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A study of self consolidating concrete for cast in place applications: Current practices, rapid wcm determination, and stability effects of pumping

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**A STUDY OF SELF CONSOLIDATING CONCRETE FOR CAST IN PLACE
APPLICATIONS: CURRENT PRACTICES, RAPID W/CM DETERMINATION, AND
STABILITY EFFECTS OF PUMPING**

Jared Hershberger

Thesis submitted to the

**Benjamin M. Statler College of Engineering and Mineral Resources
at West Virginia University**

**in partial fulfillment of the requirements
for the degree of**

**Master of Science
in
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Pumping SCC; Segregation Analysis; Air-Void Stability**

ABSTRACT

A STUDY OF SELF CONSOLIDATING CONCRETE FOR CAST IN PLACE APPLICATIONS: CURRENT PRACTICES, RAPID W/CM DETERMINATION, AND STABILITY EFFECTS OF PUMPING

Jared Hershberger

Self-Consolidating Concrete (SCC) is a relatively new type of concrete mixture that does not require external compaction during placement. Compared to traditional vibrated concrete (TVC), SCC is much more fluid, which gives it the ability to flow and fill formwork without the need for any external compaction efforts. Although the increased cement content and chemical admixtures found in SCC typically results in a higher material cost, the potential for cost savings in reduced construction time and labor are significant. The potential of this relatively new type of concrete have yet to be realized due to a lack of regulation and full understanding of its material behavior which radically differs from traditional concrete mixes. This thesis outlines a research study performed on SCC for cast-in-place (CIP) applications, which includes a comprehensive literature review, the current practices and regulations of 25 state agencies, as well as experimental findings related rapid fresh water-to-cement ratio determination and the effects of pumping SCC on segregation resistance and air-void properties.

Due to SCC's relatively high sensitivity to changes in water content, the development of on-site quality control measures to determine the fresh w/cm could be beneficial to the implementation of SCC for CIP applications. The Standard Test Method for Water Content of Freshly Mixed Concrete Using Microwave Oven Drying (AASHTO T318-02) was evaluated for potential use as an on-site quality control measure in the determination of fresh w/cm. Two testing procedures were investigated using AASHTO T318-02 which included the use of concrete samples and sieved mortar sample. Both methods predicted the w/cm for delivered concrete and laboratory batched SCC within reasonable accuracy. The average difference (taken as calculated w/cm minus the actual w/cm ratio) for concrete and sieved mortar samples were found to be 0.012 and 0.013, respectively.

The relatively low viscosity of SCC allows for the use of innovative construction methods such as pumping from various locations on the formwork. A previous research project at West Virginia University performed in 2010 proved that SCC could be pumped from the bottom of the formwork with the casting of a 12-feet SCC column. Due to the low viscosity of SCC, some researchers have suggested that the stability of the air void structure as well as the segregation resistance may be lower than traditional mixes. Adequate segregation resistance and air-void structure within a concrete structure is necessary to ensure acceptable material behavior. An image analysis was performed to evaluate the segregation resistance and air-void structure of the pumped SCC. Five concrete samples were cored along the height of the hardened SCC column. The hardened aggregate analysis showed that the pumped SCC exhibited segregation behavior at various locations within the column. Of the specimens analyzed, half did not meet the ASTM C457 recommended value for specific surface to resist moderate freeze-thaw cycling while none of the samples met the ASTM C457 recommendation of spacing factor less than 0.20 mm for structures exposed to moderate freeze-thaw conditions. Additionally, changes in the air-void size distribution were observed along the height of the pumped SCC column. The increased pressure and agitation from pumping the SCC may have resulted in reduced segregation resistance and air-void stability within the SCC.

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INTRODUCTION

Self-Consolidating Concrete (SCC) is a relatively new type of concrete mixture that does not require external compaction during placement. Compared to traditional vibrated concrete (TVC), SCC is much more fluid, which gives it the ability to flow and fill formwork without the need for any compaction efforts. The low viscosity of SCC allows for the mix to flow around reinforcement and fill voids and consolidate under its self-weight while resisting segregation. The use of SCC is a promising construction material, especially when considering situations that arise in many highway bridge applications where tightly-placed reinforcing bars or irregular geometries of structural members would hinder the compaction effort required by traditional concrete mixes.

While the material cost of SCC is typically higher as compared to traditional mixes due to the increased cement and admixture content, the reduction in construction time and skilled labor required for placement makes the use of SCC more economical in many circumstances. In addition, SCC can also reduce health risks and ergonomic strain caused from vibration and noise pollution generated from this process in the construction sites as well as ensure the integrity of concrete where mechanical consolidation is not possible. Many of the properties of SCC vary as compared to traditional concrete and in some cases are much more sensitive to change. Cast-in-place (CIP) applications of SCC pose particular difficulties in ensuring acceptable results due to the number of variables in such a placement. This difference of properties and behavior requires that standards be developed to ensure the integrity of projects in which SCC are used.

State agencies, contractors, and project owners could benefit from the development of SCC specifications which provides clear construction guidelines and requirements. The development of specifications would need to be approached cautiously, since the production of SCC is more complicated and many parameters are more sensitive to minor changes as compared to traditional mixes i.e. stability with increased or decreased water content.

OBJECTIVES AND SCOPE

The objectives of this study is to investigate areas of concern with regards to the implementation of self-consolidating concrete for cast-in-place applications. The study performed includes a comprehensive literature review, the current practices and regulations of 25 state agencies, as well as experimental findings related rapid fresh water-to-cement ratio determination and the effects of pumping SCC on segregation resistance and air-void properties.

The literature review and current practices section of this report performed such that SCC could be implemented by state agencies for CIP applications in the most efficient way. These sections will encompass the state-of-the-art practices and knowledge in this field.

The use of a potential method which the fresh water-to-cement ratio could be rapidly and accurately determined for use in on-site quality control was investigated. The Standard Test Method for Water Content of Freshly Mixed Concrete Using Microwave Oven Drying (AASHTO T 318-02) was evaluated for use as an on-site quality control measure.

In addition, the material properties of SCC allow for the use of pumping from various locations of the formwork. To gain insight into the effects of pumping SCC, specimens were cored from a pumped SCC column. These specimens were analyzed to determine the aggregate distribution and air-void structure. The purpose of this research is to determine if detrimental effects to the stability of the mix may have resulted from pumping SCC.

ORGANIZATION OF THIS DOCUMENT

The first chapter of this report contains a comprehensive literature review with regards to SCC for cast-in-place applications. The essential information is presented for a basic understanding of SCC. Topics investigated in this section include a brief history of SCC, SCC material properties, quality control, pumping and placement, creep and shrinkage, controlling water content, drop height and formwork pressure.

The second chapter presents the most current practices related to SCC taken from twenty-five state transportation agencies. This section contains relevant information related to SCC applications in these states, which were gathered from previous reports, specifications, special provisions, and/or personal communication. The information presented in this section includes current practices related to SCC materials and mix requirements, mix approval procedures, site acceptance, placement requirements, and delivery requirements. This along with the literature review can be used to aid state agencies and contractors in the use of SCC for cast-in-place applications.

The third chapter of this report reviews methods used for rapid determination of water to cement ratio. Ultimately, the Standard Test Method for Water Content of Freshly Mixed Concrete Using Microwave Oven Drying (AASHTO T 318-02) was chosen to evaluate for its potential use for on-site quality control. Both fresh concrete and sieved mortar samples were tested using this method from delivered concrete and laboratory batched SCC. This method proved to be reasonably accurate in rapidly determining the w/cm with an average magnitude error for concrete and sieved mortar samples of 0.012 and 0.013, respectfully. These values were calculated using the absolute value of the difference between the provided and calculated w/cm.

The fourth chapter of this report is related to the stability effects to the segregation resistance and air-void structure of SCC when pumped from the bottom of the formwork. To investigate this, five 4-inch diameter samples were cored from a pumped SCC column. The cored samples were then analyzed to determine the aggregate distribution and air-void properties at various positions within the column. The results of the segregation analysis suggest that the mix exhibited segregation behavior. Additionally, none of the samples analyzed met the

recommend air-void spacing factor recommended by ASTM C457 for a structure exposed to moderate freeze-thaw environments. The distribution of the air-voids along the formwork wall and center of the column were plotted and the results suggest variations in the air-void structure along the length of the column.

CHAPTER 1 CURRENT RESEARCH TOPICS FOR SELF CONSOLIDATION CONCRETE IN CAST-IN-PLACE APPLICATIONS

A BRIEF HISTORY OF SELF-CONSOLIDATING CONCRETE

In 1986, Professor Okamura of University of Tokyo, Japan first conceptualized Self-Consolidating Concrete (also known as Self-Compacting Concrete), SCC. The purpose of Okamura's research on SCC was to provide a solution to the poor performances of Japanese concrete structures in respect to durability and to reduce the number of skilled laborers required for the placement of concrete. It was determined that the main cause of this durability issue was a result of poor consolidation during the casting process.

Later it was found that the use of SCC offered many other beneficial qualities such as reduced noise production, faster construction time, improved surface quality and lower strain on concrete operators. The first publications related to SCC were released around 1989 from Japan. Since then, Japan and other Asian countries have used SCC in bridges, buildings, and tunnels. In addition, a number of SCC bridges were constructed in Europe in the late 1990's (Ouchi, Nakamura, Osterberg, Hallberg, & Lwin, 2003). In the United States, the application of SCC in highway bridge construction had begun to gain popularity in the early 2000's. SCC construction bridge construction projects using SCC were completed in Kansas, New York, Virginia, and Nebraska (FHWA, 2005). NCHRP Report 628 (2009) "Self-Consolidating Concrete for Precast, Prestressed Concrete Bridge Elements," which gives detailed information on the use of SCC in precast, prestressed bridge elements has provided findings that are also suitable for some cast-in-place applications (Khayat & Mitchell, 2009). There is an on-going NCHRP Project 18-16 of "Self-Consolidating Concrete for Cast-in-Place Bridge Components" that is aimed to develop guidelines for use of SCC in cast-in place applications.

In this chapter, some of the most recent publications related to cast-in-place SCC research have been reviewed and the most significant outcomes are summarized. Recent studies focus on the mix design characteristics, efficient mixture proportioning, batching and transportation, pumping and placing, formwork pressure and formwork design. In addition, hardened concrete

properties such as strength, creep and shrinkage, bond to reinforcement and finished surface quality are also among the subjects being investigated by many researchers.

Benefits and Current Limitations of SCC

The construction of structural members using traditional concrete mixtures for both precast and cast-in-place applications typically involves labor intensive and hazardous placement methods. A traditional concrete casting requires spreading the concrete into place (often using a rake), consolidation using mechanical vibrators, and surface finishing. The properties of the concrete member such as the geometry or spacing of the reinforcement can further complicate the construction process. Additionally, the required mechanical vibration as well as the finishing of the concrete surface can often expose concrete workers to additional health and safety risk. The implementation of SCC under many circumstances can help mitigate a variety of costs and risks associated with concrete construction.

A comparison study in the construction of two similar cast-in-place bridge sub- and super-structures, it was found that the use of SCC reduced the required man hours by up to 83% while decreasing the placement time of the concrete by 66% compared to traditional concrete. Additionally, a study within this report found a 6-10% decrease in the overall concrete operational costs when using SCC compared to TVC. (Daczko J. A., 2012) While the material cost of SCC is typically higher due to increased cement and chemical content, significant project savings can be achieved using SCC.

Additional benefits arise with the elimination of the need for mechanical consolidation techniques. This can result in significant noise reduction for both construction sites and precast manufacturing plants. This noise reduction is not only beneficial to the well-being of workers but may allow for extended construction hours in urban areas where construction noise is often regulated during certain hours. Ultimately resulting in cost savings through reduced project delivery time.

The most common type of consolidation process is performed using a pen-type vibrator. This frequently requires workers to balance on formwork for extended periods of time. This procedure exposes workers to significant ergonomic strain and health hazards. The extended use of these types of vibrators can result in what is known as “hand-arm vibration syndrome” which

can cause permanent damage to workers. The elimination of the need for mechanical vibration can lead to improved worker conditions resulting in higher levels of productivity, improved employee retention, and reduced risk of on-site injury.

While the potential benefit for the use of SCC to the contractor is clear due to the reduced labor and required casting time, the owner of a project can also benefit from its implementation. The low viscosity of SCC can result in the production of consistently high quality structural members which contain fully encapsulated reinforcement free of honeycombing. This helps to ensure the integrity of the structure to adequately perform. As will be further discussed in later sections of this report, SCC is well known for its superior surface quality when compared to traditional mixes. Therefore, the use of SCC may be the only option to achieve acceptable architectural features within a project.

Although, there are many applications of SCC which would be advantageous, currently a lack of regulations and understanding of material behavior have resulted in the underutilization for cast in place applications in the United States. Additional risks and costs may be encountered due to the higher sensitivity of SCC which typically requires more stringent quality control measures. Additionally, many contractors and engineers may be hesitant to implement SCC due to the lack of experience using the material.

Due to the repetitive nature and controlled environment of most precast applications, SCC is utilized much more frequently when compared to its use for cast in place applications. (RILEM TC-188, 2006) Although there is a high potential for significant benefits with the use of SCC for cast in place applications, there is a need to better understand the material prior to widespread implementation. The following sections of this report outline many topics of concern related to cast in place SCC as well as the research aimed to address them.

SCC Mix Design Characteristics

Mix design characteristics of SCC are mainly related with its fresh state properties. The fresh state properties for an acceptable SCC mix design are usually given as follows:

- 1) Filling ability: SCC is expected to fill the formwork completely and flow around the reinforcement horizontally and vertically in a homogeneous manner.

- 2) Passing ability: SCC is expected to pass narrow sections of the formwork and congested reinforcement without aggregate interlocking.
- 3) Resistance to segregation: SCC is expected to maintain homogeneity throughout mixing and during transportation, pumping and casting.

The increased fluidity of SCC leads to many advantages over TVC in terms of placement. To achieve the above fresh properties, typically, aggregate volume is adjusted, paste volume is increased, and superplasticizer (SP) is used with a lower water to powder ratio. Many of the same constituent materials used in standard TVC mixtures have been successfully used in SCC.

Availability of constituent materials varies based on location thus there is no universal SCC mix. However, SCC mixtures can be designed to produce satisfactory self-consolidating properties as well as hardened properties. (ACI Committee 237, 2007) (RILEM TC-188, 2006) (Khayat & Mitchell, 2009).

SCC Constituents

SCC is principally proportioned using the same constituents as conventional concrete. Currently, it is not possible to reach the same workability by only adding more SPs into the TVC mix. Therefore, SCC is generally proportioned with additional filler material so that the volume of the continuous phase is increased. The filler material is used to bind a portion of the excess water and improve the passing ability. At the same time, viscosity-modifying admixtures (VMA) can be incorporated to the mix design to prevent segregation. Today, many types of VMA's are produced in liquid form and mostly consist of different types of polymers. Air entraining admixtures (AEA) can also be used in SCC to achieve the required air-void parameters and improve the freeze and thaw durability.

Bonen and Shah (2005) categorized SCC mixtures in two different design methods; powder-type SCC and VMA type SCC. The powder-type SCC design required low water to cementitious (w/cm) ratio and high binder content to increase the plastic viscosity and segregation resistance. The second method was based on the addition of SP and VMA to control the yield strength, plastic viscosity, and segregation resistance (Bonen & Shah, 2005).

Chemical admixtures

The most common SPs being used for SCC production are known as high range water reducers (HRWRs). HRWRs belong to the third generation of comb-type dispersing surfactants that are often based on polycarboxylate (PC) technology. PC with long slump retention is critical for cast-in-place SCC applications, where SCC needs to be transported to the construction site. It was reported that SCC mixtures containing slump retention PC exhibited up to four times slump-loss-control time compared to the mixes using conventional PC (Shi, Berke, Jeknavorian, & Zhong, 2006).

Air Entraining Agents are required to provide the necessary air-void structure throughout the concrete to ensure proper freeze and thaw durability. The AEAs are typically surfactants that stabilize the air-voids by reducing the surface tension of water. Another type of AEA works as a water-repellant when mixed into concrete. For SCC, it is important to create a proper air-void system such that it remains stable during agitation, pumping, placement, and setting. Khayat and Assaad (2002) tested ten SCC mixtures to evaluate the influence of mixture proportioning on the stability of the air-void system. Their results suggest that SCC can remain stable even after agitation over time (Khayat & Assaad, 2002)

Aggregates

SCC mixtures generally have lower total aggregate content and a reduced maximum aggregate size in comparison with TVC. The amount of fine aggregate is also relatively greater than those in TVC. Aggregate properties greatly affect the fresh properties of SCC. The optimization of aggregate characteristics results in improved flow properties as well as reduces the cementitious materials, mixing water, and chemical admixture content. The most important physical properties for aggregates used in SCC mixtures are shape, angularity, texture, grading (including maximum aggregate size), and microfines (Koehler & Fowler, 2007-1).

Coarse aggregates are known to have a large influence on the workability and self-compacting ability of SCC mixes as well. International Center for Aggregates Research (ICAR) cited overall improvements in the flowability, passing ability and segregation resistance of SCC with a decrease in the maximum size of coarse aggregate (Koehler & Fowler, 2007-2). However, since decreasing the aggregate size may have adverse effects on the hardened properties of SCC, particularly the viscoelastic behavior, ACI recommends using the greatest

volume and largest size of coarse aggregate possible while still providing good stability, filling ability, and passing ability of the fresh SCC (ACI Committee 237, 2007).

Manufactured silica sand with its naturally high filler content is normally used in SCC mixes. Natural sand differs from manufactured sand by grading, particle shape and surface texture. Typically, manufactured sand has greater fines (filler), different gradation, and more angularity with rougher surface. NCHRP 628 recommends blending natural and manufactured sands to improve workability and stability of SCC (Khayat & Mitchell, 2009). It should be noted that changing the aggregate source (i.e. the quarry) has the potential to cause significant changes to the concrete properties and should be carefully evaluated (The European Guidelines, 2005).

Powders

Powders are classified as materials finer than 125 microns. Powders are intentionally proportioned into SCC mixes to increase paste content and improve the rheology. Cements, pozzolans, and fillers are classified as powders in concrete mixtures. Numerous studies have been conducted to determine different powders, with the majority focused on the influence of limestone powders on SCC properties. If powders are compared with one another or with standard straight mixtures, it is strictly recommended either to keep the paste volume constant or to use same replacement ratios by mass. In general, increasing the paste volume will affect the fresh SCC properties and can lead to erroneous conclusions regarding material comparisons (Daczko J. A., 2012).

The incorporation of high volumes of powder materials can enhance cohesiveness and increase the paste volume of SCC. Especially, the use of limestone filler as a replacement for cement can reduce water demand or HRWR demand and also increase compressive strength at early ages (Ghezal & Khayat, 2002).

Quality Control and Handling of Raw Materials

Quality control processes for concrete production ensures the quality of the concrete at the plant by obtaining immediate information about the performance, characteristics, and raw material properties of the concrete. The cement and aggregates used in SCC needs to be monitored regularly as described in procedures and specifications for monitoring raw materials such as NCPA Quality Control Manual (NCPA, 2012).

Raw materials for SCC can be stored in bins, silos, etc. similarly to storage used for the production of conventional concrete. However, ready-mix concrete plants need to be able to store various materials for SCC production, including cementitious materials, filler materials, aggregates and admixtures. Therefore, storage capacity is especially important. Installing extra storage tanks and dispersing systems may be an extra cost for the producer. Aggregate stockpiles are commonly placed in an open storage yard next to the concrete plant. Such an unprotected stockpile can have higher variation. To prevent changes due to weather, aggregates can be stored on sites with controlling systems to maintain consistent moisture content.

Consistency of raw materials, including fineness, amount under the 300 and 75 micron sieves, selected aggregate compaction, and moisture content of the aggregates should be more controlled than those used for conventional concrete. The potential of excess moisture from the aggregates may be of particular concern due to the potential increase in the water to cementitious ratio and decrease in viscosity. This can cause an unstable SCC mix with segregation, and/or bleeding due to SCC's sensitivity to changes in water content. Methods for on-site quality control with respect to water content will be explored in later sections of this report.

NCPA recommends that the aggregate moisture content needs to be determined at least daily before producing the first SCC batch even when moisture probes or meters are used with automatic mixing water adjustment systems (NCPA, 2012).

Aggregate Packing

The optimization of particle size distribution is known as aggregate packing, which has been used as a cost-optimizing tool in designing concrete mixes. Since aggregate gradation influences the performance of SCC, aggregate packing can be used as a powerful tool since the packing of aggregate particles minimizes the voids which can reduce the required amounts of paste as well as the production cost (Hwang & Tsai, 2005).

Figure 1-1. (a) Procedure of Aggregate Packing (b) Grade Curves for Different Packing Types (c) Cement Strength Efficiency of SCC, adopted from (Hwang & Tasi, 2005)

Different models for packing density have been applied to SCC. It has been reported that increasing the aggregate packing density generally results in improved SCC workability and reduces the amount of paste needed to fill voids between the aggregates (Figure 1-1a). Hwang and Tsai (2005) found that denser aggregate packing where fly-ash is incorporated as filler between the aggregates instead of as partial replacement of cement or sand in traditional method resulted in even better workability and better hardened properties. They used a “Densified Mixture Design Algorithm” (DMDA) when designing SCC and obtained high flowability and strength growth for two aggregate packing types, Dense (green, Figure 1-1b) and Gap (blue), compared to Natural packing method (red). The strength efficiency (per kilogram of cement) was shown much higher than that from traditional mix design (Figure 1c); the dense packing type SCC with the smallest void and the least cement past content had approximately four times higher strength efficiency than that of traditional concrete (Hwang & Tsai, 2005).

Other studies have also shown that SCC with near optimum aggregate packing exhibited lower viscosity, lower HRWR demand, and similar or greater filling capacity than SCC with similar or slightly lower aggregate packing density due to the higher content of fines smaller than 80 microns and lower coarse aggregate volume (Khayat, Hu, & Laye, 2002). Additionally, aggregates with standard shape and angularity increase packing density as well as improve workability by reducing friction between particles (Koehler & Fowler, 2007-2).

Monitoring Fresh Concrete Performance

It is recommended to check every SCC batch before sending to jobsite. A simple testing plan might be arranged before the start of every project (The European Guidelines, 2005). There are guidelines available showing instructions for simple testing plan at either the production plant or the casting site. There are several different test methods approved by ASTM for measuring SCC fresh characteristics:

- ASTM C1611 provides a procedure to determine the slump flow of SCC in the laboratory or the field (Figure 1-2) (ASTM Standard C1611, 2009).
- ASTM C1621 covers “determination of the passing ability of self-consolidating concrete by using the J-Ring in combination with a mold in the laboratory or the field” (ASTM Standard C1621, 2009).

Figure 1-2 Slump-flow (bottom) and J-Ring (top) patties after removal of the inverse Abrams cone (Chen et al, 2012)

- ASTM C1610 covers “the determination of potential static segregation of self-consolidating concrete by measuring the coarse aggregate content in the top and bottom portions of a column in the laboratory” (ASTM Standard C1610, 2010).
- ASTM C1712 is useful for rapid assessment of the static segregation resistance of SCC during mixture development in the laboratory as well as prior to placement of the mixture in the field (Figure 3) (ASTM Standard C1712, 2009).

Figure 1-3 Rapid Segregation Probe Test on an SCC Mix
(Baranowski, Sweet, & Chen, 2011).

According to the European Guidelines (2005), the slump flow needs to be measured for every batch of SCC to ensure the consistency of the production. It is also recommended to inspect every batch visually before it leaves the plant (The European Guidelines, 2005). NPCA Guidelines (2012) suggest that slump flow and VSI to be checked for every 50 cubic yards or 25 batches until two consecutive batches are met the requirements of the corresponding specifications. If the plant doesn't have an automated moisture monitoring system, if the mix design or raw materials changing or if there is a suspicious condition, more frequent testing is required (NCPA, 2012).

Controlling Water Content

A successful production of SCC requires better quality control than conventional concrete. One of the most important parameters during SCC production is controlling its water content, which can greatly affect the SCC fresh properties both at the plant and at the jobsite, such as filling ability, passing ability, and segregation resistance.

There are many challenges in controlling the total water content during production and delivery in a typical ready mix concrete operation. In order to minimize the human error, an

electronic system was reported to be able to integrate into a concrete truck for measuring the workability characteristics of concrete based on concrete load size, mix design, and drum speed (Koehler E. P., 2013). This new concrete truck system could continuously measure slump, slump flow, temperature, water use, admixture use, drum speed, and number of drum revolutions etc. from batching to pouring and automatically add water or admixture to reach the target workability.

It has been reported that mixtures with lower viscosity have higher sensitivity to changes in moisture content as compared to traditional concrete. Therefore, ACI recommends determining the water sensitivity of a mix as a part of the mix development process. This can be done by taking the selected concrete mixture proportions and adding successive amounts of water to the mixture while recording the stability level; the amount of added water that causes the mixture to become unstable defines the mixture's water sensitivity (ACI Committee 237, 2007).

In a previous study performed at West Virginia University, it was shown that a change of water content in an SCC mix within the range of 5 percent of the total volume of water, which is approximately 2 gallons of water per cubic yard batched, could still maintain a stable SCC mix. However, if the water content were increased beyond this point, the mix displayed signs of instability (Chen, Baronowski, & Sweet, 2010).

Due to the low viscosity of SCC, the use of flexible construction techniques are possible when using this material. Current stability tests such as the J-Ring and VSI may be inadequate in evaluating a borderline unstable mix subjected to certain construction techniques. Uncertainties inherently exist within concrete mixes with regards to water content. Larrard et al. argue that due to the industrial nature of the construction industry, often it is difficult to adequately control water content in the production of SCC. (Larrard, Cazacliu, Choplin, & Chateau, 2003)

BATCHING AND TRANSPORT OF SCC

Due to the increased fluidity of SCC, additional considerations should be made when batching and transporting SCC. Due to the low water content with respect to the amount of fines (<125 microns) and the high dosage of admixtures, SCC requires more efficient mixing, e.g.

longer mixing time (over 4 minutes) to ensure that all constituents have been mixed thoroughly (Schießl, Mazanec, & Lowke, 2007). Schießl et al. (2007) studied the effect of mixing time and mixing speed on the properties of fresh SCC and ultra-high performance concrete (UHPC). It was shown that during dispersion phase, the use of power increased significantly when the flowability of the concrete increased. They observed that the flowability of SCC was reduced when the mixing time was extended. Their results also indicate that the mixing time can be shortened for the production by changing the mixing speeds (Schießl, Mazanec, & Lowke, 2007).

Since truck mixers have a variable speed, RILEM recommends mixing SCC in a truck mixer between 15 and 25 rpm (RILEM TC-188, 2006). Mixing conventional concrete before mixing SCC may create some inconsistency in properties of SCC. Therefore, the mixer truck shall be clean but not dry before loading. ACI 237R-07 recommends limiting the volume of SCC within a truck to 80% of the drum's capacity. This is to avoid any potential spillage that could occur during mixing or transport of the SCC, as well as reducing the risk of truck overturning due to the increased movement of SCC from inertial forces (ACI Committee 237, 2007). Ozyildirim (2006) recommends holding the mixing water or HRWR to enable the full load (8 yd³) delivery without any spillage (Ozyildirim, 2006).

Literature from Grace Admixtures addresses the nature of the polycarboxylate (PC) admixtures that are typically used for SCC and recommends appropriate mixing procedures. The literature states that PC used for SCC typically develops workability more slowly than typical HRWR's, and warns that fast mixing could reduce reproducibility and induce excess foaming. Therefore, they recommend mixing at half speed for truck mixers, specifying that the mixing action should include a folding motion, as opposed to a slapping motion within the mixer (Grace Construction Products, 2005).

As previously discussed, certain quality control measures could help the producer delivering SCC mixes repeatedly and with great consistency. It is highly recommended conducting an initial slump test prior to adding the SCC admixtures to help notice material variations such as moisture content or water demand. If this "zero admixture slump" is within

1.0 inch of the target, the required amount of admixture can be added confidently. (ACI Committee 237, 2007)(Grace Construction Products, 2005).

It is known that longer transportation times and extreme weather temperatures can adversely affect the fresh properties of concrete. Typically, concrete tends to hydrate much faster during hot summer days and slower during cold winter days. It is also known that, increased mixing time can entrain more air into the concrete. These effects must be considered when attempting to deliver SCC within predefined tolerances to the job site. A study by Ghafoori and Diawara (2010) simulated extended transportation time using a variable speed mixer inside of an environmental chamber that was capable of subjecting the mix to varying ambient temperatures. It was seen that when 109°F (43°C) hauling conditions were simulated for 10, 60, and 80 minutes, SCC experienced respective reductions in slump flow of about 26%, 37%, and 45% in comparison to a control SCC mix at a temperature of 70°F (21°C) at the same times. Alternatively, when 31°F (-0.5°C) hauling conditions were simulated for 10, 60, and 80 minutes, the slump flow was about 3%, 8%, and 10% higher than the control batch (Ghafoori & Diawara, 2010). It is apparent from these results that the effect of high temperatures on the fresh properties of SCC would be much more significant than that of low temperatures.

Remediation efforts are typically attempted to account for the changes that would take place in the concrete during extended transport and assure that fresh properties are met on site; these remediation efforts could include overdosing or under-dosing of admixtures prior to transport or re-tempering of the concrete on site. A study by Ghafoori and Barfield (2010) investigated by both overdosing and re-tempering of SCC batched in an environmental chamber with simulated travel times of 20 minutes to 90 minutes. It was stated that different remediation procedures can be implemented for different SCC mixtures, however it requires extensive pre-testing before actual application. Due in part to the method of re-tempering, which did not include a reduction of AEA used prior to “transport,” the desired air content for the study could not be achieved through re-tempering, so a combination of re-tempering and under-dosing may be necessary to produce desired fresh properties in the field (Ghafoori & Barfield, 2010). Similar results with respect to field re-tempering of SCC were observed by Hodgson et. al. (2005). It was noted that the entrapped air content greatly increased in both fresh and hardened state due to

re-tempering followed by agitated mixing on the field (Hodgson, Schindler, Brown, & Stroup-Gardiner, 2005).

FORMWORK PRESSURE OF SCC

Research has been conducted to understand if the rules for pumping conventional concrete would apply for SCC. The studies indicate the pumping pressure is related to the viscosity of SCC and the lower viscosity can decrease pumping pressure as well as the cost of the placement (Feys, De Schutter, Verhoeven, & Khayat, 2010). Alternatively, it is also necessary to know whether the concrete properties after pumping are still the same as before pumping. Feys (2009) investigated effects of pumping on 18 different SCC and 1 conventional concrete mixture. He found that there was a linear relationship between SCC viscosity and pressure loss. Additionally, concrete temperature increased linearly with increasing pressure losses during pumping (Feys, 2009).

The use of HRWR reduces the yield stress and plastic viscosity of the SCC which creates higher flowability and passing ability, this increases the initial lateral pressure on the formwork. This is a result of the HRWR interfering with the structural buildup and the development of cohesiveness of the concrete. The demand for HRWR is dependent on the w/cm; i.e. the higher the w/cm, the lower the demand for HRWR. Therefore, decreasing the HRWR content, while increasing the w/cm, will cause greater lateral pressure decay for typical values of w/cm (Khayat & Persson, 2007).

In the past decade, several prediction models for lateral pressure of SCC have been developed by empirical testing in the laboratory or based on results from field studies. Many of them are based on very different parameters, such as the structural build-up, slump-loss, setting time, pressure decay, etc. Assuming hydrostatic pressure on the formwork by SCC provides a conservative estimate with respect to the actual formwork pressure during pumping. Additional guidelines with respect to placement rate along with further research regarding formwork pressure during SCC placement is needed to reduce the required formwork strength. Kim et al. (2011) described their model to predict SCC formwork stress distribution along the height. They proposed a formula to predict the maximum stress. The effect of the placement rate to the maximum lateral pressure and the pressure distribution along the height was also discussed in

their paper. In general, higher placement rate will produce a higher concrete lateral pressure within the formwork.

During the RP 221C experiment conducted at West Virginia University, the pressure exerted on the formwork during pumping of SCC was recorded. Five channels of the data acquisition system (three pressure transducers and two temperature sensors) were collecting data during pumping and continue collecting data up to 16 hours after pumping. Lateral pressure rise (during pumping) and decay (after pumping was completed) were recorded. The results confirm that SCC can be successfully pumped from the bottom of formwork during construction. The stability effects on air content and segregation resulting from the pumping of SCC will be examined in the fourth chapter of this report. Results from the pressure measurement at three different heights indicate that the maximum lateral pressure of the SCC reached the hydrostatic pressure due to a high pumping rate of about 27 ft/hr.

In 2007, report from Khayat et al. reviewed existing specifications and key parameters affecting formwork pressure, such as raw material properties, mix proportions, formwork properties, as well as formwork pressure measurement and monitoring systems. Several case studies were also summarized in the end regarding field monitoring of SCC (Khayat, Bonen, Shah, & Taylor, 2007). Studies show that the use of SCC in lieu of TVC can increase concrete casting rates significantly. However, the risk of high formwork pressures must be considered beforehand. Similarly, it is recommended to monitor the formwork pressure during casting in order to secure the integrity of the formwork, especially for cast-in place applications such as high walls and columns. Currently, when designing formwork for SCC, it is considered as a liquid and consequently full hydrostatic pressure is being used in design calculations. Other research data suggests that the design load for SCC can be lower than the hydrostatic pressure of the concrete (Proske & Graubner, 2010).

The German standard for the calculation of pressure on vertical formwork, DIN 18218, was recently updated based on research conducted at Technische Universitaet Darmstadt. According to DIN 18218, the maximum pressure for SCC was calculated as (Proske & Graubner, 2010):

$$\sigma_{hk,max} = (1.0 \text{ m} + 0.26 v \cdot t_E) \cdot \gamma_C \geq 30 \text{ kPa} \quad \text{Equation 1-1}$$

where, $\sigma_{hk,max}$ is the 95th percentile value of the maximum pressure, γ_C is the unit weight, t_E is the setting time, and v is the mean rate of concrete placement.

It was pointed out that this equation can be valid for concrete setting time from 5 hours up to 20 hours and the minimum pressure was limited to 30 kPa (600 lb/ft²) in order to protect the formwork against accidental shocks (American Concrete Institute, 2010). Figure 1-4 shows that the concrete pressure increases hydrostatically from the concrete surface to height h_s , where

$$\sigma_{hk,max} = h_s \cdot \gamma_C \text{ (Proske \& Graubner, 2010)} \quad \text{Equation 1-2}$$

The design of formwork needs to satisfy the requirements for both safety and reliability of the construction. Therefore, the required design strength of the formwork pressure, $\sigma_{hd,max}$, was calculated by multiplying the maximum pressure by the partial safety coefficient, γ_F , which was predefined as $\gamma_F = 1.5$.

Figure 1-4. Lateral pressure distribution of SCC (DIN 18218: 2010-01, adopted from (Proske & Graubner, 2010))

In May 2012, a round-robin test took place in Stockholm, Sweden, in order to evaluate those existing formwork pressure models. In total, ten different models have been evaluated and all of them were found to be capable of satisfactorily predicting the lateral formwork pressure (Billberg, et al., 2013). Updating the formwork design guidelines and standards for SCC formwork pressure is still needed in the United States.

Drop Height and Placement Distance

Congested reinforcement and SCC viscosity are indicated as the most important parameters in deciding the drop height in order to ensure that the mixture does not segregate during dropping (Daczko A. J., 2012). Daczko (2012) recommended a drop height of 3 to 10 feet (1 to 3 m) for some SCC applications. ACI 237R-07 recommends caution for dropping SCC into deep sections such as walls and columns in order to avoid trapping air-voids within the concrete and possible aggregate segregation. Alternatively, projects using SCC mixtures had been reported freefalling up to 19 feet (5.8 m.) (ACI Committee 237, 2007). Furthermore, RILEM referenced field applications from Europe with dropping height of 28 feet (8 m.) (RILEM TC-188, 2006).

During another study in Canada, Yahia et al. (2011) developed SCC mixtures for casting 20 feet long precast pipes. They compared test results from placing SCC on the top with free-fall of 20 feet to the results from pumping SCC from the bottom of the pipe. No difference on surface quality was observed, however SCC provided better pore-size distribution when pumping from the bottom. (Yahia, Khayat, & Bizien, 2011).

The Illinois DOT and Nebraska DOT currently recommends a maximum drop height of 5 feet while other sources suggest that a significantly larger drop height is acceptable. The Illinois DOT specifies a maximum placement distance of 25 feet. Further research is needed to fully understand the limit of dropping height and placement distance for SCC for cast-in-place applications.

Vibrating SCC

By definition, SCC does not require vibration or any other mechanical consolidation. In addition, ACI 237 does not consider use of external vibration for structural SCC elements since it may cause bleeding, sand-streaking and segregation (ACI Committee 237, 2007).

Chen et. al. (Chen, Baronowski, & Sweet, 2010) studied the effects of vibration on SCC by slightly modifying the segregation column apparatus and procedures for evaluating the vibrational stability of SCC mixes. The vibration of segregation columns for two SCC mixes proved a stable SCC mix was seen to have the ability to endure minor vibration should additional consolidation efforts be necessary, but a borderline unstable mix was seen to exhibit large amounts of segregation under similar conditions. Figure 1-5 shows the test apparatus used for vibrating test of SCC.

Figure 1-5. Test apparatus used for vibrating test of SCC (Chen, Baronowski, & Sweet, 2010)

Daczko (2012) studied the influence of the placement technique on the surface finish by casting 6 feet tall vertical elements, one vibrated and the other one was not. The results showed that applying vibration to SCC decreased the surface quality. In another study, it was demonstrated how vibration might affect segregation of different SCC mixtures by measuring the slump flow before and after vibration; one for 10 seconds and another one for 20 seconds. SCC mixtures segregated, aggregate piles formed in the center and the slump flow decreased as the vibration time increased. Currently, ACI 237R-07 allows a 2-3 second vibration for only one

specific situation of SCC in order to avoid pour lines, when SCC has been placed onto previously placed SCC that has gelled but has not yet reached initial set (Daczko A. J., 2012).

PROPERTIES OF HARDENED SCC

The hardened properties of concrete are typically used in design and quality control engineering. It has been shown that properly designed and mixed SCC exhibits comparable or better mechanical properties than a corresponding TVC (Bonen & Shah, 2005). European Guidelines for SCC recommends a number of hardened concrete property tests should be carried out, which are most relevant to consider when using SCC: “Compressive strength, tensile strength, modulus of elasticity, creep, shrinkage, coefficient of thermal expansion, bond to reinforcement, shear force capacity in cold joints, and fire resistance” (The European Guidelines, 2005). In addition, freeze-thaw resistance and permeability are required when long-term durability is considered.

Strength and Modulus of Elasticity

The strength development of concrete is primarily determined by the water to cement ratio and the composition of the cementitious materials. SCC can be produced with different combinations of cements, pozzolans and fine powders. Therefore, ACI 237 recommends testing SCC made with supplementary cementitious materials after 91 days of age (ACI Committee 237, 2007). It has been shown that SCC with similar water to cement or cementitious ratio typically exhibits slightly higher compressive strength as compared to TVC (The European Guidelines, 2005).

Studies show that the modulus of elasticity of SCC reduces as the mixture's paste content is increased and the aggregate content is decreased (Attigbe, See, & Daczko, 2002) (Khayat & Mitchell, 2009). It is stated that the known ACI relationship between compressive strength and modulus of elasticity for conventional concrete may not have the same goodness of fit for the corresponding SCC (The European Guidelines, 2005) (ACI Committee 237, 2007).

A recent study compared the prediction models from ACI 318, ACI 363R, and Euro Code 2 for the mechanical properties such as modulus of elasticity, tensile strength, and modulus of rupture of conventional concrete and SCC. For this purpose, an extensive database of 627

mixtures from 138 different references was created and the measured SCC properties were compared to the predicted results. The ACI 318 prediction model was found to be the most accurate in the case of the modulus of elasticity, the Euro Code 2 model was more accurate in the case of the tensile strength, and the ACI 363R model was more accurate for the modulus of rupture (Vilanova, Fernández-Gómez, & Landsberger, 2012).

Bond to Reinforcement

There have been numerous studies conducted to determine the bond performance of SCC relative to conventional concrete. De Almeida et al. (2008) determined the bond behavior of SCC and conventional concrete using pullout and beam tests and obtained similar bond strengths. It was concluded that use of European and Brazilian design codes can be adopted for SCC (De Almeida Filho, El Debs, & El Debs, 2008). Looney et. al. (2012) similarly compared bond strengths of 24 pullouts and 12 full-scale SCC and conventional concrete beams. SCC bond strength found to be comparable or slightly higher than that of the conventional concrete (Looney, Arezoumandi, Volz, & Myers, 2012). Another study from Valencia, Spain shows that SCC bond strength can be up to 30% greater than that of conventional concrete (Valcuende & Parra, 2009).

Additionally, Missouri University of Science and Technology published a report on the use of SCC for infrastructure elements. One of the objectives of their study was to determine the bond performance of reinforcing steel when using SCC. The bond performance of SCC was compared with regular MODOT standard mix designs. They determined that using SCC does not result in any increase in the required development length of the reinforcement (Missouri University of Science and Technology, 2012).

Creep and Shrinkage

Existing literature shows contradicting results about shrinkage and creep of various SCC mixtures in comparison with conventional concrete. Sweet and Chen (2012) performed an experiment for the cast-in-place SCC caissons for Stalnaker Run Bridge (Figure 1-6) in West Virginia. The compressive strength for both SCC and conventional concrete were approximately 4,500 psi. As seen in Figure 1-7, there are no significant differences in the shrinkage behavior between SCC and conventional concrete. Alternatively, the SCC used in the production of the

prestressed box beams (8,000 psi) for Stalnaker Run Bridge exhibited much higher shrinkage and creep than that of TVC (Sweet & Chen, 2012). The average shrinkage strains after six month monitoring of the TVC and SCC specimens were 344 μ strain and 425 μ strain, respectively.

Figure 1-6. Placement of rebar cage for the caisson of Stalnaker Run Bridge

Figure 1-7. Total shrinkage trends for caisson concrete (Sweet & Chen, 2012)

Daczko (2012) compared drying shrinkage behavior of 12 different SCC mixtures with a reference conventional concrete. It was confirmed that shrinkage strain increased with

increasing water content increases and decreasing coarse aggregate content. Results also suggested that conventional concrete mixtures with similar proportions exhibited similar shrinkage behavior when compared to the SCC (Daczko J. A., 2012).

Schindler et. al. (2007) produced 21 different SCC mixtures for precast, prestressed applications in the laboratory and evaluated the drying shrinkage behavior. According to the results, SCC samples produced the same or less drying shrinkage strains compared to the conventional concrete samples (Schindler, Barnes, Roberts, & Rodriguez, 2007). Vikan et. al. (2010), investigated the influence of composition of different cements on drying shrinkage of SCC using a relatively high water to cementitious ratio ($w/cm=0.55$). It was confirmed that shrinkage was increased with increased cement fineness and early reactivity (Vikan, Hammer, & Kjellsen, 2010).

Poppe and De Schutter studied the influence of limestone powder on the shrinkage and creep of SCC. In total 4 different SCC mixtures were produced with different cement to powder ratios. Results showed that SCC creep decreased with increasing cement content and decreasing water to cement ratio. Alternatively, shrinkage deformations increased with higher cement contents. It was stated that the shrinkage and creep deformations of the SCC mixtures were comparable with the deformations of conventional mixtures (Poppe & De Schutter, 2005). Khayat & Long (2010) evaluated 16 different SCC mixtures for precast, prestressed applications. The drying shrinkage of the SCC mixtures was found to be higher when compared to high performance concrete (HPC) mixtures with similar water to cementitious ratios (Khayat & Long, 2010). In addition, Long and Khayat (2011) presented creep test results that showed SCC could produce up to 20% higher creep strains compared to HPC (Long & Khayat, 2011).

Restrained Shrinkage

Restrained shrinkage behavior of SCC has been studied by researchers due to its relationship with cracking potential. See and Attiogbe (2005) studied the shrinkage and cracking potential of several SCC mixtures in comparison with conventional concrete following ASTM C 1581. Their results suggested that the 28-day shrinkage and the time to cracking were the same for each set of materials and mixture proportions (See & Attiogbe, 2005). Similarly, Hwang and Khayat (2010) evaluated the cracking potential of different SCC mixtures due to restrained

shrinkage cracking. It was reported that SCC mixtures had higher cracking potential than the conventional concrete mixtures due to higher paste volume that lead to greater drying shrinkage (Hwang & Khayat, 2010). In general, it is recommended to use shrinkage reducing admixtures, filler materials such as limestone powder or additional cementitious materials in SCC mixtures in order to control excessive shrinkage.

Concrete Surface Quality

SCC is well known for its superior concrete surface quality compared to that of TVC. Extremely smooth surfaces can be obtained using steel and wooden formwork, while patterned surfaces can be created using rough timber formwork. If temperature of the formwork contact surface is colder, higher amount of pores were observed on the hardened SCC surface (Ouchi, Nakamura, Osterberg, Hallberg, & Lwin, 2003). In particular, the precast industry can greatly benefit from using SCC to cast remarkable shapes using specially designed formwork. SCC used for cast-in-place applications can also be used to help contractors to achieve very smooth and uniform surfaces.

European guidelines recommend some basic rules in order to obtain high-quality surfaces (The European Guidelines, 2005):

- The amount of SCC needed for one panel should be accurately estimated in order to prevent color differences between different batches.
- The formwork cleaned before use, and only thin layer of special form releasing agent need to be applied.
- The top of the formwork should be covered to protect from rain. Even a small amount of rain can yield discoloring and sand stripes on the SCC surface.

In a recent study, Abd-El-Megid (2012) studied performance and surface quality of SCC mixtures with respect to concrete rheology. SCC surfaces were investigated with image analysis software and quality was quantified by determining the area of defects such as air bubbles, bug holes, segregation, and variations in surface color. According to the study, surface quality of SCC was increased when yield stress and plastic viscosity decreased and slump flow increased (Abd-El-Megid, 2012).

CHAPTER 2 CURRENT PRACTICES FOR SCC CIP APPLICATIONS

In order to fully understand the current status of SCC use for ready mix applications, efforts were focused on obtaining the most current regulations pertaining to cast-in-place SCC from state transportation agencies in the United States. In particular, the Standard Specifications, Special Provisions, Supplemental Specifications, etc., were obtained from numerous state agencies for the purpose of evaluating the amount of SCC related regulations currently available. The primary focus was to find state agencies that include cast-in-place provisions for the use of SCC. (Chen, Hershberger, Yikici, & Sweet, 2015)

CURRENT STATUS OF SCC APPLICATIONS IN UNITED STATES DOT

Twenty-five state agencies were found to have guidelines implemented which appear to be directly applicable to cast-in-place and/or precast SCC. Many of these states, including New Jersey (New Jersey Department of Transportation, 2007), Rhode Island (Rhode Island Department of Transportation, 2011), Utah (Utah Department of Transportation, 2012), Florida (Florida Department of Transportation, 2011), and Washington (Washington State Department of Transportation, 2012) have already adopted SCC guidelines into their Standard Specifications. A summary of the document types in which SCC guidelines were found for each state, as well as the pertinent applications based on those guidelines, can be seen in Table 2-1. In this table, the “Non-Specific Designation” heading indicates that either the document presented “self-consolidating” as a modification for the pre-existing classes of concrete in their Standard Specifications, as is the case for Rhode Island, or that the document did not specify a particular application or class of applications for the standard. A brief summary of some state documents related to SCC are shown below:

- IDOT (Illinois) (Appendix A) – Special Provisions for both prestressed and cast-in-place SCC, with a revised version applicable for July 2010 lettings and thereafter.
- UDOT (Utah) – 2008 Standard Specifications include SCC in Precast (non-prestressed) and “Portland Cement Concrete” (mix design) provisions. The “Concrete Drainage Structure” and “Precast Concrete Deck Panels” sections within the Specification refer to Special

Provision for acceptance criteria. The Special Provision has been approved for inclusion into 2012 Standard Specifications.

- Iowa DOT – 2009 Materials Supplement (Matls. IM 445, Appendix D) gives guidelines for approving and testing SCC mix designs for precast concrete.
- KYTC (Kentucky) (Appendix A, Figure A7) – Kentucky Method 64-320-08 covers the precast plants to obtain approval for use of SCC in precast products.
- MDT (Montana) (Appendix A) – 20068 Standard Specs do not include SCC, however Br201.68 (Bridge Special Provision) includes mix design provisions for SCC. Also, some test methods are included as “Montana Modified Methods.”
- NDOT (Nevada) – Construction Guide describes SCC in general terms, and lists required acceptance testing.
- NYSDOT (New York) (APPENDIX A, Figure A8) – SCC can be used optionally for structural concrete applications. Contractor is responsible to propose a mix design and supply specified fresh and hardened concrete properties with a quality control plan including the expected performance criteria.
- NJDOT (New Jersey) (Appendix B) – 2007 Standard Specifications include SCC provisions for precast and drilled shaft applications.
- RIDOT (Rhode Island) – 2006 Supplemental Specifications and Special Provisions include SCC guidelines for “Portland Cement Concrete” as a modification to other classes of concrete for self-consolidating purposes; updated in 2011 to include Approved Specifications for the 2012 Standard Specs.
- CADOT (State of California Department of Transportation) has a Building and Construction Special Provisions addressing the use of SCC.
- ALDOT (Alabama) (Appendix B) has a Special Provision (SP 06-0420) which specifies the use of SCC in drilled shaft construction.
- FDOT (Florida) (Appendix B) has a material specification document that describes required properties such as mix properties, mix proportions, producer and contractor quality control requirements, etc.

- NDOR (Nebraska Department of Roads) has a guide for the use of SCC in special applications, which includes mix requirements, construction requirements such as formwork, transportation, placement, and test methods for SCC.
- SDDOT (South Dakota Department of Transportation)(Appendix A) has a Special Provision for the use of SCC in box culverts, which includes mix requirements, construction requirements such as formwork, curing, transportation, placement, and test methods for SCC.
- VDOT (Virginia Department of Transportation) (Appendix A) has a special provision for the use of SCC in concrete repairs and in prestressed beams. This provision includes mix requirements, admixture, material testing, placement, finish, etc.
- WVDOT (West Virginia Division of Transportation) currently has special provisions for both precast/prestressed beams and cast-in-place caissons. This provision includes requirements for fresh properties, strength, chemical admixtures, mixing, placement, quality control, etc.

Table 2-1 Summary of State Agency Provisions^a

Agency	Document Type	Application			
		Non-Specific Designation	Cast-In-Place	Precast	Precast/ Prestressed
Alabama	Special Provision		X (Drilled Shafts)		X
California	Special Provisions			X	
Colorado	Special Provision		X		X
Florida	Materials Manual, Developmental Specification		X		X
Georgia	Special Provision				X
Hawaii	Special Provision		X (Drilled Shafts)		
Idaho*	Special Provisions			X	
Illinois	Special Provisions		X	X	
Iowa	Materials Supplement	X		X	
Kansas	Special Provision				X
Kentucky*	Special Provision (Method)			X	
Maryland*	Special Provisions			X	X
Missouri	Special Provision		X (Drilled Shafts)		
Montana	Bridge Special Provision	X			
Nebraska	Special Provision		X		
Nevada	Construction Manual	X			
New York	Standard Specifications		X	X	X
New Jersey	Standard Specifications		X (Drilled Shafts)	X	
Pennsylvania ⁺	Standard Specifications ⁺		X (Drilled Shafts)	X	X
Rhode Island	Supplemental & Approved Specifications	X	X	X	X
South Dakota	Project Specification		X (Box Culverts)	X (Box Culverts)	
Utah	Standard Specification		X	X	X
Virginia	Special Provision		X (For Repairs)		X
Washington	Standard Specification			X	
West Virginia	Special Provision		X (Drilled Caisson)	X	X
^a Reference (Morcous et al., 2013).					
*Information obtained through personal communication + being proposed for use in drilled shafts (see APPENDIX B)					

The Illinois Department of Transportation (IDOT) Special Provisions detail mix design requirements for cast-in-place SCC. The Utah Department of Transportation (UDOT) Standard Specifications refer to the ACI Manual of Concrete Practice, Section 301: Specifications for Concrete, for most mix design guidelines. The Montana Department of Transportation (MDT) has a Bridge Special Provision for SCC Mix Design, MDT Br201.68 that describes SCC mix design requirements. The New Jersey Department of Transportation (NJDOT) Standard Specifications cite specific requirements for the SCC mix design used in drilled shafts. The Nevada Department of Transportation (NDOT) Construction Guide describes SCC in general terms and lists required acceptance testing. The Rhode Island Department of Transportation (RIDOT) includes supplemental specifications that would allow for modification of most of their classes of traditional concrete to exhibit self-consolidating behavior.

The Iowa Department of Transportation (Iowa DOT) has a materials supplement that describes typical SCC mix design philosophies and regulates use and testing of SCC, but does not provide particular SCC mix design requirements. Kentucky Transportation Cabinet has a prescribed method for approval of using SCC with application limited to precast plants only. The Virginia DOT has a special provision that specifies SCC mix designs for precast/prestressed SCC and cast-in-place SCC used in the repair of existing members. WVDOT special provision specifies concrete mix design be submitted for approval to the agency at least 45 days prior to starting construction. WVDOT also stipulates that if any of the mix components are altered, the mix must be submitted for re-approval. The South Dakota DOT requires that a proposed mix design be verified by laboratory tests on trial batches. The trial batches must be done following ACI 211.1, ACI 318, and ASTM C 192 with the exception of the air content which must be within 0.5% of the maximum specified. Many of the state agencies such as Florida and Alabama allow the use of SCC on a case-by-case basis; the proposed SCC mix must be submitted to the state's materials office for approval before it can be used.

Regulation of Cementitious Materials and w/cm Ratio in SCC

In order to reduce costs and to prevent any deleterious effects that may be present in mature concrete, it is common to regulate the cement content and water to cement ratio for SCC

mixes. SCC mix design regulations for cementitious material are shown in Table 2-2 and brief descriptions for some states are shown below:

- Illinois and Montana restrict the cement content to a maximum of just over 700 lb/yd³, New Jersey limits their cement content to a minimum of 611 lb/yd³.
- Rhode Island and Nebraska limit the maximum allowable cement content to approximately 800 lb/yd³.
- Alabama, South Dakota, and Nebraska limit the maximum allowable cement content to approximately 800 lb/yd³ with Alabama and South Dakota specifying minimum cement content of 600 lb/yd³ and 700 lb/yd³, respectively.
- Virginia DOT does not put limits on cement content for cast-in-place SCC but specifies that Type I/II concrete be used.
- The water to cement ratios are limited to below 0.44 in Illinois and New Jersey, 0.40 in Utah, Colorado, Alabama, and Montana, 0.36 in Rhode Island, 0.41 in Florida, 0.37 in Nebraska, 0.45 in Pennsylvania and Virginia, and 0.46 in South Dakota.

Regulation of Supplementary Cementitious Materials in SCC

While most states refer to the cement content and water to cement ratio in their specifications, typically the inclusion of supplementary cementitious materials (SCM), such as slag or fly ash, is treated as an addition of an equivalent weight of cement. Therefore, the maximum cement content discussed throughout this section could actually refer to the maximum cementitious materials content, which is calculated as the weight of cement plus the weight of any supplementary cementitious materials. Likewise, the water to cement ratio would be equivalent to the water-to-cementitious materials, or the weight ratio of water per cubic yard to that of all cementitious materials per cubic yard.

For cement type, when a recommendation is described for cast-in-place applications it is typically recommended Type I or Type II Portland cement be used. For Supplementary cementitious materials a recommended range varying from each DOT was observed. Some of these recommendations are listed in Table 2-3. It can be seen from Table 2-3 that the use of Class F Fly-Ash can be specified from 25% to 40% of the entire cement content. Use of GGBFS is changing depending on the application type and the mix design requirements and can be used

up to 50%. Additionally, Utah DOT requires use of minimum 20% Class F Fly-Ash when alkali aggregate reactivity is a problem (Utah DOT, 2012) (Section 03056).

Table 2-2 Comparison of SCC Mix Design Parameters by State

DOT	Powder Content, lb/yd ³	Dmax	Max. w/cm	Max FA/TA	Air Content
Alabama ^a (Drilled shafts)	600-800	No. 67 or No.78 Natural sand	0.40	--	Max 6%
Colorado ^a (Limited CIP)	--	ASSHTO M43 No. 8	0.40	--	Max 8%
Florida ^a	--	--	0.41	0.50	--
Illinois ^a	565 - 705	> 95% passing ¾" sieve Dmax=1"	0.32-0.46	0.50	5% to 8%
Iowa ^a (Limited CIP)	--	Well graded Dmax= ¾ "	--	0.40-0.50	--
Missouri ^a (Drilled Shafts)	650 Min.	Dmax = ¾ "	0.32-0.45	0.35-0.50	Target 5.0%
Montana	717 Max.	≥ 90% passing ¾" sieve	0.40	--	5% to 7%
Nebraska ^a	810 Min.	Dmax = 1/2 "	0.37	0.75	Min 6%
New Jersey ^a	611Min.	No.57 (1"), No.67 (¾") or No. 8 (½")	0.443	0.50	6.5% (7.5% for No. 8 agg.)
Pennsylvania (Drilled Caissons)	Dia.< 6 ft: 564 - 752 Dia. > 6 ft:Min. 475	--	0.45	--	4% to 8%
Rhode Island	799 Max.	--	0.36	--	5.5 to 7.0% (based on agg.)
South Dakota (Box Culverts) ^a	700 - 800	Dmax = ¾"	0.46	0.55	5.0% -7.5%
Utah	*611 Min.	> 95% ¾" or ½" sieve	0.40	--	5% - 7.5%
Virginia (CIP Repairs)	--	--	0.45	--	5.0% -9.0%
^a Reference (Morcous et al., 2013) *Unless other specified, due to min. compressive strength requirement (Class AA concrete with D _{max} = ¾") Note: 1 lb/yd ³ =0.59 kg/m ³					

Table 2-3 SCM for Cast-In-Place SCC

State DOT	SCM for Cast-In-Place SCC
Alabama ^a (Drilled shafts)	Class C or F Fly Ash: $\leq 30\%$; Slag: 25% - 50%
Colorado ^a (Limited CIP)	Class F Fly Ash: 30% - 40%
Nebraska ^a	Class F Fly Ash: 25%
Pennsylvania (Drilled Caissons)	GGBFS 25%, Fly Ash 15%, Silica Fume 5% - 10%, total replacement shall not exceed 40%
Utah	Minimum 20% Class F Fly Ash; GGBFS can be used up to 50%
Virginia (CIP Repairs)	Class F and C Fly Ash or slag conforming to the requirements of ASTM C618 and ASTM C 989

^a Reference (Morcous et al., 2013)

Regulation of Aggregate Gradation in SCC

It is also common to specify the aggregate gradations for SCC; in general, SCC includes a smaller aggregate size than TVC. SCC provisions typically utilize a maximum aggregate size at or around $\frac{3}{4}$ inches. Some requirements imposed by state agencies related to the use of aggregates in SCC are summarized in Table 2-2.

A brief description of SCC regulations for aggregate gradation from some states are summarized below:

- Illinois DOT specifies aggregate gradations that have a maximum aggregate size of either $\frac{3}{4}$ " or $\frac{1}{2}$ " for typical SCC mixes, but does allow for a gradation that has a maximum aggregate size of 1" provided the contractor provides evidence that the mix will not segregate.
- New Jersey DOT appears to give the flexibility to use No. 57, No. 67 or No. 8 coarse aggregate gradations.
- Illinois DOT and New Jersey DOT specify a fine aggregate to total aggregate proportion of at most 50% by weight.
- Montana DOT specifies an aggregate gradation in which 90-100% of the coarse aggregates pass the $\frac{3}{4}$ " sieve.
- Utah DOT specifies two aggregate gradations for SCC that has either 95% of the total aggregates (including fine aggregates) passing the $\frac{3}{4}$ " sieve or 95% passing the $\frac{1}{2}$ " sieve.

Maximum coarse aggregates size is limited to 1/5th of the narrowest dimension between sides of forms, 1/3rd of the depth of slabs or 3/4th of the minimum clear cover between reinforcement (Utah DOT, 2012)(Section 03056).

Regulation of Chemical Admixtures in SCC

The use of chemical admixtures related to cast-in-place SCC were specified by many state agencies, such as Alabama, Florida, Iowa, Montana, Nebraska, New Jersey, and South Dakota. Generally, it is recommended to adhere the manufactures' instructions. Additionally, Rhode Island DOT states that the admixture content for SCC shall be within 3% (by weight) of the manufacturer's recommended dosage. Iowa DOT requires manufacturer-produced documentation of compatibility between VMA and HRWR in cases where VMAs are used. State agencies chemical admixture regulations for cast-in-place SCC are shown in Table 2-4.

Table 2-4. Requirements for Cast-In-Place SCC Chemical Admixtures

State DOT	Chemical Admixture Recommendations
Alabama^a (Drilled shafts)	Type D, Type F, VMA
Florida^a	Type F, and VMA
Iowa^a	HRWR, VMA
Missouri^a (Drilled Shafts)	AASHTO M194 Type F or G PC-HRWR, ASSHTO M194 VMA
Nebraska^a	Type B, Type F, and VMA
New Jersey^a	Type F, VMA
South Dakota^a (Box Culverts)	VMA, PC-based HRWR
Utah	AASHTO M194 HRWR, ASTM C 494 Type S VMA
Virginia (CIP Repairs)	HRWR, VMA

^a Reference (Morcoux et al., 2013)

Air Content Requirements for SCC

Air content is an important parameter for a given concrete which can be correlated to its freeze-thaw durability. The target air content for SCC is prescribed for Utah, Montana and New Jersey, while the target is project-dependent for Rhode Island; in Illinois the air content requirement for SCC is treated the same as for traditional concrete. Many state agencies have

placed restrictions on both minimum and maximum air content within a mix. A summary of those state agencies requirements for air content of SCC in cast-in-place applications is shown in Table 2-2.

Fresh Property Requirements for SCC

Illinois Special Provisions dictate a contractor-specified slump flow target value within the range of 20 inches to 28 inches. UDOT gives a permissible range for slump flow of 18 inches to 32 inches, while MDT allows a range of 18 to 26 inches. NJDOT gives an acceptable range of 21 ± 3 inches for drilled shaft SCC. Rhode Island and Alabama specifies that all SCC should be in the range of 23 ± 3 inches. Virginia DOT specifies a slump flow of mixture to fall between 25 inches to 28 inches. Iowa also allows the contractor to specify a slump flow that is application appropriate, so long as the maximum spread does not exceed 27 inches; larger spreads may be approved with the use of a VMA, though. In the NJDOT Standard Specifications, it is also required that the drilled shaft SCC retain a spread of at least 14 inches for a period of one hour more than the contractor's proposed duration of construction. Nebraska DOR requires a spread of 22 inches to 29 inches while FDOT specifies a spread of 24 inches to 30 inches. WVDOT specifies a 19 inches to 23 inches spread.

The maximum permissible J-Ring value for SCC per the California, Florida, Colorado, Illinois, Rhode Island, and Pennsylvania Standard Specifications is 2 inches. New Jersey and West Virginia require a J-ring value of less than 1.5 inches. IDOT also specifies a minimum allowable L-box blocking ratio of 80%.

Illinois, New Jersey, Utah, and California specify both fresh and hardened visual stability indices of at most 1; Alabama allows for a maximum fresh VSI of 1.5, while Iowa DOT specifies a maximum fresh VSI of 2, and may consider hardened VSI for mix acceptance. UDOT and PennDOT also specify a fresh VSI requirement of at most 1.

Discussion of Fresh Property Requirements

Table 2-5 summarizes the fresh property requirements for SCC from each state mentioned in this section. Many of the states simplified the AASHTO or ASTM tests to eliminate some of the inconsistencies that might occur when using these standards; for instance, ASTM C 1611 allows either an inverted or an upright Abrams slump cone to perform the slump

flow test, which could give slightly different results. All states require slump-flow testing to characterize the workability of the SCC in the fresh state. However, there is a discrepancy between states in the way that the target slump flow is prescribed for a given project. Some, such as Illinois and Iowa, allow the contractor to define the target for a particular application, while the range is predetermined in Rhode Island, Virginia, and New Jersey specifications.

Table 2-5. Comparison of SCC Fresh Property Requirements by State

	Slump Flow, inches	VSI	J-Ring Value, inches	L-Box Blocking Ratio	Hardened VSI	Static Segregation
Illinois	22 to 28	≤ 1	≤ 2	$\geq 80\%$	≤ 1	--
Utah	18 to 32	≤ 1	--	--	--	<10%
Montana	18 to 26	--	--	--	--	--
New Jersey	21 $\pm$ 3 (Drilled Shaft) 26 $\pm$ 2 (Precast Structural)	≤ 1	≤ 1.5	--	≤ 1	--
Rhode Island	23 $\pm$ 3	--	≤ 2	--	--	--
Iowa	27 Max.	≤ 2	--	--	may be considered	--
California (precast)	20 Min.	≤ 1	≤ 2	--	--	<10%
Alabama (Drilled Shafts)	21 $\pm$ 3	≤ 1.5	--	--	--	--
Colorado	28 $\pm$ 2	--	≤ 2	--	--	<10%
Florida	24 to 30	≤ 2	≤ 2	--	--	--
Nebraska	22 to 29	≤ 1	--	--	--	--
Pennsylvania (Drilled Caissons)	20 - 30	≤ 1	≤ 2	--	--	12% Max.
Virginia (CIP repairs)	25 - 28	--	--	--	--	--
West Virginia	21 $\pm$ 2	≤ 1.5	≤ 1.5	--	--	--

Furthermore, New Jersey DOT requires workability retention testing to ensure that the SCC maintains desirable fresh characteristics throughout construction. This brings about an interesting debate as to whether it would be better to try to develop a “one size fits all” set of parameters that produces an SCC that could work in all but extreme situations or if it is better to specify desirable SCC properties on a case-by-case basis. West Virginia DOT’s specifies self-consolidating concrete in a drilled caisson special provision with the range of fresh properties based on different classes of concrete mixes.

From what was seen in these provisions, only Illinois, New Jersey, Rhode Island and California give specific performance criteria for the passing ability of the SCC, although Utah and Virginia do not require submission of this behavior for mix qualification. IDOT, NJDOT and RIDOT issue a maximum J-Ring value for the mix, with IDOT also using the L-box test as a measure of the flowability of the SCC along with the passing ability.

Typically, in cases where the VSI is required to assess the dynamic stability of SCC, a range of 0 to 1 is deemed to be acceptable, with 0 indicating no noticeable instabilities of the SCC. Iowa allows a value of up to 2 for the fresh VSI, which indicates slightly more noticeable non-uniformities of the SCC during transport and in the slump-flow patty. Illinois, New Jersey and Iowa also include considerations for the Hardened VSI, which gives an indication of the propensity of the SCC to segregate.

Hardened Property Requirements

Concrete compressive strength is also specified in some of the cast-in-place and precast SCC applications. The specified values for hardened SCC properties are given in Table 6. In general, the compressive strength requirement for cast-in-place applications varies from 4,000 psi up to 7,000 psi, depending on the application type.

Table 2-6. Comparison of SCC Hardened Property Requirements

	Compressive Strength, psi
Alabama (Drilled Shaft)	4,000 @28 days
Colorado	4,500 @ 28 days
Illinois (precast)	4,500 @ 14 days
Nevada	6,000 @ 28 days
Missouri (Drilled Shaft)	4,000 @ 28 days
Pennsylvania (Drilled Shaft)	3,300 @ 28 days
California (Precast)	Specified + 600
South Dakota (CIP Box Culvert)	4,500 @ 28 days
Nebraska	6,000 @ 28 days
Virginia (CIP repairs)	Min. 3,000 @28 days Max. 7,000 @28 days
West Virginia (Drilled Caisson)	4,500 @ 28 days

Although mix qualification procedure varies between DOT's, an experimental batch is typically required. This experimental batch is typically tested for properties such as slump loss retention, flowability, air content, and segregation resistance. Some state agencies mix qualifications are listed below in detail.

State Provisions for Mix Qualification

Illinois Special Provisions for cast-in-place SCC require that a Level III PCC Technician submit the SCC mix design. A trial mixture must be tested by the contractor and is required to verify that the mix design will meet specification requirements; no required time frame with respect to construction is indicated for this mix. This mix design shall have a slump flow that is “near the proposed target slump flow”. IDOT also requires production of a trial batch using the specified admixture dosages. For this trial batch (minimum of 2 yd³), the slump flow must be within 1.0 in. of the maximum and the air content is required to be within the top half of the allowable specification range. This batch is to be performed in the presence of the Engineer and scheduled at least 21 days prior to its anticipated use. A new trial batch is required with new sources of component materials or proportions (exceptions: normal field adjustments, dosage of SCC admixture, batch sequence, mixing speed and time, or as determined by the Engineer).

UDOT requires a trial batch (for all concrete) composed of the same components as will be used in the project, with a UDOT representative present to witness the trial batch. MDT also requires submission of a mix design along with certifications and test results showing that the design meets the specified requirements. VDOT specifies a qualified SCC technologist must design and determine the proportioning of mixes since no standardized SCC mix design method exists for the VDOT. Admixture suppliers can also assist in determining the mix design for a project.

FDOT requires that a laboratory trial batch of the SCC mix design to be used be created in the presence of a representative from the admixture manufacture. Additionally, SCC property testing including density, VSI, T₅₀, J-Ring, etc. must be performed. The workability of the SCC must be determined by performing a slump flow test until the mix's spread drops below 5.0 inches. Using the results, a slump flow loss curve must be used to determine the cut-off time for

the lower tolerance to ensure mixing, placement, and transit times that will not cause unacceptable workability. The producer must also submit test cylinders to the State Materials Office for testing in accordance with FM 5-578.

According to SDDOT, the average concrete compressive strength of the mix design must be 1,200 psi more than the minimum 28-day compressive strength. Trial batches are required in order to satisfy the performance of the proposed mix design by laboratory tests. Tests must be conducted in accordance with the ACI 211.1, ACI 318, and ASTM C 192 with the exception that the air content shall be within $0.5\% \pm$ of the maximum specified. The Contractor is responsible to provide the test results when the mix design is submitted for a certain project.

NJDOT requires a single mix for verification of concrete properties (slump flow, air content, plastic VSI, hardened VSI and compressive strength). This should be done at least 45 days prior to the start of concrete placement. The air content and the slump flow of the SCC for drilled shafts should be in the top half of their respective allowable range for this verification batch. As was mentioned previously, the contractor must also establish that the SCC will have sufficient workability retention. NJDOT also requires a verification of pumpability for drilled shaft SCC in which the air content, slump flow, fresh VSI and hardened VSI need to meet their respective requirements after pumping; verification of pumpability should be done at least 10 days prior to use.

As with other concrete mixes, RIDOT requires approval of the mix design at least 60 days prior to production based on limited data, encompassing primarily batch quantities, fresh properties and compressive strength data. Upon initial approval, trial productions are required to ensure that the SCC satisfies requirements for fresh properties (slump flow, J-Ring) and hardened properties (compressive strength); at least 48 hours' notice are required to allow the Engineer to witness the production and to collect samples for compressive tests. Any changes in materials would require re-approval of the mix design by the Engineer.

Iowa DOT requires the producer to first report the properties of new SCC mixes, as obtained through trial batches produced within 2 inches of the target slump flow, for approval of their use; it is recommended that an admixture representative is present based on the producer's experience level with SCC. The properties of the new mix will then be validated in the presence

of the district materials engineer and the admixture representative. For ready mix applications or for mixers larger than 2 yd³, the minimum batch size for the mix verification is 2 yd³; if the capacity is less than 2 yd³, the minimum batch size for the mix verification is 1 yd³. The slump flow for this batch shall be within 1 inch of that required for use in production.

Discussion – State Provisions for Mix Qualification

While all states mentioned above require testing of the SCC material properties prior to use in construction, some states require that a verification batch be cast in the presence of DOT representatives using the actual materials and equipment that will be used for production. This verification batch will not only act as a verification of the reported properties, but it will ensure that the SCC mix design, which is typically derived in smaller batches, will translate well to production on a larger scale.

Similar to WVDOT's current materials procedures for mix qualification of concrete (MP711.03.23), Illinois and New Jersey implore more strict range of workability and air content for qualification than for production. New Jersey simply reduces the acceptable tolerances for the target slump and air content, while Illinois requires that these values fall within the top half of their allowable specification range.

Illinois and Iowa specify that the verification batch should be at least 2.0 yd³, provided the production equipment has sufficient capacity. Since SCC for cast-in-place applications would likely be transit mixed in large trucks, lower capacity mixers should not be of concern for cast-in-place SCC provisions.

As was the case with mix qualification testing, each state takes a slightly different approach to the site acceptance of SCC. A summary of the information gathered from state agencies related to current site acceptance practices is described below.

State Provisions for Site Acceptance

For cast-in-place SCC, IDOT requires testing of slump flow ($\pm 2''$), VSI, and J-Ring or L-box tests (Contractor's choice) for the first two trucks, and every 50 yd³ thereafter. IDOT allows testing of air content, strength and temperature per contract documents, but specifies a hardened VSI test for the first truck delivery of the day, and every 300 yd³ thereafter.

UDOT requires testing of slump flow, air content, temperature and compressive strength; Standard Specification refers to UDOT Minimum Sampling and Testing Requirements, which do not make any distinctions for SCC, for frequency of testing.

Montana DOT requires compression testing at 7 and 28 days; two samples are required for each test. No sampling rates are given specifically for SCC.

NJDOT requires testing of slump flow and air content at a minimum initial rate corresponding to the batches from which compressive specimens are collected: 3 times per lot (a minimum of 1 lot per concrete type per day).

Nevada Department of Transportation (NDOT) requires the testing of the slump flow and VSI of SCC within the first two trucks, and thereafter at a rate of once per every 50 yd³ of concrete delivered. J-Ring, air content and sampling for compressive specimens should be done at a rate of once per 100 yd³ of concrete placed, while unit weight should be done once every 200 yd³.

WVDOT special provision requires on-site testing of each truckload of SCC concrete for spread, Visual Stability Index, T₅₀, J-ring value, air content and casting of three specimens for 28-day compressive strength testing and two for hardened VSI determination.

SDDOT requires all the fresh concrete tests to be performed for the first three mixer trucks of every concrete placement by sampling the concrete after 5 gallons of concrete has been discharged from the truck. The slump flow and the J-Ring shall be performed at the same time or consecutively within two minutes. Slump flow and temperature must be tested at every truck

and J-Ring must be performed once out of every two trucks. Air content and unit weight must be measured once out of every four trucks.

VDOT specifies the mix must remain with the specified slump limits during the entire placement, extended delay that allows the preceding load to lose flow and not combine with the next load is unacceptable and will be cause for rejection.

RIDOT's only additional requirement for acceptance, based on their 2011 approved specification, is that the slump flow of SCC must be within 23 ± 3 inches.

Iowa DOT specifies slump flow testing on the first load of SCC, and every 3rd batch thereafter. The acceptable tolerance for slump flow is ± 2 inches, and a VSI rating of 1 is accepted; if the VSI is 2, the concrete shall be retested to ensure acceptance (2 or less), while a VSI of 3 will be rejected. Air content should be tested at a rate consistent with other types of concrete.

Discussion – State Provisions for Site Acceptance

The slump flow test is almost universally used as an indicator of an SCC mix's flowability, and due to its relative quickness and ease of performance, this test is very suitable for performance in the field. It is therefore used in all state agencies listed above that have SCC provisions include the slump flow test as their primary field assessment of concrete quality. The tolerance used for field acceptance by Illinois, West Virginia, and Iowa is ± 2 inches, while Rhode Island and New Jersey use ± 3 inches.

The rates of testing and sampling vary by state, however both Illinois and Nevada require testing of slump flow and VSI for the first two batches of SCC, followed by fresh property testing once per every 50 yd³ of concrete delivered thereafter; both also require J-ring and air content tests every 100 yd³. South Dakota recommends extensive fresh property testing during the first three truck deliveries. Following the consecutive approval of three trucks, testing frequency decreases for all fresh property testing excluding testing of slump flow and temperature. In general, the sampling rates for compressive strength specimens are the same as for traditional concrete.

Illinois, Rhode Island, West Virginia, South Dakota, and Iowa all have discussions within their guidelines for mixing and placing SCC. Alternatively, the document sources from Utah, Montana, New Jersey and many other states may not give specific guidelines for the mixing and placing of SCC beyond those for traditional mixes.

Mixing Procedures

IDOT specifies a minimum of 100 revolutions of a truck mixer for truck-mixed or shrink-mixed SCC. Also, the specifications required that the “batch sequence, mixing speed, and mixing time shall be appropriate to prevent cement balls and mix foaming for central-mixed, truck-mixed, and shrink-mixed concrete.” SDDOT specifies that the mixing of SCC must be done continuously in the concrete truck and must be discharged within 90 minutes.

WVDOT specifies the concrete truck must mix the SCC at a rate of 1-2 revolutions per minute during transport. Upon arrival at the construction site, the SCC must be agitated at mixing speed for a period of at least 3 minutes before testing and discharge. The total number of revolutions of the mixing drum from the time the cement is added to the aggregates until expulsion shall not exceed 300 revolutions.

Placement of SCC

If deemed necessary by the Engineer, under Iowa DOT provisions, a mock-up section must be produced for the verification of placement procedures. Iowa DOT instructs the contractor to deposit SCC “continuously or in horizontal layers of such thickness that no new concrete will be placed on concrete that has hardened enough to cause seams or planes of weakness,” and continues that construction joints should be formed in the case that a section couldn’t be placed continuously.

Some guidelines address restoring workability to SCC on site. IDOT does allow excitation of concrete that has lost its fluidity before the next placement by rodding with a piece of lumber, conduit, or vibrator (pencil head type, maximum 1 inch diameter). RIDOT cites current placement and finishing practices for SCC, with the exception that a “minimal amount of concrete vibrating is necessary to prevent segregation.” Iowa DOT prohibits re-tempering or vibrating of SCC without permission of the Engineer; if vibration is allowed, the maximum

insertion time during vibration is two seconds. In addition to the prospect of vibrating SCC, Iowa DOT gives the Engineer the authority to allow “other methods of consolidation,” if deemed necessary.

VDOT specifies a concrete technologist familiar with SCC be present during placement. An extended delay that causes load to lose flow and not combine with the next load is unacceptable and is cause for rejection. Ready mix concrete producer must supply concrete in such that continual placement of concrete occurs. Concrete shall be poured from one side to the other or pumped from the bottom upward so as not to encapsulate air.

SDDOT requires constant rate of delivery with a 30-minute maximum interval between batches. Set-retarding admixtures can be added to control the initial batch and when set retarding admixtures are used, the concrete delivery requirements may be adjusted. The contractor shall use the manufacturer’s recommendations and record the exact amount of admixtures that is added in the field. The surface temperature of forms, steel, and adjacent concrete, which will come in contact with the concrete being placed, must have a temperature above freezing before placement. Concrete placement on a frozen foundation is not allowed. The slope of chutes for placement must allow the concrete to flow at a speed, which does not cause segregation. Also, free fall of concrete shall not exceed 5 feet (1.5 meters). The use of drop tubes or tremies is encouraged to limit drop height experienced by the concrete. When a concrete pump is used, free fall of concrete is limited to 1 foot. The maximum horizontal flow distance is 30 feet. The Contractor is not permitted to vibrate the SCC. However, limited vibration may be allowed, when necessary, as approved by the Engineer.

Nebraska specifies SCC can be placed using a pump, skip, or chute. If there is an unanticipated interruption during placement and the concrete mix begins to set, it may be necessary to excite the placed concrete before resuming the casting operation by striking a stick or a board into the concrete.

IDOT limits drop height during placement of SCC to no more than 5 feet (tremie may be used to meet requirement if necessary), and the horizontal flow distance from point of deposit to no more than 25 feet. Iowa DOT dictates that drop distance shall be validated to ensure segregation does not take place, but guidelines do not state that this validation should take place

prior to mix approval, such as during the mix acceptance process. IDOT also requires removal of plastic concrete if mix foaming or other potentially detrimental material is observed during placement or upon completion of the pour.

Formwork Pressure

IDOT Special Provisions require monitoring of formwork pressure for forms greater than 10 feet in height to ensure the pressure does not exceed the maximum allowed. NDOT Construction Guide notes the possibility for increased formwork pressure when using SCC, but does not give specific instructions for its consideration.

SDDOT specification for box culverts specifies formwork must be complete and joints must mortar tight. The specification also states that forms should contain sufficient rigidity to maintain shape and resist form pressure. SDDOT and NDOR specify the SCC formwork must be designed for full hydrostatic pressure. Additionally, the form joints must be adequately sealed to prevent possible mortar leakage.

Discussion – Mixing, Delivery and Placement of SCC

From the document sourced of specifications, the instructions for mixing SCC were typically not extensive. IDOT gives a minimum number of revolutions for SCC, and instructions to avoid balling and foaming. Other provisions, such as the addition of admixtures in the field, tend to follow along with those already in place for traditional concrete, with the exception of Iowa prohibiting re-tempering of the SCC in the field.

Iowa mandates either continuous placement or planned construction joints as means for preventing cold joints from occurring due to a stiffening of the SCC. In cases of premature loss of workability, for instance, Illinois, Rhode Island and Iowa all allow minimal excitation (with the Engineer's approval) to ensure no cold joints form. It was seen in our previous test results (Baranowski, 2010) that it is possible to vibrate a stable SCC mix without causing segregating, so minimal vibration seems to be a reasonable method for ensuring sufficient amalgamation of subsequent layers of SCC when necessary. ACI 237R-07 allows for a 2 to 3 seconds vibration duration when SCC has been placed onto previously placed SCC that has gelled but has not yet reached initial set.

To prevent segregation of SCC during placement, Illinois and South Dakota limits drop height (without tremie) to 5 feet, while Iowa requires a demonstration of the proposed drop height. Additionally, IDOT and SDDOT limit the horizontal flow distance to 25 feet and 30 feet, respectively.

Both IDOT and NDOT acknowledge the possible risk of increased formwork pressure due to the high fluidity of SCC. IDOT mandates formwork pressure monitoring for lifts above 10 feet when SCC is used. South Dakota and Nebraska also acknowledge the increased fluidity of SCC as being a potential issue by requiring that the formwork be designed for full hydrostatic pressure and be mortar tight at joints to prevent leaking.

CHAPTER 3 RAPID DETERMINATION OF W/CM RATIO

The water-to-cement ratio (w/cm) is often considered to be the most critical parameter of a concrete mix, the w/cm of a given mix is known to be inversely proportional to both strength and modulus of elasticity. Previous researchers have shown that a w/cm ratio increase of 0.01 causes a strength decrease of approximately 125 psi (Nantung, 1998). Additionally, the rate of strength development, porosity, and heat generation during hydration are directly related to the w/cm. For projects which are sensitive to small changes in water content such as mass concrete applications and SCC, an accurate determination of the w/cm could be used as a means of on-site quality control.

Often for traditional concrete slump is the only testing requirement which related to w/cm for on-site acceptance of a delivered concrete mix. Although a relationship exists between slump and w/cm, with the addition of chemical admixtures, mixes of the same w/cm ratio can often have widely varying slump values. For on-site acceptance of SCC, ASTM standard tests such as slump flow, J-ring, VSI are used to indicate the stability and flowability of a given mix. These tests cannot be used to accurately predict the mature strength or modulus of elasticity for a mix and may not indicate a mix which is borderline unstable. Many studies suggest that the stability of SCC is much more sensitive to water content as compared to traditional mixes, this implies that the w/cm of SCC should be more closely monitored as compared to traditional mixes.

While some state agencies require fresh property testing of SCC of every delivery, other agencies require property testing based on volume delivered (i.e. every 50 yd³) or at a given rate of trucks delivered. On-site determination of w/cm ratio could be particularly beneficial to states in which fresh property testing of SCC is not being performed on every truck load. These agencies could benefit by determining the probability that a delivered mix will not be within allowable limits defined by the sensitivity of a particular mix. Additionally, the w/cm data collected on-site can be used to determine the consistency of which a concrete supplier delivers mixes within acceptable limits to further improve the quality control process of cast-in-place projects.

SCOPE AND PURPOSE

The purpose of this chapter will be to determine if a readily available method exists in which the w/cm could be accurately and rapidly determined. The following sections outline the methods explored for potential implementation, the procedure used for experimentation, and the accuracy of the results. Conclusions and recommendations from this research can be found in Chapter 5 of this report.

METHODS FOR RAPID DETERMINATION OF W/CM

During a preliminary study of this research, four available methods for the determination of on-site w/cm were considered. The potential for each methods use as a means for on-site quality control were evaluated based upon the criteria of speed, accuracy, ease of use, implementation cost, and replicability.

Buoyancy Method

The first method considered was based upon Archimedes buoyancy principle. Archimedes' principle states "A body wholly or partly immersed in a fluid is buoyed up with a force equal to the weight of the fluid displaced by the object." An experiment was performed Naik and Ramme that demonstrated this method produced reasonable degree of accuracy with an average error of approximately 4.1 percent (Naik & Ramme, 1989). Their test method required that the specific gravity of the cement, cementitious material, aggregates, and admixtures be known prior to performing the experiment. To perform the experiment, an exact volume container must be partially filled with both water and a 22 pound fresh concrete sample. The air is removed by stirring to ensure the correct underwater weight is obtained of the sample. Next, the container is completely filled with water and foam generated during the stirring process is removed by skimming along the surface. The underwater concrete weight is then record and the w/cm ratio can be calculated. This method was not chosen as an ideal on-site quality control procedure due to the tedious nature of the test, requirement for a large level working surface, the relatively large required sample size, ergonomic demand (lifting approximately 40 lb), and the large variation which may be caused by a minor change in materials used in the batch. Additionally, the use of this method in testing a concrete mixes containing supplementary

cementitious material may result in a significant amount of materials being lost when striking off foam from the sample surface.

James Instruments' "Cementometer"

The second method considered involved implementing a device built by James Instruments known as the "Cementometer." This device is a handheld unit of approximately four pounds which can be used with a two probe attachment for w/cm ratio of 0.35 to 0.65 or five probe sensor which can be used for w/cm ratio's ranging from 0.25 to 0.5. The device measures the dielectric constant of the fresh concrete. The device comes with factory setting for commonly used concrete mixes with Type I, Type II, and Type III cements. Additionally, the Cementometer has the capability to be calibrated for a particular mixture materials by creating the mix at known w/cm, probing the sample, and then repeating the process while varying the w/cm at a certain intervals. Currently the cost of this unit with either the two or five probe sensor is approximately \$2,000.

Although the Cementometer is promising in many of the criteria previously discussed for field implementation such as cost, ease of use, ergonomic demand, and speed, some researchers have found that the accuracy of this device is not suitable for determining the w/cm in a quality control context. A research study conducted by Peterson and Sutter examined both the factory and user calibrated setting in measuring the w/cm. Their research found that little correlation was observed between the actual w/cm ratio and the output produced by the Cementometer for both the factory and user calibrated settings (Peterson & Sutter, 2011). The significant amounts and different types of chemical admixtures used in concrete mixes, as is the case in SCC, are believed to have significant effects dielectric constant of the concrete which is used by the Cementometer to determine w/cm may also yield inaccuracies. Based upon the reported accuracy of previous researchers and the concerns of the effects of chemical admixtures, the Cementometer was ultimately ruled out for the purposes of this experiment.

Rapid Curing of Samples Using Microwave Energy

The third method which was explored was derived from a study performed at MIT by Leung and Pheeraphan which involved rapid strength gain of concrete using microwave energy.

They found that relatively high early age strengths could be achieved within 4.5 hours for a w/cm ratio ranging from 0.40 to 0.55 with no deterioration as compared to the 7 day strength of samples cured at room temperature (Leung & Pheeraphan, 1995).

It was conceived that the procedure could be used to determine the w/cm based upon the strength gain of a sample after a given period time in a microwave oven at a relatively low power. Preliminary experiments were performed in the West Virginia University Concrete Lab using 2 inch mortar cube samples to determine if this method would be feasible for field implementation. Mortar mix designs with w/cm ranging from 0.35 to 0.50 were created to determine if a relationship could be established between microwave strength gain and w/cm.

Although it was found that this method could be used to decrease setting time of two inch mortar cubes to under an hour, ultimately it was abandoned due to required testing time and inconsistent strength values due to a breakdown of the internal structure of the cubes.

Gravitational Analysis using the Microwave Method

The fourth and final method which was examined for the purposes of this study was based upon Water Content of Freshly Mixed Concrete Using Microwave Oven Drying (AASHTO T 318 – 02). This method involved microwaving a fresh 1.5 kg sample in set intervals using a 900 watt or greater microwave. The weight of the sample is taken between each interval and is recorded. Whenever the change in weight is less than or equal to 1 gram, the testing is concluded and the total water content can be taken from an equation provided by the standard. Although this standard method does not directly yield the w/cm of a given mix, it can be determined if the properties of the mix are known.

Some researchers have studied the procedure with an encouraging degree of success. Peterson and Sutter found that the microwave method accurately predicted the w/cm and described the method as “promising” for on-site quality control (Peterson & Sutter, 2011). Additionally, Dowell and Cramer research showed that this test could be performed in under 30 minutes and still result in reasonable accuracy (Dowell & Cramer, 2010). Although some studies have been performed on traditional mixes, no research could be found to use of this method for SCC applications. Due to the microwave methods low implementation cost, ease of use, speed,

and relatively sample size, it was decided that this procedure would be further investigated to determine its accuracy and implementability for on-site quality control.

AGGREGATE SSD DETERMINATION PROCEDURE

With the aim to determine the w/cm ratio, it was believed that it would be critical to the success of the experiment to accurately determine the saturated surface dry condition of the aggregates to precisely batch a known w/cm mix and to accurately calculated w/cm. The saturated surface dry condition (SSD) is used to describe the condition in which the aggregates moisture content is in equilibrium within the mix. This means that the aggregates will not provide or take away free water from the mix. Whenever aggregates are below SSD, they will take moisture from the mix while the aggregates are above SSD, the aggregates will give moisture to the mix. The procedure used to determine the SSD of the fine aggregates was performed in accordance with Specific Gravity and Absorption of Fine Aggregate (AASHTO T 84) which is outlined below:

1. Weigh a clean, dry metal pan and record weight as PW. With the pan resting on balance, tare weight. Thoroughly mix the sand and obtain a sample size of approximately 1000g which passes the No. 4 sieve.
2. Dry the samples overnight in an oven set at 230 ± 9 °F. Cool the sample at for 1 to 3 hours. Weigh the sample + pan and record it as DW. After cooling, immerse the fine aggregate in water at room temperature for 15 to 19 hours.
3. Decant water from the sample surface, avoiding loss of fines. Spread on flat, even, non-absorbent surface and stir occasionally to ensure homogenous drying.
4. Place the cone apparatus in drying pan with largest diameter facing downward. Fill the cone until it is over flowing. Lightly drop the tamper to compact the fine aggregate into the mold using a drop height of 1/5 inch above the surface of the fine aggregates 25 times.
5. Remove loose sand from the base of the cone and lift the cone slowly, if the compacted fine slumps then the SSD condition has been achieved. If the compact fine aggregate retains its shape then continue mixing and drying the sample until SSD condition is achieved. Record the weight of the sample + pan as SSD Weight.

*Note – The behavior of the fine aggregates changes rapidly as it approaches SSD. Therefore, step 5 should be performed frequently as the fine aggregate moves closer to SSD condition.

The SSD can be expressed as a percentage value using the following equation.

$$SSD = 100 * \{[(SSDW - PW) - (DW - PW)] / (DW - PW)\} \quad \text{Equation 3-1}$$

Where:

SSDW = the saturated surface dry weight of the sample

SSD = the moisture percentage at which the aggregates are at SSD

PW = dry pan weight

DW = dry weight of the sample + pan

The materials used in performing this experiment included a metal cone with a minimum inner diameter of 40 mm, a largest inter diameter of 90 mm, and a center inner diameter of 45 mm. Additionally, a metal tamper of weight 350 grams with a diameter of 25 mm, a balance with an accuracy of 0.1 grams, and a steel drying pan with a weight of 488.4 grams. A large sample of natural sand (approximately 100 lb) which was used in all the delivered and laboratory batches, as described in the following sections, was obtained from Central Supply Company in Morgantown, WV. From this sand, a sample weight 1282.3 grams was taken and dried overnight at 230 °F. The sample dried weight of the sample was then determined to be 1218.2 g. Therefore, the moisture content of the sand was determined to be 5.3 percent.

The SSD experimental procedure was then conducted and it was found that the saturated surface dry weight (SSDW) of the sample was determined to be 1729.7 grams. Therefore, the SSD for the fine aggregates was then calculated to be approximately 1.9%. Figure 3-1 below shows the equipment used in this experiment and the SSD condition of the fine aggregates.

Figure 3-1 SSD Experimental Equipment and Fine Aggregates at SSD Condition

The procedure for determining the SSD for large aggregates is relatively simple as compared to the procedure required for fine aggregates. The procedure for determining the SSD of the large aggregates was performed in accordance with Specific Gravity and Absorption of Coarse Aggregate (ASTM C 127). The procedure which was followed is outline below.

1. First a sample of large aggregate to be tested is obtained. The required sample size is based upon the maximum aggregate size, since #67 which have a maximum aggregate size of one inch, a 3,505.2 gram sample was taken.
2. The aggregates were dry sieved using a #4 sieve to remove any excess particles. The sample was placed onto a metal tray weighing 488.4 grams into an oven set at 230 °F overnight to dry.
3. Upon overnight drying, the sample + pan were weighed. The dried sample weight was found to be 3338.3 grams which indicated that the moisture content of the large aggregates was approximately 0.5%.
4. The samples were then allowed to cool for approximately 2 hours. The sample was then submerged in water at room temperature overnight.
5. The following morning the samples were dried using a clean towel and fan was blown across the samples. The weight was taken every twenty minutes until no weight change

was observed. The final SSD weight was determined to be 3505.9 grams indicating that the SSD of the large aggregate is approximately 0.5%.

MICROWAVE METHOD PROCEDURE

The ultimate goal of this experiment would be to determine if the microwave method could accurately predict the water content which would be used to back calculate the w/cm ratio for both traditional concrete mixes and SCC. The rapid on-site determination of the w/cm could be used in projects which are sensitive to changes in w/cm such as mass concrete applications and SCC. Additionally, ready mix concrete suppliers, construction management entities, and state agencies could all use data collected over a period of time to determine the reliability that a given batch will be delivered with an acceptable tolerance.

The required material for this experiment includes a microwave oven with a strength greater than or equal to 900 watts, a heat-resistant, microwavable glass tray capable of holding a 1600 gram sample, a balance with an accuracy of 0.1 grams or higher, and a grinding pestle. The procedure used for this experiment which is based on AASHTO T 318-02 is outlined below.

1. Determine the mass of the dry and clean glass tray and record its weight as WS.
2. Leave sample on balance and tare. Place 1500 ± 100 gram fresh specimen to be tested.
3. Determine the mass of the tray and freshly mixed concrete specimen and record its weight as WF.
4. Place tray and specimen on turntable microwave oven tray and microwave at the 900 Watt power setting for 5.0 ± 0.5 minutes.
5. At the end of the first drying cycle, the specimen shall be removed for no more than 60 seconds. During this time the large aggregate should be separated from the mortar using the grinding pestle and the mortar should be ground to break up any clumps and expose a maximum amount of mortar. Note - be careful to not lose any pieces of the specimen during mixing.
6. The specimen is then returned to the microwave for an additional 5.0 ± 0.5 min at the 900 Watt power setting. Remove the tray and specimen, stir the sample for no more than 60 seconds.

7. Return to microwave for 2.0 ± 0.5 min at the 900 Watt setting.
8. Remove the tray and specimen, lightly stir the specimen to expose mortar. Record the weight of the tray and specimen.
9. If the change in the weight of the tray is greater than 1 gram, repeat steps 7-9. If the change in the recorded weight is less than 1 gram, record the weight as WD and end the experiment.

Additionally, the method describes a calculation which can be used to determine the water content of the sample as a percentage which is shown below.

$$WC = \frac{100*(WF-WD)}{(WF-WS)} \quad \text{Equation 3-2}$$

Where:

WC = water content of the sample as a percentage

WF = mass of the tray + fresh test specimen

WD = mass of the tray + dry specimen

WS = mass of the tray + cloth

With knowledge of the distribution of the materials and assuming the sample is well mixed, the theoretical amount of each material in the sample can be estimated using the percentage of that material within the mix. For example, if mortar mix created in the laboratory experiments the total material batched is 2640 grams and that the fine aggregate is 1755 grams, the percentage of fine aggregate is calculated to be approximately 66.5% of the mortar sample. By multiplying the theoretical content of each material by the sample size, it can be estimated how much of each material is present within the sample.

These calculations can be used to determine the amount of free water present as opposed to the total evaporable water. The w/cm ratio of the concrete or mortar mix would be determined by dividing the calculated free water by the theoretical cementitious material content within the sample.

For the purposes of this experiment, all water was assumed to be recoverable. Although a fraction of the free water will begin reacting with the cement upon mixing, it is assumed that during the relatively short period an insignificant amount of water will be lost.

Using the above described process, the w/cm ratio of a mix can be calculated following the input of weight. A spreadsheet was developed to calculate the theoretical cement content, fine aggregate, and large aggregate as well as the total water and free water within the sample. This spreadsheet uses the data taken from the weight changes to determine the calculated w/cm at each step of the experiment. An example of the spreadsheet used throughout these experiments is attached in Appendix C.

LABORATORY TESTING OF MORTAR

Preliminary testing to determine if this procedure could be used to produce reasonable accuracy which would be sufficient to further investigate as a potential quality control measure. To do this, two small scale batches of mortar were created in the laboratory. The fine aggregate was oven dried overnight prior to testing such that an additional amount of water was added to account for water absorption to achieve the correct w/cm. The mix design for these mortar batches created in the laboratory is shown in the Table 3-1.

Table 3-1 Laboratory Mortar Mix

Mortar mix with w/cm of 0.50	
Material	Grams per batch
Cement	589.7
Fine Aggregate	1755
Water*	294.9
*Additional 33.3 grams water added to account for 0% moisture in fine aggregates	

The first mortar testing trial ran for approximately 30 minutes, as the sample was microwaved for 26 minutes. The change in weight was assumed to come exclusively from

evaporable water. Using the change in weight of the sample, the total water content was calculated to be approximately 205.9 grams. The total free water of the sample available to mix with cement was determine by subtracting the theoretical fine aggregate content multiplied by the SSD of the fine aggregate as shown in the equation below.

$$SFW = \Delta W - \left[\frac{SW * MFA * SSDFA}{MTW} \right] \quad \text{Equation 3-3}$$

Where:

SFW = sample free water (grams)

ΔW = total weight change over experiment (grams)

SW = sample weight (grams)

MFA= mix design fine aggregates content (lb/yd³)

MTW = mix design total weight (lb/yd³)

SSDFA = saturated surface dry of fine aggregate (1.9% for current experiment)

Similarly, the equation which will be used to calculate the free water within the concrete samples was done by subtracting both the theoretical fine aggregate content multiplied by the fine aggregate SDD and the theoretical large aggregate multiplied by the large aggregate SDD. This process is represented in equation form below.

$$SFW = \Delta W - \left[\frac{SW * MFA * SSDFA}{MTW} \right] - \left[\frac{SW * MLA * SSDLA}{MTW} \right] \quad \text{Equation 3-4}$$

Where:

SFW = sample free water (grams)

ΔW = total weight change over experiment (grams)

SW = sample weight (grams)

MFA= mix design fine aggregates content (lb/yd³)

MTW = mix design total weight (lb/yd³)

SSDFA = saturated surface dry of fine aggregate (1.9% for current experiment)

MLA= mix design large aggregates content (lb/yd³)

SSDLA = saturated surface dry of large aggregate (0.5% for current experiment)

After the free water in the sample is determined, the theoretical cementitious can be readily calculated using the process described above. The equation used to determine the cementitious content is shown below.

$$CMS = \frac{MC * SW}{MTW} \quad \text{Equation 3-5}$$

Where:

CMS = theoretical sample cementitious content (grams)

MC = mix design cementitious content (lb/yd³)

SW = sample weight (grams)

MTW = mix design total weight (lb/yd³)

The calculated w/cm ratio can then be found using the following equation.

$$\text{Calculated } w/cm = \frac{SFW}{CMS} \quad \text{Equation 3-6}$$

Where:

SFW = sample free water (grams)

CMS = theoretical sample cementitious content (grams)

The error of the test results with relation to the actual w/cm is calculated using the equation shown below.

$$\% \text{ Error} = \frac{\text{Calculated } w/cm - \text{Actual } w/cm}{\text{Actual } w/cm} \quad \text{Equation 3-7}$$

By dividing the sample free water by the theoretical cementitious content, the theoretical w/cm ratio can readily be calculate at each step of the experiment. When the change in weight of

a given sample is less than 1 gram, the experiment is stopped and the final calculation of the w/cm is performed. The same process and equations were repeated for the second laboratory mortar mix which took approximately 32 minutes to complete with 28 minutes of microwave time. The maximum error observed during the trials was 2.5%. The average of the magnitude of the error was found to be 2.0%. The results from this experiment are shown in Table 3-2.

Table 3-2 Preliminary Mortar Testing Results

Mortar Sample with w/cm of 0.50							
	Sample Size (g)	Sample Free Water (g)	Theoretical Cementitious Content (g)	Actual w/cm	Calculated w/cm	Difference	Error %
Mortar Test 1	1500.0	187.3	365.4	0.50	0.512	-0.012	2.5
Mortar Test 2	1505.0	165.6	336.2	0.50	0.493	0.007	-1.5

Additionally, a plot created using data generated after each weighing interval for w/cm vs microwave time from the second mortar trial is shown below.

FIELD TESTING OF CONCRETE AND SIEVED MORTAR

Following the success of the preliminary mortar experiments, it was decided to proceed with testing to determine if the method could be used to accurately predict the w/cm in the field. To perform this, the experiment was to be conducted on concrete delivered to West Virginia University's Concrete Lab. The concrete mixes being delivered to the laboratory were to be used in mass concrete research which is sensitive to slight changes in w/cm (i.e. early age strength and heat of hydration predictions) and therefore could benefit from the rapid testing of the fresh concrete's w/cm.

Figure 3-2 Calculated w/cm vs. Microwave Time

Following the preliminary tests, it was conceived that mortar samples potentially could produce more accurate results in the field. Therefore, a method was developed in which mortar would be extracted from fresh concrete by using a No.4 sieve. The sieved mortar would then be tested using the same procedure as the concrete samples to determine if this method achieved greater accuracy. Each batch of concrete would be tested using two concrete and two mortar samples, the results would then be compared to the manufactures provided data sheet to determine the accuracy of the method.

This method was tested on three delivered batches of traditional concrete and one laboratory batch of SCC. Although SCC is produced with relatively high amounts of chemical admixtures compared to traditional mixes, it was assumed that the increase in moisture from these admixtures could be ignored due to the relatively low dose when compared to the free water amount present with the mix. Additionally, the effects of the high range water reducer on the free water within the mix could in additional water being absorbed into previously

inaccessible voids within the large aggregates. For the purposes of this experiment, these potential effects of the chemical admixtures were assumed to be negligible.

The table shown below outlines Mix Design 1 which is a slag mix design used in the first two experiment conducted testing the microwave method on delivered concrete. Approximately 5 cubic yards of concrete were delivered by a ready-mix truck to laboratory for the first experiment and approximately 4 cubic yards were delivered for the second. Both batches were delivered to be cast into a 4 ft x 4 ft x 4 ft cube for the purpose of researching temperature rise and distribution for mass concrete applications. The following tables also outline the concrete mix proportions which were provided by the concrete supplier.

Table 3-3 Mix Design 1 for Delivered Concrete

Mix Design 1 used for Field Experiment 1 and 2 with w/cm of 0.421	
Material	lb/yd ³
Cement	254.0
Slag	254.0
#57 Limestone	1795
Natural Sand	1384
Water	25.6*
Air Entertainer	0.4**
HRWR	6.0**
*Measured in Gallons	
**Measured in Oz/cwt	

Table 3-4 Manufacture Provided Mix Proportions
from Experiment 1

Provided Mix Data for 5 yd³ Delivered Concrete for Field Experiment 1	
Material	lb
Given w/cm	0.426
Cement	1270.0
Slag	1270.0
#57 Limestone	9065
Natural Sand	7167
Water	129.7*
Air Entertainer	10.0**
HRWR	77.0**
*Measured in Gallons **Measured in Oz	

Table 3-5 Manufacture Provided Mix Proportions
from Experiment 2

Given Data for 4 yd ³ Delivered Concrete for Field Experiment 2	
Material	lb
Given w/cm	0.452
Cement	1260.0
Slag	1250.0
#57 Limestone	9065
Natural Sand	7139
Water	136.2*
Air Entrainment	16.0**
HRWR	76.2**
*Measured in Gallons **Measured in Oz	

Table 3-6 shown below outlines Mix Design 2 which is a fly ash mix design used in the third conducted on delivered concrete. Approximately 4 cubic yards of concrete was delivered to laboratory. The purpose of this delivery was to determine material properties prior to casting an additional cube for testing. The following tables outline the concrete mix proportions which were provided by the concrete supplier.

Table 3-6 Mix Design 2 for Delivered Concrete

Mix Design 2 for Field Experiment 3 with w/cm of 0.424	
Material	lb/yd ³
Cement	340.0
Fly Ash	168.0
#57 Limestone	1780
Natural Sand	1360
Water	25.8*
Air Entrainment	0.56**
HRWR	3.00**
*Measured in Gallons	
**Measured in Oz/cwt	

Table 3-7 Manufacture Provided Mix Proportions
from Experiment 3

Given Data for 4 yd³ Delivered Concrete for Field Experiment #3	
Material	lb
Given w/cm	0.419
Cement	1360.0
Fly Ash	672.0
#57 Limestone	7191
Natural Sand	5761
Water	101.6*
Air Entrainment	11.38**
HRWR	60.96**
*Measured in Gallons	
**Measured in Oz	

To determine if this procedure would be effective in predicting the w/cm of SCC, a SCC batch of 1 cubic foot was created in the Concrete Lab at West Virginia University. The mix design used for the laboratory batched SCC is shown in Table 3-8. The procedure used to produce this mix is described in the following sections.

Table 3-8 Mix Design Used for Laboratory SCC

Mix Design 3 for Laboratory Cast SCC with w/cm of 0.30	
Material	lb
w/cm	0.30
Cement	27.22
Silica Fume	2.78
#67 Limestone	54.24
Natural Sand	51.83
Water	9.00*
Air Entrainment	13.3**
HRWR	88.7**
VMA	26.6**
*Additional water added to account for aggregate absorption	
**Measured in mL	

Prior to batching the SCC, the moisture content of the aggregates to be used in the experiment were calculated following Standard Test Method for Total Evaporable Moisture Content of Aggregates by Drying (ASTM C556). To test the moisture content, two 5 gallon buckets containing the natural silica sand which would be used were thoroughly mixed using a 3 cubic feet concrete mixer. Next, a 17.82 lb sample of natural sand and placed in a steel drying tray weighing 9.51 lb giving the tray and sand a weight of 27.33 lb. Additionally, the large aggregates to be used in the mix were placed into the 3 cubic feet mixer and a 21.64 lb sample

was placed in a steel tray weighing 9.52 lb giving the tray and sample a combined weight of 31.16 lb. The mixed large aggregate and natural sand were then sealed in 5 gallon buckets to prevent any moisture loss prior to batching. Both samples were placed in the oven overnight at 230 °F. The following morning the samples were removed from the oven, covered using plastic wrap, and allowed to cool for 1 hour, and then weighed. The natural sand and steel tray weight was recorded as 27.29 lb. The process was repeated for the large aggregates and the dried weight was recorded as 31.16 lb which indicated that the large aggregate experienced no change. The equation provide by ASTM C556 to determine the total evaporable moisture is shown below.

$$p = \frac{100(W-D)}{D} \quad \text{Equation 3-8}$$

Where:

p = total evaporable moisture content of the sample, %

W = mass of the original sample

D = mass of the dried sample

Using the equation provided by ASTM C556, the moisture content of the natural sand and large aggregate was calculated to be 0.22% and 0%, respectively. The SSD condition of these materials were measured previously to be 1.9% for the sand and 0.5% for the aggregate. With both types of aggregates being below their respective SSD moisture percentage, the resulting effect will be that the small and large aggregates will absorb moisture thus gaining mass and taking free water to react with the cement away from the mix. Therefore when batching, the mass of the natural sand was reduced by 0.22% and the mass of the water was increased by 1.68% of the mass of sand used in the mix. Similarly, the to account for the moisture of the large aggregate, and the mass of the water was increased by 0.5% of the mass of sand used in the mix.

The SCC batched in the laboratory was done in accordance with Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory (ASTM C192). This procedure requires that initially first a small portion of mixing water and the coarse aggregates be placed into the concrete mixing drum. The concrete mixer is then started as the fine aggregates, cement

and then the mixing water is added, if adding these ingredients while the drum is turning is impractical, the mixer may be stopped to add ingredients. Once every ingredient was added, the batch was mixed for 3 minutes, allowed to rest for 2 minutes, and then mixed again for 2 minutes. The air entraining agent was added to the sand prior to mixing while the VMA and HRWR were added during the final two minutes of mixing. A picture of the SCC batched in the laboratory is shown below, the SCC's low viscosity can be seen as it flows around the mixing drums' fins.

Figure 3-3 Mixing of Laboratory SCC

LABORATORY FRESH PROPERTY TESTING

To ensure that the SCC batched in the laboratory was a stable and therefore suitable for this experiment, the fresh properties of the mix were evaluated using testing standards provided by ASTM. While testing the air content of SCC is the same procedure as traditional concrete, other fresh property testing procedures are radically different due to the behavior of fresh SCC. The procedures and results of the fresh property testing performed on the laboratory batch are shown in the following sections.

The Standard Test Method for Slump Flow of Self-Consolidating Concrete (ASTM C1611) is used to evaluate filling ability and stability of a mix. This test involves placing an inverted slump cone on an impermeable, flat surface. The slump cone is then filled and excess material is removed from the testing surface. The inverted slump cone is then raised 9 ± 3 inches in 3 ± 1 seconds with a steady upward lift. Once the mixture has stopped flowing, the largest observed diameter and the orthogonal diameter are recorded. For the purpose of this experiment, the target slump flow for this mix was taken to be 24 ± 1.5 inches. The ASTM test standard for slump flow provides an equation to determine slump flow which is shown below.

$$\text{Slump flow} = \frac{(d^1 + d^2)}{2} \quad \text{Equation 3-9}$$

Where:

d^1 = the largest diameter of the circular spread of the concrete (in)

d^2 = the circular spread of the concrete at an angle perpendicular to d^1 (in)

During the testing of the laboratory SCC, the maximum spread of the mix was found to be 25 inches and the orthogonal spread was found to be 24 inches. Therefore, the slump flow was calculated to be 24.5 inches. An image showing the results of the slump flow testing is shown in Figure 3-4.

Figure 3-4 Slump Flow Testing Final Spread

Additionally, the time is recorded which the slump patty spreads to a 20 inch diameter, which is known as the T_{20} time, provides further insight into the viscosity of a mix. The T_{20} time of the laboratory mix was recorded to be 8.7 seconds. Typically, a T_{20} time of 4 to 10 seconds is taken as an acceptable viscosity.

Immediately following the conclusion of the slump flow test, the mix can be assigned Visual Stability Index (VSI) which is based upon the resistance of the mix to segregation. Based on the condition of the mix spread following the slump flow test, the mix is given a VSI value ranging from 0 – 3 with 0 being highly stable with no signs of bleeding or segregation and 3 being highly unstable with a clear segregation patty in the center and mortar bleeding. Examples of each stability value were developed by BASF Chemicals and is shown in Figure 3-5. For the purpose of this experiment, a VSI of ≤ 1.0 was deemed to be acceptable. Comparing the figure provided by BASF to the image of following the slump flow patty, a VSI of 0 was given to the laboratory mix. The procedures for this test method are illustrated in ASTM C1611.

Figure 3-5 Visual Stability Index Developed by BASF Chemicals

J-Ring Test

The Standard Test Method for Passing Ability of Self-Consolidating Concrete by J-Ring (ASTM C1621) is a test used to simulate flow of a SCC through congested reinforcement areas. The J-Ring testing apparatus is a 12 inch circular ring composed of 16 to 18 reinforcement bars, an inverted slump cone is then placed between the J-Ring apparatus on an impermeable, flat surface. To perform this test, the inverted slump cone is filled with SCC and excess amounts of materials are removed from the surface. The slump cone is then raised 9 ± 3 inches in 3 ± 1 seconds with a steady upward lift with no lateral or torsional movements. Once the SCC has finished flowing, the maximum spread is measure and recorded as d^1 , then the flow perpendicular to the maximum is measured and recorded as d^2 . ASTM test standard for J-Ring testing provides an equation to determine J-Ring flow which is shown below.

$$JRing\ flow = \frac{(d^1 + d^2)}{2} \quad \text{Equation 3-10}$$

Where:

d^1 = the largest diameter of the circular spread of the concrete (in)

d^2 = the circular spread of the concrete at an angle perpendicular to d^1 (in)

The J-Ring value is then calculated by subtracting the J-Ring flow the Slump flow to determine the passing ability of the mix. The ASTM testing standard defines the J-Ring values of 0 to 1

inch as “no visible blocking”, greater than 1 inch to 2 inches as “minimal to noticeable blocking” and greater than two inches as “noticeable to extreme blocking.” For the purpose of this experiment, a J-Ring value of less than 1.0 was deemed to be acceptable.

During the J-Ring testing of the laboratory SCC, the largest observed spread was 25.5 inches and the orthogonal spread was observed at 23 inches. Therefore, the J-Ring spread was calculated at 24.25 inches. Taking the difference between the slump flow and the J-Ring flow yields a J-Ring value of 0.25 inches indicating that no visible blocking had occurred. The image shown below shows the experimental setup prior to beginning the J-Ring test and the spread of the mix after performing the test. *Note that the moisture ring surrounding the SCC patty is due to moisture on the board and is not caused from bleeding of the SCC.

Figure 3-6 (a) Equipment used in J-Ring Experiment (b) Final J-Ring Spread

Fresh Air Content

Although it is assumed that the fresh air content would not directly affect the results of this experiment, it was performed on the mix as air entrained in SCC is thought to assist in the flowability by acting as a lubricant between mortar and aggregates. The fresh air content of the laboratory SCC was testing in accordance with the Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method (ASTM C231). For this experiment, a pressurized air meter was used. The experimental procedure outlined in ASTM C231 involves first cleaning the air meters chamber using a small amount of water. The excess water is then

removed from the air meter camber. Next, the air meters chamber is filled completely with the concrete sample and the excess concrete is struck off the top using a striker bar. The container's top edge is then cleaned using a damp rag or sponge. The top apparatus is then attached and sealed to the bottom chamber. Next, potable water is then pumped through the bleeder valve to remove any air trapped between the top apparatus and concrete sample. The chamber is then pressurized using a hand pump. The testing apparatus is then struck using a rubber mallet and the air content of the sample is displayed on the pressure gauge as a percentage. For the purpose of this experiment, the target air content was decided to be 5.0 ± 1.5 %. The testing of the SCC yielded a fresh air content of 3.5%.

Table 3-9 shown below summarizes the fresh property testing results of the SCC laboratory batch.

Table 3-9 Fresh Properties of Laboratory Batched SCC

Summary of Laboratory SCC Fresh Properties	
Slump Flow	24.5 in
T ₂₀	8.7 sec
J-Ring Flow	24.25 in
J-Ring Value	0.25 in
Air Content	3.5 %

EXPERIMENTAL RESULTS AND STATISTICAL ANALYSIS

The tables below show the results of the obtained experimentally using the microwave method for three delivered batches of concrete and one batch of SCC which was mixed in the Concrete Laboratory at West Virginia University. This table includes information from each experiment including the sample weight, the calculated free water, theoretical cementitious content of the sample, as well as the w/cm ratio provided by the manufacturer, and the calculated w/cm given determined from the mix design. Although the w/cm ratio of the provided data sheet

is inexact due to the variability of manufactures equipment, human error, etc., it was taken as the actual w/cm ratio for comparative purposes. Each delivered batch was tested four times, twice using concrete and twice using mortar.

Table 3-10 W/cm Results for Concrete Samples

Calculated W/cm of Concrete Samples from Field Experiment								
		Sample Size (g)	Sample Free Water (g)	Theoretical Cementitious Content (g)	Given w/cm	Calculated w/cm	W/cm Difference	% Error
Field Testing 1 (Cube #1)	Concrete Test 1	1500.7	84.5	196.5	0.426	0.430	-0.004	1.0
	Concrete Test 2	1490.1	87.7	195.1	0.426	0.450	-0.024	5.5
Field Testing 2 (Cube #2)	Concrete Test 1	1500.8	87.8	196.5	0.452	0.447	0.005	-1.1
	Concrete Test 2	1500.7	92.0	196.5	0.452	0.468	-0.016	3.6
Field Testing 3 (Cylinder Casting)	Concrete Test 1	1501.3	81.4	196.6	0.419	0.414	0.005	-1.2
	Concrete Test 2	1500.4	84.4	196.4	0.419	0.430	-0.011	2.6
Laboratory SCC Casting	Concrete Test 1	1536.0	92.9	317.6	0.300	0.292	0.008	-2.5
	Concrete Test 2	1505.4	86.3	311.3	0.300	0.277	0.023	-7.6

Table 3-11W/cm Results for Mortar Samples

Calculated W/cm of Sieved Mortar Samples from Field Experiment								
		Sample Size (g)	Sample Free Water (g)	Theoretical Cementitious Content (g)	Given w/cm	Calculated w/cm	W/cm Difference	% Error
Field Testing 1 (Cube #1)	Mortar Test 1	1501.6	146.7	365.8	0.426	0.401	0.025	-5.8
	Mortar Test 2	1500.8	155.3	365.6	0.426	0.425	0.001	-0.3
Field Testing 2 (Cube #2)	Mortar Test 1	1501.1	162.8	365.7	0.452	0.445	0.007	-1.5
	Mortar Test 2	1501.9	158.7	365.9	0.452	0.434	0.018	-4.0
Field Testing 3 (Cylinder Casting)	Mortar Test 1	1505.7	147.9	366.8	0.419	0.403	0.016	-3.8
	Mortar Test 2	1502.5	144.2	365.8	0.419	0.397	0.022	-5.5
Laboratory SCC Casting	Mortar Test 1	1515.3	146.3	486.7	0.300	0.301	-0.001	0.2
	Mortar Test 2	1500.1	136.7	481.8	0.300	0.284	0.016	-5.4

To gain further insight into the accuracy of both testing methods used in this experiment, the average values of the deviation of the given w/cm to the calculated w/cm, the average error, and the standard deviation of the data was calculated. The average values and standard deviation were calculated using the equations shown below. The results from this analysis are shown in the table below.

$$\mu = \sum x_i / n \quad \text{Equation 3-11}$$

Where:

μ = the mean of the data set

x_i = the value of each member of the data set

n = total number of values in the data set

$$\sigma = \sqrt{\frac{\sum (x - \mu)^2}{n-1}}$$

Equation 3-12

Where:

σ = standard deviation of the data set

μ = the mean of the data set

x_i = the value of each member of the data set

n = total number of values in the data set

Table 3-12 Average Magnitude of Error and Standard Deviation of w/cm Testing

Average Magnitude % Error and Standard Deviation of Microwave Testing Method		
	Average Magnitude w/cm Deviation (Calc. vs Actual)	Average Magnitude Error
Concrete	0.012	3.17%
Sieved Mortar	0.013	3.30%

Table 3-13 - Average Error and Standard Deviation of w/cm Testing

Average % Error and Standard Deviation of Microwave Testing Method				
	Average w/cm Deviation (Calc. vs Actual)	Standard Deviation of w/cm Deviation	Average Error	Standard Deviation of Error
Concrete	-0.0018	0.0151	0.01%	4.15%
Sieved Mortar	0.013	0.0096	-3.21%	2.42%

To determine the experimental correlation to the actual w/cm ratio, both methods were plotted were created using the given w/cm versus the calculated w/cm. These plots were created for both the sieved mortar and concrete samples using the data shown above. These plots were used to determine how closely correlate the data obtained during this experiment. The correlation value, R^2 value displayed on the plot, corresponds to the goodness of fit between the two data sets and ranges between zero and one. A value close to one implies a strong correlation while a

value closer to zero implies a poor correlation. As can be seen below, the both data sets can be shown to be closely correlated with the correlation being slightly higher for the concrete samples with an R^2 value of 0.9779 as compared to a R^2 value of 0.9771 for the sieved mortar samples.

Figure 3-7 Correlation Factor for Concrete Samples

Figure 3-8 Correlation Factor for Sieved Mortar Samples

Additionally, the errors resulting from each experiment are shown are plotted below. It is noted that 7 out of the 8 sieved mortar experimental trials under-estimated the w/cm. It can be seen from Table 3-13 that the standard deviation is significantly lower for the sieved method. This implies that the method may offer more accurate results with the implantation of a correction factor or a modification to the experimental method such as decreasing the tolerance for stopping the experiment. The conclusions and recommendations of this experiment will be further discussed in Chapter 5 of this report.

Figure 3-9 Concrete Error vs Trial Number

Figure 3-10 Sieved Mortar Error vs Trial Number

CHAPTER 4 STABILITY EFFECTS OF PUMPING SCC

The durability of concrete structures exposed to freeze-thaw cycling has been directly related to the air-void structure within a mix. Freeze-thaw cycling describes the effects of water penetrating a concrete structure then freezing and thawing during winter conditions. Freeze-thaw durability of concrete depends on the materials characteristics such as cement paste tensile strength, quality of the aggregates, properties of the hardened air-void system, as well as the exposure conditions of the structure. SCC can be proportioned and produced with proper air-void parameters so that its freeze-thaw durability can be equivalent to that of conventional concrete with same cement content and water to cement ratios (Daczko J. A., 2012).

Although air is naturally present in every concrete mix due to the mixing process, this amount is relatively low and varies between 1-3% without chemical admixtures. Four to nine percent of air-entrainment is typically recommended for sufficient and stable air-void systems in SCC (Khayat & Persson, 2007). Hwang and Khayat (2005) reported that SCC mixtures proportioned with maximum large aggregate size of 3/8 inches (10 mm) needed 5 to 8 percent fresh air with naphthalene-based HRWR, or 6 to 9 percent fresh air with PC-HRWR, to achieve a maximum spacing factor of 0.23 millimeters, which is close to the highest typical value for freeze-thaw durable concrete (Hwang & Khayat, 2005).

ACI 237 denoted that, sometimes the hardened air-void parameters could be influenced because of the fluidity of SCC and high amount of HRWR. In such case, the mixture might be unstable and can generate larger air bubbles (ACI Committee 237, 2007). It was stated that specifically, SCC could be unstable when PC-HRWR is used since it can lead some air entrainment, and it was recommended to use air entrainment agents that are more effective in stabilizing air bubbles in the mixture. It was also recommended to keep water to cement ratio as low as possible and increase the cement content when proportioning SCC mixtures that may be exposed to freeze-thaw conditions (Khayat & Persson, 2007).

NCHRP 628 (2009) stated that a higher overall air content might be necessary in freeze-thaw environments, especially when using certain PC based HRWR, which sometimes results in entrapment of relatively large air-voids. It is believed that these larger voids, while increasing

the overall air content of SCC, do not have the same effectiveness in combating freeze-thaw degradation as smaller air-voids; the NCHRP report suggests air contents of high-strength prestressed SCC ranging from 6% to 9% in the most severe freeze-thaw environments (Khayat & Mitchell, 2009). Determining the structure of the air-voids is time consuming and tedious in comparison to fresh air content determination, therefore construction projects typically only require the fresh air content be determined to ensure an acceptable level of risk in regards to freeze-thaw durability.

One potential benefit of SCC is that its high flowability can allow for the mix to be pumped from various positions within the formwork thus allowing the contractor to optimize the construction process. While this flowability of SCC can be beneficial, some researchers suggest that the increase in flowability may result in a less stable mix in regards to segregation resistance and air-void stability. Szwabowski and Piekarczyk found that creating a proper air structure within SCC can be problematic (Szwabowski & Piekarczyk, 2009). They went on to describe that the flowability of the mix may create an unstable air structure which can result in the fading of some air bubbles less than 0.10 mm in diameter or the coalescence of air bubbles. Khayat and Assaad found that the use of relatively high amounts of HRWR can act to destabilize the air-void system of concrete thus increasing the probability of instability (Khayat & Assaad, 2002).

Ghafoori et. al. (2001) conducted research to determine the influence of pumping on SCC fresh properties. SCC was pumped for 200 feet (60 m.) and the slump flow, T50, VSI, J-ring and air content was measured. Additionally, yield stress and plastic viscosity was determined using a rheometer, and air-void characteristics of fresh mortar sample were analyzed using an air void analysis. According to the test results, pumping adversely affected the fresh properties of SCC; slump flow and J-Ring measurements decreased, and T50 increased. Although the air content remained the same, the specific surface value decreased (Ghafoori, Diawara, Nyknahad, Barfield, & Islam, 2011).

It has been assumed that pumping of SCC is similar to pumping of conventional concrete. However, SCC differs from conventional concrete in its composition and rheological behavior. Due to its flowability, SCC may require a slower pumping rate to avoid high pressure built up in the pipes that may cause concrete segregation, air-void instabilities, and pump breakdown. For

lower-viscosity mixtures, it is usually recommended to start pumping at a lower pressure until concrete flow begins; once the mixture starts pumping, the rate can be increased. Another option is to pump SCC from the bottom of the formwork using specially designed connector ports constructed into the formwork (RILEM TC-188, 2006). Although the effects of pumping SCC at relatively high pressures are not fully understood, it is believed that the increase in pressure and agitation of the mix during the pumping may increase the probability of instability.

PREVIOUS RESEARCH – RP 221 C

In 2010, a preliminary formwork pressure test was conducted during the RP 221C study at West Virginia University. SCC was pumped from the bottom of the formwork in the construction of a 12-foot column. The pumping process lasted about 27 minutes until concrete level reached the top of the formwork. The average rate of concrete rise was found to be approximately 27 feet/hour with a volumetric flow rate of the pumping calculated to be 1.31 ft³/min. The primary purpose of this experiment was to investigate the pressure exerted on the formwork when pumping SCC from the bottom. As the concrete level steadily rose, large air bubbles were observed escaping the surface of the mix. The escaping air could be a combination of both trapped air from the pumping process and entrained air being coalescence as the mix was being pumped. The dimensions of the column were 35.5 inches wide, 24 inches deep and 12 feet high. The figures below show column formwork as well as the pumping trailer used to pump SCC in this experiment. Additionally, the mix design used for this experiment is shown in Table 4-1.

(a)

(b)

(c)

(d)

Figure 4-1 (a) Front View of SCC 12-ft Column Formwork (b) Side View of SCC 12 ft Column Formwork (c) Pumping Trailer used in Experiment (d) Internal View of Pump Used in Experiment (Chen, Sweet, Yikici, & Lin, 2013).

Table 4-1 Mix Design Used for SCC Pressure Column

Mix Design SCC Column with w/cm of 0.35	
Material	lb/yd ³
Cement	735
Silica Fume	75
#67 Crushed Stone	1469
Natural Sand	1415
Water	284.0
Air Entrainment	1.5*
HRWR	10*
VMA	3*
*Measured per CWT	

Fresh property testing for SCC was performed in accordance with ASTM standards. The fresh property testing results offer insight into the stability of the mix prior to pumping. From the data collected prior to pumping, no signs of instability were observed and stable behavior with respect to segregation and air content was expected. The table shown below summarizes the fresh property testing of the SCC prior to beginning the column casting.

Table 4-2 SCC Pressure Column Fresh Properties

Summary Pressure Column SCC Fresh Properties	
Slump Flow	20.5 in
T ₂₀	3.0 sec
J-Ring Flow	20 in
J-Ring Value	0.50 in
Air Content	5.6 %

Additionally, the results from the formwork pressure testing of this experiment as well as the compressive strength testing data are shown in Figure 4-2 and Figure 4-3, respectively.

Figure 4-2 SCC Formwork Pressure vs Height (Chen et al. 2013)

Figure 4-3 SCC Column Mix Compressive Strength vs Time

SCOPE AND PURPOSE

The purpose of this study is to determine if detrimental property effects may have resulted from pumping the SCC used during the pressure column experiment. To achieve this, 5 specimens were cored from the column prior to its demolition. The five cored specimens would then be cut in half to be analyzed, with the “side” samples corresponding to the region closest to the formwork and the “middle” corresponding to the region toward the middle of the column. These samples were cut and polished to perform a segregation and air-void analysis. The following sections outline the research which was performed to determine the above described properties.

SPECIMEN REMOVAL

As previously described in the literature review section of this report, SCC typically exhibits a relatively smooth high surface quality when compared to traditional mixes. The interface between the formwork and hardened SCC column exhibited a high amount of “bug holes” which are typically result from poor consolidation, trapped air, or segregated water which has dried to form a hole. Given the shape, size, and distribution of these bug holes, it is believed

that they were caused by a combination of segregated water and trapped air. Figure 4.4 shows the observed bug holes on the column surface.

Figure 4-4 Observed Bug Holes on Column Surface

To determine the effects on the segregation resistance and air structure of the pumped SCC, five specimens were taken from the hardened column which was on-site (Figure 4-1) in the summer of 2013. The specimens were taken at strategic locations on the column in order to gain insight into the effects of pumping the SCC at various locations. The column was then removed for disposal. The specimens were then taken to the Concrete Lab at West Virginia University to be analyzed. The figure below shows the locations of the cored specimens along the concrete column as well as their respective sample number which was carried throughout the analysis.

Figure 4-5 SCC Column Cored Specimen Positions

The five cored specimens were all 4 inches in diameter and range in length from 7.5 inches to 10.5 inches. Following coring, approximately 1 inch was removed from the top surface of the specimens to remove surface imperfections which could negatively impact the accuracy of the analysis. This resulted in the length of cored specimens ranging from 6.5 inches to 9.5 inches. An image taken following the removal of the top inch of the cored specimens is shown in Figure 4-6.

Figure 4-6 Cored Specimens Following Surface Removal

SPECIMEN PREPARATION PROCEDURE FOR SEGREGATION ANALYSIS

The specimens were then prepared to be polished for an aggregate segregation analysis. This procedure involved cutting the specimens into halves along their lengths using a diamond edged concrete wet saw. In order to compare the aggregate distribution and air-void structure of region closest to the formwork wall to the middle of the column, the cored specimens were then cut into 4 inch by 3 inch samples. The cut specimens for polishing are shown in Figure 4-7.

Figure 4-7 Cored Specimens Prepared for Polishing

Next, each specimen was carefully polished using the Struers TegraPol 31 polishing machine located in the Concrete Laboratory at West Virginia University. The Struers polishing machine wet grinds the samples using a polishing wheel and a steady stream of water which acts to lubricate the polishing process and remove any particles from the polishing wheel. The stream of water can be adjusted by the user in both flowrate and direction in order to achieve an optimum grinding process. Additionally, the speed of the polishing wheel can be operated at 150 or 300 revolutions per minute (RPM). Shown in Figure 4-8 is the mechanical polishing of a specimen used in this experiment.

Figure 4-8 Example of Specimen Being Polished using Struers TegraPol 31

For the purposes of this experiment, the polishing wheel was set at 300 RPM. Each specimen underwent the same polishing which included using four grades of polishing wheel with 120, 200, 600, and 1200 grit. The time spend on each grade of grit varied between 15 minutes to 55 minutes depending on the surface imperfections. To ensure that each specimen was properly polished, the specimen was ground for a minimum of 15 minutes then removed, cleaned using an ultra-sonic water reservoir, then dried using compressed air. If the specimen

showed imperfections which were unacceptable for a given grit level, the specimen would be returned to the polisher for 10 minutes after which time it would again be examined using the same process. This was repeated until an acceptable specimen had been produced. Figure 4-9 shows a polished specimen taken from this study. The images of the specimens used in the aggregate segregation analysis can be found in Appendix D.

Figure 4-9 Polished Specimen Used in Aggregate Segregation Analysis

SEGREGATION ANALYSIS PROCEDURE AND RESULTS

Upon completing the polishing process, the concrete specimens were then evaluated using an image analysis program to gain insight into the segregation of the SCC at various locations on the column. To achieve this, an image of the specimen was created using a high resolution flatbed scanner. The image was then analyzed using a program known as JMicroVision. This program separates the large aggregates from the mortar based upon color differences. The program determines and outputs the percent of the image which is designated as large aggregate. The figure below shows a sample being analyzed using JMicroVision. Additionally, a figure containing only the outlined large aggregates is shown to clearly demonstrate how the program analyzes the image.

Figure 4-10 (a) JMicroVision Analysis of Middle Specimen 4 (b) JMicroVision Analysis with Image of Specimen Removed

To determine the theoretical aggregate distribution, the specific gravity of each of the mix constituents was used to determine the volume percentage of each material within the mix. Although this calculation does not take into account the shrinkage effect of the dried cement paste, accurate estimations can still be drawn as these effects are considered negligible for the purposes of this experiment. The specific gravity of the cement, silica, large aggregates, and fine aggregates were provided by the concrete producer as 3.15, 2.2, 2.72, and 2.63, respectively. Using the equation shown below, the theoretical percentage of volumes for each material was calculated. Using a weighted average of the large aggregates, the theoretical volume of aggregates within the mix was determined to be approximately 33.1%.

$$\text{Theoretical Volume of Material} = \frac{WB}{SG_M * 1700} \quad \text{Equation 4-1}$$

Where:

WB = the weight of material used per cubic yard of concrete, lb

SG_M = the specific weight of the material

1700 = conversion factor equal to the weight of one cubic yard of pure water, lb/yd³

The results from the aggregate analysis for all the specimens tested is shown in the Table 4-3. Additionally, the largest percentage difference between specimens was approximately 25.3% which corresponded to the side specimen at location 1 and the side specimen at location 3. It can also be observed that four out of five locations analyzed exhibited a lower aggregate contents along the formwork wall relative to the section closest to the middle of the column. The average percent aggregate content for all the specimens was determined to be approximately 36.6% with a standard deviation of 7.41%.

Table 4-3 Aggregate Distribution Analysis Results

Aggregate Distribution of Polished Specimens		
Location	Side Specimens	Middle Specimens
1	53.0%	42.0%
2	26.9%	34.2%
3	27.7%	39.0%
4	35.3%	38.2%
5	34.4%	35.2%

Table 4-4 Deviation of Samples from Theoretical Content

Deviation of Sample Aggregate Content from Theoretical Content		
Location	Side Specimens	Middle Specimens
1	19.9%	8.9%
2	-6.2%	1.1%
3	-5.4%	5.9%
4	2.2%	5.1%
5	1.3%	2.1%

The Standard Test Method for Static Segregation of Self-Consolidating Concrete Using Column Technique (ASTM C1610) describes a method in which the segregation of a mix can be evaluated. In this method, a column apparatus is composed of three removable pieces. The mass change between the bottom and top are used to determine the segregation of the mix. In a previous research study performed at West Virginia, a precast SCC bridge beam was constructed for use at Stalnaker Run Bridge in West Virginia. During this project, the concrete producers allowed a tolerance of 12% segregation prior to considering the mix segregated (Chen, Sweet, & Yikici, 2013). For the hardened aggregate analysis of the SCC column, a method was adapted from ASTM C1610 in which the equation below was used to determine the segregation (Ma & Chen, 2015).

$$S = \frac{|(C_L - C_U)|}{C_{avg}} \quad \text{Equation 4-2}$$

Where:

S = the segregation value

C_L = % aggregate at lower sample

C_U = % aggregate at upper sample

C_{avg} = % aggregate average of both samples

During this analysis, the samples were cored orthogonal to the direction of gravity, therefore the difference between the aggregate samples at each height were considered for the middle of the cored specimens. For the purpose of this analysis, a 12% value of S was considered to be noticeable segregation behavior. The results of the comparison of the middle specimens can be found in Table 4-5. Additionally, the segregation value, S, was determined for each sample by comparing the aggregate content of the top of the specimen to the bottom of the specimen. The results of this comparison can be seen in Table 4-6.

Table 4-5 Results of Segregation Analysis for Middle Specimens

Results of Segregation Value, S, for Middle Specimens		
Location	Difference (%)	S (%)
1-3	3.0	7.4
2-3	-4.8	13.1
3-4	0.8	2.1
4-5	3.0	8.2
Average	0.5	7.7

Table 4-6 Results of Segregation Analysis for Middle Specimens

Results of Segregation Value, S, for Each Specimens		
Location	Difference (%)	S (%)
1	11.0	23.2
2	-7.3	23.9
3	-11.4	34.2
4	-3.0	8.2
5	-0.8	2.3
Average	2.3	18.3

The relatively large value of S at the middle location of specimens 2 to 3 indicates that the pumped SCC mix exhibited significant segregation behavior at this location. The differences experienced may have been caused by instabilities within the mix at isolated positions. Under the criteria imposed for determining segregation, one location along the middle of the column exhibited relative segregation behavior. Additionally, three out of the five samples exhibited relative segregation behavior when comparing the side most location to the middle most location of the samples. Out of the five samples tested, four exhibited a lower aggregate content along the side most location of the sample as compared to the middle most location of the sample.

It is believed that the segregation may have been caused by aggregates separating from the paste as the mix entered the formwork at a relatively high velocity which would account for the relatively large volume of aggregates at the bottom of the column. This separated paste may have been able to flow with less resistance to the walls of the column resulting in reduced aggregate content along the side surface compared to the center location of the pumped SCC column.

The specimen's air-void structure was analyzed based upon a test method developed in the 1950's known as the Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete (ASTM C457). There are two methods contained within the testing standard, the linear transverse method and the point count method. The linear transverse method was used to analyze the specimens, therefore only its procedure, which is taken from ASTM C457, will be described.

In ASTM C457, the procedure for manual analysis is provided. The procedure involves placing the sample in an apparatus containing a microscope which is capable of moving accurately and smoothly along straight, parallel lines along the samples surface. An example of such an apparatus is provided in the standard and is shown in Figure 4-11.

Figure 4-11 Apparatus Used for Manual Perform of Air-Void Analysis (ASTM C457)

Using this device the number of required traverses or parallel passes, which is provided by the standard, over the specimen's surface is determined. During this test, the total number of

voids intersected (N), total length traversed (T_t), total length traversed through air (T_a), and the total length traversed through paste (T_p) is recorded. The following section outline the equations used in the analysis and gives meaning to their importance in relation to the air structure of a sample.

The total air content of the sample is given by the equation shown below. This value can be compared to the fresh air content testing and offers insight to the amount of air present within a sample. Research performed by Khayat and Assad found that the hardened air content of SCC is lower than fresh air content by approximately $1 \pm 0.5\%$ (Khayat & Assaad, 2002).

$$A = \frac{T_a * 100}{T_t} \quad \text{Equation 4-3}$$

Where:

A = air content of the sample, %

T_a = total length traversed through air in sample

T_t = total length traversed through sample

The void frequency, n , is related to the rate as a function of distance in which voids are encountered. This parameter offers insight into the average spread of air-voids within the sample.

$$n = \frac{N}{T_t} \quad \text{Equation 4-4}$$

Where:

n = void frequency

N = total number of air-voids intersected in the sample

T_t = total length traversed through sample

The average cord length, $\bar{l}$, is calculated using the equation shown below. This value is necessary for use in determining the specific surface of the sample.

$$\bar{l} = \frac{T_a}{N} \quad \text{Equation 4-5}$$

Where:

$\bar{l}$ = average cord length

T_a = total length traversed through air in sample

N = total number of air-voids intersected in the sample

The specific surface, α , is used to relate the area of an air-void to its volume. A higher value for specific surface area corresponds to a higher frequency of smaller air-voids as opposed to a lower specific volume of which corresponds to a higher frequency of larger air-voids. According to ASTM C457 recommends a value between 25 to 45 mm⁻¹ for specific surface to resist freeze-thaw loading.

$$\alpha = \frac{4}{\bar{l}} \quad \text{Equation 4-6}$$

Where:

α = specific surface

$\bar{l}$ = average cord length

The paste to air ratio, p/A , of the sample is calculated using the equation below. This value is used in determine which is to be used to calculate the spacing factor of the sample.

$$\frac{p}{A} = \frac{T_p}{T_a} \quad \text{Equation 4-7}$$

Where:

p/A = paste to air ratio

T_p = total length traversed through paste in sample

T_a = total length traversed through air in sample

Generally, the spacing factor, $\bar{L}$, is considered to be the most critical air-void parameter in relation to freeze-thaw resistance. The $\bar{L}$ value represents the largest distance from any given point within the cement paste to the nearest air-void. This value helps to relate the ability of the air-void structure in relieving stresses caused by dilating freezing water within concrete. ASTM C457 recommends a maximum value of the spacing factor for a moderately exposed structure of 0.20 mm. A physical interpretation taken from a report by Rusin (2002) is shown in Figure 4-12.

Figure 4-12 Physical Representation of Spacing Factor (Rusin, 2002)

The equations used for calculating the spacing factor is shown below.

When the p/A is less than or equal to 4.342, Equation 4-8 is used to calculate $\bar{L}$ shown below is used.

$$\bar{L} = \frac{T_p}{4N} \quad \text{Equation 4-8}$$

Where:

$\bar{L}$ = the spacing factor

T_p = total length traversed through paste in sample

N = total number of air-voids intersected in the sample

If the p/A is greater than 4.342, Equation 4-9 used is to calculate $\bar{L}$ shown below is used.

$$\bar{L} = \frac{3}{\alpha \left[1.4 \left(1 + \frac{p}{A} \right)^{1/3} - 1 \right]} \quad \text{Equation 4-9}$$

Where:

$\bar{L}$ = the spacing factor

α = specific surface

p/A = paste to air ratio

The testing standard requires that specimen used in the analysis needs to meet minimum polished surface area based upon the maximum aggregate size contained within the mix. For this mix, #67 stone was used indicating a maximum aggregate size of 1 inch, therefore a minimum of 12 in² needs to be used in the analysis. Due to the constraints of this experiment, the minimum polished surface area used was 4 x 3 inches.

HARDENED AIR-VOID ANALYSIS TECHNIQUES

The previously described manual method for the determination of a hardened air-void analysis is labor and time intensive. Previous researchers have estimated that manual completion of the linear traverse method may take upwards of 6 hours to complete for each specimen and may result in large variations due to human error. Automated methods have been developed to remove the human element from this testing procedure.

One technology aimed to automate this process was developed by Concrete Experts International is known as the RapidAir 457 Air Void Analyzer. This equipment uses a motorized stage with a high resolution camera to determine the air-void content based on parallel lines of the sample being analyzed. The equipment is reported to produce results in less than 15 minutes. A research project conducted by the Iowa Department of Transportation concluded that the RapidAir 457 successfully predicted the hardened air-void structure with less variation when compared to the manual traverse method (Hanson, 2012). Although the Rapid Air system is a promising technology, the equipment is relatively expensive and require skilled labor to operate it therefore it was not chosen for this research.

Another procedure which has been successfully implemented to analyze air-void structure involves using a computerized analysis of a high resolution specimen image obtained using a flatbed scanner. Researchers at Michigan Tech found the use of a flatbed scanner technique closely replicated the results obtained by using the Rapid Air system (Carlson , Sutter, Peterson, & Van Dam, 2008). Ultimately, this system was chosen as the optimal method to analyze the air-void structure of the specimens.

SPECIMEN PREPARATION PROCEDURE FOR AIR-VOID ANALYSIS USING A FLAT BED SCANNER

Following the segregation analysis, the specimens were then prepared for an air-void analysis. In this procedure, barium sulfate was chosen due to its pure white color, fineness, and compactability. The specimens were scanned at a resolution of 3200 dpi and were saved in .tiff format. The procedure used in preparing each specimen for an air-void analysis is outlined below.

1. Once a specimen had been polished to an acceptable level with no noticeable surface imperfections, the specimen was cleaned using an ultra-sonic water reservoir for 5 seconds to remove any particulates from the air-voids.
2. Next, the specimens were dried overnight in an oven with a set temperature of 220 °F. The following morning, the specimens were removed and allowed to cool for approximately 2 hours. *Note that special care must be taken to not touch the polished surface as to avoid damaging the surface quality with oil.
3. Once the specimens had cooled, a black marker was used to paint the polished surface. This was done by carefully creating two perpendicular rows. The samples were then place in an oven at 110 °F to dry overnight.
4. The following morning, compressed air was blown across the surface to remove any residual ink from painting the surface.
5. Next, barium sulfate was tapped into the air-voids. This was done by placing a small amount of barium sulfate onto the surface and tapping a rubber stopper across the surface in perpendicular rows.

6. The specimens were then examined using a computer microscope with a 15 times zoom. If voids remained unfilled, the process of filling voids using barium sulfate and the rubber stopper where repeated.
7. Once the air-voids had been completely filled, the excess barium sulfate was carefully removed using the palm of the hand at low pressure and extreme care.
8. Images of the prepared specimens were produced using a flatbed scanner.

A sample of a specimen prepared for an air-void analysis is shown in the following tables. The specimens used for the air-void analysis are shown in Appendix E.

Figure 4-13 Prepared Air-Void Analysis Specimen

HARDENED AIR-VOID ANALYSIS RESULTS AND DISCUSSION

An Adobe Photoshop® script was developed by researchers at Michigan Tech which is known as Bubble Counter. This script requires that a 3200 dpi image of the specimen be carefully prepared for an air-void analysis. The image is then opened in Adobe Photoshop® and the script is ran. The user is prompted to “Set White Balance” which corresponds to defining what is going to be considered white within the program. Next, the aggregate content of each sample is input into the prompt window. The user can also define the number of traverses performed in the analysis. The script then outputs the total air content, spacing factor, specific

surface, and air-void frequency into an excel file. The results from this analysis are shown in the table below.

Table 4-7 Summary of Air-Void Analysis Results of Side Specimens

Side Specimen Location	Percent Air (%)	Spacing Factor, $\bar{L}$ (mm)	Specific Surface, α (mm ⁻¹)	Air-Void Frequency, n (intercepts/mm)
1	2.86	0.2830	24.242	0.173
2	3.16	0.3542	25.316	0.200
3	2.58	0.3513	27.778	0.179
4	2.95	0.3924	21.858	0.161
5	4.48	0.2073	35.088	0.395

Table 4-8 Summary of Air-Void Analysis Results of Middle Specimens

Middle Specimen Location	Percent Air (%)	Spacing Factor, $\bar{L}$ (mm)	Specific Surface, α (mm ⁻¹)	Air-Void Frequency, n (intercepts/mm)
1	3.44	0.3205	24.242	0.208
2	4.69	0.2602	27.397	0.322
3	2.43	0.4695	19.802	0.120
4	3.59	0.4020	19.512	0.175
5	3.54	0.2461	32.787	0.290

Table 4-9 Average and Standard Deviation of Air-Void Analysis Results

Average and Standard Deviation of Percent Air, Spacing Factor and Specific Surface of Samples Analyzed						
	Average Percent Air (%)	Standard Deviation of Percent Air (%)	Average Spacing Factor, mm	Standard Deviation of Spacing Factor, mm	Average Specific Surface, mm ⁻¹	Standard Deviation of Specific Surface, mm ⁻¹
Side Location	3.21	0.74	0.32	0.07	26.86	5.07
Middle Location	3.54	0.80	0.34	0.10	24.75	5.63
All Samples	3.37	0.75	0.33	0.08	25.80	5.14

As previously discussed, the percent air in hardened concrete is typically $1.0 \pm 0.5\%$ lower than concrete fresh state. Prior to pumping the SCC, a tested fresh air content of 5.6% was observed, therefore the expected range of percent air within the mix is 5.1% to 4.1%. The average air content for all the samples tested was approximately 3.4%. This value is significantly below the lower bound of the expected range of air content within the mix. This implies that some of the entrained air may have been lost during the pumping process. Although it is not possible to directly determine an exact value for the expected hardened air content, the difference between samples can be used to determine the effects of pumping.

The average percent air for the side and middle specimens was determined to be 3.2% and 3.5% which indicates that pumping effects on the air-void structure SCC were not likely dependent on the middle or side position within the column. Two locations which exhibited relatively high air content percentages relative to the other specimens analyzed were at middle location at 2 and side location at 5. The middle location 2 corresponds to the area just to the left of the pumping entrance. It is believed that the relatively high air content may have been a result of high pressure, caused by the pumping process, pushing additional air to this region. The relatively high air content at position 5 may have resulted from air being pushed to the top of the column during pumping.

As previously mentioned, the specific surface helps to gain insight into the distribution of large and small air-voids within an analyzed sample. ASTM C457 recommends a value between 25 to 45 mm^{-1} for freeze-thaw resistance. Of the ten samples analyzed, the average specific surface (SF) was determined to be 25.8 mm^{-1} with a standard deviation of 5.14 mm^{-1} . Out of these ten specimens' analyzed, five did not fall within the ASTM C457 recommended range. It is believed that the low specific surface value were a result of a relatively high number of entrapped air voids (larger than 1 mm) caused by the coalescence of air-voids caused by the viscosity of the mix and the use of HRWR with increased agitation from pumping.

The spacing factor, $\bar{L}$, is considered to be the most critical parameter within a concrete mix to resist freeze-thaw cycling. Previous researchers have shown that a structure exposed to moderate freeze-thaw conditions required a spacing factor less than 0.20 mm to ensure adequate durability. Therefore, ASTM C457 recommends a maximum spacing factor value of 0.20 mm for structures exposed to moderate freeze-thaw conditions. None of the ten samples analyzed met this requirement. It was observed by inspection that many of the samples contained relatively large, non-circular air-voids. Although ASTM C457 does not make a distinction between entrained and entrapped air, researchers have found that a network work of small circular air-voids is necessary for adequate freeze-thaw resistance.

Generally, researchers consider air-voids with a diameter greater than 1 mm as entrapped air while air-voids with a diameter less than 1 mm as entrained air. Additionally, researchers have argued that although large, non-circular entrapped air voids are taken into account during analysis to determine the air-void structure, they offer little benefit in regards to freeze-thaw resistance. It is commonly believed that a network of uniform, circular entrained air-voids are required to adequately resist freeze thaw cycling. Figure 4-14 shows a section of a specimen used in this analysis containing these relatively large, non-circular entrained air-voids. These non-uniform voids may have been caused by the high pressure and agitation of pumping the SCC which resulted in the coalescence of small, entrained air-voids to form larger, non-uniform air-voids. This observance of these larger, non-uniform air-voids was common among the samples analyzed.

Figure 4-14 Image Taken From Specimen Used in Analysis
Containing Irregular Air-Voids

Figure 4-15 Air-Void Distribution at Middle Location 3

The Bubble Counter program records the size and frequency of each size of air-void observed during the analysis. The number of air-voids recorded is a function of the air content

and the number of traverses completed during the analysis. By holding the analyzed area and number of traverses constant during the analysis, the relative number and shape of the distribution graphs from the air-void within each sample can be compared. The air-void distribution as well as the specimens used in the air-void analysis can be found in Appendix E.

As can be seen in the figures in Appendix E, it appears that a significant variation occurred in the air-void distribution along the height of the column. As previously discussed, it is generally believed among researchers that entrained air-voids (greater than 1 mm) do not adequately contribute to the freeze-thaw of a concrete mixture. It is believed that the optimal distribution of air-void size versus number of voids follows a log-normal distribution. This distribution implies that the majority of the air-voids within the concrete mix fall within the range to be considered entrained air which likely are more effective at resisting freeze-thaw cycling as compared to a higher concentration of entrapped air.

As can be observed from the figures in Appendix E, the side specimens at location 3, 4, and 5 and middle specimens at locations 1, 3, 4, and 5 appear to follow a log-normal distribution. Additionally, it can be seen that side specimen at location 1 and 2 and the middle specimen at location 2 seem to follow a distribution closer to linear as compared to the other specimens. This distribution implies that a relatively larger number of entrapped air-void may be present within these three samples as compared to the seven other samples analyzed during this experiment. Additionally, a relatively high number of air-voids were observed at location 5 indicating that the air-voids may have been pushed towards the top of the column during the pumping process. It is believed that this may have been caused by a combination of pressure and agitation causing a destabilization of the mix during pumping.

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

Cast-In-Place SCC

There are many considerations for implementing SCC technology on a wide scale for cast-in-place applications. Since the behavior of a particular SCC mix is highly dependent on its ingredients, specifications for mix design with locally available aggregates and admixtures need to be developed. Also, there are only a limited number of tests designated for evaluating the performance of a given SCC mix with respect to self-compaction and segregation behaviors, so the performance criteria of acceptable SCC need to be investigated and specified. Certain logistical issues such as formwork design and methods for transporting the SCC to the job site will also have to be addressed before it can be used for cast-in-place applications. In addition, the general curing characteristics and long-term behaviors of the SCC will affect the cracking potential and longevity of the structure and hence, time-dependent behaviors such as shrinkage, creep and durability of the SCC need to be studied. With the use of the literature reviews presented within the first two chapters within this report, a state agency, engineer, or contractor could benefit in implementing SCC in the most efficient manor by drawing from researchers' experience with the material and state specifications taken from across the country.

Determination of Water Cement Ratio

Following the experiments performed related to the rapid determination of the w/cm based on AASHTO T318 02, it is believed that this method can be implemented for quality control use in the field for mixes which are sensitive to small changes in water content such as SCC. Although the sieved mortar method resulted in a higher average magnitude of error when compared to the concrete sample testing (0.013 vs 0.012, respectively), the standard deviation of error was found to be lower for the sieved mortar method as compared to the concrete samples (0.0096 vs 0.015) while seven out of the eight experiments conducted on the sieved mortar underestimated the w/cm. This suggests that a correction factor and adjusted procedure could be implemented to obtain more accurate results when compared to sampling concrete for determination of w/cm using the microwave method. Due to the relatively accurate results of this

experiment and availability of testing equipment, it is believed that this method could have widespread applications in determining the fresh w/cm provided that the mix design information used in the cement calculation are accurate. Further research should be done to develop confidence intervals and sensitivity limits when using this method for a variety of concrete mixtures. A testing method to accurately determine the quantity of cementitious material used in the w/cm calculation is also needed.

A concern with the method used in calculating the w/cm is assuming that the moisture content within the large aggregates is recoverable. Although maximum temperatures of over 400 °F were observed during the experiment, this does not guarantee that all the moisture content within the large aggregate will be recovered. This method determined the total free water of the mix by reducing the SSD moisture from the large and small aggregates from the total evaporated water. Although the moisture within the fine aggregates is readily evaporated, this is not necessarily the case for large aggregates. This reduction of free water may be acting as a correction factor for water lost during a slight amount of the cement hydration. Further research should be performed to determine the validity of these assumptions and to better understand the previously described effects.

Stability of Pumped SCC

Under the criteria imposed for evaluating the segregation behavior of the pumped SCC column, the results from the segregation analysis suggest that the mix exhibited segregation behavior. The comparison of the aggregate content for the middle specimen locations suggest that the mix did not segregate in the direction of gravity although segregation behavior between middle locations 2-3 was observed with a significantly higher concentration of large aggregates at location 3. The relatively large concentration of aggregates to either side of the pumping location also indicate that segregation may have occurred as the SCC entered the column. Additionally, three out the five cored specimens exhibited a significantly higher concentration of aggregates at the center most section of the specimen as compared to the side most location of the specimen. It is believed that the segregation may have been caused by aggregates separating from the paste as the mix entered the formwork at a relatively high velocity which would account

for the increased volume of aggregates at the bottom of the column. This separated paste may have been able to flow with less resistance to the walls of the column resulting in reduced aggregate content along the side surface compared to the center location of the pumped SCC column.

According to the experimental results, the air-void structure stability of the SCC may have been significantly deteriorated due to the pumping process. The unacceptable spacing factor observed in all the specimens as well as the specific surface of five specimens being outside the acceptable range indicates that the pumped SCC column does not contain the recommended air-void structure suggested by ASTM C457 to resist moderate freeze-thaw cycling. Additionally, as can be seen from the results of the air-void size distribution in Appendix D, the change in the air-void distribution along the column height may also indicate detrimental effects due to pumping. Due to the high rate of pumping used in the column, it cannot be confirmed that all pumping would be detrimental to the air-void structure, although the author believes that pumping SCC should be done with caution as the results of this analysis indicates that detrimental effects on the air void stability may result from this construction technique.

Additional research should be performed on pumping SCC mixes of various viscosities to determine SCC's air-void stability. The author recommends that samples be cast prior to pumping such that the air-void structure can be directly compared prior to and after pumping SCC. The fluidity of SCC allows for the implementation of innovative construction techniques which can significantly benefit the concrete construction industry. Although there exists significant benefits in implementing such techniques, the material response of SCC in regards to the segregation resistance and air-void stability to such construction methods should be further researched prior to implementation.

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APPENDIX A – SAMPLE OF EXISTING SCC SPECIFICATIONS

MARYLAND STATE HIGHWAY AGENCY SPECIAL PROVISIONS FOR SCC

SPECIAL PROVISIONS
902 — PORTLAND CEMENT CONCRETE AND RELATED PRODUCTS

CONTRACT NO.
1 of 1

SECTION 900
MATERIALS

SECTION 902 — PORTLAND CEMENT CONCRETE AND RELATED PRODUCTS

682 **ADD:** The following after 902.14 RAPID HARDENING CEMENTITIOUS MATERIALS FOR CONCRETE PAVEMENT REPAIRS

902.15 SELF CONSOLIDATING CONCRETE (SCC). The SCC mixture must meet the following minimum requirements.

Self-Consolidating Concrete Properties		
	Prestress Beams	Precast
Compressive Strength AASHTO T23	As per Contract Documents	As per Contract Documents
Min. Cement Factor lb/yd ³	700	615
W/C ratio	.32 - .45	.32-.50
Total Air Content	5.5 +/- 1.5	6.5 +/- 1.5
Concrete Temperature F	65 +/- 15	70 +/- 20
Slump Flow ASTM C1611	22 – 28 in.	22 – 28 in.
Visual Stability Index (VSI)	0 to 1	0 to 1
T20(T50)	2 – 10 sec.	2 – 10 sec.
J-Ring ASTM C1621	+/- 2 in. design slump flow	+/- 2 in. design slump flow
Column Segregation* ASTM C1610	12 % maximum	-
Rapid Chloride Permeability*	2500	-
Freeze Thaw* ASTM C666	Minimum durability factor 80	-
Shrinkage at 28 Days* C 157	400	-

Note 1: For ASR Mitigation use Table 902 B.

Note 2: High Water Reducing admixtures must be Type F or Type G and meet AASHTO M194.

Note 3: Viscosity modifying admixtures may be used only with prior approval by the Administration.

Note 4: Slump Flow and VSI testing shall be performed at the beginning of placement on the first two consecutive batches and when concrete is in question

06-27-13

Figure A1. Maryland State Highway Agency Special Provisions for SCC

ILLINOIS DOT SCC CAST IN PLACE SPECIAL PROVISION

All Regional Engineers

Scott E. Stitt

Special Provision for Self-Consolidating Concrete for Cast-In-Place
Construction

January 13, 2012

This special provision was developed by the Bureau of Materials and Physical Research. It has been revised to have tighter requirements on the development of the self-consolidation mix design and also the placement of the concrete.

This special provision should be inserted in contracts where the district wants to allow the use of self-consolidating concrete in cast-in-place construction. If QC/QA for concrete is part of the contract, the special provision Quality Control/Quality Assurance of Concrete Mixtures should also be inserted in conjunction with this special provision.

The districts should include the BDE Check Sheet marked with the applicable special provisions for the April 27, 2012 and subsequent lettings. The Project Development and Implementation Section will include a copy in the contract.

This special provision will be available on the transfer directory
January 13, 2012.

80152m

Figure A2. Illinois DOT SCC Cast in Place Special Provision (Page 1/5)

SELF-CONSOLIDATING CONCRETE FOR CAST-IN-PLACE CONSTRUCTION (BDE)

Effective: November 1, 2005

Revised: April 1, 2012

Description. This work shall consist of constructing cast-in-place items involving Class DS or SI concrete with self-consolidating concrete. The concrete shall be according to the special provision, "Portland Cement Concrete", except as modified herein.

Definition. Self-consolidating concrete is a flowable mixture that does not require mechanical vibration for consolidation.

Mix Design Criteria. Article 1020.04 shall apply, except as follows:

- (a) The slump requirements shall not apply.
- (b) The concrete mixture shall be uniformly graded, and information in the "Portland Cement Concrete Level III Technician Course – Manual of Instructions for Design of Concrete Mixtures" shall be used to develop the uniformly graded mix design. The coarse aggregate gradations shall be CA 11, CA 13, CA 14, CA 16, or a blend of these gradations. However, the final gradation when using a single coarse aggregate or combination of coarse aggregates shall have 100 percent pass the 1 in. (25 mm) sieve, and 95 percent pass the 3/4 in. (19 mm) sieve. The fine aggregate proportion shall be a maximum 50 percent by weight (mass) of the total aggregate used.
- (c) The slump flow range shall be 22 in. (560 mm) minimum to 28 in. (710 mm) maximum.
- (d) The visual stability index shall be a maximum of 1.
- (e) The J-ring value shall be a maximum of 2 in. (50 mm).
- (f) The L-box blocking ratio shall be a minimum of 80 percent.
- (g) The hardened visual stability index shall be a maximum of 1.

Test Methods. Illinois Test Procedures SCC-1, SCC-2, SCC-3, SCC-4, SCC-6, SCC-8 (Option C) and Illinois Modified AASHTO T 22, 23, 121, 141, 152, 177, 196, and 309 shall be used for testing of self-consolidating concrete mixtures.

Mixing Portland Cement Concrete. In addition to Article 1020.11, the mixing time for central-mixed concrete shall not be reduced as a result of a mixer performance test. Truck-mixed or shrink-mixed concrete shall be mixed in a truck mixer for a minimum of 100 revolutions.

The batch sequence, mixing speed, and mixing time shall be appropriate to prevent cement balls and mix foaming for central-mixed, truck-mixed, and shrink-mixed concrete.

Figure A2. Illinois DOT SCC Cast in Place Special Provision (Page 2/5)

Falsework and Forms. In addition to Articles 503.05 and 503.06 of the Standard Specifications, the Contractor shall ensure the design of the falsework and forms is adequate for the additional form pressure caused by the fluid concrete. Forms shall be tight to prevent leakage of fluid concrete.

When the form height for placing the self-consolidating concrete is greater than 10.0 ft (3.0 m), direct monitoring of form pressure shall be performed according to Illinois Test Procedure SCC-10. The monitoring requirement is a minimum, and the Contractor shall remain responsible for adequate design of the falsework and forms. The Contractor shall record the formwork pressure during concrete placement. This information shall be used by the Contractor to prevent the placement rate from exceeding the maximum formwork pressure allowed, to monitor the thixotropic change in the concrete during the pour, and to make appropriate adjustments to the mix design. This information shall be provided to the Engineer during the pour.

Placing and Consolidating. Concrete placement and consolidation shall be according to Article 503.07 of the Standard Specifications, except as follows:

Revise the third paragraph of Article 503.07 of the Standard Specifications to read:

“Open troughs and chutes shall extend as nearly as practicable to the point of deposit. The drop distance of concrete shall not exceed 5 ft (1.5 m). If necessary, a tremie shall be used to meet this requirement. The maximum distance of horizontal flow from the point of deposit shall be 25 ft (7.6 m). However, when the maximum distance of horizontal flow from the point of discharge exceeds 15 ft (4.6 m), the dynamic segregation index shall be a maximum 10.0 percent. If the maximum is exceeded, the maximum distance of horizontal flow from the point of deposit will not be allowed to exceed 15 ft (4.6 m). For drilled shafts, free fall placement will not be permitted.”

Delete the seventh, eighth, ninth, and tenth paragraphs of Article 503.07 of the Standard Specifications.

Add to the end of the eleventh paragraph of Article 503.07 of the Standard Specifications the following:

“Concrete shall be rodded with a piece of lumber, conduit, or vibrator if the material has lost its fluidity prior to placement of additional concrete. The vibrator will be permitted if it can be used in a manner that does not cause coarse aggregate separation from the mortar as determined by the Engineer. Any other method for restoring the fluidity of the concrete shall be approved by the Engineer.”

If the contract requires QC/QA for concrete, the following four sections shall supplement the special provision Quality Control/Quality Assurance of Concrete Mixtures. If QC/QC is not required, the following four sections shall be disregarded by the Contractor and the Engineer will perform QA testing as appropriate.

Figure A2. Illinois DOT SCC Cast in Place Special Provision (Page 3/5)

Quality Control by Contractor at Plant. The specified test frequencies for aggregate gradation, aggregate moisture, air content, unit weight/yield, and temperature shall be performed as indicated in the contract.

Slump flow, visual stability index, and J-ring or L-box tests shall be performed as needed to control production. The hardened visual stability index test will not be required to be performed at the plant.

Quality Control by Contractor at Jobsite. The specified test frequencies for air content, strength, and temperature shall be performed as indicated in the contract.

Slump flow, visual stability index, and J-ring or L-box tests shall be performed on the first two truck deliveries of the day, and every 50 cu yd (40 cu m) thereafter. The Contractor shall select either the J-ring or L-box test for jobsite testing.

If the self-consolidating concrete horizontal flow will exceed 15 ft (4.6 m), the dynamic segregation index test shall be performed at start of production for each mix design and per contract.

The hardened visual stability index test shall be performed on the first truck delivery of the day, and every 300 cu yd (230 cu m) thereafter. Slump flow, visual stability index, J-ring value or L-box blocking ratio, air content, and concrete temperature shall be recorded for each hardened visual stability index test.

The Contractor shall retain all hardened visual stability index cut cylinder specimens until the Engineer notifies the Contractor that the specimens may be discarded.

If mix foaming or other potential detrimental material is observed during placement or at the completion of the pour, the material shall be removed while the concrete is still plastic.

Quality Assurance by Engineer at Plant. For air content and aggregate gradation, quality assurance independent sample testing and split sample testing will be performed as indicated in the contract.

For slump flow, visual stability index, and J-ring or L-box tests, quality assurance independent sample testing and split sample testing will be performed as determined by the Engineer.

Quality Assurance by Engineer at Jobsite. For air content and strength, quality assurance independent sample testing and split sample testing will be performed as indicated in the contract.

For slump flow, visual stability index, J-ring or L-box, dynamic segregation index, and hardened visual stability index tests, quality assurance independent sample testing will be performed as determined by the Engineer.

Figure A2. Illinois DOT SCC Cast in Place Special Provision (Page 4/5)

For slump flow and visual stability index quality assurance split sample testing, the Engineer will perform tests at the beginning of the project on the first three tests performed by the Contractor. Thereafter, a minimum of ten percent of total tests required of the Contractor will be performed per plant, which will include a minimum of one test per mix design. The acceptable limit of precision will be 1.5 in. (40 mm) for slump flow and a limit of precision will not apply to the visual stability index.

For the J-ring or the L-box quality assurance split sample testing, a minimum of 80 percent of the total tests required of the Contractor will be witnessed by the Engineer per plant, which will include a minimum of one witnessed test per mix design. The Engineer reserves the right to conduct quality assurance split sample testing. The acceptable limit of precision will be 1.5 in. (40 mm) for the J-ring value and ten percent for the L-box blocking ratio.

For dynamic segregation index, quality assurance split sample testing will be performed as determined by the Engineer. The acceptable limit of precision will be 1.0 percent.

For each hardened visual stability index test performed by the Contractor, the cut cylinders shall be presented to the Engineer for determination of the rating. The Engineer reserves the right to conduct quality assurance split sample testing. A limit of precision will not apply to the hardened visual stability index.

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Figure A2. Illinois DOT SCC Cast in Place Special Provision (Page 5/5)

MONTANA SPECIAL PROVISION SCC

1. SELF-CONSOLIDATING CONCRETE (SCC) MIX DESIGN (REVISED 12-9-08)

A. Description. Use concrete meeting the requirements of this special provision for the concrete barrier rail.

B. Materials. Provide materials that meet the requirements of Subsection 551.02 of Standard Specifications and as listed below:

- 1) Minimum cementitious factor – 425 kg/m³
- 2) Maximum water cement ratio – 0.40
- 3) Air Content - 5 to 7%
- 4) Minimum Compressive Strength for 1.0 pay factor 21 MPa
- 5) Coarse Aggregate 19mm in accordance with Table 701-4 of the Standard

Specifications

- 6) Spread by Slump Flow Test– 455mm to 660mm diameter using MT 116 Method

C. Construction Requirements. Provide a mix design to the MDT Materials Bureau for approval. Incorporate a high range water reducer conforming to ASTM C494 Type F in the mix design and meet the above requirements. Include certifications with test results showing that the mix design meets the specified requirements.

D. The requirements of Subsections 551.03.3 and 551.03.7 apply except as noted below:

- 1) Pay Factor

1.0	0.95	0.85	0.70
21 MPa or greater	21 – 20 MPa	20-18 MPa	less than 18 MPa

E. Testing and Acceptance of Concrete. Requirements for testing and acceptance of SD concrete apply to Self-Consolidating Concrete (SCC)

F. Method of Measurement and Basis of Payment. Include all costs associated with the performance of this special provision in the price bid per cubic meter of Class SCC Concrete (Self-Consolidating Concrete).

Figure A3. Montana DOT SCC Special Provision

II.8 Virginia

II.8.1

ROUGH DRAFT- 08/19/05

**VIRGINIA DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION FOR
SELF-CONSOLIDATING CONCRETE (SCC) FOR USE IN REPAIRS
August 19, 2005**

I. DESCRIPTION

This work shall consist of designing and furnishing a self- consolidating concrete mix design for use in the repair of concrete structural elements. The Contractor shall perform structural repairs in accordance with applicable sections of the Specifications and the specifications herein.

II MATERIALS

Material components for self-consolidating concrete use in repairs shall conform to the following:

- A. **Cement:** Portland Type I/II
- B. **Class F and N fly ash or slag** conforming to the requirements of ASTM C618 and ASTM C 989, Grade 100 or 120 respectively
- C. **Coarse Aggregate** conforming to the requirements of ASTM C33. Maximum size of aggregates to meet project requirements.
- D. **Fine Aggregate** shall conform to the requirements of ASTM C33
- E. **Water** shall be potable. Otherwise must be approved by the Engineer before use.
- F. **Air entraining admixtures** shall conform to the requirements of ASTM 260
- G. **Water reducing, retarding or accelerating admixtures** shall conform to the requirements of ASTM C494.
- H. **High-range water-reducing admixtures (HRWR)** or (super plasticizers) shall conform to the requirements of ASTM C494 Type F or G or ASTM C1017.
- I. **Viscosity modifying admixtures** can be used to attain desired stability and flow characteristics, if all other specified properties are met (approved by the Engineer).
- J. **Fibers** – Synthetic fibers shall conform to the requirements of ASTM C1116 and can be used to control cracking

Figure A4. Virginia DOT SCC Special Provision (Page 1/4)

- K. **Shrinkage-reducing admixtures**, as approved by the Engineer, may be added to control cracking
- L. **Forming Materials:** Forming material shall be steel, steel framed plywood, resin impregnated plywood, plastic or paper faced plywood, or other material, all to be approved by the Engineer. Form shall not have voids or cracks that would permit the flow of concrete and shall be strong enough to stand the form pressures.

III. CONCRETE REQUIREMENTS

A qualified SCC technologist shall design and determine the proportioning of mixes since there is no standardized SCC mix design method. Experienced admixtures' suppliers can also be of assistance in determining mix design for project requirements. The following characteristics are very important for successful application of SCC and must be conformed to by the Contractor's mix design:

Flowability (Filling Ability) - ability of SCC to fill the forms and consolidate without vibration.

Stability- (segregation resistance) – ability of SCC to remain homogeneous during transport, placement and subsequent to placement.

Passing ability – ability of SCC to flow through reinforcement without aggregate blocking the flow.

Maximum water-cementitious materials ratio: 0.45

Air content - $7 \pm 2\%$

Slump-flow - 25 to 28 inches

Compressive Strength - Minimum 28-day - 3,000 psi minimum, 7,000 psi maximum. Loading carrying sections shall have a minimum of 3,000 psi compressive strength before opening to traffic.

Shrinkage - 0.04% or less at 28 days.

IV. QUALIFIED SCC TECHNOLOGIST

The Contractor shall employ the services of a qualified SCC Technologist, who is a person with experience in proportioning, batching, testing, and placing SCC. The

Figure A4. Virginia DOT SCC Special Provision (Page 2/4)

Engineer, based upon a resume submitted to the Engineer, shall approve the SCC Technologist.

V. CONCRETE TESTS (subject to change)

1. Slump-flow: To determine flowability and segregation: Conducted by a standard slump cone (either upright or inverted cone) and placed on a nonabsorbent smooth surface. It is filled in 1 lift without consolidation. It is pulled in an upward motion at a speed not causing a break in the flow. The concrete should flow into a consistent circle. The diameter of the spread is measured at two perpendicular points and an average is taken to give slump flow in inches. At this time it should be checked visually to ensure that there is no evidence of segregation in the concrete spread, no ring of mortar halo around the spread, or aggregate pile in the spread.
2. J-Ring: To determine the passing ability: A J-Ring will be placed on the base plate. For a nominal maximum aggregate size of 1-in, J-Ring shall have 16 stainless steel rods with $\frac{1}{2}$ in diameter spaced equally in a circle having a radius of 12 in. The slump cone will be placed in the middle of the J-Ring either upright or inverted. If upright, the handles of the slump cone may need to be removed to fit inside the J-Ring. The slump flow with the J-Ring and the difference in height between the SCC inside and that just outside the J-Ring will be measured.
3. Air content: Freshly mixed concrete by the pressure method, ASTM C231, or the volumetric method, ASTM C173.
4. Strength at 7 and/or 28 days: ASTM C39
5. Shrinkage: ASTM C 157 (28 days air dried at $50 \pm 4\%$ RH)
6. Permeability at 28 days after 1 week of moist curing at 73F and 3 weeks at 100F: ASTM C1202
7. Specimens shall be prepared by filling the molds in one lift without any consolidation.

VI. SURFACE PREPARATION

Remove the deteriorated concrete and soak the prepared surface to a SSD condition.

Figure A4. Virginia DOT SCC Special Provision (Page 3/4)

Also, immediately before concrete placement, thoroughly wet moisture-absorbing material that will be in contact with concrete. There shall be no standing water at time of concrete placement.

Adequate anchors for fixing wire mesh or reinforcement for mechanically anchoring SCC shall be provide Immediately before concrete placement, thoroughly wet moisture-absorbing material that will be in contact with concrete.

VII. CONCRETE PLACEMENT AND CONSOLIDATION

A concrete technologist (such as the admixture supplier) experienced in the production of SCC representing the Contractor or the concrete producer shall be present during placement.

Concrete shall stay plastic and within the slump flow specified during the placement. Any extended delay that allows the preceding load to lose flow and not combine with the next load is unacceptable and will be cause for rejection.

Ready mix concrete producer shall supply concrete in such a manner as to provide continual placement of concrete.

Concrete shall be poured from one side to the other or pumped from the bottom upward so as not to encapsulate air.

If finishing work is necessary, the exterior face of exterior surfaces shall be finished free from blemishes and then rubbed with burlap.

VIII. FINISH

Final surface shall have a smooth finish without large holes (larger than 3/8 inch) and without sand streaks except as may be required by project requirements.

II.8.2

ROUGH DRAFT- 08/19/05

VIRGINIA DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION FOR

SELF-CONSOLIDATING CONCRETE (SCC) FOR PRESTRESSED BEAMS

August 19, 2005

Figure A4. Virginia DOT SCC Special Provision (Page 4/4)

STATE OF SOUTH DAKOTA
DEPARTMENT OF TRANSPORTATION

SPECIAL PROVISION
FOR
SELF-CONSOLIDATING CONCRETE FOR BOX CULVERTS

PROJECT NUMBER, PCN NUMBER
NAME COUNTY

MARCH 7, 2008

Modify Section 460 of the Standard Specifications for Roads and Bridges as follows. These modifications apply only to concrete produced under the bid item for Class A45 Concrete, Self Consolidating. These modifications to Section 460 of the Standard Specification for Roads and Bridges do not apply to any other structural concrete.

Delete Section 460.1 and replace with the following:

460.1 DESCRIPTION

This work consists of falsework and form construction, and the furnishing, handling, placing, curing, and finishing of self-consolidating concrete (SCC) for box culverts. The SCC shall be Class A45 Concrete, Self Consolidating.

Delete Section 460.2 and replace with the following:

460.2 MATERIALS

Materials shall conform to the following Sections:

- A. Cement:** Section 750. Type I/II Portland Cement shall be used for all SCC. No substitutions will be allowed.
- B. Fine Aggregate:** Section 800.
- C. Coarse Aggregate:** Coarse aggregate for SCC shall meet the requirements of Section 820 with the following exceptions:

Coarse aggregate used in SCC shall be either quartzite or limestone aggregate conforming to the following gradation requirements:

Sieve Size	Percent Passing
1 inch (25.0 mm)	100
3/4 inch (19.0 mm)	90 to 100
3/8 inch (9.50 mm)	30 to 100
No. 4 (4.75 mm)	0 to 30
No. 8 (2.36 mm)	0 to 15*

Figure A5. South Dakota DOT SCC Special Provision (Page 1/6)

* The combined mixture of fine and coarse aggregate shall be such that not more than 1.5 percent passes the No. 200 (75 µm) sieve.

The maximum amount of flat and elongated particles for the coarse aggregate shall not exceed 30% when tested according to ASTM D 4791-99. Flat and elongated particles are defined as those particles having a ratio of maximum to minimum dimension greater than three to one. The aggregate tested shall be the material retained on a No. 4 (4.75 mm) sieve and larger.

The percent of flat and elongated particles for the coarse aggregate shall be tested at the same frequency as the coarse aggregate gradation.

D. Water: Section 790.

E. Admixtures: Sections 751 and 752. The Contractor may use viscosity modifying admixtures (VMA) to attain the desired SCC performance. VMA for use in SCC must be submitted to the Concrete Engineer for approval with the mix design.

F. Reinforcing Steel: Section 1010.

G. Curing Materials: Section 821.

H. Fly Ash: Section 753.

Delete Section 460.3 A and replace with the following:

A. Concrete Quality and Proportion: The Contractor shall design and be responsible for the performance of all concrete mixes used in structures. The mix proportions shall produce SCC that is sufficiently workable and finishable for all uses intended and shall conform to the following requirements:

1. **Minimum Cement Content:** The SCC shall contain a minimum cement content of 700 pound per cubic yard (415 Kilograms per cubic meter).
2. **Maximum Cementitious Content:** The maximum cementitious content (total cement, fly ash, and other cementitious admixture) content shall be 800 pounds per cubic yard (475 Kilograms per cubic meter).
3. **Maximum Water Cement Ratio:** The mix design shall establish a maximum water cement ratio for all SCC produced. This maximum water cement ratio shall never exceed 0.46.
4. **Minimum Coarse Aggregate Content:** The SCC shall consist of a minimum coarse aggregate content of 45 percent.
5. **Entrained Air Content Range:** The SCC shall contain an entrained air content of between 5 and 7.5 percent. The procedure for testing of entrained air content shall be performed as described in SD 403 with the following exceptions:

The air content meter bucket shall be filled in one continuous lift. Rodding of the concrete shall not be permitted. Light tamping by hand or rubber mallet on the side of the bucket may be allowed to remove cavities and large air bubbles.

Figure A5. South Dakota DOT SCC Special Provision (Page 2/6)

6. Slump Flow at Time of Placement: The slump flow at time of placement for SCC shall be between twenty-two and twenty-eight inches (22" - 28") when tested according to ASTM C 1611/C 1611M - 05, filling procedure B (inverted mold).

7. Visual Stability Index (VSI) at Time of Placement: The VSI of the SCC at the time of placement shall not exceed 1 when tested according to ASTM C 1611/C 1611M - 05.

8. Difference between J-Ring Spread and Slump Flow Spread: The difference between the J-Ring spread and the slump flow spread shall not be greater than 2.0 inches. The J-Ring spread shall be tested according to ASTM C 1621/C 1621M - 06. The slump flow spread shall be tested according to ASTM C 1611/C 1611M - 05, filling procedure B (inverted mold).

9. Minimum 28 Day Compressive Strength: The SCC shall obtain a minimum 28 day compressive strength of 4500 psi (31 MPa). The procedure for filling molds and beams shall be performed as described in SD 405 with the following exceptions:

The concrete cylinder molds shall be filled in one continuous lift. Rodding of the concrete shall not be permitted. Light tamping by hand or rubber mallet on the side of the mold may be allowed to remove cavities and large air bubbles.

10. Admixtures: VMA and polycarboxylate, if added, shall be added to the SCC at the location of placement or at an alternate location approved by the Engineer.

The absolute volume of mix proportions shall yield 27.0 to 27.25 cubic feet.

The mix design shall be based upon obtaining an average concrete compressive strength 1,200 psi above the specified minimum 28 day compressive strength.

Satisfactory performance of the proposed mix design shall be verified by laboratory tests on trial batches. Trial batches shall be conducted in accordance with the American Concrete Institute Publication ACI 211.1, ACI 318, and ASTM C 192 except that the air content shall be within 0.5% $\pm$ of the maximum specified.

The results of such tests shall be furnished by the Contractor to the Engineer at the time the proposed mix design is submitted.

Concrete mix design previously used in other work will be considered in compliance with the mix design requirements provided all of the following conditions are met:

The concrete mix proportions should be in accordance with this provision.

The mix design including all materials, gradations, and admixtures are identical to those previously used and tested.

The average 28 day compressive strength of 10 or more test results from an approved testing facility is at least 1.34 standard deviations above the specified strength. These strength test results shall be submitted to the Engineer, with

Figure A5. South Dakota DOT SCC Special Provision (Page 3/6)

companion batch tickets, air content, slump flow, VSI, and J-Ring test results. No strength test results may be below the minimum specified strength.

All mix designs and any modifications thereto, including changes in admixtures, shall be submitted for approval. Mix design data and test results shall be recorded on a DOT Form 24 and submitted to the Engineer.

Delete Section 460.3 C.3 and replace with the following:

- 3. Formwork:** Formwork shall be complete and joints made mortar tight. Concrete formwork shall be in accordance with Section 423 Temporary Works. Because of the casting properties of SCC, concrete forms shall be rigid enough to maintain dimensional tolerances and withstand form pressure that is developed by the concrete in its plastic state. Formwork shall be designed for full fluid pressure. The form joints shall be sealed sufficiently to prevent the mortar leakage that could occur with SCC.

Delete Section 460.3 H and replace with the following:

- H. Delivery Requirements:** SCC must be continuously agitated in the hauling unit, SCC shall be discharged within 90 minutes, and discharged and screeded within 105 minutes after the cement has been placed in contact with the aggregates.

The rate of delivery shall be uniform. The interval between batches shall not exceed 30 minutes.

The Contractor may be allowed to use a set retarding admixture to control initial set when approved by the Engineer. When set retarding admixtures are allowed, the concrete delivery requirements may be adjusted. The Contractor shall submit proposed delivery requirement changes to the Concrete Engineer for approval.

The contractor, using the manufacturer's recommendations, shall establish the amount of admixtures that may be added in the field when approved by the Engineer.

If, after additional admixture adjustments in the field, the concrete does not conform to the quality requirements of Section 460.3 A the concrete shall be considered for rejection.

Delete Section 460.3 K and replace with the following:

- K. Placing Concrete:** The Contractor shall give sufficient notice before starting to place concrete to permit inspection of forms, reinforcing steel, and preparation for placing. Concrete shall not be placed without approval of the Engineer.

Placement of concrete on a frozen foundation will not be permitted. The surface temperature of forms, steel, and adjacent concrete which will come in contact with the concrete being placed shall be raised to a temperature above freezing prior to placement.

The temperature of concrete immediately after placing shall be no less than 50° F (10° C) and no more than 85° F (29° C).

Figure A5. South Dakota DOT SCC Special Provision (Page 4/6)

Before placing concrete, sawdust, chips, debris, and extraneous matter shall be removed from the interior of forms. Temporary struts, stays, and braces holding the forms in the correct shape and alignment, shall be removed when the fresh concrete has reached an elevation rendering their service unnecessary. These temporary members shall not be buried in the concrete.

The slope of chutes for concrete placement shall allow the concrete to flow slowly without segregation. Chutes and spouts shall be kept clean and shall be thoroughly flushed with water before and after each run. The flush water shall be discharged outside the forms.

Free fall of concrete shall not exceed 5 feet (1.5 meters). In thin walls or columns where the reinforcement prohibits the use of chutes the method of placement shall not lead to segregation of the concrete. The use of drop tubes or tremies is encouraged to limit concrete drop heights, to keep reinforcement clean, and to limit segregation. When a concrete pump is utilized, free fall of concrete shall not exceed 1 foot (.3 meters). Horizontal flow distance shall not exceed 30 feet (9 meters).

The sequence of placing concrete, including the location of construction joints, shall be as specified. Concrete shall be placed in continuous horizontal layers. Each layer shall be placed before the preceding layer has attained its initial set.

The Contractor shall not vibrate the SCC. Limited vibrating may be allowed, when necessary, as approved by the Engineer.

Accumulations of mortar splashed upon the reinforcing steel and the surfaces of forms shall be satisfactorily removed. Care shall be exercised not to injure or break the concrete to steel bond at and near the surface of the concrete while cleaning the reinforcing steel. Dried mortar chips and dust shall be removed and not left in the unset concrete.

Add the following to Section 460.3:

- T. Frequency of Testing:** Sampling and testing by the Department shall be in accordance with the Materials Manual with the following exceptions:
1. **First Three Truckloads:** The fresh (plastic) concrete tests listed in Section 460.3 T.2 shall be performed on the concrete from the first three truckloads of any individual concrete placement. Sampling of the concrete for this application shall be at the beginning of the batch after 5 gallons of concrete has been discharged from the mixing drum. This material shall be wasted and not included in the finish product. The slump flow spread and the J-Ring spread tests shall be performed concurrently or subsequently with no more than two minutes elapsed time between the slump flow spread and the J-Ring spread tests. Samples of concrete for entrained air content shall be obtained from the discharge end of the pump in accordance with the Materials Manual.
 2. **Subsequent Truckloads:** After the first three truckloads, fresh (plastic) concrete tests shall be performed on the concrete from all subsequent truckloads at the following frequency:

Figure A5. South Dakota DOT SCC Special Provision (Page 5/6)

Delete the first paragraph of Section 480.3 C and replace with the following:

C. Placing and Fastening: Reinforcing steel shall be accurately placed and firmly held in the positions specified using steel chairs or other approved methods. Bars shall be tied at all intersections.

* * * * *

Figure A5. South Dakota DOT SCC Special Provision (Page 6/6)

UTAH DOT SCC SPECIFICATION

SECTION 03056 SELF-CONSOLIDATING CONCRETE (SCC)

PART 1 GENERAL

1.1 SECTION INCLUDES

- A. Materials and procedures for producing self-consolidating concrete.

1.2 RELATED SECTIONS

- A. Section 03055: Portland Cement Concrete

1.3 REFERENCES

- A. AASHTO M 6: Fine Aggregate for Portland Cement Concrete
- B. AASHTO M 80: Coarse Aggregate for Portland Cement Concrete
- C. AASHTO TP 73: Slump Flow of Self-Consolidating Concrete (SCC)
- D. AASHTO TP 74: Passing Ability of Self-Consolidating Concrete (SCC) by J-Ring
- E. AASHTO TP 80: Visual Stability Index (VSI) of Self-Consolidating Concrete (SCC)
- F. ASTM C 494: Chemical Admixtures for Concrete
- G. ASTM C 1602: Mixing Water Used in the Production of Hydraulic Cement Concrete
- H. ASTM C 1610: Static Segregation of Self-Consolidating Concrete Using Column Technique
- I. American Concrete Institute (ACI) Standards
- J. UDOT Materials Manual of Instruction
- K. UDOT Minimum Sampling and Testing Requirements
- L. UDOT Quality Management Plans

1.4 DEFINITIONS

- A. Self-Consolidating Concrete (SCC) – A highly flowable and non-segregating concrete mixture that spreads into place, is able to flow and fill all corners of the formwork, even in the presence of congested reinforcement by means of its own mass with no mechanical vibration.

1.5 SUBMITTALS

- A. Mix design for each mixture to the Engineer for approval before use.
 - 1. Mix designs will be approved based on results of trial batches or on history from Department projects within the last year.

Figure A6. Utah DOT SCC Specification (Page 1/5)

2. Use the same components in the trial batches that will be used in the project. Accelerators and site-added air-entrainment can be incorporated in the trial batch but are not required. The Contractor assumes responsibility for the compatibility of all admixtures with the mix design and their potential effects on concrete properties
 3. Personnel performing and witnessing trial batches and performing compressive and flexural strength testing must be Department TTQP Concrete and Concrete Strength Testing qualified.
 4. The Department or its representative may witness the trial batch.
 5. Mix concrete trial batches as specified in UDOT Materials Manual of Instruction 974: Guidelines for Portland Cement Concrete Mix Design.
 6. Compressive strength testing for verification of trial batches will be performed by an AASHTO accredited laboratory, approved through the Department Laboratory Qualification Program.
- B. Test results verifying the coarse and fine aggregate used meets this Section, article 2.3.
 1. Meet the operating bands shown in Table 2.
 - C. Product data and manufacturer's recommendations for use for the Viscosity Modifying Admixture (VMA).
 - D. Test results for any proposed mix design for potential reactivity of coarse and fine aggregates according to the requirements of the UDOT Quality Management Plan for Ready-Mix Concrete.
 - E. Results from appropriate testing to determine the ability of the combinations of cementitious materials and aggregates to control the reactivity when using potentially reactive aggregates in a mix design.
 - F. Verification that cement used is from a pre-qualified supplier. Refer to this Section, article 2.2.
 - G. Verification that fly ash or other pozzolan used is from a pre-qualified supplier. Refer to this Section, article 2.6.
 - H. Verification that the batch plant meets the requirements of the UDOT Quality Management Plan for Ready-Mix Concrete.
 - I. Cold and hot weather plans according to this Section, article 3.5 Limitations.
 - J. The Materials Engineer approves submittal.
- 1.6 ACCEPTANCE**
- A. Acceptance sampling and testing of material according to UDOT Minimum Sampling and Testing Requirements.
 - B. Refer to this Section, Part 2.
 - C. Concrete below specified strength and the item does not have a separate strength pay factor.
 1. The Department may accept item at a reduced price.
 2. The pay factor will be applied to items represented by the strength tests that fall below the specified strength.
 3. The Department will calculate the pay factor on 28 day compressive strength. Refer to Table 1.

Figure A6. Utah DOT SCC Specification (Page 2/5)

Table 1

28 Day Compressive Strength	
Psi Below Specified Strength	Pay Factor
1 – 100	0.95
101 – 200	0.90
201 – 300	0.85
301 – 400	0.80
More than 400	Reject

4. The Engineer may allow a "reject" lot to remain in place based on an engineering analysis and concurrence from the Materials Engineer. Apply a pay factor of 0.50 if a rejected lot is allowed to remain in place.

PART 2 PRODUCTS

2.1 MIX REQUIREMENTS

- A. Air content – 5.0 percent to 7.5 percent
- B. Slump Flow – 18 to 32 inches. Refer to AASHTO TP 73.
- C. Compressive Strength
 - 1. AA(AE) compressive strength requirements unless otherwise specified. Refer to Section 03055.
- D. Visual Stability Index rating 0 – 1. Refer to AASHTO TP 80.
- E. Static Segregation – less than 10 percent. Refer to ASTM C 1610.
- F. Maximum nominal size of coarse aggregate:
 - 1. Not larger than $\frac{1}{5}$ of the narrowest dimension between sides of forms.
 - 2. Not larger than $\frac{1}{2}$ the depth of slabs.
 - 3. Not larger than $\frac{3}{4}$ of the minimum clear distance between reinforcing bars or between bars and forms, whichever is least.
- G. Do not exceed water/cementitious ratio of 0.40.
- H. Calculate the water/cementitious ratio (w/c) according to the following formula:

$$\frac{W}{C} = \frac{\text{Water}}{\text{Cement} + \text{Pozzolan}}$$

2.2 CEMENT

- A. Refer to Section 03055.

2.3 AGGREGATES

- A. Use Coarse Aggregate according to AASHTO M 80 physical properties and the combined gradation requirements of Table 2.
 - 1. Do not exceed percentages of deleterious substances as shown in AASHTO M 80, Table 2, for Class A aggregates.

- B. Use Fine Aggregate according to AASHTO M 6 physical properties and the combined gradation requirements of Table 2.
1. Do not exceed percentages of deleterious substances according to AASHTO M 6 for class A aggregates, using class B for material finer than the No. 200 sieve.

Table 2

Aggregate Gradations Percent Passing by Dry Weight of Aggregate		
Sieve Size	¾ inch Operating Bands	½ inch Operating Bands
¾ inch	95 – 100	–
½ inch	65 – 95	95 – 100
¾ inch	58 – 83	65 – 95
No. 4	35 – 65	50 – 80
No. 8	25 – 50	30 – 60
No. 16	15 – 35	20 – 45
No. 30	10 – 35	12 – 35
No. 50	5 – 20	5 – 20
No. 100	1 – 12	2 – 12
No. 200	0 – 5	0 – 5

2.4 WATER

- A. Use potable water or water according to ASTM C 1602, including Table 2.

2.5 ADMIXTURES

- A. Refer to Section 03055
- B. Viscosity Modifying Admixtures (VMA) according to ASTM C 494, Type S.
1. Do not exceed manufacturer recommendations for the use of the viscosity modifying admixture.
 2. Show the amount of admixture used on batch tickets.
 3. Site-added VMA – Record amount used on batch ticket.

2.6 POZZOLAN

- A. Refer to Section 03055.

PART 3 EXECUTION

3.1 PREPARATION

- A. Refer to Section 03055.

3.2 FIELD PRODUCTION TEST PLACEMENT

- A. Perform a test placement of the designed SCC mix in the presence of all Department and Contractor personnel involved with the placement.
- B. Demonstrate appropriate quality tests and associated procedures during test placement including, but not limited to temperature, slump flow, air content, casting strength specimens, and Passing Ability of SCC by J-ring. Refer to AASHTO TP 74. Meet the requirements of this Section, Part 2.

3.3 BATCHING MATERIALS

- A. Refer to Section 03055.

3.4 MIX DESIGN

- A. Design and proportion mix according to ACI 301 and project specific criteria.
- B. Design the cementitious system to mitigate potential alkali-aggregate reactivity.
 - 1. Use a minimum of 20 percent by weight of the total cementitious system when using fly ash.
- C. Use only concrete mixes that have been approved. The Engineer may allow adjustments to sand/aggregate ratios to maintain the combined gradation.
- D. Obtain concurrence from the Resident Engineer for the project specific application of an approved mix.

3.5 LIMITATIONS – GENERAL

- A. Refer to Section 03055 with the following exception:
 - 1. Concrete Temperature – Place concrete when the concrete temperature is between 60 and 90 degrees F unless otherwise specified.

3.6 CYLINDER STORAGE DEVICE

- A. Refer to Section 03055.

END OF SECTION

Figure A6. Utah DOT SCC Specification (Page 5/5)

Kentucky Method 64-320-08
Revised 03/21/08
Supersedes 64-320-06
Dated 03/03/06

METHOD FOR APPROVAL OF USING
SELF CONSOLIDATING CONCRETE (SCC)

1. SCOPE: This method covers the process for precast plants to obtain approval for use of SCC in precast products.
2. BASIC REQUIREMENTS:
 - 2.1. Qualified manufacturers must submit a revised quality control plan utilizing SCC to the Kentucky Transportation Cabinet (KYTC) for approval, and meet all applicable requirements of the Kentucky Standard Specifications for Road and Bridge Construction and the Prestress/Precast Manual.
3. PROCEDURES:
 - 3.1 Submit a written request for SCC approval to: Director, Division of Materials, 1227 Wilkinson Boulevard, Frankfort, KY 40601. The request must include:
 - 3.1.1. Mix Designs.
 - 3.1.1.1. Minimum cementitious material - 564 pounds per cubic yard.
 - 3.1.1.2. Maximum w/c ratio of .46 (Type F or G high-range water reducer required).
 - 3.1.1.3. Air content of $6\% \pm 2\%$
 - 3.1.1.4. Spread limits (Indicate low end and high end of spread range)
 - 3.1.2 SCC quality control procedures.
 - 3.1.3 Plastic test methods and limits imposed.
 - 3.1.4 SCC plant production records.
 - 3.1.5 28 day strength data.
 - 3.1.6 Core testing data, if available.

- 3.2 If qualified manufacturers meet the requirements set forth herein, KYTC will require a SCC

KM 64-320-08

1

demonstration for each qualifying plant. This demonstration should include representation from admixture and cement manufacturers and plant officials. A plant may receive a 90-day conditional approval if it can demonstrate a good quality mix using SCC. These approvals will be granted on a case by case basis. The KYTC will need to witness a SCC batch at the minimum and maximum spread indicated on the submitted mix designs.

- 3.3 During the 90-day conditional approval, KYTC will initially require that each plant provide the following:
 - 3.3.1 Obtain 4 cores from the demonstration pours and submit them to an independent lab for air analysis in accordance with the current edition of ASTM C-457.
 - 3.3.2 Perform and record the spread, visual rating of spread and temperature of every batch of SCC (spread test should be performed next to forms if transporting SCC by any method other than cranes) for the first 30 days of production. Provide these test results to the Division for review. This requirement may be waived for plants approved in another state using SCC for over one year.
- 3.4 Continue to use the approved mix design (unless additional mix designs are submitted and approved prior to use).
- 3.5 Maintain the spread approved by KYTC during demonstration and visually inspect for segregation and any paste outline around spread. Perform test in accordance with ASTM C-1611 and document all results.
- 3.6 Have a working moisture probe and compensator or KYTC approved alternative.

KM 64-320-08

2

Figure A7. Kentucky TC Method 64-320-08 (Page 2/3)

4. DISQUALIFICATION OF MANUFACTURERS: If the 90-day conditional approval procedures are not followed or if any problems arise that cannot be immediately corrected, the plant will be disqualified to use SCC in any KYTC product.

APPROVED _____
DIRECTOR
DIVISION OF MATERIALS

DATE 03/21/08

Kentucky Method 64-320-08
Revised 03/21/08
Supersedes KM 64-320-06
Dated 03/03/06

Km32008.doc

KM 64-320-08
3

Figure A7. Kentucky TC Method 64-320-08 (Page 3/3)

NYSDOT OPTIONAL USE OF SCC NOTE

581A5

D262276 – Amendment 1

Any galvanized surfaces required to be painted shall be painted in accordance with the requirements of section 657 of the standard specifications.

The contractor shall verify dimensions necessary for the proper fit of steel pieces prior to the fabrication of the steel. The cost of field verifying dimensions shall be included in the price bid for structural steel items.

SELF CONSOLIDATING CONCRETE FOR PLACEMENT OF STRUCTURAL CONCRETE:

The contractor shall submit a proposed mix design for Self Consolidating Concrete (SCC). This mix shall be used under the Materials Requirements for Placement of Structural Concrete.

The contractor shall create a mix design, and prepare a trial batch using those materials to be used on the project. The contractor must demonstrate the mix's ability to achieve the specified properties to the Regional Materials Engineer's satisfaction. At least three weeks prior to placement, the contractor shall supply:

- Mix design and compressive strength results, including rate of strength gain for 1, 3, 7, 14, and 28 days, or maturity curves with corresponding temperatures as appropriate.
- Proposed target limits for spread, indicating acceptable low and high spread limits and proposed actions when mixture testing is outside of the target limits.
- Proposed Visual Stability Index (VSI) allowable measurements for acceptance.
- Air content.

The contractor shall provide a proposed quality control plan, including how the above performance criteria will be maintained and actions taken when test results are not acceptable. Once a mixture design is accepted by the Department, changes other than minor fluctuations in admixture dosage rates will require a new mix design. All other provisions of Item 555 apply, unless otherwise directed by the Engineer.

Accelerated Bridge Program – Phase 1A, Contract 9
Delavan Avenue over NY Rte 33
City of Buffalo, Erie County
BIN 1022660 PIN SABP.12

DL-50A1

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Figure A8. NYSDOT SCC NOTE (retrieved from https://www.dot.ny.gov/main/business-center/ABPphase1/repository/D262276_Amendment_01.pdf)

APPENDIX B – LINKS TO STATE DOCUMENTS RELATED TO CIP SCC

This appendix contains website links to specific documents related to SCC used in the development of this report which we felt were important but too long to include in Appendix A. A brief description is provided with each link to illustrate the document origin and purpose.

1. <http://etd.auburn.edu/handle/10415/2317> - This document is a master thesis by Phillip Alain Gallet at Auburn University which contains the Alabama DOT Special Provision 06-0420 for the construction of SCC Drilled Caissons.
2. <http://www.state.nj.us/transportation/eng/specs/2007/spec900.shtm#s903> - This is a document from the New Jersey Department of Transportation Standard Road and Bridge Construction Specification. This document contains SCC specifications (section 903.6) related to the material requirements, precast/prestressed applications, and cast-in-place caissons.
3. <http://www.wsdot.wa.gov/publications/manuals/fulltext/M41-10/SS2012.pdf> - This document from the Washington Department of Transportation Standard Road, Bridge, and Municipal Construction Specification 2012 contains SCC specifications related to the material requirements and precast/prestressed applications
4. <http://www.dot.state.fl.us/specificationsoffice/OtherFDOTLinks/Developmental/Files/Dev346SCC.pdf> - This is from Florida Department of Transportation which contains SCC specifications related the material requirements, placement requirements, and quality control of Self-Consolidating Concrete.
5. Rhode Island Department of Transportation. (2011). Standard Specification for Road and Bridge Construction - Section 606 - Self Consolidating Concrete. Retrieved from http://www.dot.ri.gov/documents/engineering/BlueBook/Compilation_of_Approved_Specs_2011.pdf
6. <http://nlcs1.nlc.state.ne.us/epubs/R6000/B016.0119-2007.pdf> - This document is a final project report that contains the Nebraska DOR Guide for Special Applications of Cast-in-Place Self-Consolidating Concrete.

7. <http://www.iowadot.gov/erl/current/im/content/445ad.htm>;
<http://www.iowadot.gov/erl/current/im/content/445.htm> - This document is links Iowa DOT's IM445D - Guidelines for Approving and Testing SCC Mix Design. IM 445 is for precast concrete application.
8. <http://library.modot.mo.gov/RDT/reports/TRyy1103/cmr13-03.pdf> - This link is to the summary of SCC research for MoDOT; it provides a proposed specification for precast SCC for MoDOT and results of cast-in-place SCC applications in Missouri.
9. <http://www.cee.hawaii.edu/reports/UHM-CEE-12-09.pdf> - This document provides the draft SCC specifications developed for use of the drilled shafts at the North Kahana Bridge Replacement project in Oahu, Hawaii.
10. ftp://ClearPartner:External_R7@ftp.dot.state.pa.us/Bureau_of_Project_Delivery/Clearance_Transmittals/B-13-018/Step_2/07092013/Self%20Consolidating%20Concrete%20Special%20Provision.pdf
Pennsylvania DOT has proposed a standard specification for self-consolidating concrete for use in drilled shafts.

APPENDIX D – POLISHED SPECIMENS USED IN AGGREGATE SEGREGATION ANALYSIS

Location

Side Specimens

Middle Specimens

1

2

3

4

5

APPENDIX E – BUBBLE COUNTER AIR-VOID DISTRIBUTION OUTPUT FOR AIR VOID ANALYSIS SPECIMENS

Side 1

Side 2

Side 3

Side 4

Side
5

Middle
1

Middle
2

Middle
3

Middle
4

Middle
5