen for 0.5-25-H after 30 cycles of freezing and thawing.

Figure 6.21 0.5-25-H after 30 freezing and thawing cycles.

Figure 6.22 shows the specimen for both 0.75-35-L and 0.75-35-H after 30 cycles of freezing and thawing.

Figure 6.22 (Left) 0.5-35-L and (right) 0.5-35-H after 30 freezing and thawing cycles.

7. CONCLUSION AND RECOMMENDATIONS

7.1 Conclusions

The results were purely experimental, and their acceptability were determined with reference to ASTM standards. The following conclusions were based on the experimental results as well as from visual inspection of the specimens.

7.1.1 Fresh Properties of SCC

The fresh properties of each SCC mixture were found acceptable with reference to ASTM standards. Target slump flows were closely attained as result of the inclusion of ADVA 195 and V-MAR 3. The stability of fresh concrete masses were enhanced by incorporating fly ash and V-MAR 3.

7.1.2 Passing Ability

The passing ability of the mixtures was acceptable, according the J-Ring test (ASTM C1621). However, L-Box tests showed that the flow and passing ability were impaired, predominantly as result of the level of angularity of the coarse aggregate. Rounded to well-rounded aggregates will ensure ease of flow of the concrete mass. SCC mixtures with 0.5-in coarse aggregates exhibited improved overall passing ability over the SCC mixtures with 0.75-in coarse aggregates. This improvement in performance can be attributed to size, since smaller aggregates can move freely past the restraining bars.

Tests conducted using static column segregation (ASTM C1610) indicated that the stability of the mixtures was acceptable with no signs of segregation. Visual inspection of the internal structures of hardened concrete bodies (after splitting tensile testing) strongly supports this finding. The fly ash and the viscosity-modifying agent (V-MAR 3) seem to be the main causative agents that contributed to the improved cohesive energy in the concrete mass.

7.1.3 Compressive Strength

The results of the compressive strength test, carried out the fabricated specimen when aged seven days, strongly reinforces the consensus findings from previous studies of the effect that fly ash has during early-age compressive strength. The addition of fly ash to concrete mixtures retards early-age hydration of the concrete. In this study, SCC with 25% fly ash replacement had higher gains in compressive and splitting tensile strength at the age of 7 days, compared to SCC with 35% fly ash replacement. The strengths are indirectly proportional to the amount replacements of FA. Likewise, the tensile strength had the same relationship with the amount of FA replacements (Table 5.5).

7.1.4 Chloride Permeability

Values from the rapid chloride permeability test indicate that the SCC mixtures were very resistant to chloride permeability. The amount of charge passed over time was designated as very low or low according to ASTM C1202. Thus, the inclusion of fly ash and the resultant enhanced microstructure has been known to contribute to the improved durability of SCC mixtures.

7.1.5 Sulfate Attack

The fabricated specimens proved to be durable against sulfate attack after one week of immersion in Na_2SO_4 solution. The mass differentials were insignificant, which corroborated their high resistance to sulfate. However, the capability of the specimens beyond the immersion periods from this study cannot be confidently established.

7.1.5 Resistance to Deicing Chemicals

The ability of the various mix designs to withstand the surface scaling due to deicing chemicals was assessed for 5 and 15 cycles. The surface of the specimens showed very high resistance to the brine solution after 5 cycles. However, the effect of the brine solution, even though not extensive on most of the mix designs, was very pronounced on 0.75-35-L after 15 cycles of freezing and thawing. Experimentation on more types of mixtures will be required to ascertain the core reason for this discrepancy. In total, the specimens had very good durability capability to deicing chemicals.

7.2 Recommendations

Based on the laboratory experiments and review of relevant literature, recommendations are as follows.

7.2.1 Slump Loss

Slump loss is inevitable, especially when the batching plant is not located in close proximity to the construction site. Certain steps need to be taken to ensure the right consistency of the concrete mass by the time of placement. First, certain remediation processes can be embarked upon, such as:

- Overdosing of the concrete mass at the batching plant with high-range water-reducing admixtures before the mixing truck departs for the construction site, and
- Re-tempering by the addition of more HRWR to ensure the correct fresh properties at the construction site before placement.

At best, the further addition of water at the construction site should be avoided, as this will lead to a significant reduction in concrete strength.

Second, the incorporation of certain supplementary cementitious materials have proven to be very helpful in controlling bleeding, which is a very common phenomenon with concrete under constant re-tempering. Metakaolin, used in conjunction with fly ash, is capable of pushing the limit of balance between fluidity and stability of the fresh concrete mass (Mehdipour et al., 2012). Further research should be undertaken with materials local to Nevada and the admixtures VMA and ADVA 195 in order to confidently establish the capability of these design mixture to maintain the consistency of concrete during the desired lapse of time in hauling and remediation.

7.2.2 Aggregate Size

The maximum aggregate size of the coarse aggregate influences a great deal the passing ability of SCC. Size plays a major role, especially when tight and congested reinforcement configurations are planned. Moreover, depending on the SCC application, certain aggregate sizes might be too large to ensure flow in places of limited accessibility. For instance, placement of concrete for drilled shaft construction will require an aggregate size that supports high passing ability of the concrete mass. Even though other variables contribute to the passing ability of SCC – viscosity and fluidity – aggregate size was the focal point of this study in assessing passing abilities for all the mixture designs having similar composition of admixtures and supplementary cementitious materials. The research indicated that a 0.5-in aggregate size was a better fit than 0.75-in aggregate for SCC applications.

APPENDIX A: ACRONYMS

ASTM	American Standards for Testing Materials
ACI	American Concrete Institute
$CaCl_2$	calcium chloride
DOT	Department of Transportation
HRWR	high-range water reducing
NaCl	sodium chloride
NaOH	sodium hydroxide
Na_2So_4	sodium sulfate
NDOT	Nevada Department of Transportation
NVC	normal vibrated concrete
PSI	pound per square inch
RCPT	rapid chloride penetration test
SCC	self-consolidating concrete
SCM	supplementary cementing material
VMA	viscosity-modifying admixtures
VSI	visual stability index

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