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PERFORMANCE AND ACCEPTANCE OF SELF-CONSOLIDATING CONCRETE: FINAL REPORT

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16. Abstract

Self-consolidating concrete (SCC) is an important emerging material that can be used for many applications related to transportation infrastructure. SCC has an advantage over conventional concrete in that it can be easily placed without vibration or mechanical consolidation.

The project was initiated to better understand how SCC performs in fresh and hardened states and to provide engineers involved in writing specifications and test procedures protocols and associated acceptance criteria to deliver successful SCC mixtures and construction practices that ensure acceptable material properties.

This research project was conducted from July 2004 to June 2007. The extensive re-construction of I-74 through Peoria, IL underway during this timeframe used SCC for over 20 miles of retaining wall structures. The research served as a partnership between engineers involved in the Peoria project and the research team at the University of Illinois.
This final report serves as a summary of five MS theses and Ph.D. dissertations produced by the UIUC team [1-5]. In partnership with IDOT BMPR, the project contributed to six new test methods for measurement of SCC performance [6-10].

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EXECUTIVE SUMMARY

Self-consolidating concrete (SCC) is an important emerging material that can be used for many applications related to transportation infrastructure. SCC has an advantage over conventional concrete in that it can be easily placed without vibration or mechanical consolidation.

The project was initiated to better understand how SCC performs in fresh and hardened states and to provide engineers involved in writing specifications and test procedures protocols and associated acceptance criteria to deliver successful SCC mixtures and construction practices that ensure acceptable material properties.

This research project was conducted from July 2004 to June 2007. The extensive re-construction of I-74 through Peoria, IL underway during this timeframe used SCC for over 20 miles of retaining wall structures. The research served as a partnership between engineers involved in the Peoria project and the research team at the University of Illinois.

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CHAPTER 1 INTRODUCTION

Self-consolidating concrete (SCC) is a high-performance material that is designed to flow into formwork under its own weight. It was first used in Japan in the 1980's to reduce the labor cost associated with placing concrete. Since then it has gained international popularity and is now a focus of interest in the United States. Research and development of SCC materials is widespread, but the goal of uniformity and acceptance for practical use has not yet been fully realized.

SCC has an advantage over conventional portland cement concrete in that it can be easily placed without vibration or mechanical consolidation. Flowable properties are typically achieved with one or more of the following mix design attributes: high cementitious materials content (greater than 750 lb/yd^3 (445 kg/m^3)), next generation superplasticizers (possibly in combination with a viscosity modifying admixture (VMA)), mineral admixtures, and careful selection of aggregate volume and gradation. Low aggregate volume and smaller coarse aggregate size are often needed to improve flow around steel reinforcement to reach restricted areas. To reduce the potential for segregation, mineral admixtures such as silica fume, fly ash, ground-granulated blast furnace slag (GGBFS), calcined clay, and pulverized limestone may be added. A viscosity modifying agent can also be added to enhance segregation resistance. The hardened properties of SCC are influenced by the increase in cementitious materials content, which may affect strength gain, elastic modulus, creep, and shrinkage (autogenous and drying).

The project, a partnership between UIUC and IDOT BMPR, addressed concrete materials research needs related to transportation structures. This partnership of IDOT and UIUC expertise serves the central goal of defining successful SCC mixtures and construction practices that can deliver improved material properties and long service life in the field.

This final report serves as a summary of five MS theses and Ph.D. dissertations produced by the UIUC team:

> Lin Shen, Role of Aggregate Packing in Segregation Resistance and Flow Behavior of Self-Consolidating Concrete, Ph.D. dissertation, University of Illinois, 2007. [1]
>
> Andrew J. Brinks, A Layered Finite Element Model for the Analysis of Segregation of Self Consolidating Concrete, MS Thesis, University of Illinois, 2005. [2]
>
> Fernando Tejeda-Dominguez, Laboratory and Field Study of Self Consolidating Concrete Formwork Pressure, MS Thesis, University of Illinois, 2005. [3]
>
> Benjamin Frederick Birch, Formwork Pressure Exerted by Self Consolidating Concrete, MS Thesis, University of Illinois, 2007. [4]
>
> Matthew Dominick D'Ambrosia, Early Age Creep and Shrinkage of Self Consolidating Concrete, Ph.D. Dissertation, University of Illinois, 2008. [5]

In partnership with IDOT BMPR, the project contributed to five new test methods for measurement of SCC performance that are included in an appendix:

> Illinois Test Procedure SCC-6, Standard Test Method for Static Segregation of Hardened Self-Consolidating Concrete Cylinders [6]
>
> Illinois Test Procedure SCC-7, Provisional Test Method for Static Segregation of Fresh Self-Consolidating Concrete Cylinders Using the Static Segregation Probe [7]
>
> Illinois Test Procedure SCC-8, Provisional Test Method for Assessment of Dynamic Segregation of Self-Consolidating Concrete During Placement [8]
>
> Illinois Test Procedure SCC-9, Provisional Test Method for Dynamic Segregation of Fresh Self-Consolidating Concrete by Flow Trough [9]
>
> Illinois Test Procedure SCC-10, Standard Test Method for Determining Formwork Pressure of Fresh Self-Consolidating Concrete Using Pressure Transducer Sensors [10]

CHAPTER 2 EXPERIMENTAL STUDIES

The project focused on three topics related to SCC performance in transportation structures. First, SCC is more sensitive to segregation problems than is conventional concrete, and so this project assessed the mechanism of segregation, measurement of segregation, and the effect of segregation on hardened properties [1]. Second, formwork pressure is a controversial issue because the greater fluidity of SCC means that standard guidelines for formwork pressure under-estimate the pressures exerted by SCC mixtures [3,4]. Third, SCC mixtures tend toward greater cement content and lower aggregate content, and so the shrinkage, creep, and other hardened properties of SCC require greater understanding to permit use of SCC in transportation structures [5].

The following sections provide an overview of the test program for each of the three topics.

2.1 SEGREGATION OF SCC [1,2]

2.1.1 Overview

Segregation resistance is important for SCC because its low viscosity and yield stress facilitate segregation. Poor segregation resistance can reduce flowability, induce blocking around reinforcement, induce high drying shrinkage, and cause non-uniform compressive strength when the concrete hardens. Much research has studied flow behavior and segregation of SCC with aggregate properties such as volume, size, and gradation.

Concrete can segregate in both vertical and horizontal directions. Vertical segregation normally occurs when fresh concrete is at rest (static) and is thus called static segregation. Typical static segregation is observed as more and larger aggregates settle to the bottom, resulting in a layer of mortar at the top. Horizontal segregation occurs during the flowing state of concrete and is thus called dynamic segregation. Typical dynamic segregation is observed as a paste or mortar layer leading the flow path of concrete.

Research was conducted to modify existing methods and develop new methods to satisfy different application situations [11,12]. This project focused upon the roles of aggregate packing in segregation resistance and flow behavior of SCC based on scientific theories such as rheology, flow mechanics, and particle packing.

2.1.2 Theory of Segregation

A major part of the study of segregation was focused on rheological models and theory of segregation of aggregate within a suspension [1,13]. The work considered a great amount of literature and developed mathematical expressions that apply to vertical and horizontal segregation. This fundamental work formed the basis for understanding the many physical experiments that were conducted.

One of the most important accomplishments was to identify and differentiate static segregation from dynamic segregation. The literature on segregation of SCC is almost exclusively focused upon static segregation. Static segregation occurs when aggregate settle in a fresh concrete mixture that is at rest. This study also placed attention on dynamic segregation, a phenomenon that occurs when the SCC flows over considerable distance and the aggregates strip out of the concrete as a function of distance. Dynamic segregation and static segregation occur under very different mechanisms, and this work developed mathematical expressions for both types of segregation. It was shown that static and dynamic segregation do not always occur in the same concrete, and static segregation tests alone cannot predict dynamic segregation.

2.1.3 Experimental Program

To study segregation of SCC, accurate and reliable test methods are necessary. The first objective of the research project was to characterize the two types of segregation of SCC: static segregation and dynamic segregation. Research was conducted to modify existing methods and develop new methods to satisfy different application situations.

A hardened visual stability index (HVSI), an image analysis method, and a segregation probe method were developed and applied for static segregation. The segregation probe was shown to be quick, easy, and accurate. It correlates well with image analysis and HVSI. A flow trough was developed to characterize dynamic segregation.

2.1.3.1 Hardened Visual Stability Index (HVSI) [6]

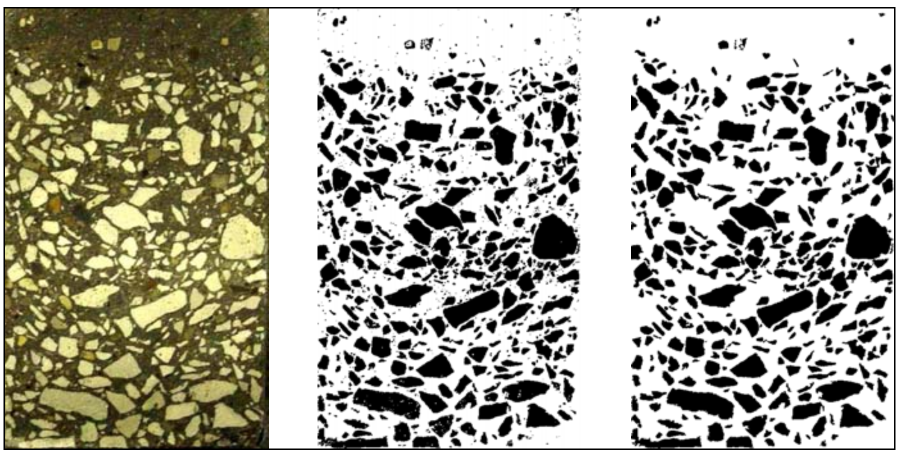
A method was developed to assess static segregation of SCC by using a hardened cast cylinder of the material. The test produces a parameter known as the Hardened Visual Stability Index (HVSI). HVSI is a qualitative measurement of the distribution of coarse aggregate from a sectioned cylinder. The method is conducted by placing SCC in a standard 6 × 12 in. cylinder and allowing the concrete to harden. The cylinder is then cut length-wise with a concrete saw, exposing a section of the cylinder to view the top-to-bottom distribution of coarse aggregate. The ratings shown in Table 1 are assigned on the basis of visual observation.

Table 1. Hardened Visual Stability Index (HVSI) [1,6]

HVSI	**Criteria**
0 stable	No paste/mortar layer on top of the cylinder, and no difference in size and area percentage of coarse aggregates lengthwise.
1 stable	No paste mortar layer on top of the cylinder, but slight difference in size and area percentage of coarse aggregates lengthwise.
2 unstable	Slight paste/mortar layer- less than 1-in. (25-mm) - on top of the cylinder.
3 unstable	Significant paste/mortar layer – greater than 1-in. (25-mm) – on top of the cylinder, and/or clear evidence of difference in size and area percentage of coarse aggregates lengthwise.

2.1.3.2 Image Analysis Method Of Measuring Segregation

A section of a hardened SCC cylinder can be assessed using image analysis to provide greater quantification of segregation when compared to the simpler, qualitative HVSI method. A digital photo of the section can be acquired and processed by an image analysis procedure to compute the area fraction of coarse aggregate, and the areas can be represented for the quartiles from top to bottom. The processing of the image is summarized in Figure 1, and the presentation of typical results is shown in Figure 2. This method takes much more time than the observation of HVSI by visual judgment, but may be useful if standardized procedures are required.



(a) (b) (c)

Figure 1. Images of 6 × 12 in. (150 × 300 mm) cylinder in different stages of image analysis: (a) original image; (b) binary image; (c) final image [1,6].

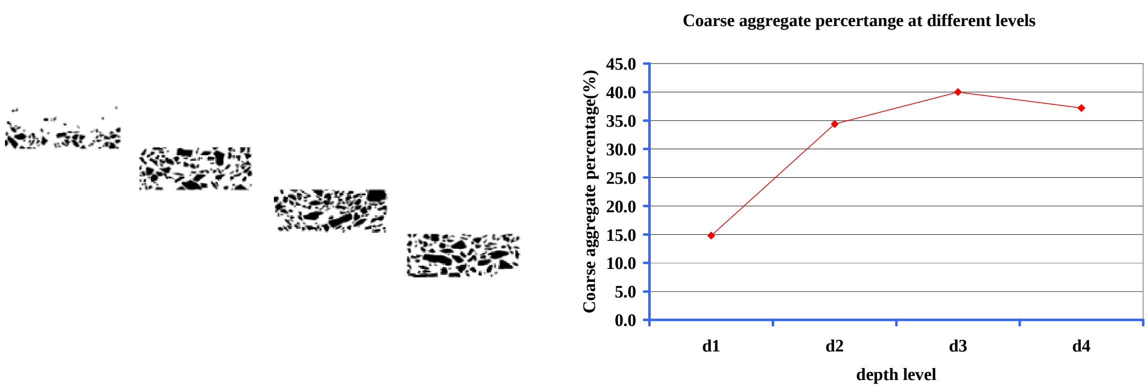


Figure 2. Coarse aggregate percentages at different quartiles [1,6].

2.1.3.3 Segregation Probe [1,7]

A segregation probe was developed to measure static segregation of fresh SCC. The segregation probe is placed on the top of a sample of SCC in a 6 × 12 in.

(150 × 300 mm) cylinder that has been allowed to rest undisturbed for two minutes. Any static segregation will be revealed by the probe as it comes to rest on top of the coarse aggregate that may have settled. The segregation probe used in the study at UIUC was made from a 3/32-in. (2.38-mm) diameter steel wire, and shaped to have a circular base with a diameter of 4-in. (100-mm). The penetration depth is an indicator of the thickness of the paste layer that exists at the top of a segregated sample of SCC. An illustration of the probe is shown in Figure 3. The interpretation of results is shown in Table 2.

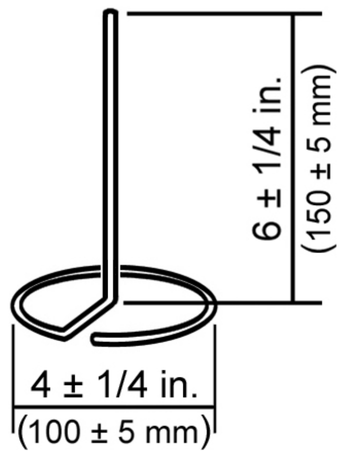


Figure 3. Segregation probe [1,7].

Table 2. Measured Stability Index (MSI) for Segregation Probe Method [1,7]

Settlement Depth, in. (mm)	MSI	Corresponding HVSI from a Cut Cylinder
< 1/8 (3)	0 stable	0 stable
1/8 - 1/4 (3 - 6)	1 stable	1 stable
1/4 - 1 (6 - 25)	2 unstable	2 unstable
> 1 (25)	3 unstable	3 unstable

2.1.3.3.1 Use of Segregation Probe to Measure Robustness [7]

A self-consolidating concrete (SCC) mixture is said to be robust when its key properties (flowability and stability) are not sensitive to small changes in water content or admixture dosage. The segregation probe can be very useful to assess the robustness of an SCC mixture. The procedure involves mixing SCC in a pan mixer, and incrementally adding water. Adding water, re-mixing, and testing for segregation can reveal the mixture's sensitivity to water content.

A small batch of concrete is prepared, batched, and mixed according to standard laboratory procedures (ASTM C 192, AASHTO R 39, et al.). The initial w/cm ratio is 0.02 less than the design target (which typically results in an initial slump flow 1-in. (25-

mm) less than the design target). Water is added to increase the w/cm ratio 0.01, the mixture is re-mixed for 1 minute, and allowed to stand undisturbed for 2 minutes before the segregation probe is set onto the surface of the mix. The depth of settlement is measured after 1 minute, and the process of adding water and re-mixing is repeated until the mix has significant segregation, that is, the probe settles at least 1-in. (25-mm).

Typical results for three different SCC mixtures are shown in Figure 4.

SCC mixtures that exhibit excellent robustness are those that display a more gradual slope in the settlement depth curve and can resist segregation at water contents considerably above the design w/cm ratio. In the figure, the VMA mixture is the most robust of the three mixtures.

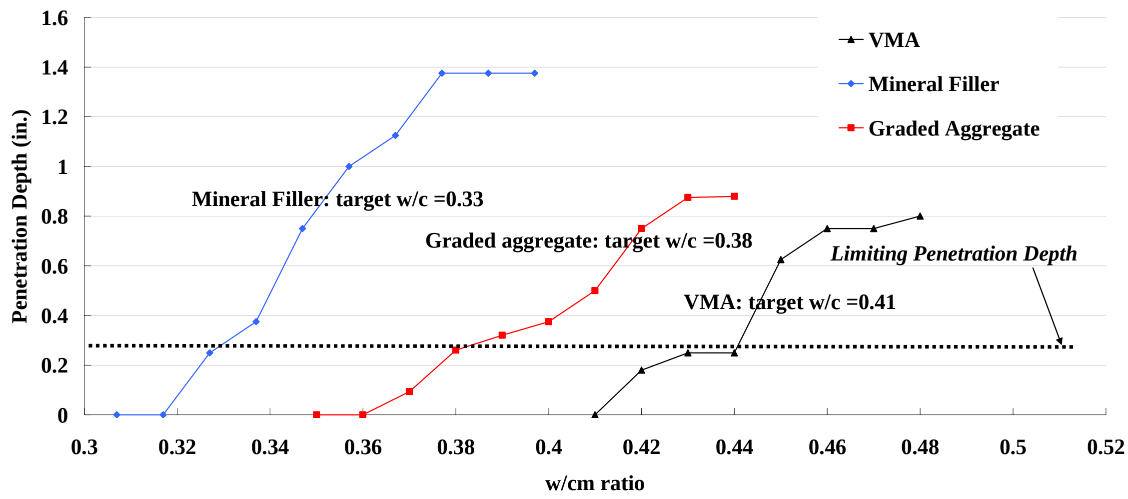


Figure 4. Effect of SCC Type on Robustness [1]. (1 in. = 25 mm).

2.1.3.4 Flow Trough for Measuring Dynamic Segregation [2]

A successful laboratory method for dynamic segregation needs to satisfy several requirements. First, the flow distance of concrete needs to be long enough to give useful information about dynamic segregation in typical field conditions. Typical flow distance of SCC in the field ranges from 10 to 30 ft (3 to 9 m) and in some cases can be as long as 100 ft (30 m). It was not desirable to make a 20-ft (6-m) long apparatus for a dynamic segregation test; however, a test method with an overly short flow distance may not reveal dynamic segregation observed with long flow distances.

Based on these requirements, a flow trough was developed as shown in Figure 5. It was made by assembling 1-in. (25-mm) thick wood boards to form a 6 × 6 × 72 in. (150 × 150 × 1800 mm) trough. The inclined angle is 7° (9-in. (230-mm) height difference between the two ends). The surface of the trough was painted to make it water-resistant and easy to clean.

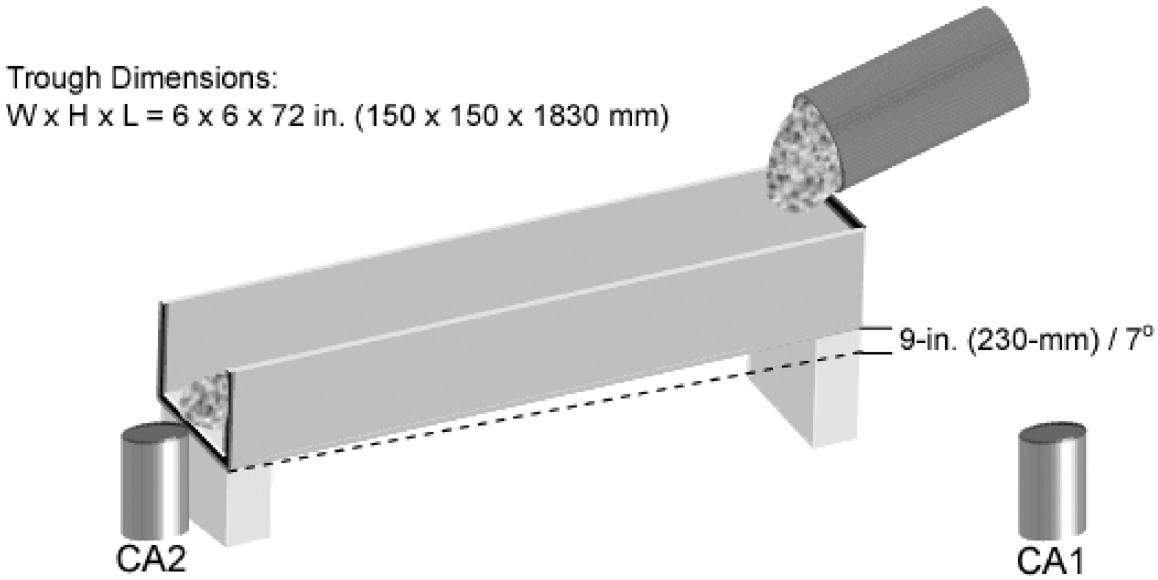


Figure 5. Flow trough for dynamic segregation [2].

The test is conducted by pouring a sample of SCC at the top end of the trough, and collecting a sample at the bottom end. The coarse aggregate contents of the two samples collected in 4 × 8 in. (100 × 200 mm) cylinders is obtained by washing the material over a #4 sieve and weighing the aggregate remaining on the sieve. The dynamic segregation index (DSI) is then calculated as

$$DSI = \frac{(CA1 - CA2)}{CA1}$$

where CA1 is weight of coarse aggregate from the sample of original SCC and CA2 is weight of coarse aggregate from the sample collected at the bottom of the trough.

The reliability of the flow trough method was shown through limited field tests where it was possible to also measure dynamic segregation directly in the formwork using Illinois Test Procedure SCC-8 [8]. The purpose was to observe dynamic segregation over a long flow distance and see how well the flow trough can reproduce dynamic segregation that occurs in the formwork. The field and trough tests were very similar, indicating promise that this trough method may be an effective approach.

2.1.4 Maximum Travel Distance for SCC

The flow trough method has potential to provide insight into maximum travel distance for SCC projects. An empirical relationship was established on the basis of results of this study. The empirical relationship involves material characteristics such as w/c ratio, air content, bulk density and both the design cementitious content and the maximum allowable cementitious content. The design cementitious content is determined by the original mixture proportions. The maximum allowable cementitious content may refer to specified limits. For example, the Illinois Department of Transportation requires that the maximum cement factor does not exceed 7.05 cwt/ yd^3 (418 kg/m^3). In the absence of such a specified limit, the maximum allowable cementitious content could be computed for a level of dynamic segregation deemed acceptable. An estimate for the maximum recommended travel distance to be used for an SCC project without undue risk of dynamic segregation is:

$$DSI_{max} = 1 - \frac{1000 - 10c - e(b - \frac{1}{d})}{1000 - 10c - a(b - \frac{1}{d})}$$

Where *a* = design cementitious content, kg/m^3
b = w/c ratio
c = air content, percent
d = bulk density of cement and finely divided minerals, g/cc
e = maximum cementitious content, kg/m^3

Figure 6 is a design chart for selecting a maximum travel distance to be permitted for a project using SCC. DSI is measured by experiment and DSI_{max} is determined from the above equation.

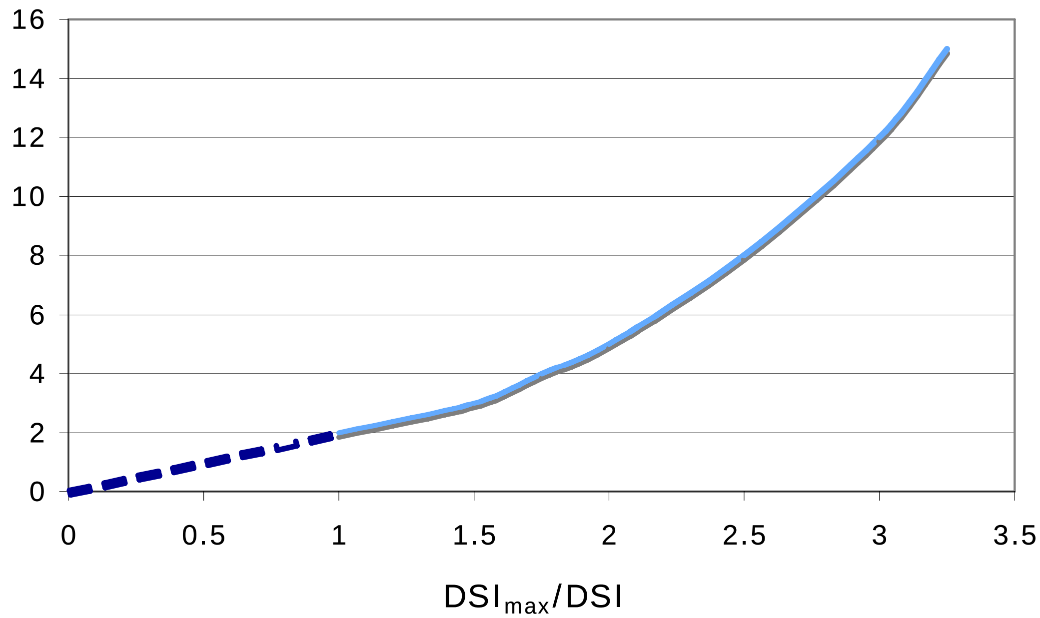


Figure 6. Design chart to determine Maximum Travel Distance (1 m = 3.25 ft).

2.1.5 Validation of Segregation Effects [2]

An experimental study was conducted to validate the material models developed by this project, and to demonstrate that segregation of SCC could induce high stresses in structures that are restrained. An experiment was created that used a cantilever cast with an SCC mixture with segregating behavior, thus creating an inhomogeneous profile.

The cantilever was 25-in. (630-mm) long and had a 3 × 3 in. (75 × 75 mm) cross-section. The SCC was cast and cured in an orientation so that static segregation would occur in the Z-direction as shown in Figure 7. The specimen was sealed with aluminum foil so that no external drying would take place, but the material would experience autogenous shrinkage.

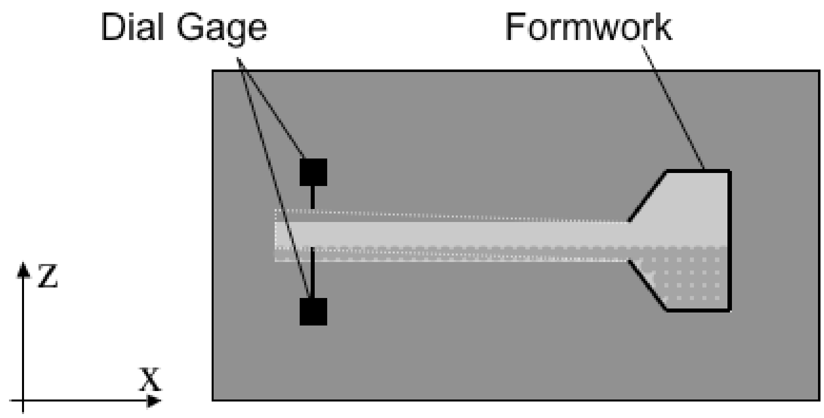


Figure 7. Cantilever test measurement orientation [2].

After the SCC had set, the hardened specimen was repositioned so that the Z-direction was parallel to the table surface. Dial gages were installed at the cantilever ends so that any deflection of the cantilever under drying conditions would be measured. Testing continued for 14 days.

After 14 days, the test was complete, and the specimen was sectioned to reveal the segregation in the specimen. A typical cross-section is shown in Figure 8.

The image of the cross-section was analyzed to discern the composition of layers. A layered finite element model (FEM) was created using ABAQUS software, describing the layers that appeared in the segregated test specimen. Separate experiments were conducted to independently replicate the materials of each layer so that material properties and autogenous shrinkage of each layer could be determined. The FEM analysis was then able to predict cantilever deflection driven by autogenous shrinkage. The effect of segregation was apparent in these results. Figure 9 shows that the FEM analysis produced the deflected shape, and Figure 10 indicates a reasonable match between the actual experimental values and the model results.

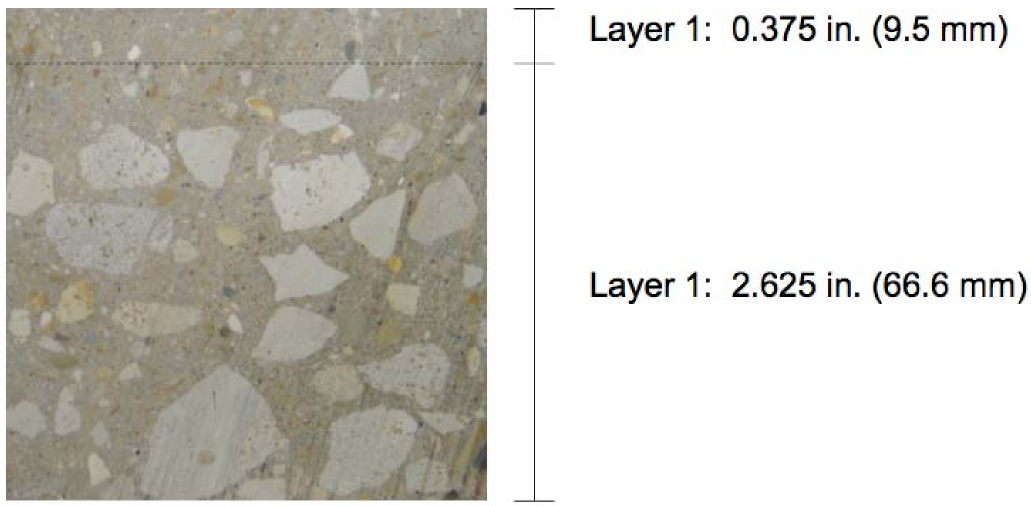


Figure 8. Validation trial two cut cross section [2].

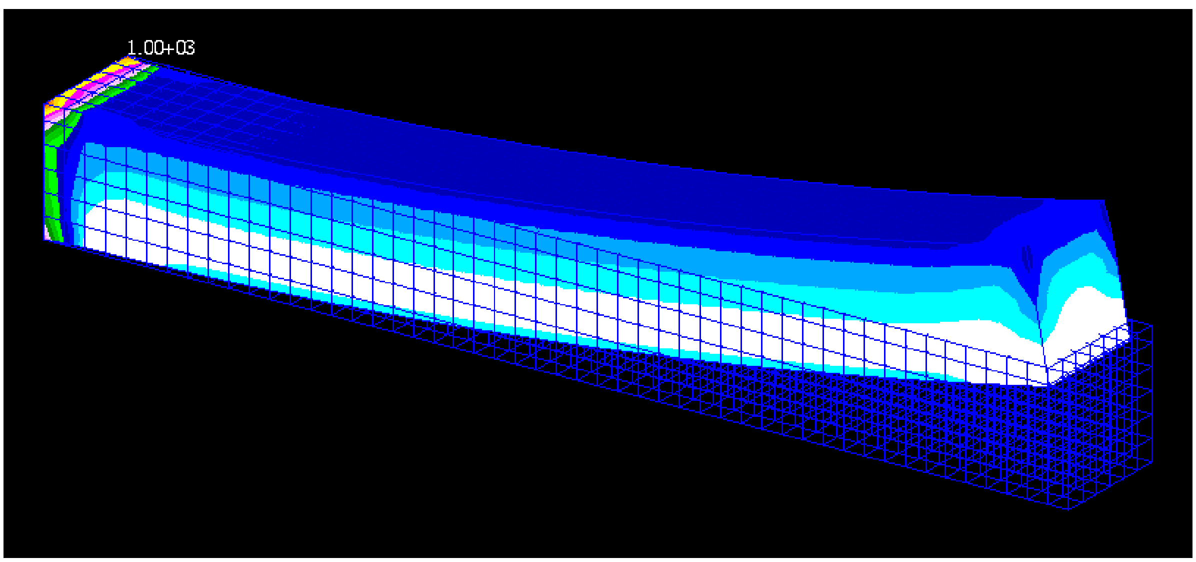


Figure 9. FEM deformed shape and stress values at 14 days [2].

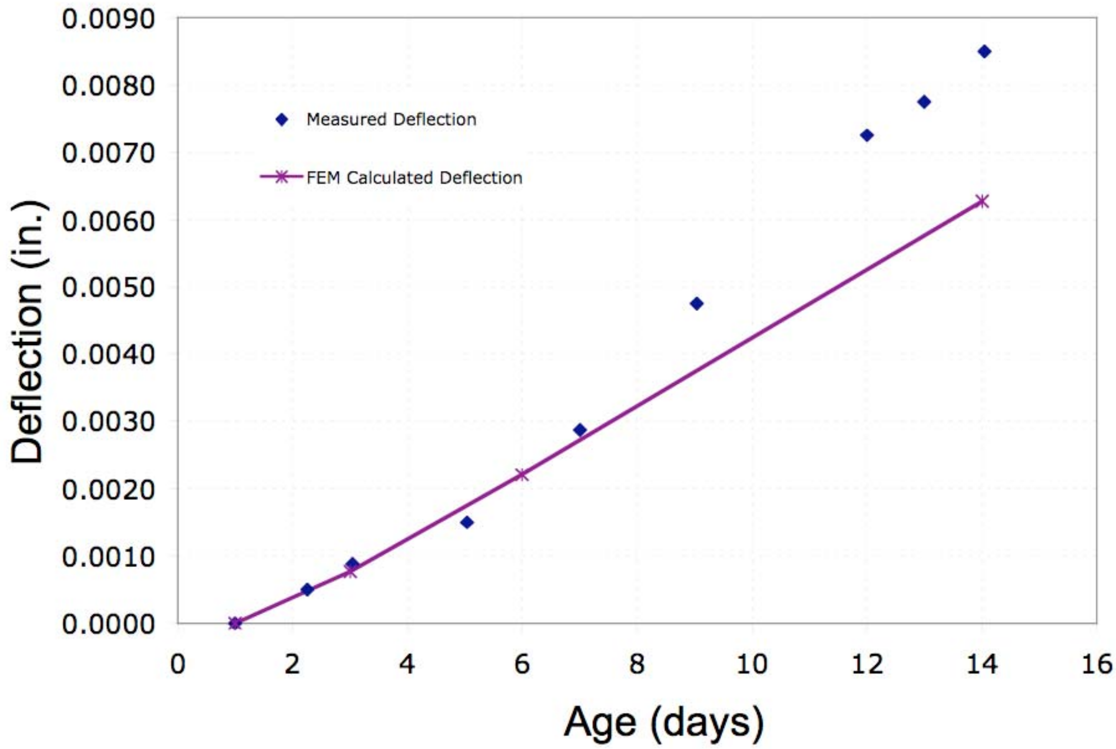


Figure 10. Calculated vs. measured cantilever deflection [2]. (1 in. = 25 mm*).

The FEM study served to validate material modeling concepts that were developed in the project. The FEM study showed how tensile stress is created by inhomogeneous layering caused by segregation, and this tensile stress leads to deformation of an unrestrained cantilever specimen.

The FEM analysis, once validated for the unrestrained case, was repeated under full restrained conditions. Stress in the restrained case was about 13 times greater than the maximum stress observed in the unrestrained case.

The experiment was conducted for SCC materials matching HVSI indices of 0, 1, 2, and 3. The results of this study confirmed that SCC having HVSI indices of 0 or 1 are correctly considered to be "stable" without significant stress development due to segregation. SCC having HVSI indices of 2 or 3 were shown to generate high stresses, and thus the characterization of these materials as "unstable" is appropriate.

2.1.6 Findings

The study produced recommended theoretical models that provide a basis for understanding the fundamental mechanisms of static and dynamic segregation.

The study produced new test methods for assessing segregation in the lab and in the field. A Hardened Visual Stability Index (HVSI) method was developed. An image analysis method was also developed to assess segregation using a cut cylinder of SCC.

A segregation probe was developed to measure static segregation, and a flow trough was developed to measure dynamic segregation.

Static segregation decreases with smaller aggregate size, smaller density difference of aggregate and paste, higher viscosity and yield stress of paste, higher aggregate fraction, and lower maximum packing density of aggregate.

Dynamic segregation is highly affected by the mix proportions and characteristics of constituents. Dynamic segregation can be reduced by adjusting mixtures toward smaller aggregate size, wider and more continuous aggregate gradation, lower aggregate density, and higher paste viscosity and yield stress. The dominate factors for dynamic segregation are aggregate size, gradation, density, and paste rheology. Less important factors are aggregate volume and initial concrete flow velocity.

The cantilever experiments and FEM analysis confirmed that SCC having HVSI indices of 0 or 1 are relatively inconsequential for stress development, and may be considered to be stable materials. On the other hand, SCC having HVSI indices of 2 or 3 were shown to generate high stress, and should be considered unstable materials.

2.2 FORMWORK PRESSURE OF SCC [3,4]

2.2.2 Overview

Effective formwork design is fundamental to assure a successful construction project since formwork itself constitutes one of the major costs on concrete structures. The cost of formwork may exceed the cost of concrete and steel materials combined. An efficient selection of the formwork system will increase jobsite productivity and improve safety. Failure of formwork is a serious concern. The failure of formwork is always dangerous and costly. Failures can also create distortion that will require expensive repair.

Pressure of fluids at rest is governed by the hydrostatic law, which establishes that the pressure at any point is a function of the unit weight and head of the fluid. Concrete has a much more complicated behavior that varies with time. Past studies on lateral pressure exerted by conventional concrete have shown that the pressure is less than the full hydrostatic head of concrete.

Self-consolidating concrete (SCC) is able to flow under its own weight, completely filling formwork and achieving full consolidation, even in the presence of congested reinforcement. It is known that SCC exerts greater pressure on forms for a more sustained period of time than conventional concrete, but there exist no standard equations to predict that pressure. Therefore, users of SCC for tall wall applications often assume that formwork must support full hydrostatic pressure. This assumption is generally conservative, and it leads to conservative limitations on lift height and overly strong forms.

2.2.3 Experimental Program

A method was developed for measuring formwork pressure that was applicable to both laboratory and field testing [14,15]. The approach used a commercially available pressure sensor and mounting apparatus to allow direct measurement of pressure at specific heights in the form. In the laboratory, a PVC column was used and a Honeywell sensor was installed to measure pressure (Figure 11). The system was able to directly measure pressure as a function of time (Figure 12). In the field, mounting brackets were designed to allow sensors to be installed in holes drilled in the formwork (Figure 13).

Figure 11. PVC column (left) and pressure sensor (right) used in laboratory tests [4].

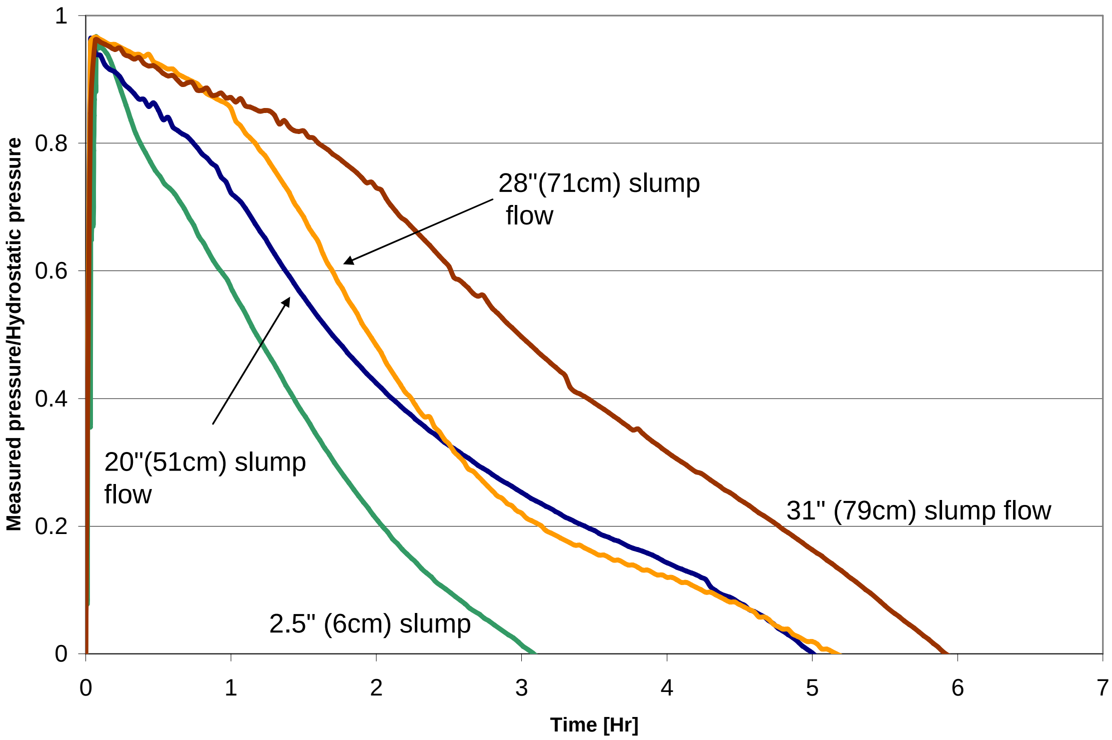


Figure 12. Typical pressure decay curves obtained from column test [4].

Figure 13. Typical forms (left) and sensor brackets (right) used in the field [4].

Many different SCC mixtures were tested, including materials with various admixtures, temperatures, and aggregate gradation. The SCC materials were fully characterized, including flow behavior, strength and shrinkage behavior.

Experimental work was conducted in two Phases. In Phase I, techniques were developed and lab and limited field experiments were conducted. In Phase II, the laboratory testing continued and many field measurements were made in order to validate the model.

2.2.4 Modeling Formwork Pressure Decay

A model was developed to predict pressure in a tall wall application. The model uses the characteristic pressure decay curve measured on a three foot tall column as a material parameter to govern how the SCC gels and becomes self-supporting in the first few hours after placement. The model also accounts for a change in pressure head as the form is filled.

The intent of this model is to provide a tool for users of SCC to predict formwork pressure for a given SCC and rate of placement. The users can use the model to guide them in designing formwork and specifying maximum pour rates for field construction.

A typical prediction from the model is shown in Figure 14. One can see that the pressure at the sensor location will rise as the pressure head is increased, but that there will be a subsidence of pressure as the concrete at the sensor location gels and becomes self-supporting. This gelation should not be confused with “set” of concrete. The gelation occurs as the thixotropic fresh concrete gains structure even before set.

Guidelines (Illinois Test Procedure SCC-10) were prepared to provide procedures for measuring formwork pressure and conducting the analysis using the model equations to produce predictions of formwork pressure for given pouring rates [10].

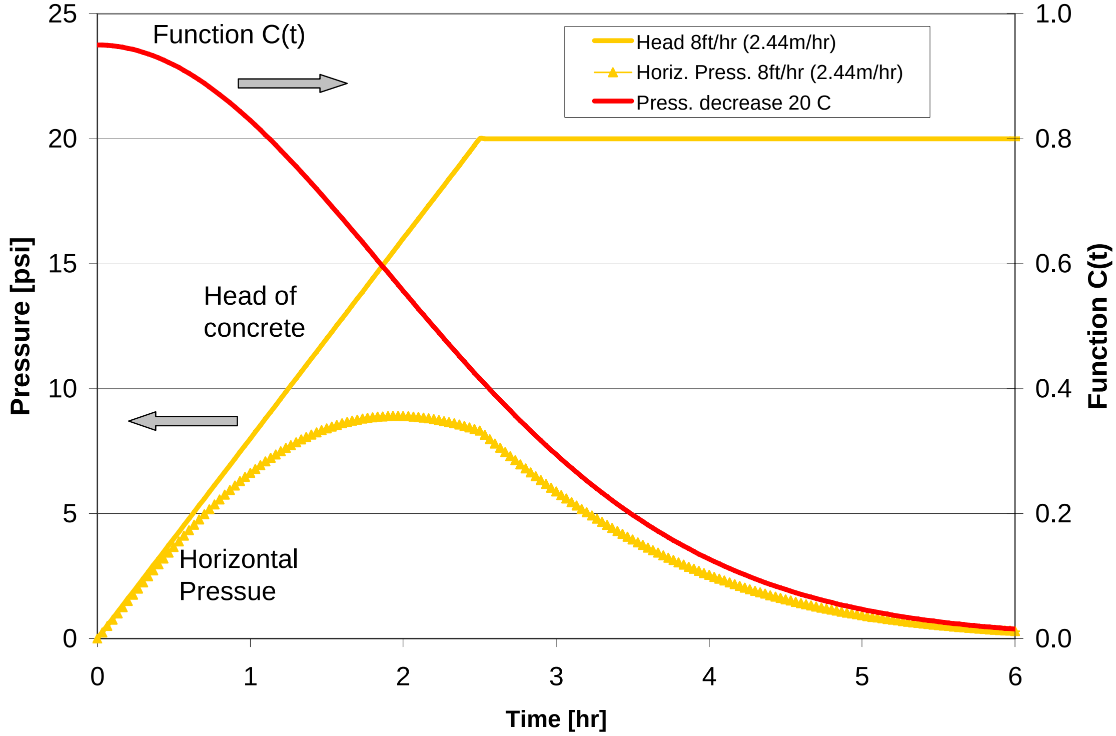


Figure 14. Model predicts horizontal formwork pressure for a given SCC with behavior described by C(t) while the pressure head increases as a function of concrete depth above the sensor location [4]. (1 psi = 7 kPa).

2.3 HARDENED PROPERTIES OF SCC [5]

2.3.1 Overview

This study included a literature review, an extensive experimental program, and material modeling to predict impact of SCC mixture proportioning on hardened properties such as elastic modulus, drying shrinkage and creep [16, 17, 18, 19].

A database of over 150 SCC mixtures obtained from the literature and from industry application was compiled for understanding the major categories of SCC proportioning. Figure 15 shows the fine aggregate to coarse aggregate ratio vs. aggregate content for those mix designs obtained. Specific materials that were examined in this study are also identified. A shaded oval on the figure represents what are considered conventional concrete proportions according to the ACI method for mixture proportioning. Most notably, the average water to cementitious material ratio (w/cm) was 0.41, and the average water to powder (w/p, where p refers to cementious materials plus mineral fillers) was 0.35, indicating a trend towards lower water contents for SCC. The aggregate content tends to be lower for SCC than for conventional concrete because additional paste volume is needed for improving the flowability and passing ability of SCC. There is also a tendency for SCC mixtures to include a relatively high proportion of sand in the mixture to improve segregation resistance.

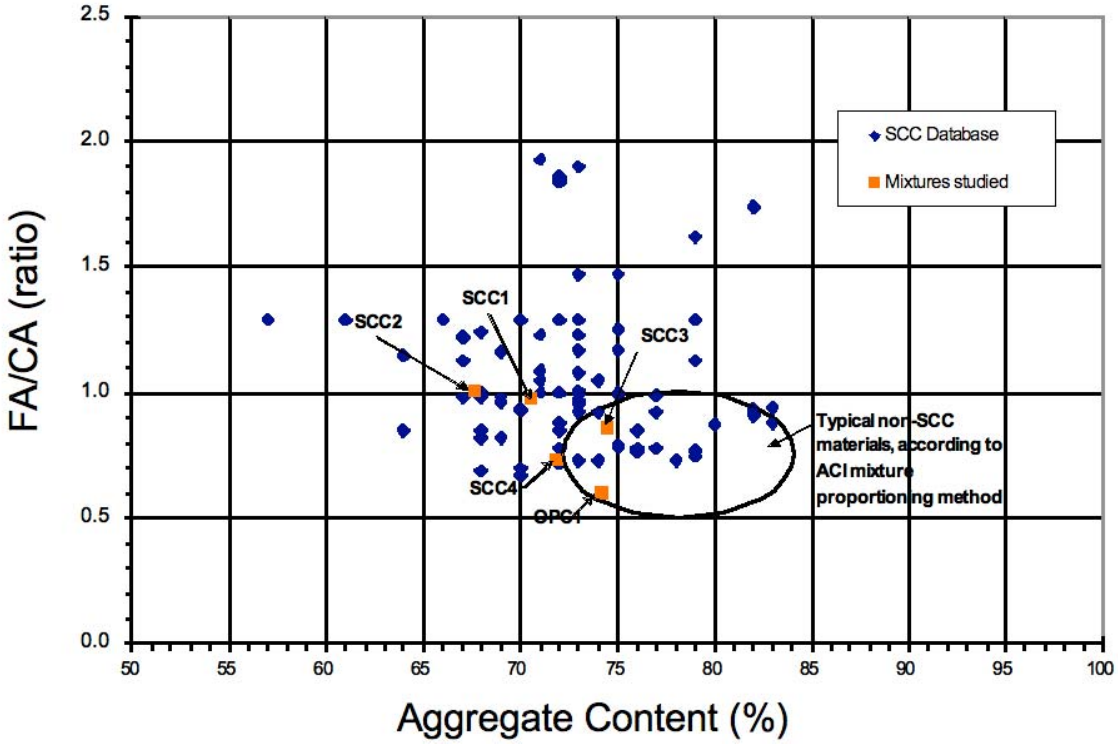


Figure 15. Fine to coarse aggregate ratio vs. aggregate content for SCC database [5].

SCC has been known to be more susceptible than conventional concrete to segregation. Segregation that occurs in the fresh state can lead to a poorly consolidated or inhomogeneous material that will have diminished strength and durability. Differential shrinkage may occur due to higher paste content in the surface layers of segregated concrete. Abrasion resistance, frost durability and toughness were affected as well, leading to potential long term durability problems. A lack of experimental data on the durability of segregated concrete makes prediction of durability difficult and more research is required to assess the nature of this problem.

SCC may be made with a viscosity modifying admixture (VMA). VMA is not believed to significantly affect hardened properties. Past studies have overdosed VMA by 3 to 6 times without significant effects on chemical shrinkage or compressive strength.

2.3.2 Experimental

An extensive experimental program was conducted to explore the impact of SCC mixture proportions on hardened properties. The test program utilized:

- Restrained Stress Test Machine (RSTM)
- Constant Compressive and Tensile Creep Tests
- Compressive and Tensile Strength Tests
- Elastic Modulus Tests under Compression and Tension

- Internal Temperature and Relative Humidity Measurements
- Autogenous Shrinkage Measurements
- Drying Shrinkage Measurements

2.3.3 Evolution of Properties and Behavior

2.3.3.1 Strength and Modulus Development

SCC is special concrete, but it still obeys many of the same behaviors of conventional concrete. SCC strength development, like conventional concrete, is governed by w/cm ratio. Many SCC materials tend to have w/cm ratios that are relatively low, and thus SCC is often reported to have relatively high strength. Concrete materials with low w/cm ratios tend to gain strength fairly rapidly (e.g. largely within 3 days), and the elastic modulus also tends to develop within an even shorter period of time.

2.3.3.2 Shrinkage

Concrete materials with relatively low w/cm ratios tend to consume mix water before hydration is complete, and therefore the internal microstructure suffers from "self-dessication." This kind of internal drying—commonly called autogenous shrinkage—can cause significant shrinkage stresses which can lead to cracking. High shrinkage can occur even on sealed prisms that are not exposed to external drying. The level of autogenous shrinkage is largely dependent on the w/cm ratio. Figure 16 shows results for autogenous shrinkage for a set of typical SCC mixtures with various w/c ratio and one OPC (ordinary portland cement) mixture. Figure 17 shows results for total shrinkage for the same materials when they are exposed to external drying. One can see that the autogenous shrinkage has potential to be a large component of total shrinkage. Based on results of this study, autogenous shrinkage becomes a major concern for shrinkage below a w/cm ratio of 0.38, although this level may vary depending on cement paste content and aggregate type. A w/c range of 0.40 to 0.42 may be specified under circumstances when it is necessary to eliminate nearly all autogenous shrinkage in most concretes.

A general finding of this study is that SCC behavior is governed by many of the same factors known to govern OPC (ordinary portland cement). For example, the dominant factor for total shrinkage of both OPC and SCC is w/c ratio. SCC materials may tend to have higher paste contents, and when that is the case, higher total shrinkage can be expected. The chemical admixtures used in SCC to impart fluidity and control viscosity do not in themselves have great influence on hardened properties such as total shrinkage.

The Restrained Shrinkage Test Machine (RSTM) was used to measure the stress developed in drying concrete. Typical results for the same concrete materials discussed above are shown in Figure 18. One can see that the stresses can reach well above 300 psi in tension, and thus these materials are susceptible to cracking when restrained.

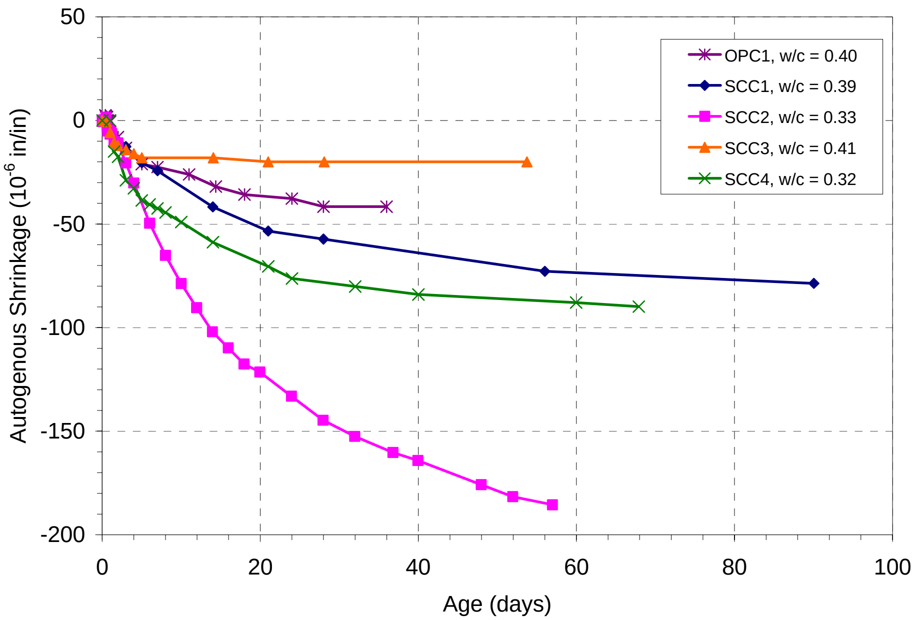


Figure 16. Autogenous shrinkage of 4 x 8 in. (100 × 200 mm) cylinders sealed at 73°F (23°C). OPC is conventional PCC and SCC are self consolidating concrete mixtures [5].

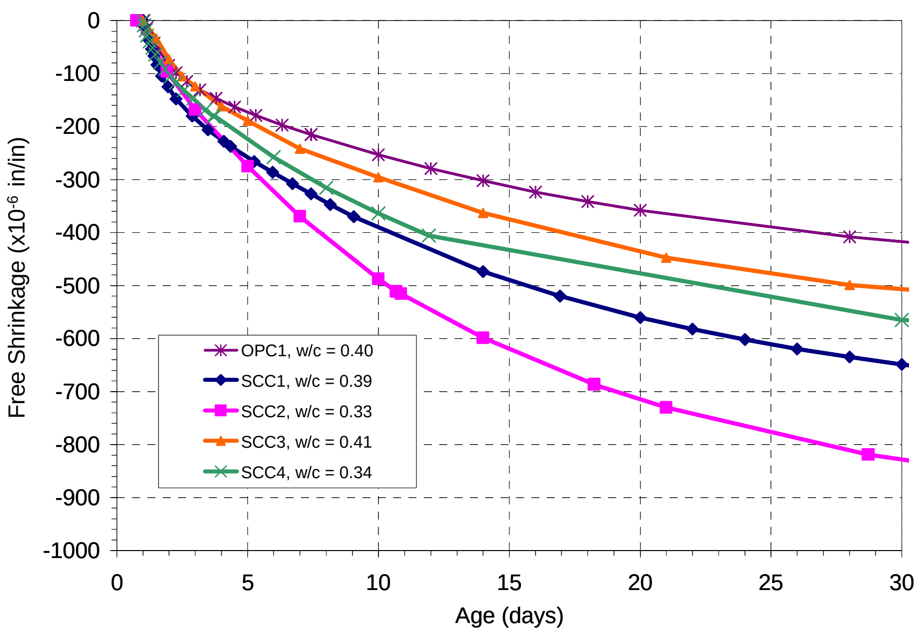


Figure 17. Total shrinkage of 3 × 3 × 24.5 in. (75 × 75 × 600 mm) prisms during drying at 50% relative humidity, 73°F (23°C). OPC is conventional PCC and SCC are self consolidating concrete mixtures [5].

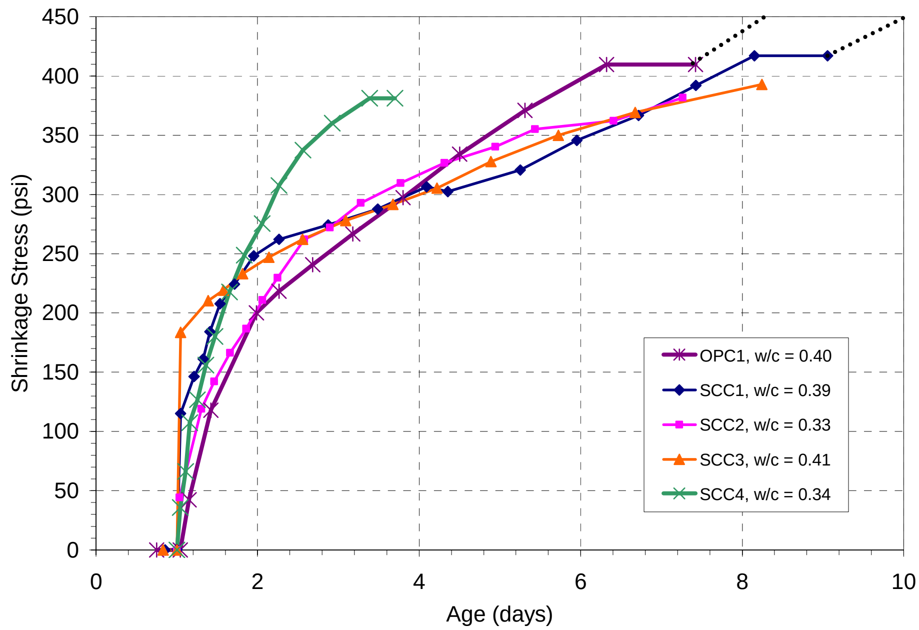


Figure 18. Shrinkage stress development of 3 × 3 × 24.5 in. (75 × 75 × 600 mm restrained prisms during drying at 50% relative humidity, 73 °F (23°C)). OPC is conventional PCC and SCC are self consolidating concrete mixtures. (1 psi = 7 kPa) [5].

2.3.3.3 Creep

The RSTM permits measurement of restrained shrinkage and tensile creep behavior in early age concrete. Other experiments were used to measure creep in compression and tension. ASTM C 512 describes the apparatus used for compressive creep measurements. A new dead load creep apparatus was designed at UIUC and used for tensile creep measurements. These various experiments enabled multiple tests to be performed and run simultaneously for longer periods of time, since only two RSTM frames were available. Creep of SCC (and conventional concrete) is significantly greater in tension than in compression. A typical result illustrating the general relationship is shown in Figure 19 [How does SCC compare to conventional concrete?]. Not all mixtures were directly compared, so a general statement cannot be made.

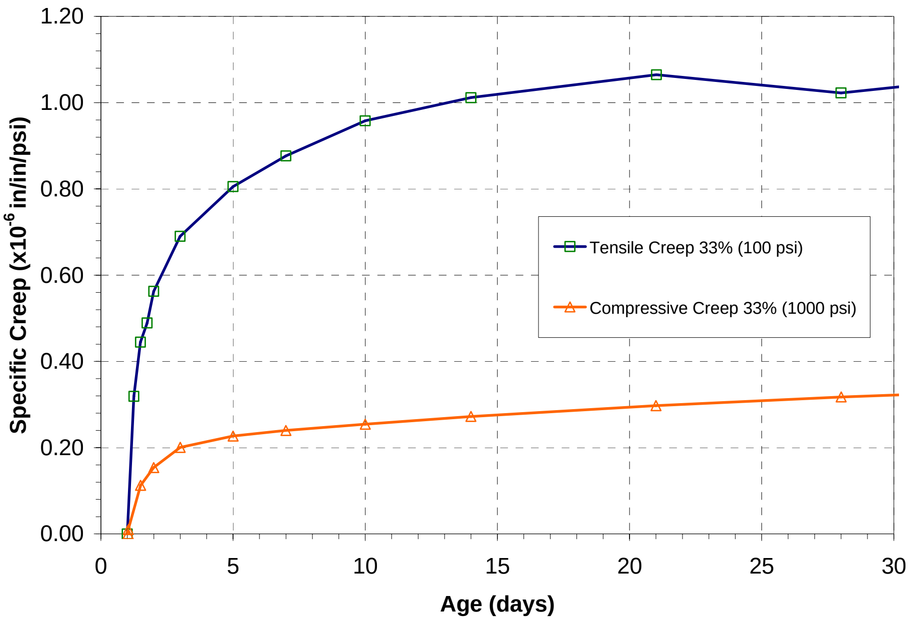


Figure 19. Compressive creep vs. tensile creep at early age [5].

2.3.3.4 Long Term Volume Change

The study included limited measurement of long term shrinkage. Figure 20 compares data for five mixtures—one ordinary Portland cement mixture (OPC) and four SCC mixtures. The experiments used prisms exposed to drying conditions starting at one day. The results show that long term shrinkage is governed by cement paste content, whether the material is an OPC or SCC. The results also show that the prisms reached a maximum shrinkage at about one year.

Long term shrinkage has implications for structural applications because the steel reinforcement does not undergo any shrinkage. Thus, there can be transfer of load from concrete to steel in structural elements. In prestressed elements, there will be a loss of prestress when the concrete undergoes shrinkage. When SCC materials have higher cement content than conventional structural concrete, a designer may find it appropriate to investigate the impact of mixture proportioning on long term shrinkage. Existing material models for creep and shrinkage are available (B3, GL2000, ACI 209) for incorporation into design equations for prestress loss prediction. The material models that utilize the key concrete mixture parameters of **w/cm** and **cement paste content** are attractive for predicting the performance of SCC. Utilizing a material model prediction, there are several prestress loss calculation procedures available in the literature that can be used with such material model predictions to supplement the AASHTO design method. The worst case scenario for prestress loss would be encountered with an SCC with an extremely high cement paste content that undergoes significant shrinkage and creep, such as SCC2.

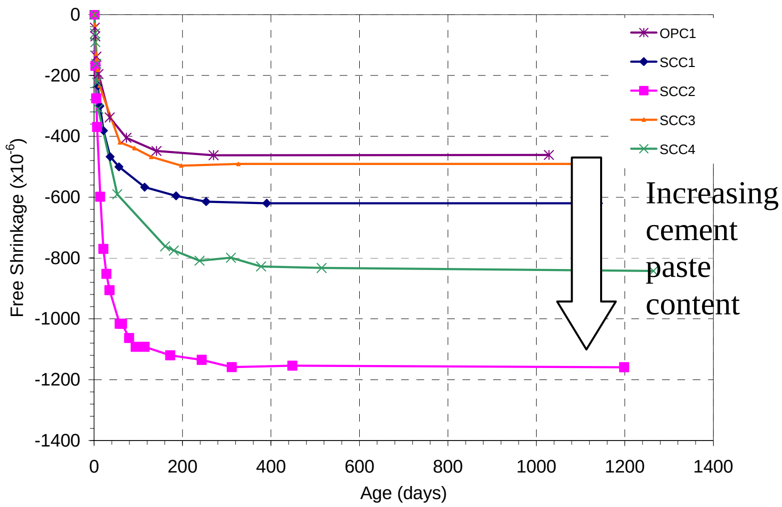


Figure 20. Long term shrinkage and role of cement paste content [5].

2.3.4 Modeling

A mathematical material model was developed to predict stress and strains associated with internal and external drying of SCC. The study developed models that help explain shrinkage and creep in terms of basic driving forces. Internal relative humidity is the driving force that causes shrinkage to take place, and the models developed in this study use fundamental physical laws that govern water in capillary pore structure to predict stress in the material. The model utilizes internal relative humidity measured with embedded gages. This kind of modeling is a powerful tool for advanced analysis of structures exposed to drying conditions at early ages.

The study included evaluation of existing models for shrinkage and creep such as those in ACI 209 and the B3 model. These mathematical models are more fully described elsewhere [5]. The ACI 209 model is an empirical model whereas the B3 model incorporates more parameters that describe the mixture proportions and aging affects. Revisions of these models are suggested by this study, particularly when the user desires a careful and complete understanding of stresses and volume changes at early ages under drying conditions. The revisions are general, and apply to both OPC and SCC, for predication of shrinkage and creep that occurs at early age. The revised models were implemented using finite element analysis software to predict volume change of SCC and OPC materials. The model was calibrated and validated by comparing the predictions to experimental results. The experiments include several different configurations, including prisms, cantilevers with one-sided drying, and ring tests.

2.3.5 Significance of Gradients

Drying gradients are very significant factors in developing stresses that lead to undesired cracking and deformation in the field. One of the best known problems occurs when pavement slabs curl under early age temperature and drying shrinkage gradients. The one-sided cantilever test shown in Figure 21 was used to assess the effect of drying gradients and prove the viability of the models developed in this study. Figure 22 shows the success of the model to predict how the cantilever would deform. The drying gradient, measured with embedded relative humidity gages, drives volume change in this model.

Figure 21. Differential shrinkage test for validation of ICON 3-D finite element model [5].

2.3.6 Findings And Recommendations For SCC Mixture Design

SCC mixtures tend to have high paste content and low w/cm ratios compared with conventional concrete. Thus, SCC often has high shrinkage and rapid development of physical properties, factors that make SCC susceptible to thermal and shrinkage cracking. SCC mixtures can and should be designed with cracking in mind.

Limits for proportioning can be suggested based on the results of this study. The proportioning parameters that are most influential (i.e. w/cm ratio and paste content) should be scrutinized with regard to limitations that should be imposed for certain applications. A minimum w/cm ratio should be imposed in many cases to limit autogenous shrinkage. The experimental and modeling work was used to identify the correct limits and to establish guidelines for optimizing proportions to achieve the necessary properties (strength, flowability) without sacrificing long term durability. It may be possible to establish a category of “low shrinkage” concrete using these guidelines.

Recommended limits for SCC cement paste content are presented in Table 3. Recommended limits for SCC w/cm ratio to avoid early age cracking is shown in Table 4. In both tables, three categories are identified to suggest how structural restraint plays a role in determining how restrictive the limits should be.

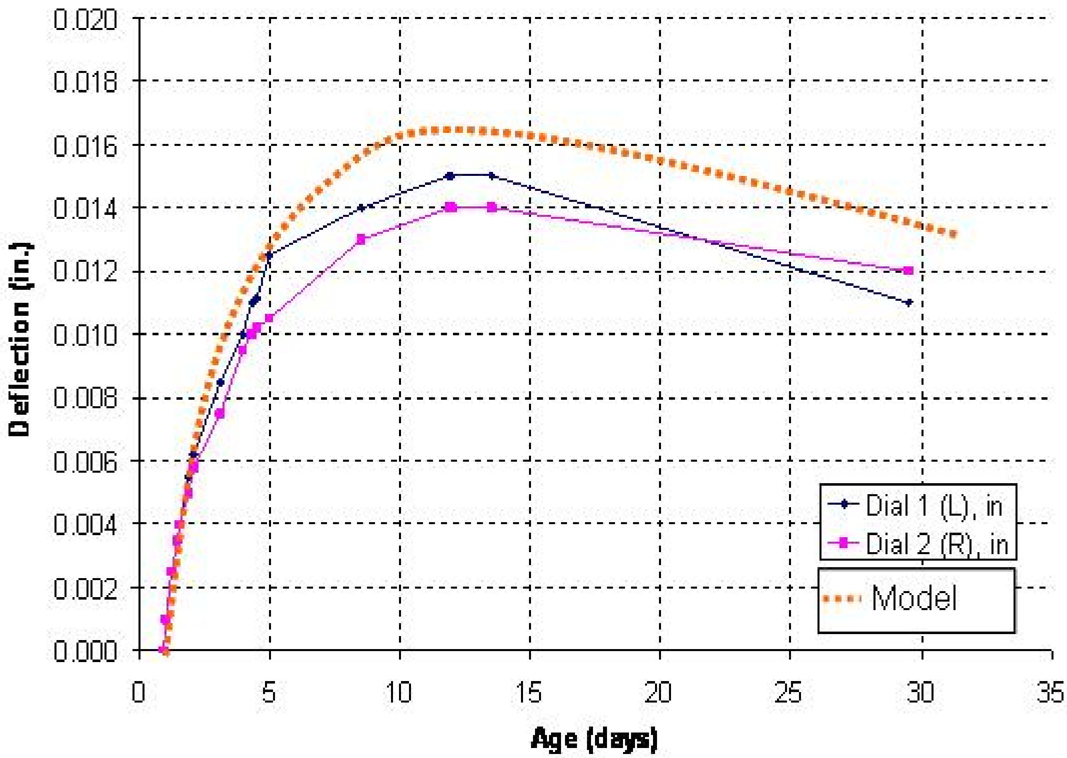


Figure 22. Model prediction of differential shrinkage deflection [5]. (1 in. = 25 mm)

Table 3. Maximum Cement Paste Content Specification [5]

Category	Examples	Cement Paste Content Limit by wt	Approximate Cement Content @ 0.44 w/cm ratio
High Restraint	Bridge decks, pavement, slabs, big volume-to-surface area	30%	605 lb/yd^3 (360 kg/m^3)
Medium Restraint	Beams, pipe, precast, substructures, mass concrete	34%	705 lb/yd^3 (420 kg/m^3)
Low Restraint	Only cases where restraint is minimal and creep and shrinkage are not a concern	36%	750 lb/yd^3 (445 kg/m^3)

Table 4. Recommended Limitations for W/Cm Ratio To Avoid Early Age Cracking [5]

Category	Examples	Minimum w/cm ratio	Approximate Autogenous Shrinkage @ 28 days (microstrain)
High Restraint	Bridge decks, pavement, slabs, big volume-to-surface area	0.42	0
Medium Restraint	Beams, pipe, precast, substructures, mass concrete	0.38	80
Low Restraint	Only cases where restraint is minimal and creep and shrinkage are not a concern	0.32	200

CHAPTER 3 NEW TEST METHODS

The project developed several new test methods that are applicable to qualification of SCC materials in a laboratory setting or acceptance testing of SCC at the construction site. The new methods were developed with assistance from James Krstulovich and Doug Dirks at the IDOT Bureau of Materials and Physical Research.

In partnership with IDOT BMPR, the project contributed to six new test methods for measurement of SCC performance that are included in an appendix:

> Illinois Test Procedure SCC-6, Standard Test Method for Static Segregation of Hardened Self-Consolidating Concrete Cylinders [6]
>
> Illinois Test Procedure SCC-7, Provisional Test Method for Static Segregation of Fresh Self-Consolidating Concrete Cylinders Using the Static Segregation Probe [7]
>
> Illinois Test Procedure SCC-8, Provisional Test Method for Assessment of Dynamic Segregation of Self-Consolidating Concrete During Placement [8]
>
> Illinois Test Procedure SCC-9, Provisional Test Method for Dynamic Segregation of Fresh Self-Consolidating Concrete by Flow Trough [9]
>
> Illinois Test Procedure SCC-10, Standard Test Method for Determining Formwork Pressure of Fresh Self-Consolidating Concrete Using Pressure Transducer Sensors [10]

CHAPTER 4 SUMMARY

Major accomplishments of the project include:

a. **Advances in Theory and Modeling:** SCC is more susceptible to segregation than is conventional concrete, and this study provided theoretical modeling to explain the mechanisms of static and dynamic segregation. The study provided for the first time a theoretical model for dynamic segregation that related behavior to rheological properties of SCC. SCC can be more susceptible to shrinkage and cracking than conventional concrete. This study provided new models of volume change based on internal relative humidity and temperature.

b. **New Test Methods and Procedures:** New test methods were developed that could be used for acceptance tests for SCC in the field. The Hardened Visual Stability Index (HVSI) provides a guide by which segregation can be quantified. The Segregation Probe is a simple and effective tool to measure static segregation in the field. The Dynamic Segregation Trough provides a means to assess how aggregate volume may change as a function of flow distance. The Formwork Pressure Test Method provides a way for engineers and contractors to monitor formwork safety during construction.

c. **Recommended Limits for SCC Mixture Design:** The study identified the role of w/cm ratio and paste content on performance of SCC and recommended guidelines for SCC mix design.

d. **A Forum for Exchange of Ideas:** The project served as a forum for IDOT and UIUC to discuss SCC material behavior and issues related to IDOT construction practices. The project provided a partnership between IDOT and UIUC during construction of I-74 in Peoria, IL which used SCC for miles of retaining wall structures.

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6. Illinois Test Procedure SCC-6, Standard Test Method for Static Segregation of Hardened Self-Consolidating Concrete Cylinders

7. Illinois Test Procedure SCC-7, Standard Test Method for Static Segregation of Fresh Self-Consolidating Concrete Cylinders Using the Static Segregation Probe

8. Illinois Test Procedure SCC-8, Standard Test Method for Assessment of Dynamic Segregation of Self-Consolidating Concrete During Placement

9. Illinois Test Procedure SCC-9, Standard Test Method for Dynamic Segregation of Fresh Self-Consolidating Concrete by Flow Trough

10. Illinois Test Procedure SCC-10, Standard Test Method for Determining Formwork Pressure of Fresh Self-Consolidating Concrete Using Pressure Transducer Sensors

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Appendix A: IL Test Procedures produced during this project

Illinois Test Procedure SCC-6, Standard Test Method for Static Segregation of Hardened Self-Consolidating Concrete Cylinders

Illinois Test Procedure SCC-7, Standard Test Method for Static Segregation of Fresh Self-Consolidating Concrete Cylinders Using the Static Segregation Probe

Illinois Test Procedure SCC-8, Standard Test Method for Assessment of Dynamic Segregation of Self-Consolidating Concrete During Placement

Illinois Test Procedure SCC-9, Standard Test Method for Dynamic Segregation of Fresh Self-Consolidating Concrete by Flow Trough

Illinois Test Procedure SCC-10, Standard Test Method for Determining Formwork Pressure of Fresh Self-Consolidating Concrete Using Pressure Transducer Sensors

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