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16. Abstract

The goal of the project was to develop a new type of self-consolidating concrete (SCC) for slip-form paving to simplify construction and make smoother pavements. Developing the new SCC involved two phases: a feasibility study (Phase I sponsored by TPF-5[098] and concrete admixtures industry) and an in-depth mix proportioning and performance study and field applications (Phase II).

The phase I study demonstrated that the new type of SCC needs to possess not only excellent self-consolidating ability before a pavement slab is extruded, but also sufficient "green" strength (the strength of the concrete in a plastic state) after the extrusion. To meet these performance criteria, the new type of SCC mixtures should not be as fluid as conventional SCC but just flowable enough to be self-consolidating. That is, this new type of SCC should be semi-flowable self-consolidating concrete (SFSCC). In the phase II study, effects of different materials and admixtures on rheology, especially the thixotropy, and green strength of fresh SFSCC have been further investigated.

The results indicate that SFSCC can be designed to (1) be workable enough for machine placement, (2) be self-consolidating without segregation, (3) hold its shape after extrusion from a paver, and (4) have performance properties (strength and durability) comparable with current pavement concrete. Due to the combined flowability (for self-consolidation) and shape-holding ability (for slip-forming) requirements, SFSCC demands higher cementitious content than conventional pavement concrete. Generally, high cementitious content is associated with high drying shrinkage potential of the concrete. However, well-proportioned and well-constructed SFSCC in a bike path constructed at Ames, IA, has not shown any shrinkage cracks after approximately 3 years of field service. On the other hand, another SFSCC pavement with different mix proportions and construction conditions showed random cracking. The results from the field SFSCC performance monitoring implied that not only the mix proportioning method but also the construction practice is important for producing durable SFSCC pavements.

A carbon footprint, energy consumption, and cost analysis conducted in this study have suggested that SFSCC is economically comparable to conventional pavement concrete in fixed-form paving construction, with the benefit of faster, quieter, and easier construction.

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Self-Consolidating Concrete—Applications for Slip-Form Paving: Phase II

Final Report
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The *Self-Consolidating Concrete – Applications for Slip-form Paving* project (Phases I and II) was conducted under DTFH61-06-H-00011 Work Plan 6 (Phase II) and FHWA Transportation Pooled Fund Program TPF-5(098), involving the following state departments:

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EXECUTIVE SUMMARY

In the present project, a new type of self-consolidating concrete, semi-flowable self-consolidating concrete (SFSCC), has been developed for slip-form paving construction. This new SFSCC not only self-consolidates but also holds its shape immediately after being extruded from a slip-form paver. Compared to conventional slip-form paving, SFSCC is a quiet, cost-effective, energy saving, and low carbon footprint concrete due to the absence of vibrators. Furthermore, it increases quality and reduces deterioration of concrete since the vibrator trails, which frequently result from overconsolidation in pavement construction, are eliminated.

The project had two phases: Phase I (2004–2005)—a feasibility study, and Phase II (2007–2011)—an in-depth study of mix proportioning, performance, and field applications of SFSCC. In the phase I study, the characteristics and test methods that can appropriately measure characteristics of SFSCC were investigated. The primary factors affecting SFSCC performance were examined. The essential material components of SFSCC were identified. Some potential mix proportions of SFSCC were developed. The results from phase I have demonstrated that to meet criteria of SCC for slip-form paving, a concrete mixture should have appropriate flowability, consolidating ability, and sufficient shape-holding ability. The balance of these fresh concrete properties can be achieved by tailoring mix proportions of commonly used concrete materials. It was found that plasticizer can significantly influence concrete flowability as well as green strength. Addition of fines and nano-clay materials is very effective in manipulating the shape stability of concrete. To evaluate flowability of SFSCC, use of the modified flow table test, rheometer tests, modified slump test for slump, and the mini-paver test are proposed. To assess consolidating ability of SFSCC, use of the compaction factor test and the slump shape of the modified slump test are recommended. A mini-paver was developed to simulate the field SFSCC paving in laboratory. The shape holding ability of SFSCC can also be measured with green strength and mini-paver tests. These phase I results suggested that it is feasible to proportion a new type of SFSCC that can not only self-consolidate but also have timely shape-holding ability. The phase I report, completed in November 2005, can be found at the CP Tech Center's website, http://www.cptechcenter.org.

The phase II study has focused on developing a method/procedure for mix proportioning of SFSCC, refining the test methods for measuring characteristics of SFSCC, evaluating the fresh and hardened concrete properties, conducting field applications for the newly developed SFSCC, and monitoring the performance of field SFSCC. In the phase II study, a performance-based mix proportioning procedure was developed based on the investigation into the effects of different materials on the key properties of SFSCC that were obtained from the phase I study. This mix proportioning procedure is verified by performance tests of SFSCC designed and cast with different sources of cementitious materials and aggregates from Iowa and Wisconsin.

Fresh material properties, such as flow, "green" strength, and rheological properties, of SFSCC paste, mortar, and concrete were studied using Brookfield, Haake Rheostress, and IBB rheometers, as well as slump and flow table test methods. Hardened SFSCC properties, such as compressive strength, rapid chloride permeability, freeze-thaw durability, scaling resistance, shrinkage behavior and cracking potential, were evaluated. The shrinkage effects of different nano-clay admixtures were also studied by testing for autogenous shrinkage, drying shrinkage, and restrained ring shrinkage. Additionally, efforts were made to reduce portland cement content in the SFSCC mixtures through optimum uses of available aggregates, supplementary cementitious materials, and limestone dust while maintaining the required fresh and hardened properties.

Based on the results from the lab studies described above, three field SFSCC applications were conducted. The first application (2005) was geared toward checking the feasibility of SFSCC for field application, i.e., to observe whether or not SFSCC could be placed without consolidation and hold its shape right after paving under field conditions and operations. After the success of the first field trail, the second SFSCC application (2007) was conducted for an 8 ft by 60 ft by 5 in. bike path at South 4th Street in Ames, IA. In the second field application, more attention was given to controlling the SFSCC processing and construction procedure as well as to post-paving techniques (such as pavement sawing and curing). Shortly after the second SFSCC field application, the third one (2007) was a 13 ft by 135 ft by 5 in. street pavement at North Riverside Drive in Ames, IA. Concrete cylinders cast and cured at the field site and cores taken from the field pavement were tested for strength and permeability. Performance of the field SFSCC bike road and street pavement were monitored. In addition, the cost and carbon footprint of SFSCC materials and its construction were also assessed and compared with those of conventional pavement concrete and construction methods.

The following are major observations and findings from the Phase II study:

1. The performance-based mix proportioning procedure contains three major steps: (1) to design SFSCC mortar mix proportion for specified flowability, (2) to determine coarse aggregate content in SFSCC based on required flowability and compactibility, and (3) to verify the initial SFSCC mix proportions with a mini-paver test that simulates field slip-form paving. Adjustments were suggested to the mix proportions and to the proper admixtures so as to make the concrete mixture meet the SFSCC mix design criteria. Experimental test results have shown that well-proportioned SFSCC mixes not only meet the criteria for flowability, consolidation, and shape holding, but also show adequate properties for hardened concrete.
2. The in-depth study on the fresh concrete properties of SFSCC has showed that SFSCC generally has a lower viscosity when compared with conventional concrete due to less volume of coarse aggregates. The required force for SFSCC to flow is shown to be inversely proportional to its slump. The addition of fines and nano-clay materials has significant effects on the flowability and shape-holding ability of SFSCC. Increasing the nano-clay (Actigel) content of a cement-based material considerably increases its yield stress, viscosity, and thixotropy. (Thixotropy is a time-dependent behavior in which viscosity of a material decreases with time under shearing but recovers to its original value when the shearing ceases.) A high value of thixotropy of a cement-based material indicates a yield stress recovery, and it controls timely shape-holding ability. Addition of water reducer (WR) and air entraining agent (AEA) reduces the thixotropy of cement-based materials.
3. The compressive strength and rate of the strength development of SFSCC tend to be higher than conventional concrete due to the lower water-to-binder (w/b) ratio. The elastic modulus of SFSCC is lower due to its low coarse aggregate content.The porosity and rapid chloride ion permeability of SFSCC are noticeably higher than conventional pavement concrete at 28-days, but they become comparable at the later ages, probably

due to the extensive use of supplementary materials. The heat of cementitious material hydration of SFSCC is comparable to or lower than that of conventional pavement concrete. The freeze-thaw durability of SFSCC is also comparable to that of conventional concrete, which is primarily dependent upon durability of the aggregates used. Scaling resistance to deicing chemicals varies with SFSCC mixes; however, the addition of nano-clay Actigel generally provides SFSCC with a better scaling resistance to deicing chemicals.

4. Under a lab drying condition (T=23ºC±2ºC and RH=50%±4%), compressive strength of SFSCC is similar to or slightly higher than that of conventional concrete, while shrinkage of SFSCC is noticeably higher than that of conventional concrete at a given age. Addition of nano-clay materials (Actigel and Metamax) in SFSCC slightly increases autogenous shrinkage, while another nano-clay material (Concresol) decreases autogenous shrinkage. With 2% addition (by weight of cementitious materials), Actigel and Concresol increase drying shrinkage, while Metamax decreases drying shrinkage of SFSCC. A shrinkage-reducing agent works effectively for SFSCC.
5. In reducing the amount of portland cement content in SFSCC mixtures, optimum use of coarse aggregates in the SFSCC mixture resulted in 11.5% decrease of portland cement. The use of slag and addition of coarse aggregates reduced the cement content by 24%. Addition of limestone dust decreased the cementitious materials by 20.9% and the cement by 15%.
6. The field applications show that SFSCC can successfully be prepared in a commercial batching plant. SFSCC that passes the proposed criteria for a modified slump test is suitable for field paving. The paving equipment needs to be able to uniformly distribute sufficient amounts of SFSCC in front of the paver and have sufficiently long side forms (skids) to hold the freshly extruded SFSCC for an adequate time, thus allowing the SFSCC to develop enough green strength to hold its shape. SFSCC requires minimal finishing. Texturing, jointing, and curing of SFSCC pavements can be done using the same methods as those for conventional slip-form concrete pavement. To facilitate cement hydration and prevent shrinkage cracking, proper curing of SFSCC is essential for quality SFSCC products. The field applications of SFSCC have demonstrated that although having high shrinkage, well-proportioned and well-constructed SFSCC in a bike path constructed at Ames, IA, has not shown any shrinkage cracks after approximately 3 years of field service, while another street pavement at North Riverside Drive in Ames, IA, made with different mix proportions and under different construction conditions, showed random cracking. The results suggest that not only the mix proportioning method but also the construction practice is important for producing durable SFSCC pavements.
7. A comparison analysis shows that the material cost of SFSCC is equal to or greater than that of conventional pavement concrete. The main contributors to the higher cost in SFSCC are the use of more cementitious materials and admixtures/additives. The total costs, the sum of material and construction costs, of SFSCC mixes are comparable to those of conventional fixed form and slip-form pavement concrete. CO_2 production from concrete construction is small compared with that from materials used in the concrete mixes. Despite having a higher cementitious content, the carbon footprint of SFSCC is comparable to that of conventional pavement concrete (Iowa DOT C3 and C-3WR-C20 mixes).

Based on the above-mentioned study, the following recommendations are proposed for implementing the results from the present research:

1. SFSCC appears to be well-suited for slip-form construction of bike paths, sidewalks, and local street pavements. It can also be used for cast-in-place concrete, such as bridge decks and pavement cross sections, where flowable concrete is desirable but conventional SCC is unable to make a crown or slope for the structures. In the present study, the maximum thickness of SFSCC used in field constructions is about 6 in. To avoid side slump, it is suggested that multiple lift construction be explored if much thicker pavements are constructed.
2. Field application of SFSCC would be extended if a paver specifically designed for SFSCC were available. Development of such new paving equipment hasn't been included in the present study, but it should be considered in the future. It is suggested that the new paver for SFSCC paving be able to uniformly distribute SFSCC in front of the paver, provide a minimal pressure on the concrete during its extrusion, and have a sufficient length of side legs to mold and hold the extruded concrete for a sufficient time so as to allow the SFSCC to develop sufficient shape-holding ability as the paver is moving forward.
3. Among five SFSCC mixes tested for scaling resistance to deicing chemicals, some SFSCC showed a comparable or higher resistance to that of conventional pavement concrete, while others displayed a lower resistance. The lab test results were not consistent with those of field concrete. More studies should be conducted on the potential factors affecting SFSCC scaling resistance (e.g., effects of fines and nano-clay additions). While shrinkage reduction technology, such as self-curing technology, is explored for SFSCC, other durability properties of SFSCC, such as thermal expansion, alkali-silica reaction, and sulfate resistance, may also be investigated.

1. INTRODUCTION

1.1 Background

The goal of this research project was to develop a new type of self-consolidating concrete (SCC) for slip-form paving construction—semi-flowable self-consolidating concrete (SFSCC). Being self-flowing, self-consolidating, and easy to finish, such concrete is expected to be able to provide the paving industry with more uniform, durable, and smoother pavements, as well as faster, safer, and quieter construction. Elimination of internal vibration can also reduce energy consumption in construction.

The project was conducted in two phases. Phase I was a feasibility study, which was completed in 2005 (Wang et al. 2005). In this phase, flowability, self-consolidating ability, and shape-holding stability of concrete mixes made with various materials and proportions were studied. It was found that a good balance between flowability and shape stability could be achieved by adopting and modifying the mix proportions of conventional SCC to provide a high content of fine materials. Addition of both fine particles and the modification of the type of plasticizer significantly improved fresh concrete flowability. The addition of nano-clay materials (such as Actigel) significantly affected concrete "green" strength and provided the concrete with improved shape-holding ability. Through a lab simulation of slip-form paving using a mini-paver, the research team demonstrated that it is possible to proportion and manufacture a new SFSCC that not only self-consolidates but also holds its shape right after paving.

Phase II was designed to focus on developing a mix proportioning method and applying the new SFSCC in the field. Started in 2007, this phase included three major tasks: (1) further mix proportioning study, (2) conduct field applications, and (3) monitor performance. In this phase, the research team developed a performance-based mix proportioning procedure and used it in proportioning of SFSCC mixtures with field materials from different sources (three in Iowa and one in Wisconsin). Three field SFSCC applications (an initial trial, a bike path, and a local street) have been conducted in Iowa. The performance of the field SFSCC (in the bike path and the local street) has been monitored. During the study, two critical concerns have arisen: the cost and shrinkage behavior of SFSCC. Therefore, additional studies were performed to reduce cement content in SFSCC and to further assess the shrinkage behavior of SFSCC.

The project was conducted by a collaborative research team consisting of researchers from the National Concrete Pavement Technology Center (CP Tech Center), Iowa State University (ISU), and the Center for Advanced Cement-Based Materials (ACBM), Northwestern University (NU).

1.2 Research Objectives

The major objectives of this phase of the study are as follows:

1. To further study effects of materials and mix proportions on SFSCC properties and to develop a mix proportioning procedure for functional SFSCC.
2. To further characterize fresh SFSCC properties and evaluate the general engineering properties of hardened SFSCC, in comparison with those of conventional pavement concrete (such as IA DOT mix C3).

3. To develop quality control tests, conduct field applications of SFSCC, and monitor the field performance of the SFSCC
4. To develop guidelines for proportioning, testing, production, and construction of SFSCC.

2. PHASE I OVERVIEW

A challenge for this research is that the new SFSCC must possess not only excellent self-consolidating ability without segregation before extrusion, but also shape stability to sustain its self-weight, or to hold the slab in shape, without support from any formwork after casting. Previous research has suggested that to obtain self-consolidating ability, a concrete mixture must overcome the stress generated by the friction and cohesion between the aggregate particles; while holding the freshly cast products in shape, the fresh concrete must have a certain strength or stability. A critical issue in this project is to achieve these two conflicting needs for the concrete at the appropriate time. Phase I of this project was a feasibility study—to determine whether or not developing successful SFSCC was possible.

The following tasks were performed in the phase I study:

1. Determined the key characteristics of SFSCC
2. Developed test methods for characterization of SFSCC mixtures
3. Studied the factors affecting SFSCC characteristics
4. Identified proper SFSCC mix proportions
5. Simulated the slip-form paving process in the lab using a mini-paver.

2.1 Characteristics of SFSCC Mixtures

The key characteristics of SFSCC were identified based on the current practices of slip-form paving and the performance of current pavement concrete. As described previously (Wang et al. 2005), the SFSCC has the following characteristics:

1. SFSCC should be workable enough for machine placement. In slip-form paving construction, the concrete should be easily placed in front of the paver, spread uniformly along the width of the paver formwork, and extruded without mechanical vibration. In this process, the mixture should self-consolidate and fill the formwork without segregation.
2. SFSCC should be able to hold shape right after casting. Different from conventional SCC, which is highly flowable, SFSCC should have limited flow ability but rapid green strength development to maintain the shape of the pavement after extrusion. The green strength development is related to the thixotropical behavior of concrete.
3. SFSCC should have comparable or superior performance properties (such as strength and durability) compared to conventional concrete.

To ensure the above properties, SFSCC mixtures should be evaluated for flowability, compactibility, and shape-holding ability.

2.2 Methods for SFSCC Mixture Characterization

Various test methods have been developed for evaluating flow ability, compactibility, and shape-holding ability of fresh SFSCC (Wang et al. 2005).

Flowability of SFSCC was assessed by the following tests:

1. Flow table tests. The flow table described in ASTM C230 was used to perform flowability tests for pastes and mortars. A large flow table (Voigt 2010) was used for concrete. In the tests, a sample in a cone shape was molded on a drop table. The spread of the sample after several drops indicated flowability
2. Rheometer tests. Brookfield rheometer (at ISU) and Haake rheometer (at NU) were used for pastes and mortar. IBB rheometer (at ISU) was used for concrete. Yield stress and viscosity of tested mixtures were measured.
3. Modified slump tests. The slump and spread of an unrodded slump test were measured to describe flowability of SFSCC. The slump cone in ASTM C143 was filled with concrete without rodding, similar to ASTM C1611, Method A.
4. Mini-paver test. A mini paver was developed to simulate field slip-form paving in the lab. A consolidation pressure was maintained at the front end of the paver and the mixture was extruded through the form without any vibration. Flowability in the mini-paver test was demonstrated by the concrete's ability to fill the paving form while the mini-paver was being dragged forward.

Consolidation of SFSCC was evaluated by the following tests:

1. Compaction factor test. The compaction factor is the ratio of the unit weight of unrodded concrete to the unit weight of rodded concrete. Good self-consolidating concrete should have a compaction factor close to, or equal to, 1.
2. Modified slump tests. It is believed that the shape of the concrete after an unrodded slump test is related to the uniformity of aggregate particle distribution and consolidation of concrete. A regular cone shape generally indicates well-consolidated concrete with uniform particle distribution, while a tilted cone shape implies weak spots in the concrete, assuming that no sideway stress is applied during lifting.

Shape holding ability of SFSCC was estimated by the following tests:

1. Green strength test. The test measures the amount of compressive load molded fresh concrete can carry until it collapses.
2. Mini-paver test. The degree of the edge slump of the concrete after being extruded from the mini-paver indicates the shape-holding ability of the concrete. A straight, perpendicular edge suggests the concrete has a good shape-holding ability.

Details of these test methods are presented in the project phase I report (Wang et al. 2005) and are shown in Appendix A.

2.3 Factors Affecting SFSCC Mixture Characteristics

Both concrete materials and mix proportions were studied to assess the flowability, consolidation, and shape-holding ability of SFSCC in a fresh state. Three material parameters were considered: fine materials, aggregates, and admixtures. The fine materials studied were slag, fly ash, limestone dust, gypsum, and nano-clay (Actigel, metakaolinite, and kaolinite). The mix proportion parameters included the dosage of the additives and admixtures, water-to-cement ratio, and aggregate content.

The effects of some fine materials on the rheological behavior of pastes are listed in Table 2–1.

Table 2-1. Effects of different fine materials addition on paste materials

Material	Viscosity	Yield stress
Slag	Increase	Increase
Fly ash	Decrease	Decrease
Limestone dust	No change	Increase
Gypsum	Increase	Increase
Acti-gel	Increase	Increase

The addition of nano-clay materials showed significant effects on concrete green strength and flowability. Actigel was found to be very effective at reducing the flowability and increasing the green strength of conventional SCC. Metakaolinite increased flowability while maintaining green strength. Kaolinite increased concrete green strength with only minimal reduction of flow. Nano-clay dosages ranged from 1%-2% by weight of cement.

Six coarse aggregate gradations were selected and studied for their effects on concrete compactability. The aggregates were first evaluated for their loose (unrodded) bulk density and compacted (rodded) bulk density. Compaction factor tests were then performed for the concrete mixtures made with these aggregates. It was found that the difference between the two densities (as percentage of the compacted bulk density) of the aggregates could be used as an indicator of the energy needed to consolidate the corresponding concrete. The smaller the difference in the aggregate bulk densities, the higher the compaction factor of the corresponding concrete, or the easier the concrete is consolidated.

Naphthalene- and polycarboxylate-based plasticizers were studied. Drop table tests showed that for a given dosage, the concrete containing naphthalene-based plasticizer exhibited higher flowability than that containing polycarboxylate-based plasticizer. That is, naphthalene-based plasticizer generally provides a positive effect on concrete flowability under the influence of external compaction energy.

2.4 Approaches to SFSCC Mix Proportion

The SFSCC mix proportioning development started with a conventional SCC mixture, which was modified by gradually adding different fine materials, such as fly ash, nano-clay, and cement, until the concrete reached a shape-stable condition. Figure 2–1 shows the effects of different fine materials (FM) and water-to-fine material ratio (W/FM) on the flowability and shape stability of concrete pastes, where the paste flow was measured by the flow drop table as described in ASTM C230. The high degree of effectiveness of the fine materials in shape stability improvement appeared closely related to the finer particle size. With the fine material addition, a flowable, low-shape stability paste was changed into a nonflowable, highly shape-stable paste.

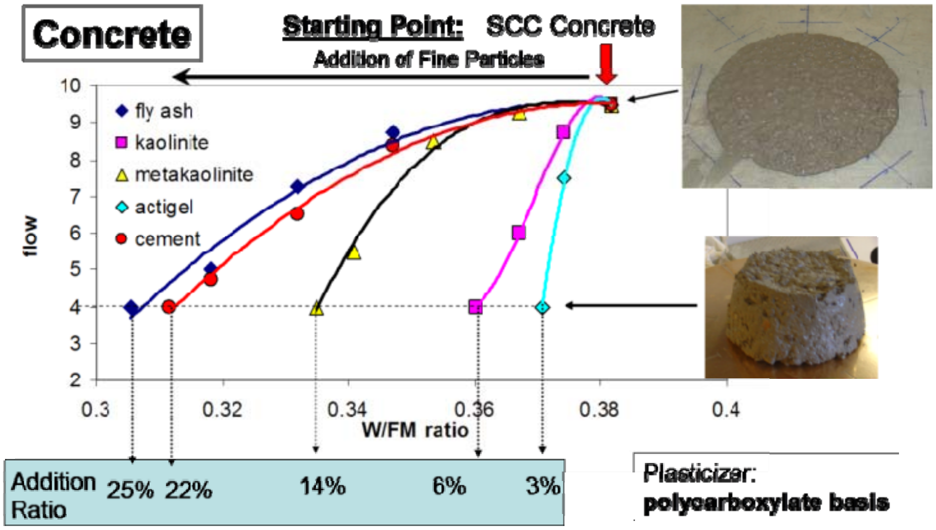


Figure 2–1. Effects of different fine materials on shape stability of cement pastes (Pekmezci et al. 2007)

Fugure 2–2 shows the results from the modified slump and compaction factor tests of various concrete mixtures. As observed from the figure, the tested concrete mixtures can be divided into three different groups. In Group I, the concrete mixtures generally have low flowability, with a slump lower than 6 in. and a spread less than 11 in. The self-consolidating ability of this group of concrete mixture is also low, with a compaction factor (CF) less than 95%. The bent cone shape of the mixtures at the end of the modified slump test indicates that honeycombing likely exists inside the tested concrete, and the aggregate particles in the mixture are not uniformly distributed (Wang et al. 2005). Therefore, this group of mixtures cannot be used as SFSCC. In Group III, the concrete mixtures have very high flowability, with a slump higher than 10 in. and a spread over 24 in. This group of mixtures has a CF value of 100%, indicating high self-consolidating ability. However, due to their large spread, they are unable to hold their shape right after casting and cannot be used as SFSCC either. In Group II, the concrete mixtures have a slump in the range from 7 to 9 in. and a spread in the range from 12 to 15 in. The regular cone shape of the mixtures at the end of the modified slump test implies that the aggregate particles in the mixtures are uniformly distributed, and the mixtures are able to hold their shape to a certain degree after casting. The CF values of the mixtures are greater than 95%, slightly lower than that of conventional SCC. This group of mixtures appears suitable for SFSCC application.

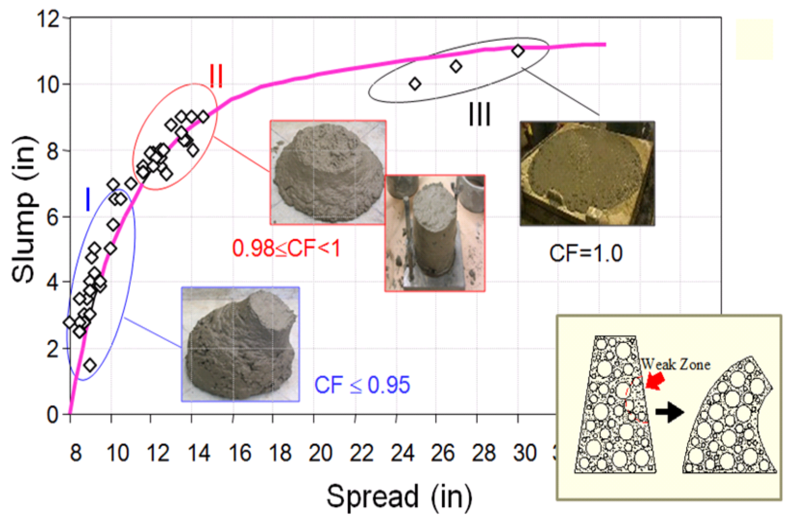


Figure 2-2. Relationship between concrete slump and spread

SFSCC should be designed to have a maximum self-consolidating ability with a minimum flowability. Based on the results from more trial-and-error tests (Figure 2–2), it was proposed that a successful SFSCC mixture should have 5 to 8 in. of slump, approximately 12 in. of the slump spread, a regular cone shape at the end of the modified slump test, and a compaction factor of approximately 98%. It was noted that the consolidating ability of the SFSCC can be further improved during field construction because an external extrusion pressure is often applied to the concrete by the slip-form construction equipment.

2.5 Lab Simulation for Slip-Form Paving (Mini-Paver Tests)

The mini-paver test simulates the field slip-form paving process. After a SFSCC candidate was selected from Group II, a mini-paver test was performed to verify its potential field performance. Figure 2–3 shows a SFSCC slab extruded from the mini-paver and the cross section of the concrete slab. The top surface of the final pavement section was smooth, and little or no edge slump was observed (Figure 2–3[a]). The cross-section of the SFSCC showed no visible honeycomb and segregation (Figure 2–3[b]). It demonstrates that a well-proportioned SFSCC mixture could not only self-consolidate but also hold its shape very well after extrusion.

(a) Concrete slab from a mini-paver test

(b) Cross section of the above concrete slab

Figure 2-3. Mini-paver test results of SFSCC

Subsequent to the hardening of the SFSCC, cores were taken from the slab for compression and split tensile strength tests. The results indicated that SFSCC had strength higher or comparable to conventional pavement concrete. It was also found that SFSCC had set time, heat evolution, and strength development comparable to conventional pavement concrete. The concrete was well bonded with simulated dowel bars.

As a result of phase I, it was concluded that proportioning and manufacturing SFSCC was feasible and further research should be conducted.

3. DEVELOPMENT OF SFSCC MIX PROPORTIONING METHOD

3.1 SFSCC Materials and Trial Mix Proportions

Various materials and mix proportions were studied throughout the research project. This section introduces those used in the major SFSCC mixes of the phase II study.

Concrete materials (cement, fly ash, fine, and coarse aggregates) were collected from five field project sites (Ames, Guthrie, Ottumwa, and Webster cities in Iowa and Alma Center in Wisconsin) and used to study SFSCC mix proportioning. The properties of the course aggregates are shown in Figure 3–1 and Table 3–1.

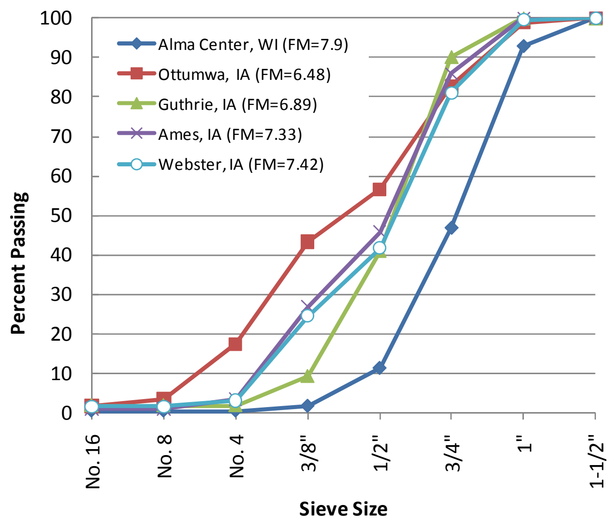


Figure 3-1. Sieve analysis results of field coarse aggregates

Table 3–1. Coarse aggregate properties

Source	Type	Bulk specific gravity	Absorption (%)	Voids (%)
Alma Center, WI	Crushed rock	2.87	0.33	45.0
Ames, IA	Limestone	2.68	0.72	39.5
Guthrie, IA	River gravel	2.68	1.95	38.9
Ottumwa, IA	Limestone	2.87	3.69	39.4
Webster, IA	Limestone	2.60	2.68	37.9

All the coarse aggregates were crushed stones except the one from Guthrie, which was smooth and rounded river gravel. The coarse aggregate from Alma Center had the highest amount of large particles, while the aggregate from Ottumwa had the highest amount of small particles. The gradation of the coarse aggregates from Ames and Webster were similar. The fineness modulus of the coarse aggregate ranged from 6.48 to 7.90. The specific gravity of the aggregates ranged from 2.60 to 2.87, absorption ranged from 0.33 to 3.69, and compact voids ranged from 37.9% to 45%.

The properties of the fine aggregates are shown in Figure 3–2 and Table 3–2. All the fine aggregates are river sand. The gradations of the fine aggregates from Alma Center and Ottumwa were similar, and the gradations of the aggregates from Guthrie and Webster were also similar. The gradation of the fine aggregate from Ames was between these two groups. The aggregates had high fineness modulus values between 2.95 and 3.36. The specific gravity of the fine aggregates was similar—between 2.6 and 2.65, but the absorption varied from 1.09 to 2.32.

Type I cement from Ashgrove, Class C fly ash from Lafarge, and ground granulated blast furnace slag (slag) from Holcim were used as cementitious materials. Ground limestone fines with a particle size less than 75 μm (also called limestone dust) were used as an additive.

Admixtures were used in some of the SFSCC mixes studied. Polycarboxylate-based high-range water reducer (HRWR) Glenium 7700 was used in mixes 1, 2, and 7 through 17, and lignin-based water reducer (WR) Eucon WR91 was used in mix 19. Rheology-modifying admixture (RMA) Navitas 33 and viscosity-modifying admixture (VMA) Rheomac VMA358 were also evaluated. A nano-clay material, purified magnesium alumino silicate, Actigel 208, was used to improve SFSCC shape-holding ability. A custom-modified cellulose polymer fiber, with an average length of 0.0827 in. and average diameter of 708×10^{-6} in., was used for reducing the concrete shrinkage cracking.

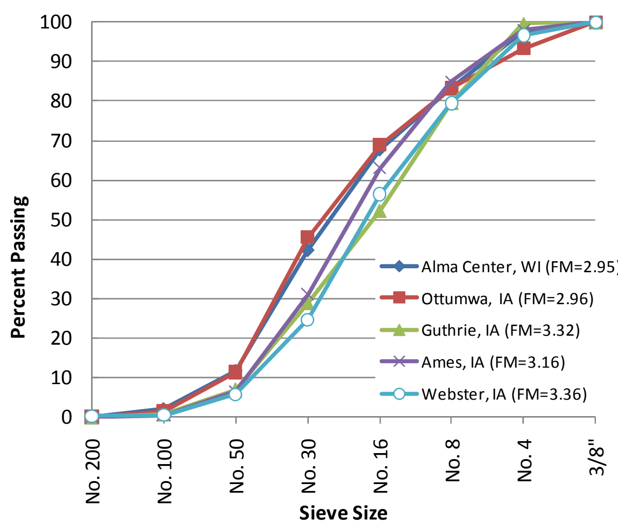


Figure 3–2. Sieve analysis results of field fine aggregates

Table 3–2. Fine aggregate properties

Source	Material	Bulk specific gravity	Absorption (%)
Alma center, WI	River sand	2.65	1.60
Ames, IA	River sand	2.64	1.09
Guthrie, IA	River sand	2.64	2.16
Ottumwa, IA	River sand	2.62	1.32
Webster, IA	River sand	2.60	2.32

A total of seventeen SFSCC mixes and three conventional pavement concrete mixes were examined. The mix proportions are listed in Table 3–3. Mixes 1, 2, and 7 through 19 were made of materials from Ames, IA. Mixes 3 through 6 were made with the materials collected from field sites. Mix 11 was used for the first field SFSCC test (see Section 6.1). Mixes 2 and 12 were used for the second and third field tests (see Section 6.2). Mixes 13, 15, and 16 were used in the field test discussed in Section 6.3. After the field tests, mixes 7 through 10 were studied to reduce the cementitious materials in SFSCC. Mixes 13 through 17 were used to study the shrinkage and scaling resistance of SFSCC. Mix 20 is a conventional pavement concrete that has relatively low cement content and is analyzed here for its cost and carbon footprint.

Table 3–3. SFSCC and conventional pavement concrete mix proportions

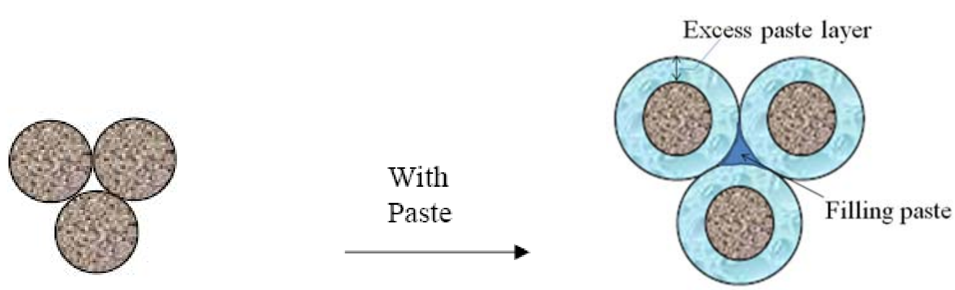
No	Designation	Cement (pcy)	Fly ash (pcy)	Slag (pcy)	Limestone Dust (pcy)	Water (pcy)	F.A. (pcy)	C.A. (pcy)	AEA (oz/cy)	HRWR/ WR (oz/cy)	RMA (oz/cy)	VMA (oz/y)	Thixotrop e (pcy)	Fiber (pcy)	Unit Wt (pcy)	w/b
1	Ames 0.35	595	249	-	-	295	1307	1373	6.3	-	67.4	-	-	1.5	3818	0.35
2	Ames 0.39 (S4TH-M2)	560	243	-	-	310	1226	1450	6.0	-	-	-	3.5	1.5	3788	0.39
3	Guthrie	540	231	-	-	293	1205	1544	5.8	-	-	-	-	-	3813	0.38
4	Ottumwa	589	252	-	-	320	1311	1384	6.3	-	-	-	-	-	3856	0.38
5	Webster	569	244	-	-	301	1242	1387	6.1	40.65	-	-	-	1.0	3742	0.37
6	Alma Center	619	265	-	-	336	1380	1238	6.6	-	-	-	-	-	3838	0.38
7	SFSCC-Control	569.7	246.5	-	-	289.7	1245.1	1472.3	6.1	-	-	-	-	-	3823	0.35
8	SFSCC-Max-Agg	504.2	217.9	-	-	250.5	1341.4	1563.9	5.4	14.8	43.0	-	-	1.5	3878	0.35
9	SFSCC-BFS	432.9	144.2	144.2	-	250.3	1340.9	1563.4	5.4	21.0	34.6	-	-	1.5	3876	0.35
10	SFSCC-LD	484.3	161.3	-	162.4	264.6	1504.5	1273.4	4.9	28.1	30.4	-	-	-	3850	0.41
11	SFSCC-Field1	596	265	-	-	285	1341	1364	6.5	100	-	2.5	-	-	3851	0.33
12	S4TH-M1	594.6	248.5	-	-	294.6	1306.7	1373.3	6.3	1.7	67.4	-	-	1.5	3818	0.35
13	NR-M1-A	559.8	242.6	-	-	318.1	1226.2	1449.7	6.0	-	-	-	3.5	1.5	3796	0.39
14	NR-M1	559.8	242.6	-	-	318.1	1226.2	1449.7	6.0	-	-	-	-	1.5	3796	0.39
15	NR-M2-A	559.8	242.6	-	-	326.0	1226.2	1449.7	6.0	-	-	-	3.5	1.5	3804	0.41
16	NR-M3-A	559.8	242.6	-	-	321.2	1226.2	1449.7	6.0	-	-	-	3.5	1.5	3800	0.40
17	NR-M3	559.8	242.6	-	-	321.2	1226.2	1449.7	6.0	-	-	-	-	1.5	3800	0.40
18	C3	595	-	-	-	295	1340	1686	3.0	-	-	-	-	-	3885	0.43
19	C-3WR-C20	457	114	-	-	246	1375	1698	2.9	13.71	-	-	-	-	3890	0.43
20	QMC	443	111	-	-	222	1291	1846	2.8	-	-	-	-	-	-	-

3.2 SFSCC Mix Design Concept

A fresh SFSCC mixture should have (1) sufficient flowability for self-consolidation, (2) adequate viscosity for resisting aggregate segregation, and (3) a proper "green" stress for holding the shape of the concrete right after being extruded from the slip-form equipment. The flowability, self-consolidating ability, and shape-holding ability should be considered simultaneously in the concrete mix design and achieved timely in the slip-form concrete construction.

Conventional SCC is generally characterized by its special rheological properties: low yield stress, which ensures high flowability, and adequate viscosity, which prevents aggregate segregation. For SFSCC, high flowability is not necessary because it will have adverse effect on concrete shape-holding ability. To balance self-consolidating ability and shape-holding ability, flowability of SFSCC should be just enough to ensure self-consolidating ability. Since slip-form construction is actually an extrusion process, a certain external pressure is often applied to the concrete by a slip form, which helps the concrete in consolidation. Thus, the self-consolidating ability of SFSCC can even be slightly less than that of conventional SCC.

Kennedy (1940) first proposed the "excess paste theory" to explain the mechanism governing the workability of concrete. Based on this theory, to ensure good flowability, there must be a sufficient amount of paste in mortar or concrete, which not only fills up the spaces between aggregate particles but also coats the surface of the particles to minimize the friction between these particles. This layer of paste that coats aggregate particles is called "excess paste layer." The rheological properties and the thickness of this excess paste layer significantly contribute to the flowability and shape-holding ability of the fresh concrete (Figure 3–3). The degree of inter-particle friction greatly influences the requirement for the properties and thickness of this excess paste layer.



Aggregate particles without "excess paste" ➔ difficult to flow

Aggregate particles with "excess paste" ➔ easy to flow

Figure 3–3. Excess paste layer and its effect on concrete flowability

Nielsson and Wallervik (2003) proportioned SCC with decreased filling ability by only altering the paste composition while keeping the aggregate composition the same, and they confirmed the theory that flowability is primarily a function of the paste matrix.

In the present project, the shape stability of SFSCC should be controlled by the mortar. This is because mortar is the only filling material in concrete and it connects the discrete coarse aggregate particles. First, the mortar should have a minimum yield stress to ensure easy flow. Then, the mortar should have a sufficiently high viscosity, or flow resistance, to prevent the aggregate segregate (Okamura and Ouchi 1999) and to hold the shape of the fresh concrete right after casting. The amount of mortar should be appropriate so that the thickness of the excess mortar layer is sufficient for balancing concrete flowability and shape-holding ability. For the present study, the amount of relative excess mortar thickness should be at least 0.25 when the aggregates have a spherical or regular shape with a smooth surface, while the relative excess mortar thickness should be at least 0.45 when the coarse aggregates are highly angular. The following relation between excess mortar and aggregate particles is used to calculate the relative excess mortar thickness:

$$\Gamma = \frac{P_e}{\sum_{i}^{n} n_i s_i D_{pi}} \tag{1}$$

where Γ– relative thickness of excess mortar, the ratio of the volume of excess mortar to the total surface area of aggregate; P_e – volume of mortar (in^3); n_i – number of aggregate size i; s_i – surface area of each aggregate size i (in^2); and D_{pi} – diameter of aggregate size i (in.).

3.3 SFSCC Mix Proportioning Methodology

Considering SFSCC as a two-phase material (a coarse aggregate phase distributed in a mortar phase), the research team proposed a performance-based procedure for SFSCC mix proportioning. The mortar of SFSCC should be designed so that gravity will overcome the mortar yield stress and allow the mortar to flow into the voids among coarse aggregate particles. The amount of mortar should be sufficient to fill up the voids and coat the aggregate particles slightly, thus ensuring good self-consolidating ability. On the other hand, the mortar should also have adequate viscosity and cohesion so as to be able to drag the coarse aggregate particles when the concrete flows, thus preventing the concrete mixture from segregation. The coarse aggregate particles form a skeleton in concrete. The interlock and friction of the aggregate particles also provide the concrete with a certain shear resistance in the fresh state. An optimal aggregate gradation and volume fraction should be selected to maximize the shear resistance of the concrete mixture for desirable shape-holding ability. Hence, there are two key components in the SFSCC mix design: (1) to design a proper mortar and (2) to find adequate ratios of mortar and coarse aggregate. In each of the design components, the flowability or self-consolidating ability and shape stability of the designed material need to be evaluated.

A performance-based method for the SFSCC mix proportioning contains three steps: design SFSCC mortar mix proportion, determine coarse aggregate content in SFSCC, and verify SFSCC mix proportion with a lab simulation.

Step 1: Design SFSCC Mortar Mix Proportion

A modified flow table test, adapted from ASTM C230, “Standard Specification for Flow Table for Use in Tests of Hydraulic Cement,” is proposed to be used for balancing the flowability and shape-holding ability of a SFSCC mortar. ASTM C230 was originally designed to determine the water content needed for a cement paste sample to obtain a given flow spread 4.4±0.2 in. after a standard flow table drops 25 times. In the modified test, a potential mortar sample is placed on the ASTM C230 flow table. Right after the placement, the initial flow spread of the mortar is measured (at zero drops). Another flow spread measurement is taken after the flow table drops 25 times. Based on a number of flow table test results in the present study, if a mortar has an initial flow (at zero drops) of 10% or slightly higher and a final flow (at 25 drops) of about 155% or slightly lower, it would have a desirable flowability and shape-holding ability.

It is noted that the mortar having a flow of 155% generally advances beyond the size of the standard flow table. The following equation can be used to calculate the mortar flow at 25 drops (F_{25}) (Hu and Wang 2007):

$$F_{25} = F_t + 46.779\left(\ln 25 - \ln t\right) \quad (2)$$

where F_t is the mortar percentage flow at t drops.

Since the standard flow table can accommodate the maximum flow spread of approximately 8 in., an alternative method was developed to achieve similar mortar flowability to that required for F_{25}. In this alternative method, the standard flow table is dropped so that the sample reaches a flow spread of 9.5±0.2 in., and the number of drops is recorded. The mortar is desirable if the number of drops at which the mortar mixture reaches a flow spread of 9.5±0.2 in. is between 16 and 18.

Step 2: Determine Coarse Aggregate Content in SFSCC

After the mortar mix proportion is determined, SFSCC can then be achieved by adding coarse aggregate to the mortar. The amount of coarse aggregate to be used for a SFSCC can be determined by a modified slump test, where ASTM C143, “Standard Test Method for Slump of Hydraulic Cement Concrete,” is followed but no rodding is applied. Both slump and slump spread are measured. In addition, the shape of the concrete mixture is evaluated after the slump cone is removed.

Based from the findings in phase I, if the concrete has slump of 5 to 8 in. and slump spread of about 12 in. and has a regular cone after the slump cone is removed; it should be evaluated in the mini-paver.

Before a mini-paver test, a modified compaction factor test should be performed on the potential SFSCC mixture (Figure A–2 in Appendix A). The mixture is considered to have sufficient self-consolidating ability if the compaction factor is 0.98 or higher.

Depending on the aggregate properties (such as gradation, particle shape, and surface texture), an optimal volume fraction of coarse aggregate in SFSCC is found to be approximately 40% to 45%. If the tested concrete does not meet the proposed mix design performance criteria, adjustments can be made by modifying aggregate gradation, aggregate volume fraction, and/or using various dosages of admixtures.

Step 3: Verify SFSCC Mix Proportion with a Lab Simulation

After the initial SFSCC mix proportion is achieved from Steps 1 and 2, this SFSCC candidate must be verified with a lab simulation of a slip-form construction process for final approval of its self-consolidating ability and shape-holding ability. As described in Appendix A (Figure A–5), the mini-paver test simulates the field slip-form paving process. The SFSCC mix proportions are acceptable for field application only when the concrete slab made by the mini-paver shows satisfactory shape with little or no edge slump and no visible honeycomb and aggregate segregation observed on the cross section of the hardened slab. Otherwise, the mix should be adjusted. The results from phase I indicated that the addition of nano-clay materials (such as Actigel) and chemical admixtures (such as superplasticizers) had significant effects on concrete green strength and flowability. This information can be used for SFSCC mix adjustment.

It should be pointed out that these three steps ensure only fresh SFSCC constructability. The mechanical properties (such as strength) and durability of the hardened concrete should also be evaluated to ensure a desirable long-term performance (see Step 4 in Figure 3–4).

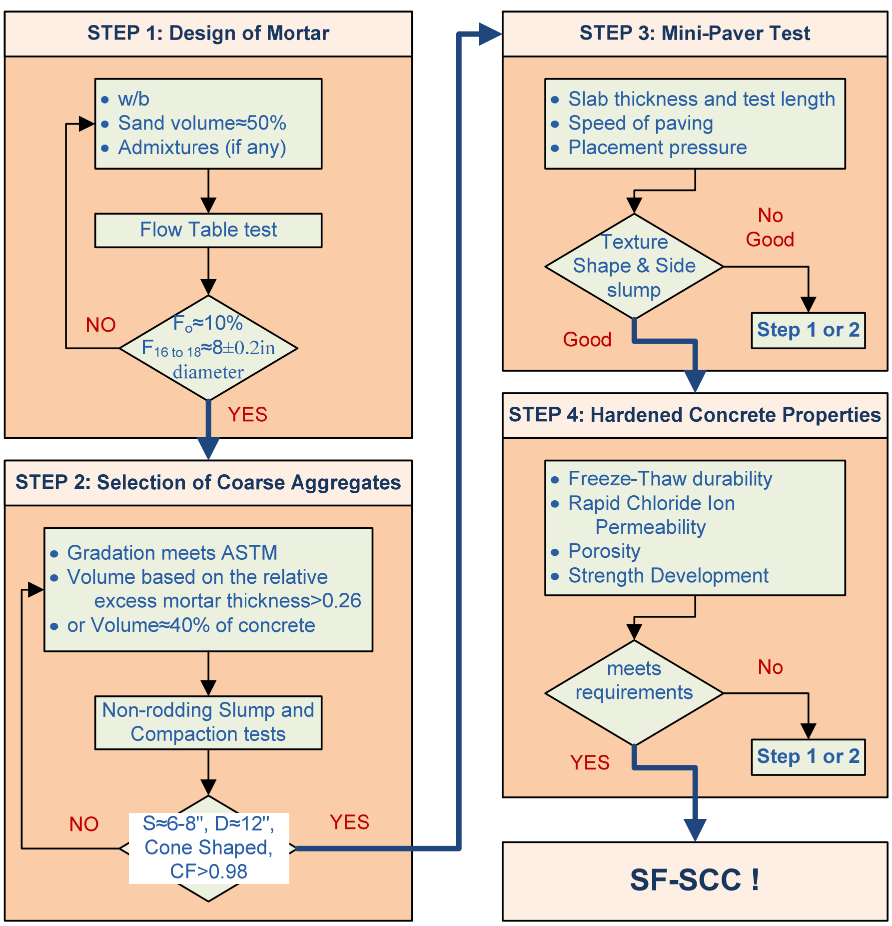


Figure 3–4. SFSCC mix proportioning procedure

3.4 Evaluation of the Proposed SFSCC Mix Proportioning Method

In order to verify the applicability of the mix proportioning method, six SFSCC mixes were developed (mixes 1 to 6 in Table 3–3) using the materials collected from five different pavement construction sites and ready mix plants (Alma Center in Wisconsin and Ottumwa, Guthrie, Webster, and Ames in Iowa). Among these six mixes, two were made with the materials from Ames—one with a water-to-binder ratio (w/b) of 0.35 and the other with a w/b of 0.39.

Alma Center, WI

Ottumwa, IA

Guthrie, IA

Webster, IA

Ames, IA (W/C = 35)

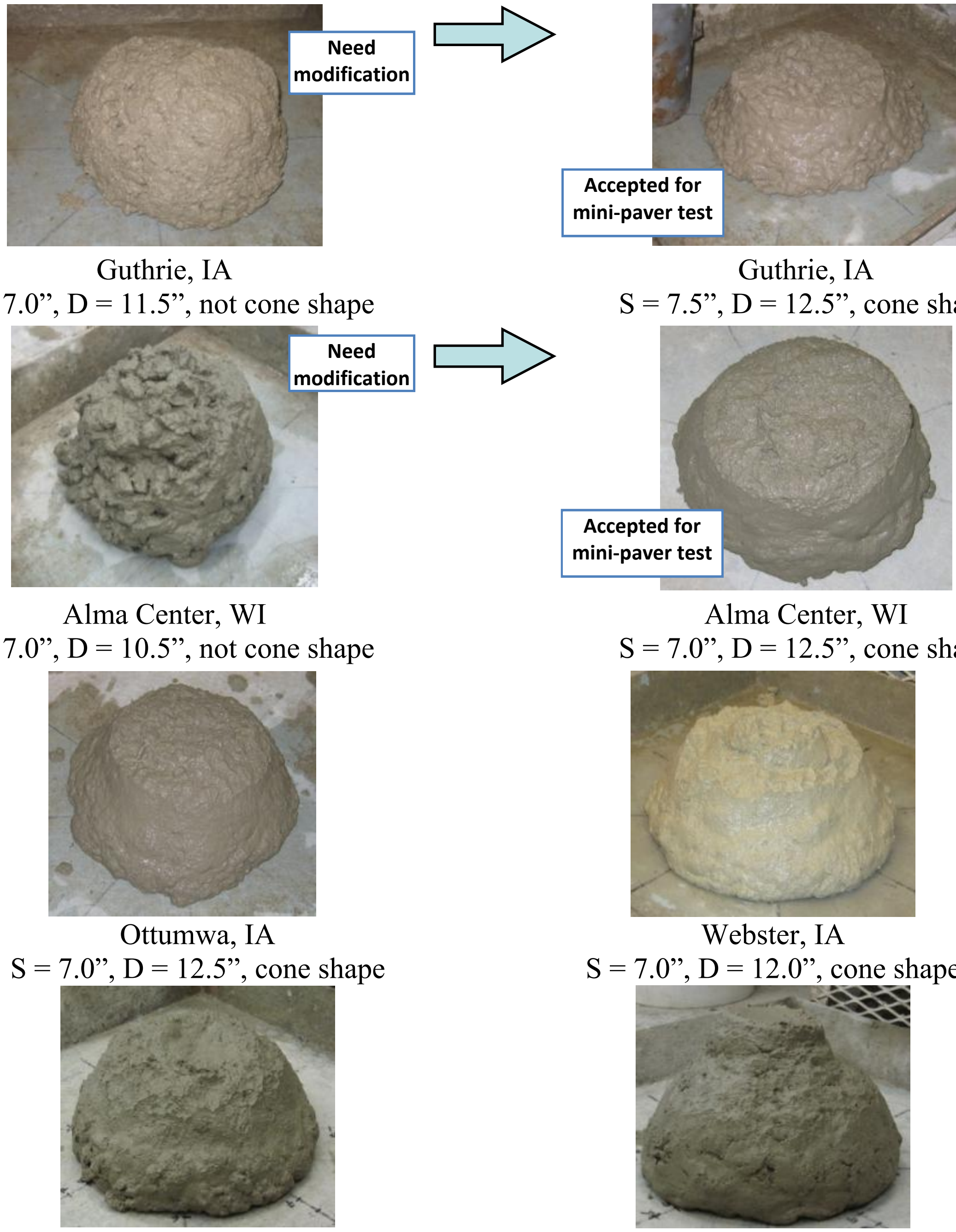
Ames, IA (W/C = 39)

Figure 3–5. Mortar flow table results for field materials (F_0 = 10%, F = 8±0.2 in. flow spread at 16 to 18 drops)

According to the mix proportioning procedure described in Section 3.3, the mortars were first designed (Step 1) to have an initial flow of 10% and a flow after 25 drops of approximately 155% (or a drop number of 16 to 18 when the flow spread reached 9.5±0.2 in.). Figure 3–5 shows the flow table results of the mortars designed.

After obtaining desirable mortar mixes, coarse aggregates were added to the mortars to obtain the concrete mixes (Step 2). The modified slump cone (unrodded) and compaction factor tests were used for evaluating the flowability and self-consolidating ability of the mixtures. The shapes of the mixtures were inspected at the end of the modified slump cone tests to assess the shape-holding ability of the mixtures.

As shown in Figure 3–6, the first trial of some mixtures might not meet the specified mix design criteria having slump (S) of 5 to 8 in, slump spread (D) of about 12 in, a regular cone after removal of the slump cone, and compaction factor (CF) of 0.98 and higher. Modifications through the adjustment of coarse aggregate content and/or use of admixtures are therefore required.



Guthrie, IA
S = 7.0”, D = 11.5”, not cone shape

Guthrie, IA
S = 7.5”, D = 12.5”, cone shape

Alma Center, WI
S = 7.0”, D = 10.5”, not cone shape

Alma Center, WI
S = 7.0”, D = 12.5”, cone shape

Ottumwa, IA
S = 7.0”, D = 12.5”, cone shape

Webster, IA
S = 7.0”, D = 12.0”, cone shape

Ames, IA (w/c =0.39)
S = 7.0”, D = 12.0”, cone shape

Ames, IA (w/c =0.35)
S = 6.0”, D = 11.0”, not very good cone shape

Figure 3–6. Slump test results from SFSCC mix trials

Table 3–4 shows the process in the development of three SFSCC mix proportions. It was noted that the coarse aggregate from Guthrie, IA, was river gravel with round shape and smooth surface and had low void content of 38.9% (Table 3–1); therefore, it should require less mortar for given flowability. The coarse aggregate from Ottumwa, IA, was crushed limestone with a fairly cubical shape and a relatively rough surface and had void content of 39.4%, close to that of the coarse aggregate from Guthrie, IA. Differently, the coarse aggregate from Alma Center, WI, was crushed rock with angular shape and a rough surface and had the highest void content (45.0%), which should require more mortar to coat the aggregate for a proper concrete flow. Therefore, these mix proportions were adjusted with increased mortar content for the SFSCC made with materials from Alma Center, WI, and reduced mortar content for the SFSCC made with materials from Ottumwa and Guthrie, IA.

Table 3–4. Mix proportions for different trials (pcy)

	Source	Cement	Class C fly ash	Water	Sand	C. Agg.
1st trial mix	Alma Center, WI	565	241	307	1257	1846
	Ottumwa, IA	597	256	324	1330	1706
	Guthrie, IA	597	256	324	1330	1706
2nd trial mix	Alma Center, WI	610	261	330	1359	1654
	Ottumwa, IA	589	252	320	1311	1384
	Guthrie, IA	540	231	293	1205	1544
3rd trial mix and mini-paver	Alma Center, WI	619	265	336	1380	1238
	Ottumwa, IA	589	252	320	1311	1384
	Guthrie, IA	540	231	293	1205	1544

Figure 3–7 shows the relative excess mortar thickness (see equation 1) of different SFSCC mixtures from the three different trials discussed. The details in the calculations of the relative excess mortar thickness can be found in Hu (2005) and Oh et al. (1999). In the Figure 3–7, the mixtures marked as mini-paver are those used in the third trial. It can be observed from the figure that due to the characteristics of the coarse aggregate from Alma Center, WI, a thicker excess mortar layer was required for proper SFSCC flowability, self-consolidating ability, and shape-holding ability.

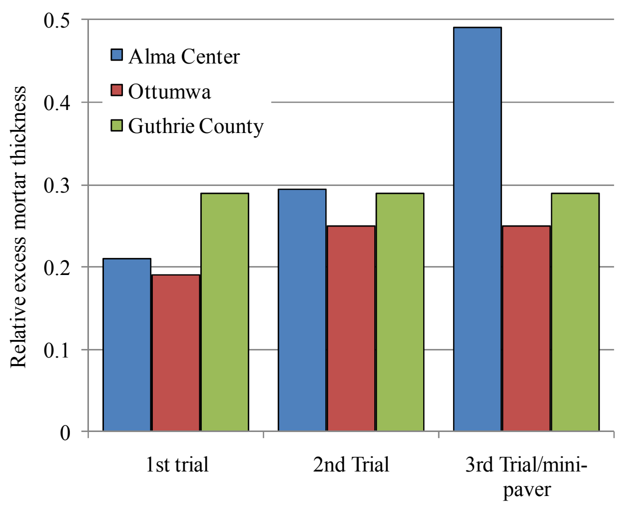


Figure 3–7. Relative excess mortar thickness for different trials

After meeting the modified slump and compaction factor test criteria, the mixtures were then evaluated using a mini-paver. The mixture proportions for the mini-paver tests are listed in Table 3–5.

Table 3–5. Mixture proportions for mini-paver tests

	Cement (pcy)	Fly ash (pcy)	Water (pcy)	F.A. (pcy)	C.A. (pcy)	AEA (oz/cy)	WR (oz/cy)	RMA (oz/cy)	Thixo tropy (pcy)	Fiber (pcy)	w/b
Ames, IA	595	249	295	1307	1373	6.3	-	67.4	-	1.5	0.35
Ames, IA	560	243	310	1226	1450	6.0	-	-	3.5	-	0.39
Guthrie, IA	540	231	293	1205	1544	5.8	-	-	-	-	0.38
Ottumwa, IA	589	252	320	1311	1384	6.3	-	-	-	-	0.38
Webster, IA	569	244	301	1242	1387	6.1	40.65	-	-	1.0	0.37
Alma Center, WI	619	265	336	1380	1238	6.6	-	-	-	-	0.38

It should be noted that in the mix proportion adjustments, no chemical admixture, except for air entraining agent (AEA), was added into the Guthrie, IA, Ottumwa, IA, and Alma Center, WI, SFSCC mixtures because the adjustments were done in the lab. If an adjustment is needed in field application, use of chemical admixtures may be quicker and more effective.

After meeting the criteria specified for the modified slump cone (unrodded) and compaction factor tests, the SFSCC candidates were further evaluated with mini-paver tests (*Step 3)*. Figure 3–8 shows the concrete slabs paved with mix proportions as indicated in Table 3–5. The slab thickness was 5 in. for the one made with materials from Webster, 6 in. for the one made with materials from Ames (w/b = 0.35), and 4 in. for the rest. All the mini-paver tests were successful. The concrete was extruded from the mini-paver by its self-weight with no form work or additional consolidation. The edges of all the concrete slabs looked vertical and sharp. The top surface was smooth. As a result, the two mixes made with materials from Ames were recommended for the field construction tests in Ames (Section 6.2).

Alma Center, WI

Ottumwa, IA

Guthrie, IA

Webster, IA

Ames, IA (w/c=0.39)

Ames, IA (w/c=0.35)

Figure 3–8. Mini-paver results of SFSCC candidates

3.5 Reduction of Cementitious Materials for SFSCC Mixtures

The cementitious content in the SFSCC mixtures presented in the previous sections ranges from 771 to 884 pcy, 60% to 70% of which is portland cement and 30% to 40% is fly ash. Though much lower than that in conventional SCC, which ranges from 880 to 950 pcy (Kosmatka et al. 2006), the cementitious content of SFSCC is significantly higher than that of conventional pavement concrete, which is about 600 pcy. The high cementitious content of SFSCC has become a concern since it leads to a high cost and high potential of shrinkage cracking. After random cracking was found in the local street pavement constructed with SFSCC in Ames, IA (see Section 6), a special task was added to the project to reduce the amount of portland cement used in SFSCC.

A control mix with a cementitious content of 816 pcy and a w/b of 0.35 (mix 7 in Table 3–3) was selected for the cement reduction study, and the following approaches were used to reach the objective without losing necessary characteristics of SFSCC:

1. Adding more coarse aggregates
2. Using granulated blast furnace slag (slag) to replace portland cement
3. Using limestone dust as fines to improve concrete flowability.

In this first part of the cement reduction study, coarse aggregate was gradually added into the control mix until the mixture no longer satisfied the slump of 6 to 8 in. and slump spread of 12 in. The final mix, with the maximum aggregate addition, was noted as SFSCC-Max-Agg (mix 8 in Table 3–3).

Slag is commonly used in conventional pavement concrete. In the second part of this study, after obtaining a mix with the maximum amount of coarse aggregate addition, slag was introduced in the mixture to replace a portion of portland cement. While maintaining cement content of 60% of the total cementitious material in the concrete, the amount of slag used varied from 10% to 20%, with the remaining 30% to 20% as fly ash. The final mix, with the maximum slag replacement for portland cement, was labeled as SFSCC-BFS (mix 9 in Table 3–3).

Limestone dust is increasingly used in conventional powder type SCC for the purpose of improving flowability. In most powder type SCC, the amount of cement (powder) provides the needed viscosity and flowability for self-consolidation. As the third part of this study, limestone dust was used in SFSCC as a fine material to replace the amount of cement that contributes to the viscosity and flowability properties of SFSCC. Limestone dust was tested at 8%, 16%, 25%, and 33% of cementitious material. The final mix, with the optimum limestone dust addition, was labeled as SFSCC-LD (mix 10 in Table 3–3). All the final mix proportions resulting from the cementitious material reduction study are given in Table 3–6. The fresh concrete properties of the mixes are given in Table 3–7. Figure 3–9shows that the final mixes resulting from the cementitious material reduction study all met the slump and slump spread criteria. The unit weights of the fresh SFSCC were similar to those of conventional pavement concrete. The compaction factors of the mixes were at least 97.5%, and the air contents were within acceptable range for freeze-thaw durability.

Table 3–6. SFSCC mixes with reduced cementitious content (mixes 7 to 10 in Table 3–3)

ID	Cement (pcy)	Fly Ash (pcy)	Slag (pcy)	Limestone Dust (pcy)	Water (pcy)	F.A. (pcy)	C.A. (pcy)	AEA (oz/cy)	HRWR (oz/cy)	RMA (oz/cy)	Fiber (pcy)	w/b
SFSCC-Control	569.7	246.5	-	-	289.7	1245.1	1472.3	6.1	0	0	0	0.35
SFSCC-Max-Agg	504.2	217.9	-	-	250.5	1341.4	1563.9	5.4	14.8	43.0	1.5	0.35
SFSCC-BFS	432.9	144.2	144.2	-	250.3	1340.9	1563.4	5.4	21.0	34.6	1.5	0.35
SFSCC-LD	484.3	161.3	-	162.4	264.6	1504.5	1273.4	4.9	28.1	30.4	0	0.41

Table 3–7. Fresh concrete properties of mixes with reduced cementitious content

	Slump (in)	Spread (in)	UnitWt (pcf)	CF (%)	Air (%)
SFSCC-Control	7.00	11	140.2	98.7	6.5
SFSCC-Max-Agg	6.75	12	124.6	97.5	6.0
SFSCC-BFS	7.00	13	135.6	99.0	6.0
SFSCC-LD	7.00	13	140.2	99.0	8.0

The following can be observed from the Table 3–6:

1. Addition of more coarse aggregates in the control SFSCC mix resulted in a decrease of portland cement from 569.7 pcy to 504.2 pcy and a decrease of cementitious content from 816.2 pcy to 722.1 pcy, approximately 11.5%.
2. The use of slag and the addition of coarse aggregates reduced the cement content by 24%.
3. Addition of limestone dust decreased the cementitious materials by 20.9% and the cement by 15%.

SFSCC-Control mix

SFSCC with max. aggregate addition

SFSCC with 20% slag replacement

SFSCC with 33% limestone dust addition

Figure 3–9. Modified slump test results from cement reduction study

4. PROPERTIES OF FRESH SFSCC

The rheological properties of SFSCC mixes, mortars, and pastes were studied. The rheology parameters—viscosity, yield stress, and thixotropy—relate to the concrete ability to flow, consolidate, and hold its shape. The main drawback to using rheology-based measures is the need for specialized equipment that has not been standardized or readily accepted in the field. For the SFSCC mixes, viscosity would relate to the concrete's ability to continue to flow under a minimal consolidation pressure and fill slip forms. The yield stress would give an indication of SFSCC's ability to hold its shape given its form shape and thickness.

4.1 Paste Rheology

The rheology of pastes in SFSCC consists of studying the effects of the different admixtures, cementitious materials, and the change in flow properties with time. The materials used for the study were Type I cement, Class C fly ash, AEA, HRWR, and Actigel. The water-to-binder ratio for the paste mixtures was 0.4.

In the rheology tests, the viscosity, yield stress, and thixotropy were determined using a Brookfield rheometer. To obtain these properties, the loading history given in Figure 4–1 was employed. The loading history is composed of an increasing shear rate from 0 to 100 1/s in 60 seconds, and a decreasing shear rate from 100 to 0 1/s in 60 seconds. Because of these two segments in loading, the shear stress in the paste has an up curve and a down curve (Figure 4–2). The up curve is produced by increasing the shear rate, while the down curve is produced by decreasing the shear rate. The viscosity and yield stress were determined from the down curve of the shear stress—strain rate curve, while the measure of the paste thixotropy was calculated from the difference in area between the up curve and the down curve, as shown in Figure 4–2.

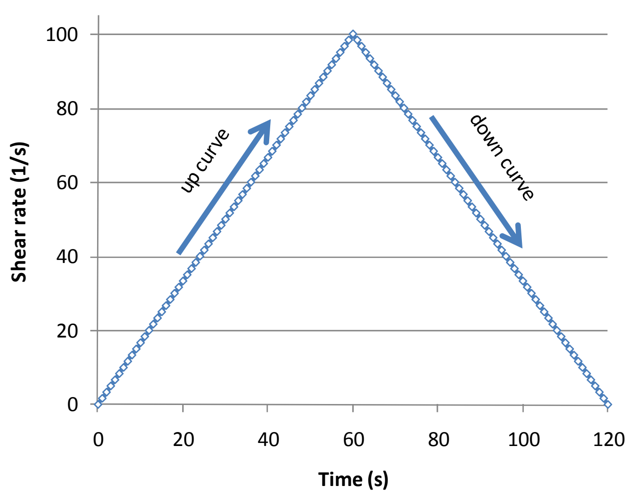


Figure 4–1. Loading history for paste with Brookfield rheometer

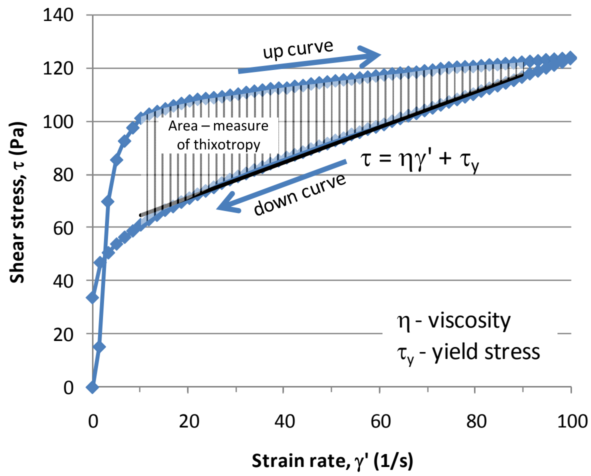


Figure 4–2. Typical paste flow curve for Brookfield rheometer

The effects of Actigel on thixotropy were determined by testing paste with increasing Actigel. The change of thixotropy of the paste with time after mixing was also studied by testing pastes right after mixing and 15 minutes after. The thixotropy values are shown in Figure 4–3. The results showed that Actigel increases paste thixotropy. This property is beneficial when concrete is to consolidate under its own weight and motion of the paver and hold its shape as it goes out of the paver. The results also show that there is an increase in thixotropy with the time after mixing. This is because cementitious materials create bonds between particles as they hydrate.

The yields stress and viscosity of pastes with increasing Actigel are given in Figure 4–4 and Figure 4–5. Both yield stress and viscosity increase with Actigel content. While thixotropy significantly increases with time, viscosity and yield stress only increase slightly within the 15 minutes of testing.

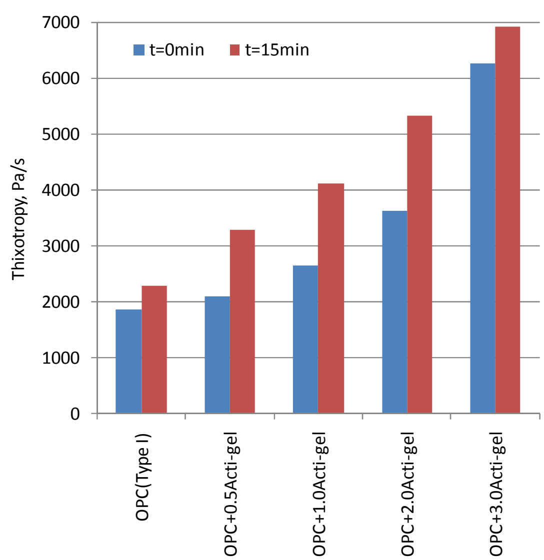


Figure 4–3. Paste thixotropy with increasing Actigel content and hydration time

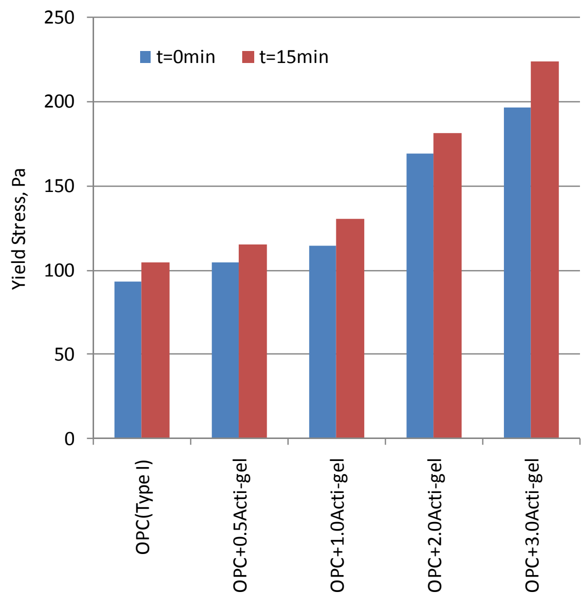


Figure 4–4. Paste yield stress with increasing Actigel content and hydration time

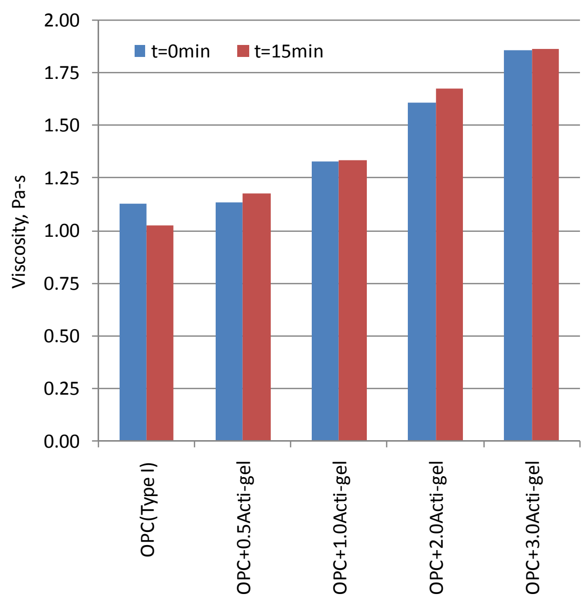


Figure 4–5. Paste viscosity with increasing Actigel content and hydration time

The effects of admixtures on paste rheology were determined. The admixture dosages were based on the proportions given in mix 13 in Table 3–3. From the results shown in Figure 4–6, it can be observed that HRWR and AEA reduce thixotropy, while Actigel increases thixotropy. The increase in thixotropy with time is present even with the presence of the different admixtures.

The yield stress and viscosity of paste with different admixtures are given in Figure 4–7 and Figure 4–8. The results showed that HRWR did not affect the yield stress, while the AEA increased the yield stress. This may be due to the small dosage of the HRWR used. Viscosity decreased with the use of HRWR and AEA, but increased with Actigel. Fifteen minutes after mixing, the viscosity and yield stress had decreased in mixtures containing HRWR and AEA, and the viscosity remained high in mixtures containing Actigel.

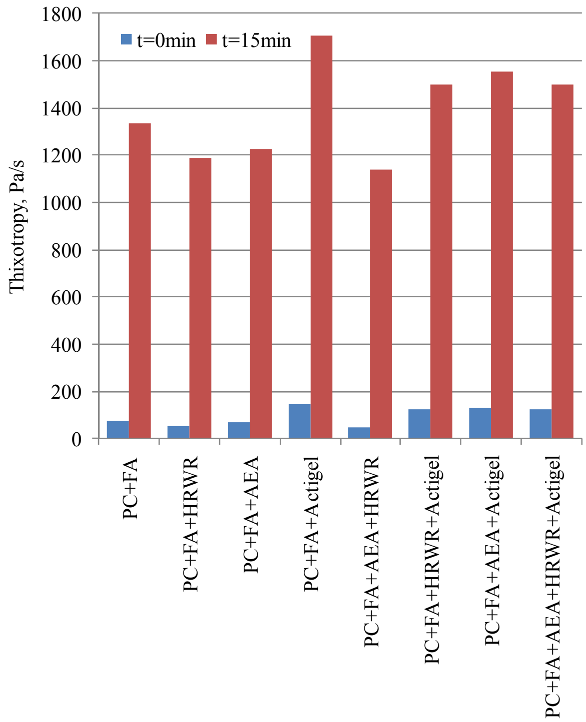


Figure 4–6. Paste thixotropy with different admixtures immediately and 15 minutes after mixing

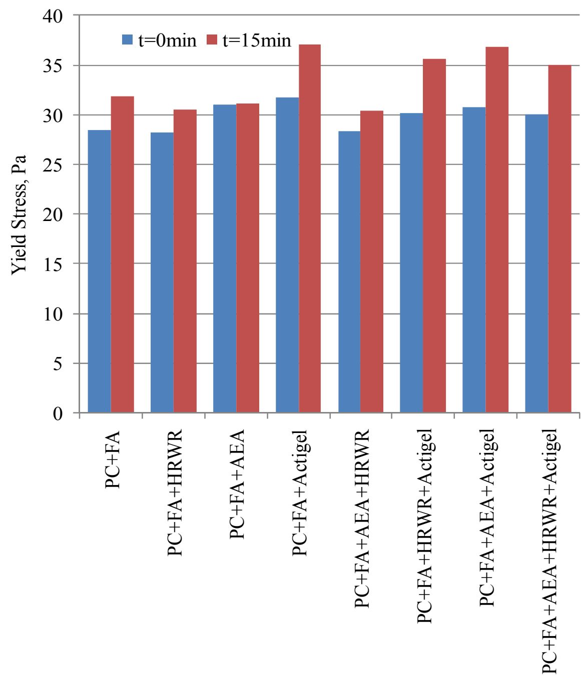


Figure 4–7. Paste yield stress with different admixtures immediately and 15 minutes after mixing

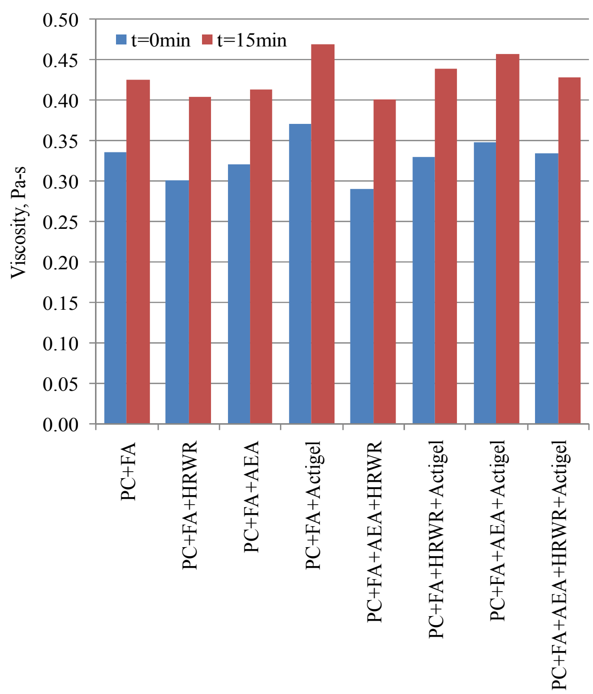


Figure 4–8. Paste viscosity with different admixtures immediately and 15 minutes after mixing

4.2 Rheology of SFSCC

For SFSCC, the rheometer used in the tests was the IBB rheometer (Banfill et al. 2000). The IBB rheometer used an H-shaped impeller that rotated and revolved though the concrete. The amount of torque required for the impeller to move the concrete and the torque required to maintain its motion was recorded during the test. A typical loading history for the test is shown in Figure 4–9. The loading started with a preshear of 0.2 rev/s for 25 seconds to remove local restraints, then 25 seconds of rest, followed by 100 seconds of increasing impeller speed of 0 to 1 rev/s, and 100 seconds of decreasing impeller speed to 0. The yield torque (G) and slope (H) , which were the torque required to put the concrete in motion and the torque required to keep the concrete moving given a shear rate, respectively, were taken from the unloading part of the torque-shear rate curve (Figure 4–10). The SFSCC mixtures tested are given in Sections 3.4, 6.2, and 6.3. Mixtures in Sections 6.2 and 6.3 are concrete cast in the field, while NR-M1 and NR-M3 are NR-M1-A and NR-M3-A mixtures removed of thixotrope, thus making them more flowable.

Figure 4–11 shows the flow curves of the SFSCC mixes and the conventional pavement mix C-3WR-C20. The slope from the SFSCC mixes was from 3.0 to 7.4 N-m-s, and the yield torque was from 1.7 to 4.5 N-m. It can be seen that the SFSCC mixes had a lower slope compared to C-3WR-C20, which had a slope of 9.3 N-m-s. The yield torque of SFSCC mixes was only slightly lower compared to C-3WR-C20, which had a yield torque of 4.76 N-m. The removal of thixotrope from the SFSCC mixes reduced the yield torque. The yield torque and slope values are tabulated in Table 4–1.

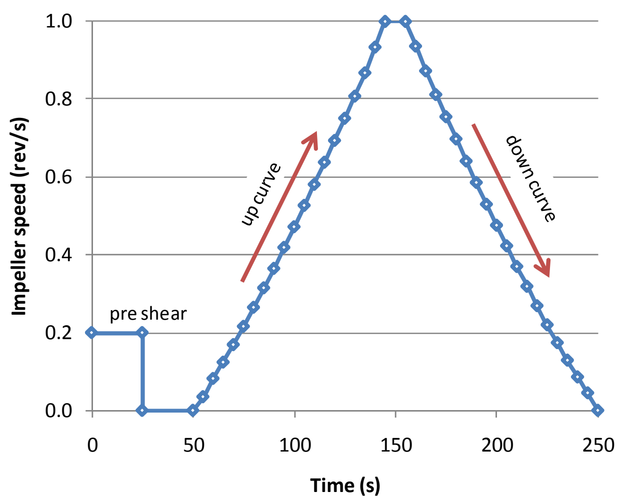


Figure 4–9. Loading history for concrete with IBB rheometer

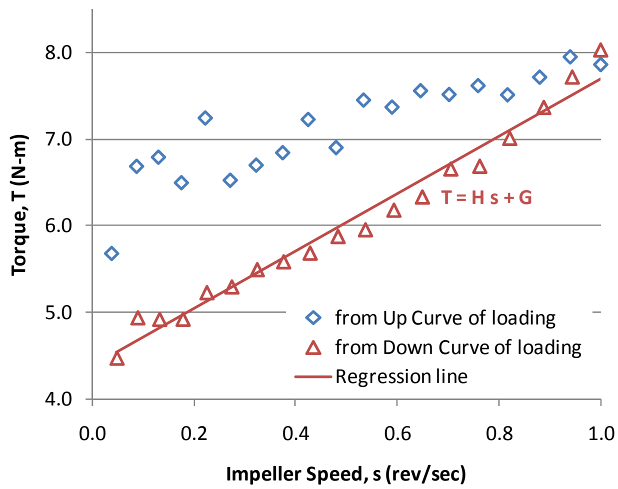


Figure 4–10. Typical concrete flow curve for IBB rheometer

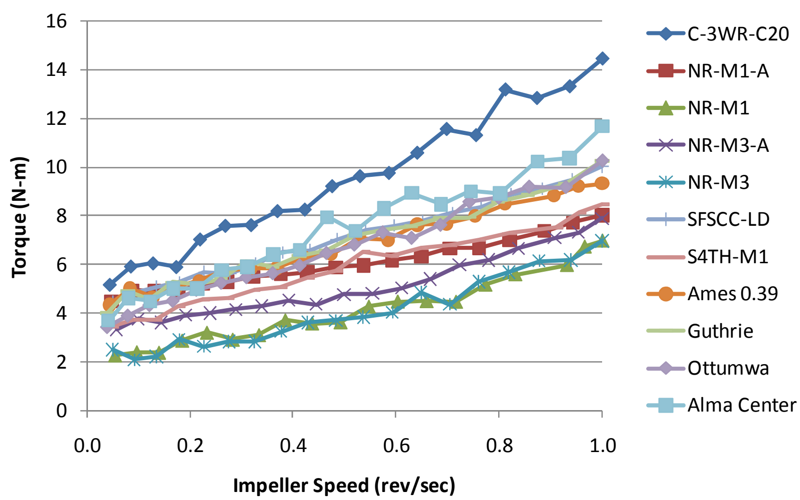


Figure 4–11. Concrete flow curve from the loading down curve of SFSCC and a conventional pavement mixture

Table 4–1. Rheological properties of concrete and mortar from SFSCC and C-3WR-C20

	Slump (in)	Spread (in)	IBB-slope (N-m-s)	IBB-yield torque (N-m)	BRF-viscosity (Pa-s)	BFD-yield stress (Pa)	Initial flow (%)	Final flow (%)
C-3WR-C20	6.25	10	9.30	4.76	1.78	129.08	11.33	142.15
NR-M1-A	6.25	10	3.04	4.46	1.54	154.79	9.75	150.53
NR-M1	9	16	4.08	1.95	1.64	111.17	20.42	170.24
NR-M3-A	8	12.5	3.98	3.00	1.79	163.03	14.00	161.68
NR-M3	8.5	14	4.49	1.71	1.58	126.49	26.58	171.65
SFSCC-LD	6.75	11	5.44	4.31	2.84	191.91	8.33	136.45
S4TH-M1	7.5	12	4.92	3.34	2.25	151.34	10.50	157.12
Ames39	7	12	5.08	4.21	1.94	140.48	12.00	156.00
Guthrie	7.5	12.5	5.53	4.10	1.90	164.74	10.00	156.00
Ottumwa	7	12.5	6.59	3.38	2.25	167.74	10.00	156.00
Alma Center	7	12.5	7.42	3.70	1.90	144.51	12.00	156.00

Mortar was taken from fresh concrete by using a #4 sieve. The rheological parameters of the mortars were determined using a Brookfield rheometer. The loading history for the mortar mixtures is shown in Figure 4–12 and a typical mortar flow curve is shown in Figure 4–13. In the same way as the concrete samples, the mortar yield stress τ_y and viscosity η were taken from the down curve portion of the loading curve. The curves from the downward portion of the loading are shown in Figure 4–14. The viscosity of the mortars from SFSCC was similar to the conventional pavement concrete, except for SFSCC-LD. Limestone dust had a significant effect on the viscosity of the mortar in concrete. Since the viscosity of the mortar from C-3WR-C20 was similar to the mortar from SFSCC, this would mean that the high slope of the concrete flow curve from the IBB test was due to the coarse aggregate. The yield stress of SFSCC mortar was higher compared to the yield stress of C-3WR-C20 mortar. This may be due to the greater amount of cementitious materials in SFSCC mortar. The viscosity and yield stress values of the mixes are given in Table 4–1.

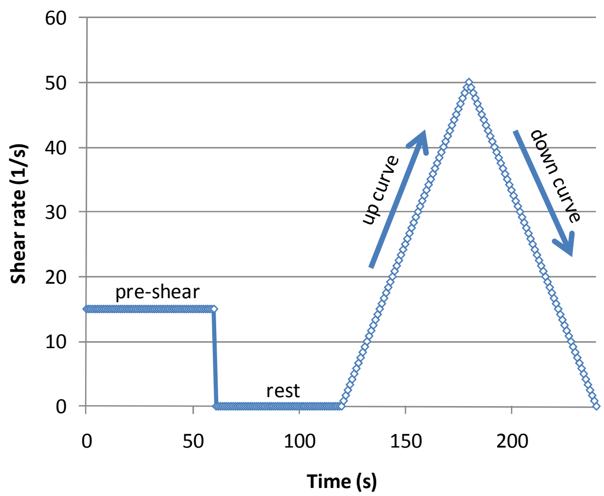


Figure 4–12. Loading history for mortar with Brookfield rheometer

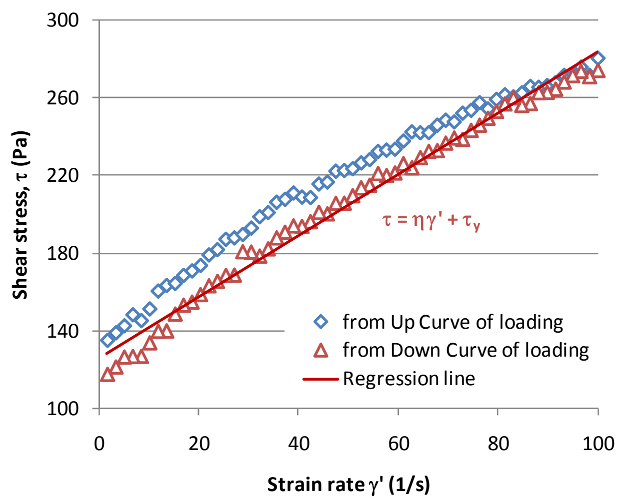


Figure 4–13. Typical mortar flow curve for Brookfield rheometer

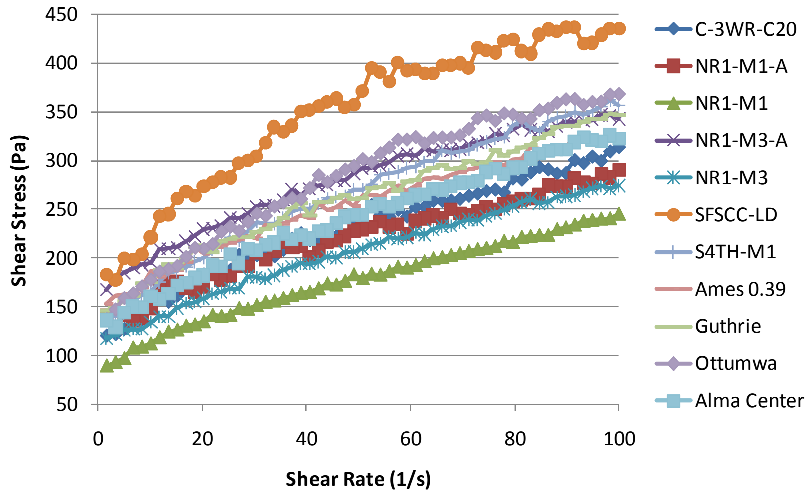


Figure 4–14. Mortar flow curve from the loading down curve of SFSCC and a conventional pavement mixture

The following figures show the relation of fresh SFSCC flow properties with the slump, rheometer, and flow table tests. The slump, spread, and IBB results are from concrete mixes and the flow, yield stress, and viscosity are from mortars sieved from concrete.

Figure 4–15 shows that slump has a good inverse relation with IBB torque intercept. With the design guidelines for SFSCC of 6 to 8 in. slump, the IBB torque intercept for SFSCC should be between 3 and 5 N-m. The relation between SFSCC spread and IBB slope is weak (Figure 4–16); however, it can be clearly deduced that for a spread requirement of ~12 in., the IBB slope should be between 3 and 7.5 N-m-s. This IBB slope is much lower than for conventional pavement concrete.

An inverse relation may be found between mortar initial flow and yield stress. From the mix design of SFSCC with the initial flow of mortar $F_0 \approx 10\%$, the yield stress should be at least 140 Pa and up to 195 Pa, as shown in Figure 4–17. Less than 140 Pa would be too flowable. The relation between mortar final flow and viscosity is shown in Figure 4–18. For a design final flow of ≈156%, the SFSCC mortar should range between 1.50 and 2.25 Pa-s.

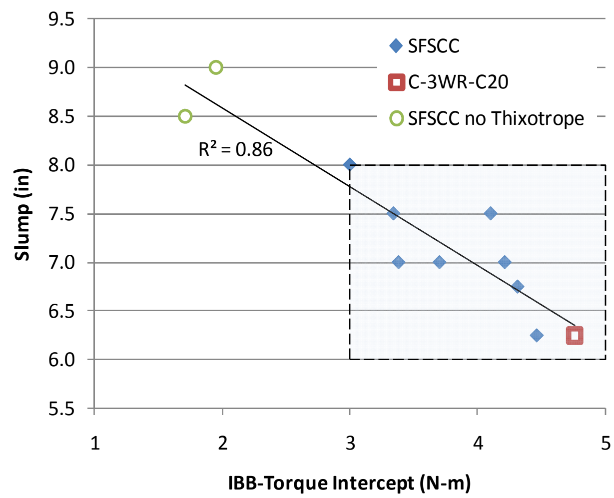


Figure 4–15. Relationship between slump and IBB torque intercept

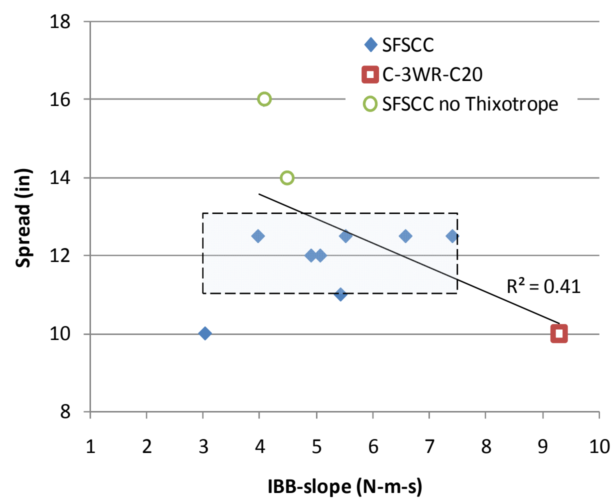


Figure 4–16. Relation between spread and IBB slope

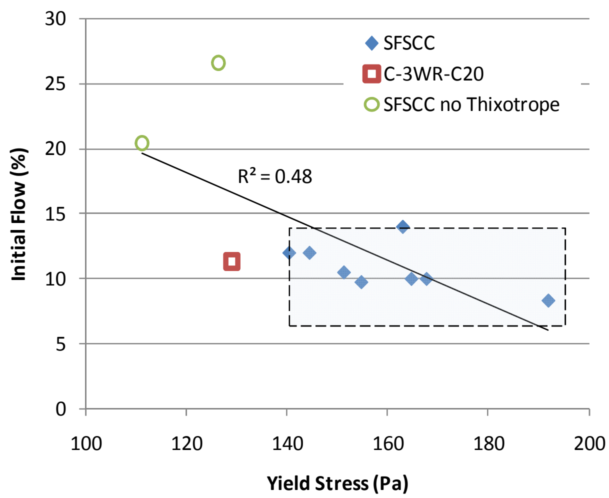


Figure 4–17. Relation flow table initial flow and Brookfield rheometer yield stress

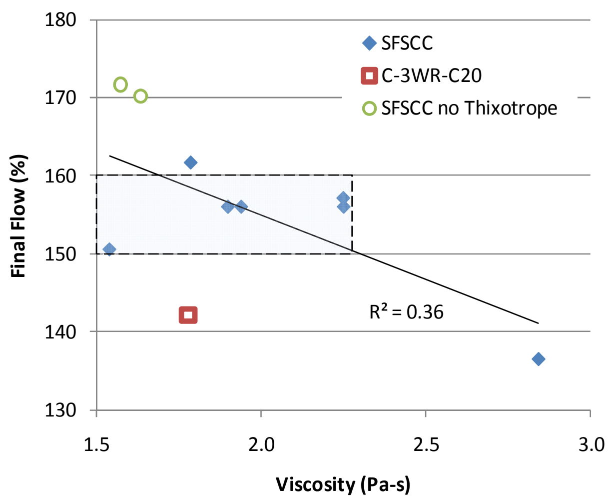


Figure 4–18. Relation flow table final flow and Brookfield rheometer viscosity

4.3 Green Strength of SFSCC

The green strength test is most suited for developing SFSCC mixes starting from conventional concrete mixes, either conventional slip-form concrete (SFC) or conventional SCC, using the alternative method of SFSCC proportioning discussed in Section 2.4. The SCC is modified by the addition of chemical admixtures and fine materials until it reaches the maximum consolidation at minimum compaction energy and maintains its shape after the consolidation process (Voigt et al. 2010). The flowability will decrease and the green strength will increase.

Two procedures for conducting the green strength test are given in Appendix A. The SFSCC green strength values given in this section were obtained with Method B discussed in Appendix A. Method B involved loosely filling a 4 by 8 in. cylinder with concrete, placing this cylinder on the drop table, and then applying 15 drops. After that, cylinder was demolded. Immediately after demolding, the green strength of the cylinder was determined by applying a vertical load until the specimen collapsed. The maximum force was used to calculate the green strength of the tested cylinder.

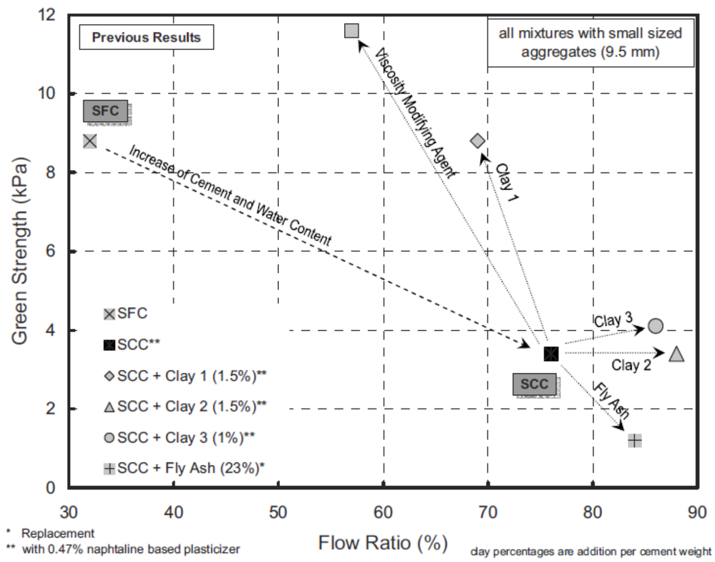


Figure 4–19. Effect of mineral and chemical admixtures on flowability and green strength of fresh concrete with small-sized aggregates

Figure 4–19 shows the effects of mineral and chemical admixtures on flowability and green strength of fresh concrete. Table 4–2 lists the different materials used in the green strength study. Addition of viscosity modifying admixture (VMA) and Clay 1 resulted in an increase of green strength, accompanied by a moderate decrease in flowability. These two mixtures had green strength equal to or higher than that of the SFC mixture. Addition of Clays 2 and 3 increased the flowability of the concrete mixture while maintaining the green strength at the same level of the "Plain" concrete mixture. When fly ash was used as a portland cement replacement, the mixture had an increase in flowability, accompanied by a decrease in green strength. Except for the SFC mixture, all mixtures could be consolidated without the use of internal or external vibration using a model paver that simulates the slip-form casting process.

Table 4–2. Materials for analysis of green strength

Material	Description	Mean particle size/dimensions
Cement	Portland type I	590×10^{-6} in (15 μm)
Fly ash	Class F	945×10^{-6} in (24 μm)
Clay 1	Metakaolinite	138×10^{-6} in (3.5 μm)
Clay 2	Kaolinite, illite, silica	512×10^{-6} in (13 μm)
Clay 3	Purified magnesium alumino silicate	2558×10^{-6} in (65 μm)
Magnesium oxide	MgO	512×10^{-6} in (13 μm)
Fibers	Polypropylene	0.2-0.6 in (5–15 mm) long, D<0.002 in (0.05 mm)

An SFC mixture that is currently used for slip-form paving was modified to achieve better flowability and sufficient green strength. This was done mainly by increasing the cement content from 594 to 870 pcy and slightly modifying the contents of water and aggregates. All changes in the mixture composition were done with the objective to match the composition of a conventional SCC. The comparison of flowability and green strength for the SFC and the modified mixture SCC is shown in Figure 4–20. It can be seen that the modified mixture exhibited a much higher flowability but maintained sufficient green strength that rendered excellent shape stability to the demolded cylinder.

In the second step, the cement content of the SCC mixture was reduced by replacing 30% of cement weight with fly ash. This composition is labeled SCCF. This allows decreasing the cement content to the same level of the conventionally used SFC and, at the same time, maintaining the amount of fine materials needed for improved flowability. As seen in Figure 4–20, the fly ash replacement for cement increased the flowability of the mixture further, but this time it did not provide sufficient green strength for the demolded cylinder to hold its shape. Although the cylinder did not collapse completely, a reliable green strength value of the concrete could not be determined, and it was therefore assumed to be zero.

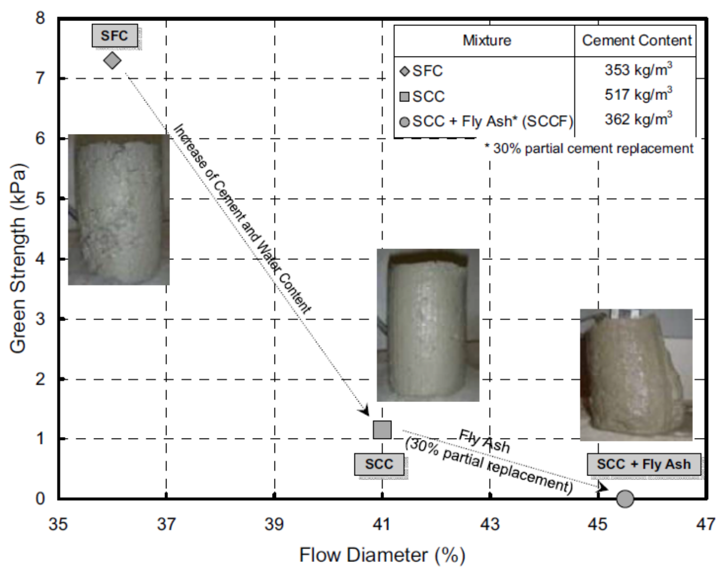


Figure 4–20. Flowability and green strength for SFC, SCC, and SCCF mixtures

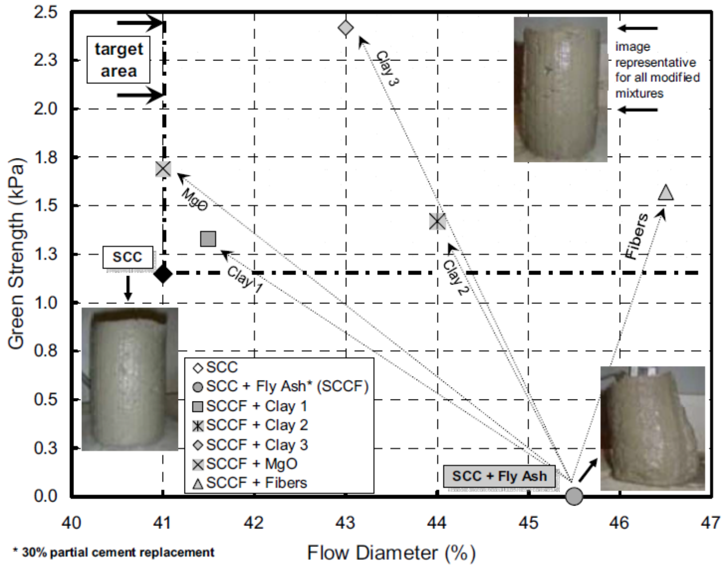


Figure 4–21. Effect of different additives on green strength and flowability for the SCCF mixtures

The effect of additional fine materials on concrete properties was investigated by adding different nano-clays in amounts of 1% to1.5% of cement weight. The changes in green strength and flowability of those mixtures are shown in Figure 4–21. All three types of nano-clay provided the mixture with a significant increase in green strength—beyond the value measured for the SCC mixture that had much higher cement content. The flowability of the three mixtures decreased due to the nano-clay addition; however, it was still greater than that of the SCC mixture. It should be pointed out that Clays 2 and 3 are especially efficient at affecting the green strength and hence the shape stability of the mixtures since the reducing effect on flowability is minimal. In addition to nano-clay, tests were conducted to see if the green strength could be improved with magnesium oxide (MgO) or polypropylene fibers. The results in Figure 4–21 show that MgO can increase the green strength and maintain the flowability to the same level of the SCC concrete mixture. The increase in green strength was caused by the ionic charge of the MgO particles, giving the concrete mixture a higher cohesion. The addition of propylene fibers proved to be beneficial for both green strength and flowability. Green strength was increased beyond that of the SCC mixture, and the flowability was even higher than that of the SCCF mixture. Based on the experimental results presented, the target green strength ranges from approximately 1.3 to 2.5 kPa.

The flowability and consolidation ability of a stiff concrete mixture can be significantly improved by increasing the content of fine materials in the mixture. This modification improves stability of the fresh concrete. The high cement content generally required for SCC can be significantly reduced by use of fly ash as a replacement for portland cement. The fly ash replacement can further increase concrete flowability but reduce concrete green strength or shape stability. However, when fly ash is used together with nano-clay additives or propylene fibers, the resulting concrete possesses not only desirable properties but also reduced costs.

4.4 Effect of nano-clay addition on rheology, green strength, and SFSCC paving applicability

This section aims to investigate the effect of different dosages of various micro and nano-clays to produce SFSCC compositions with the highest green strength without sacrificing the required flowability. This was approached from three different tests: a micro-level analysis investigating the compressive yield stress, a macro-level analysis investigating the green strength, and an applicability test involving a laboratory-scale paving test. A portion of the results in this section has been published in Tregger et al. (forthcoming).

Four main mix proportions were tested: a cement control mix containing both naphthalene-based superplasticizer and a class C fly ash, designated modified-CM (MCM), and three different cement nano-clay mixes, designated modified-CM1-3 (MCM1-3). Nano-clays for MCM1-3 are Clays 1 through 3 given in Table 4–2. Only the compressive yield stress and green strength methods were used in this section to determine the effects of nano-clay dosages. For the green strength tests, a larger drop table was used as shown in Figure 4–22 due to the size of the larger aggregates.

Concerning the compressive rheology tests, all compositions had the same initial solids volume fraction of 0.45, which corresponds to a w/b of about 0.43 for the CM mix. The mix compositions for the cement compositions are shown in Table 4–3, while the mixing protocols for the cement and concrete mixes are described in Tables 4–4 and 4–5. Mixes were designated by the type (MCM or MCM1-3) and the addition of nano-clay (0.5%, 1.0%, and 1.5% by mass of binder). For the concrete mixes derived from the paste mixes, a coarse aggregate to fine material ratio of 1.75 and a fine aggregate to fine material ratio of 1.54 were used. The coarse aggregate consisted of limestone gravel with a maximum size of 1.0 in., while the fine aggregate consisted of river sand with a maximum size of 0.187 in (4.75 mm). A small planetary mixer was used for the cement pastes, while a rotary drum mixer was used for the concrete.

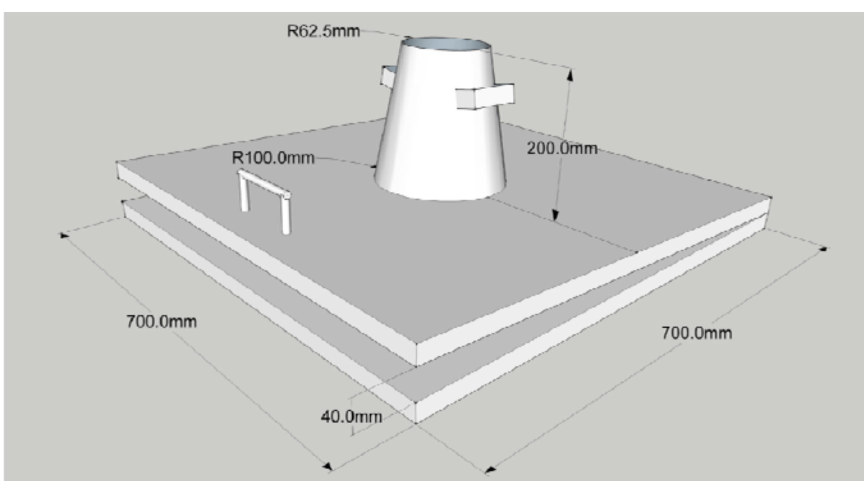


Figure 4–22. Large drop table used to determine green strength of concrete mixes with large aggregates

Table 4–3. Cement mix compositions for compressive rheology tests for one liter of paste

Mix	Cement (g)	FA (g)	Water (g)	SP (g)	Nano-clay addition (g)
MCM	891	382	545	6.4	0
MCM1-05	887	380	545	6.3	6.3
MCM1-10	882	378	545	6.3	12.6
MCM1-15	877	376	545	6.3	18.8
MCM2-05	886	380	545	6.3	6.3
MCM2-10	881	378	545	6.3	12.6
MCM2-15	877	376	545	6.3	18.8
MCM3-05	886	380	545	6.3	6.3
MCM3-10	881	378	545	6.3	12.6
MCM3-15	877	376	545	6.3	18.8

Table 4–4. Cement paste mixing protocol

Time (mm:ss)	Task
0:00	Mix dry materials at low speed
1:00	Add water and SP and mix at low speed
3:00	Stop to scrape sides of mixer
4:00	Mix on high speed
6:30	Stop to scrape sides of mixer
7:30	Mix on high speed
10:00	Perform tests

Table 4–5. Concrete mixing protocol

Time (mm:ss)	Task
0:00	Mix dry including fine aggregate materials at low speed
1:00	Add water and SP and mix at low speed
3:00	Stop to scrape sides of mixer
4:00	Mix on high speed
6:30	Stop to scrape sides of mixer
7:30	Mix on high speed
10:00	Mix in coarse aggregate on high speed
10:00	Perform tests

4.4.1 Nano-clay dosage effects on compressive rheology and green strength

The compressive yield stress is plotted against the sediment volume fraction for each addition rate (0.5%, 1.0%, and 1.5% by mass of cement) for each nano-clay type in Figures 4–23 through 4–25. All of the nano-clays increase yield stress (σ_0) over the range of volume fractions (φ) shown. However, MCM1 shows a higher increase as highlighted in Figure 4–26, which compares all nano-clays at an addition of 1.0% by mass of cement to MCM. Figures 5.23 through 5.25 also show the optimal dosage as 1.0% for each nano-clay type. Any additional nano-clay decreases σ_0 (as high as 3% by mass of cement) have been investigated (Mbele 2006). Kuder and Shah (2006) also reported similar optimal dosages of nano-clays for extrusion applications. It is clear that nano-clays are able to increase the compressive yield stress even in the presence of super-plasticizer (SP) and fly ash.

In addition to the rheology methods, the green strength or strength immediately after casting was determined. These tests were conducted on concrete mixes derived from the cement pastes used in the previous tests. Green strength results are shown in Figure 4–27. Similar to the compressive yield stress results, the nano-clays improve green strength. In addition, MCM1 performs better than both MCM2 and MCM3 at each dosage amount. Optimal dosages are seen for 1.0% by mass of cement for all nano-clays.

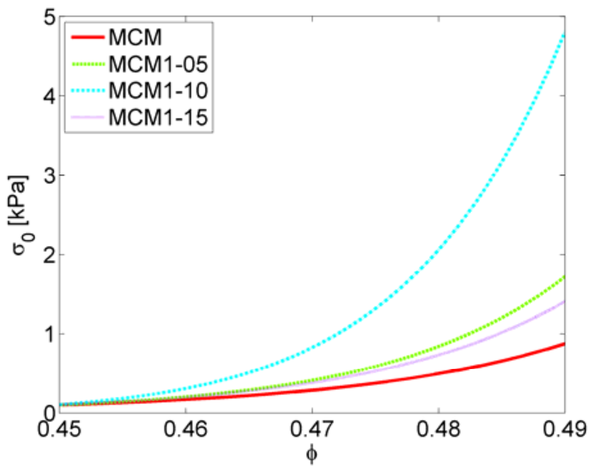


Figure 4–23. Compressive yield stress as a function of sediment volume fraction for Clay 1 at dosages of 0.5%, 1.0%, and 1.5% by mass of cement compared to the modified control mix

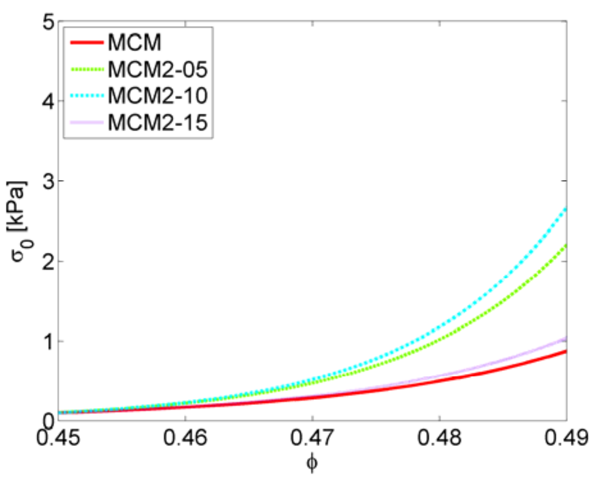


Figure 4–24. Compressive yield stress as a function of sediment volume fraction for Clay 2 at dosages of 0.5%, 1.0%, and 1.5% by mass of cement compared to the modified control mix

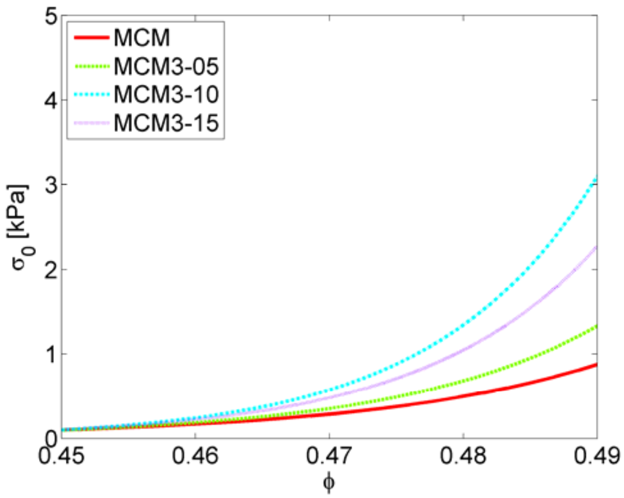


Figure 4–25. Compressive yield stress as a function of sediment volume fraction for Clay 3 at dosages of 0.5%, 1.0%, and 1.5% by mass of cement compared to the modified control mix

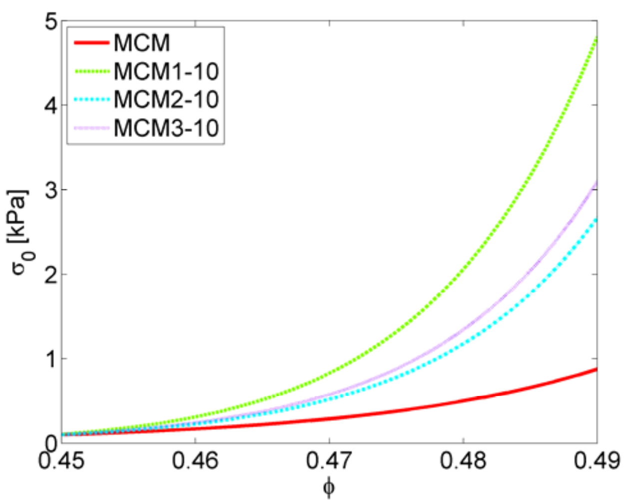


Figure 4-26. Compressive yield stress as a function of sediment volume fraction for all nano-clays at a dosage of 1.0% by mass of cement compared to the modified control mix

4.4.2 Testing applicability of SFSCC mixes using the mini-paver

Finally, a model laboratory mini-paver was used on select mixes to demonstrate the applicability of each mix. Results from the mini-paver for MCM, MCM1-10, MCM2-10, MCM3-10, and MCM1-05 are shown in Figures 4–28 through 4–32. The images shown in these figures are a plan view of the slabs with the casting direction from the top of the page to the bottom of the page.

From the plan views, the surface smoothness, which indicates proper consolidation, and edge stability, which indicates sufficient green strength, can be observed. The MCM mix is shown in

Figure 4–28. Without any nano-clay, although the pavement surface is smooth, the edges are not parallel. In addition, the surfaces near the edges are not smooth due to the excessive slump. Results for mixes containing 1.0% nano-clay show improved edge straightness, while maintaining a degree of surface smoothness. However, for MCM1, the surface is much rougher compared to the other nano-clay mixes (Figure 4–29). Using only 0.5% Clay 1 results in both superior smoothness and edge stability, as shown in Figure 4–32.

In order to quantify shape stability, the edge slump ratio was measured. The edge slump was taken as the ratio between the height of the pavement at the centerline and the average height of the pavement at the outer edges. A ratio of 1 would indicate zero edge slump and high shape stability, while an edge slump ratio less than 1 would indicate less than ideal shape stability. The results of this test are given in Figure 4–33. These results along with the photos confirm that the composition with 0.5% Clay 1 produced the pavement with the smoothest surface and straightest edges. The results are also consistent with those obtained by Mbele (2006) for other SFSCC mixes.

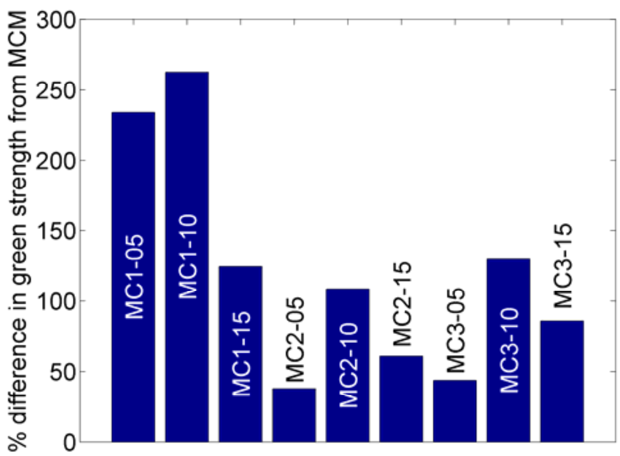


Figure 4–27. Effect of nano-clay dosage on green strength results

Figure 4–28. Plan view of MCM pavement from the mini-paver

Figure 4–29. Plan view of MCM1-10 pavement from the mini-paver

Figure 4–30. Plan view of MCM2-10 pavement from the mini-paver

Figure 4–31. Plan view of MCM3-10 pavement from the mini-paver

Figure 4–32. Plan view of MCM1-05 pavement from the mini-paver

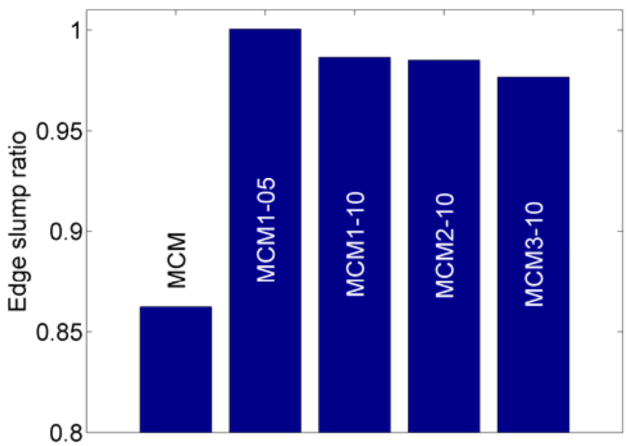


Figure 4–33. Edge slump for select SFSCC mixes tested with the mini-paver

5. PROPERTIES OF HARDENED SFSCC

The general engineering properties of SFSCC were investigated and compared with conventional pavement concrete. The properties studied are compressive strength development, permeability and porosity, freeze-thaw durability and scaling resistance to deicing chemicals, and drying shrinkage behavior and cracking potential due to shrinkage.

5.1 Compressive Strength Development

To test the compressive strength of SFSCC, 4 by 8 in. concrete cylinders were cast without rodding. Samples were demolded after 24 hours and moist cured and tested. Three samples were tested at each age: 3, 7, 28, and 56 days.

As shown in Figure 5–1, the compressive strength of SFSCC mixes was higher than that of the IA DOT C3 mix. This is mainly due to the lower w/c ratios.

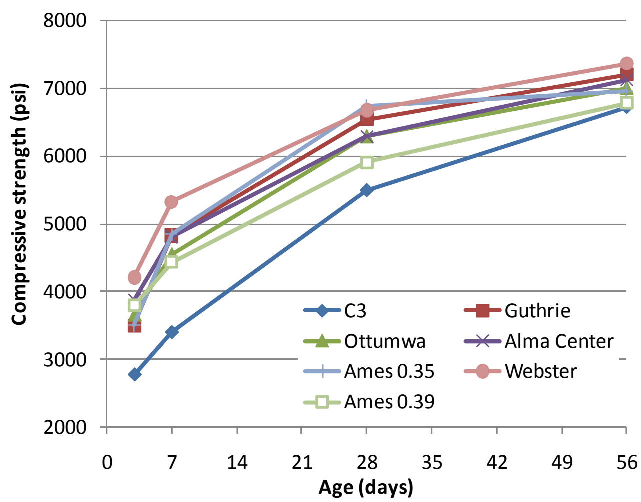


Figure 5–1. Compressive strength development of SFSCC and C3

5.2 Permeability and Porosity

The rapid chloride permeability and porosity of SFSCC and conventional pavement concrete mixtures were determined. From a 4 by 8 in. concrete cylinder, three samples were made—2 in. thick each. Two samples were tested for rapid chloride ion permeability (RCP), while one sample was tested for porosity at 28 days. Due to the high RCP obtained, several additional samples were tested to check the RCP of SFSCC over a long period.

The rapid chloride ion permeability test results are shown in Table 5–1. All SFSCC samples showed higher chloride ion permeability at 28 days compared to C3 mix. However, results for older SFSCC concrete were comparable to C3. The porosity test results are also given in Table 5–1. They show that the porosity of the SFSCC concrete was slightly higher than that of the C3 concrete.

Table 5–1. Rapid chloride ion permeability and porosity

Mixture	Charge passed (coulombs)		Porosity %
	28 days	180 days	
C3	1162	-	11.0
Guthrie County	5514	879	12.6
Ottumwa	5216	634	15.2
Alma Center	4735	1058	16.5
Ames (w/c=39)	4811	-	13.8
Ames (w/c=35)	2499	-	11.1
Webster	2904	-	15.6
SFSCC-Control	3173	-	15.0
SFSCC-Max-Agg	3106	-	14.7
SFSCC-BFS	1275	-	11.1
SFSCC-LD	2326	-	12.5

5.3 Freeze-Thaw Durability and Scaling Resistance to Deicing Chemicals

Three prisms of each mixture type, 3 by 4 by 16 in., were cast for freeze-thaw durability testing. The samples were moist cured for 28 days before testing. The freeze-thaw durability of the SFSCC mixtures is presented in Figure 5–2. As shown, some of the SFSCC mixtures were more freeze-thaw durable than the C3 mixture. With the exception of Webster, all SFSCC mixtures have a durability factor greater than 85%. In the case of Webster, the aggregates deteriorated during the test, resulting in the lower durability factor.

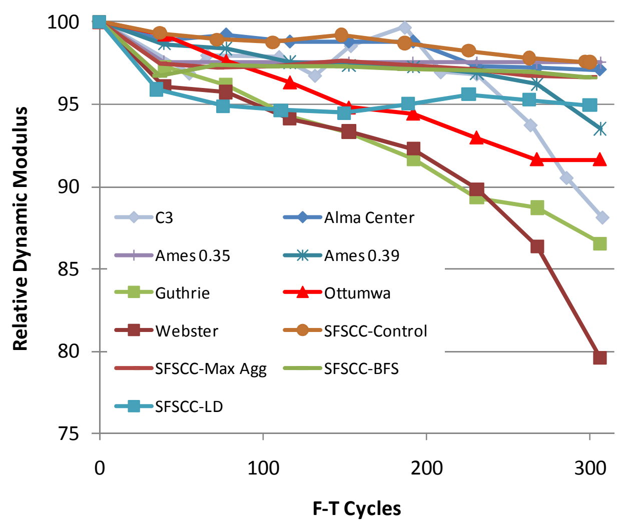


Figure 5–2. Relative dynamic modulus vs. number of freeze-thaw cycles

Table 5–2. Compressive strengths and freeze-thaw durability factors

Mixture	fc 28 days (psi)	fc 56 days (psi)	DF (%)
Alma Center	6283	7119	97.1
Ames (w/c=39)	6382	6758	93.5
Ames (w/c=35)	6738	6958	97.5
Guthrie County	6539	7198	86.5
Ottumwa	6283	6992	91.6
SFSCC-Control	5953	6094	97.6
SFSCC-Max-Agg	4562	5662	96.6
SFSCC-BFS	5554	5920	96.6
SFSCC-LD	5798	6819	95.0
Webster	6670	7030	79.6
C3	5493	6717	88.1

The scaling resistance of selected SFSCC mixes (mixes 10, 13 through 14, and 16 through 17) to deicing chemicals was evaluated, and the results were compared with that of a conventional pavement concrete (mix 19). Three samples of each SFSCC mix were tested. The samples were trowel finished and had a surface area of 81 in^2. The concrete was moist cured for 56 days. Chemical deicer solution was poured on the concrete surface, and the sample was bagged and sealed to prevent water loss. The deicer solution was calcium chloride at 4 grams per 100 ml solution. Three hundred freeze-thaw cycles were completed between 0ºF and 50ºF, with each cycle taking 5 hours. Every 50 cycles, concrete that scaled from the samples was collected by wash sieving, and pictures were taken. The collected flakes were dried and weighed.

The pictures of the samples before and after the scaling tests are shown in Figures 5–3 and 5–4, respectively. The visual rating of the test sample surfaces after 300 freeze-thaw cycles following the scale in ASTM C672 is given in Table 5–3. Visually, it can be seen that NR-M1-A had the least scaling. For a quantitative evaluation, the weight loss of each sample per unit surface is presented in Figure 5–5. NR-M1-A had the least deterioration—better than C3WR-C20. The mixes without Actigel had more scaling compared to concrete with Actigel.

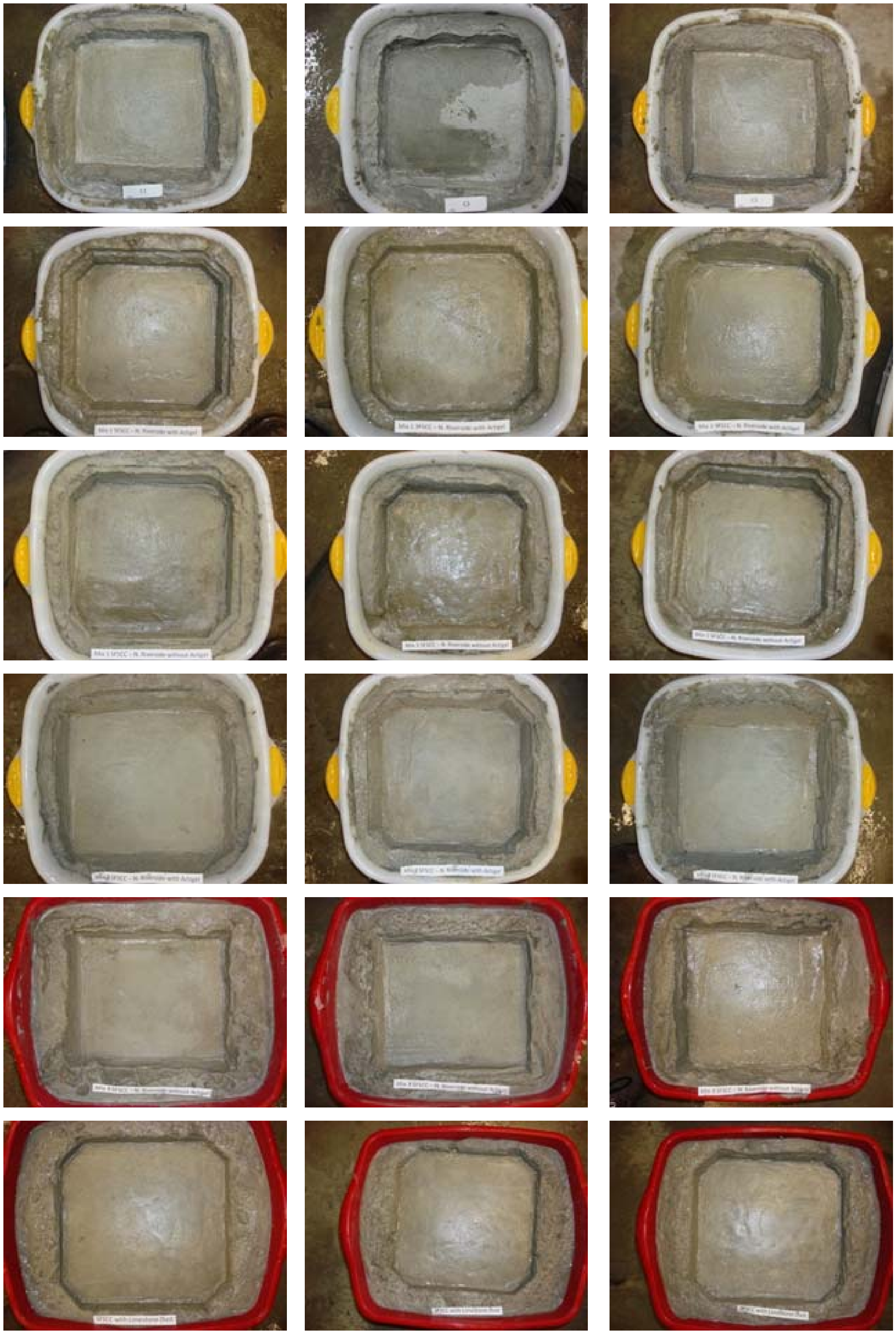


Figure 5–3. Concrete surfaces before testing

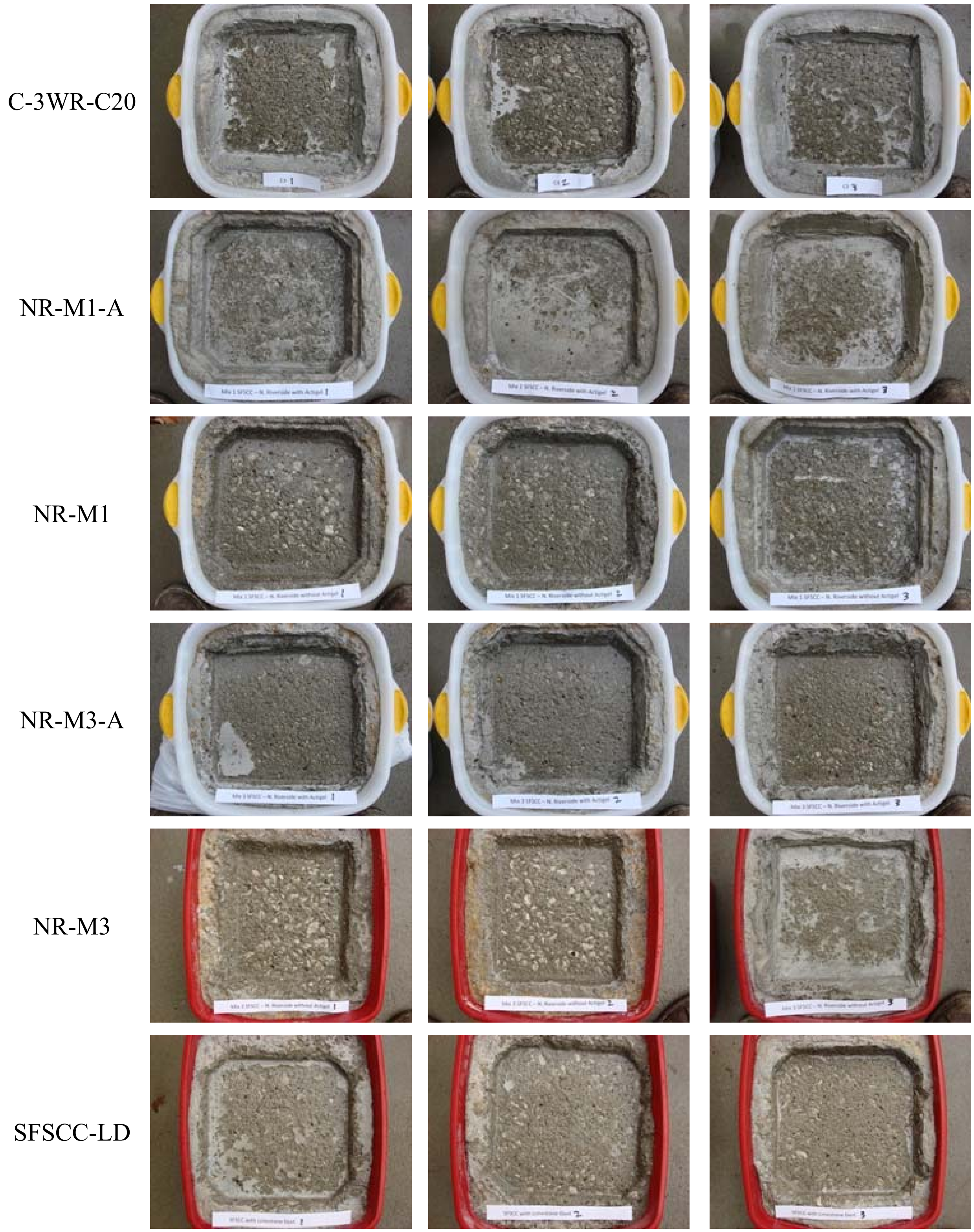


Figure 5–4. Concrete surfaces after testing

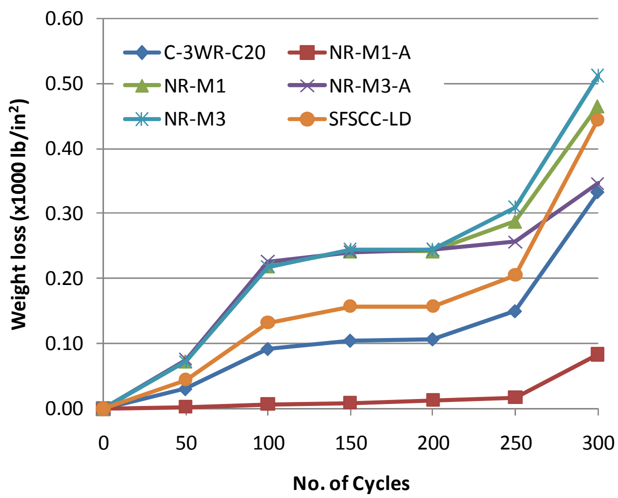


Figure 5–5. Weight loss vs. number of cycles of concrete surfaces

Table 5–3. Visual rating of surface after 300 freeze-thaw cycles

Mix	Rating
C-3WR-C20	3
NR-M1-A	1
NR-M1	5
NR-M3-A	3
NR-M3	5
SFSCC-LD	4

5.4 Shrinkage Behavior of SFSCC

Due to the large amount of cement in SFSCC, it is important to study its shrinkage behavior. The mixes tested were numbers 10, 13, 14, 16, 17, and 19 given in Table 3–3.Two methods were employed in studying the shrinkage behavior of SFSCC. The first method employed was the measurement of the free shrinkage of 3 by 3 by 11.25 in. prisms. Three prisms were made of each mix. The prisms were moist cured for 7 days and then dried at 50%±4% relative humidity and 23ºC±2ºC. The changes in length of the prisms were measured at 0, 4, 7, 14, and 28 days of drying.

The second method employed was the restrained ring shrinkage test, which gives an indication of the potential for cracking of the concrete sample due to shrinkage stresses. The geometry of the concrete rings is shown in Figure 5–6. Two strain gages were attached to each steel ring. Three rings were prepared for each type of mix. The rings were demolded and the tops were sealed with paraffin wax 24 hours after casting. Drying was started immediately after demolding. The drying conditions are the same as for the prism samples. Readings from the strain gages were taken immediately after casting, up to 28 days or when the concrete cracked (Figure 5–7).

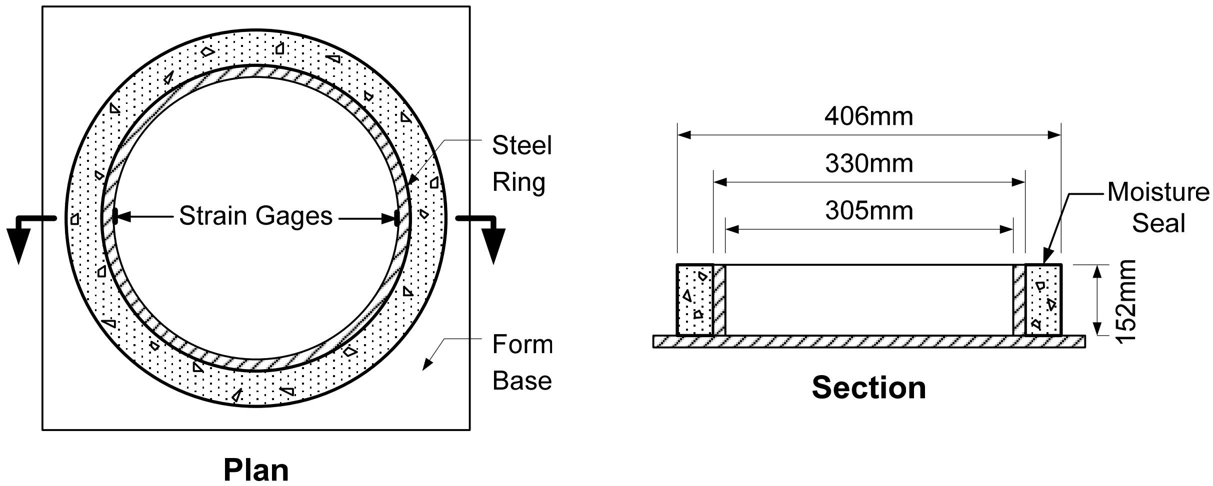


Figure 5–6. Geometry of concrete and steel rings and strain gage location

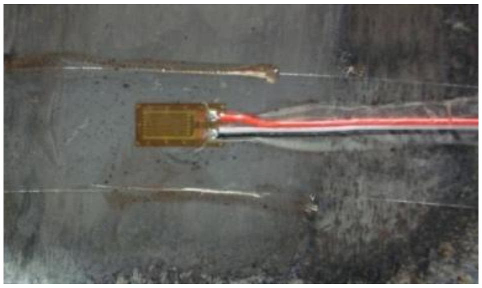
The length change of prism samples over 28 days of drying is given in Figure 5–8. The mix with limestone dust had the least shrinkage among the SFSCC mixes. The mixes with Actigel (NR-M1-A and NR-M3-A) had greater shrinkage than corresponding mixes without it (NR-M1 and NR-M3). The conventional pavement mix C-3WR-C20 had the least shrinkage among the mixtures, which may be attributed to the cement content. The length change of the prisms at 28 days is given in Table 5–4.

The steel ring strains are shown in Figure 5–9. Since the concrete rings of the same mix did not crack at the same time, the vertical lines in the figure are for the earliest cracking time. For all samples, the steel rings initially expanded before they started to contract. All of the SFSCC samples cracked within 8 to 13 days. C-3WR-C20 did not crack. At 12 days, the strain started to plateau.

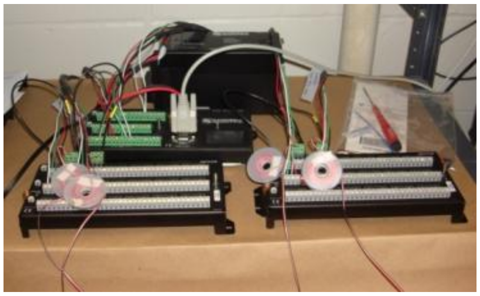
To compare the shrinkage of the prisms and restrained rings, the strain rate factor α of the mixes was also computed. The strain rate factor is calculated with

$$\varepsilon_s = \alpha\sqrt{t} + k \tag{3}$$

where ε_s is the concrete shrinkage, t is time in days, and k is a regression constant. Attiogbe et al. (2003) showed that the square root function could be used to fit ring shrinkage data. The strain rate factors are given in Table 5–4. The relations of the mixes in both tests were the same when compared with the strain rate factor. C-3WR-C20 had the least strain rate, and the mixes without Actigel had a lesser rate than mixes with Actigel. Among the SFSCC mixes, SFSCC-LD had the least rate. The relations were the same when analyzing the shrinkage strain of the prisms at 28 days, though this was not evident when comparing maximum strains of rings due to the cracking of SFSCC mixes.



Strain gage attached to the steel ring



Data logger with two multiplexers

Newly cast concrete ring

Concrete ring with paraffin wax

Cracked concrete ring

Figure 5–7. Restrained concrete ring testing

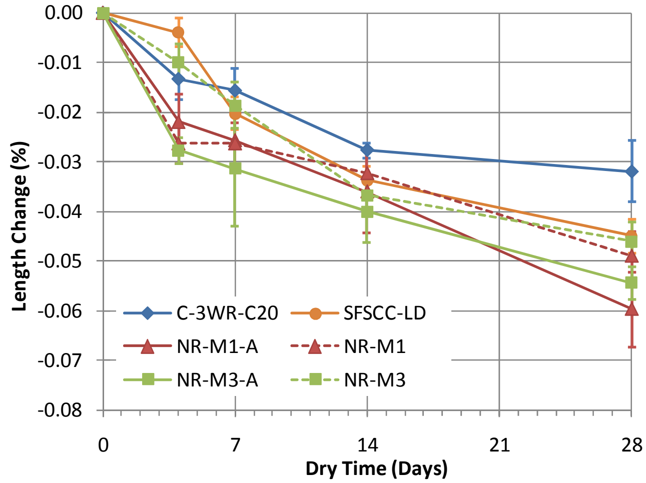


Figure 5–8. Length change of prisms

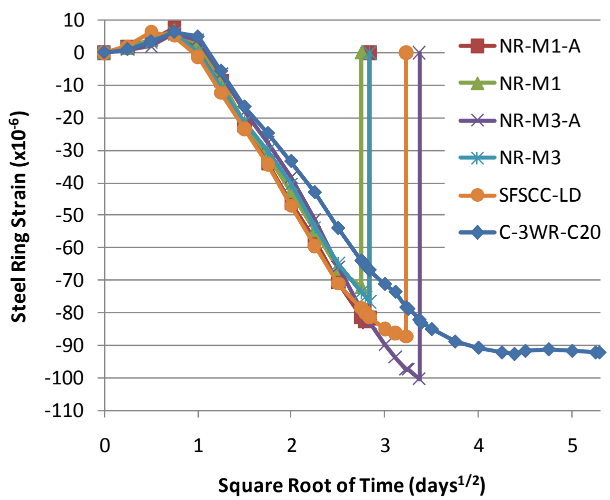


Figure 5–9. Steel strains due to concrete ring shrinkage

Table 5–4. Average strain rate factor and maximum strain and time of cracking

Mix	Ave. strain rate factor (strain×10^{-6}/day$^{1/2}$)		Ave. max. length change or strain (×10^{-6})		Ave. time of cracking (days)
	Prism	Restrained ring	Prism	Restrained ring	
C-3WR-C20	63.2	36.3	320.0	96.4	No cracking
NR-M1-A	109.3	47.0	596.7	88.3	8.2
NR-M1	87.3	43.9	490.0	77.9	8.0
NR-M3-A	100.1	46.4	543.3	97.7	11.5
NR-M3	93.3	42.2	460.0	86.1	12.9
SFSCC-LD	86.5	41.0	450.0	90.0	12.2

The concrete compressive strength and elastic modulus in compression 4×8 in cylinders cured in the same conditions as the ring were also determined. The concrete was removed from the molds after 24 hours and was dried. Three samples were tested for each mix type. The tests were conducted at 1, 3, 7, 14, and 28 days after casting. The compressive strength and elastic modulus development are shown in Figures 5–10 and 5–11.

The compressive strengths of the SFSCC samples were similar to the compressive strengths of the conventional pavement concrete, except for SFSCC-LD. The samples no longer gained significant strength after 14 days. The compressive strength of SFSCC-LD at 14 to 28 days was between 4200 and 4400 psi, while the other samples were within 2500 and 3500 psi. For the case of concrete elastic modulus, C-3WR-C20 had higher elastic modulus compared to SFSCC. Among the SFSCC mixes, the mix with limestone dust had the highest elastic modulus.

Using the restrained ring test, the effectiveness of controlling the drying shrinkage by using a shrinkage reducing admixture (SRA) was studied. The SRA used was Tetraguard AS20. The geometry of the restrained ring and the drying conditions were as discussed above. The mix tested was NR-M1-A. The dosages of SRA were 2.5, 5.0, and 7.5 l/m^3 of concrete.

The strain in the rings with increasing dosage of SRA is shown in the Figure 5–12. At a low dosage of SRA, 2.5 l/m^3, the amount of shrinkage was significantly reduced but the mixture was still susceptible to cracking. Increasing the SRA to 7.5 l/m^3 decreased the amount of drying shrinkage and also reduced the susceptibility to cracking.

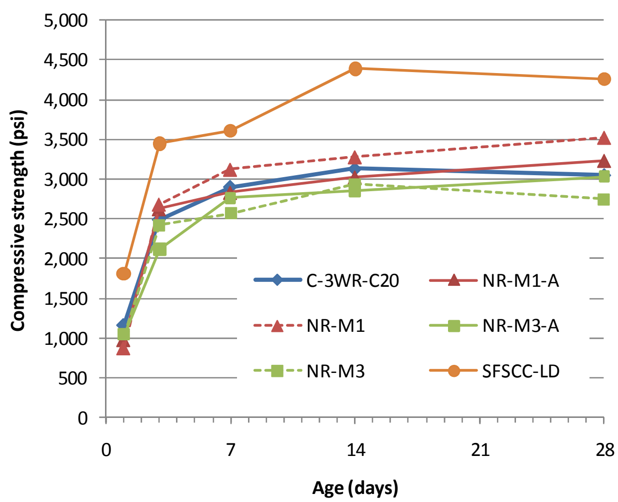


Figure 5–10. Compressive strength development of dried concrete cylinders

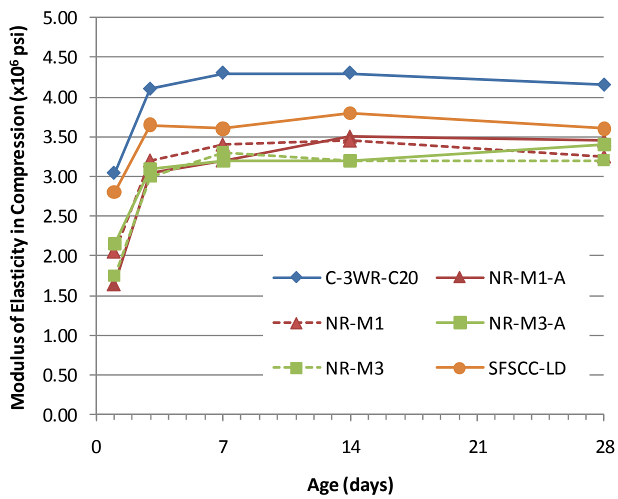


Figure 5–11. Elastic modulus development of concrete cylinders in compression

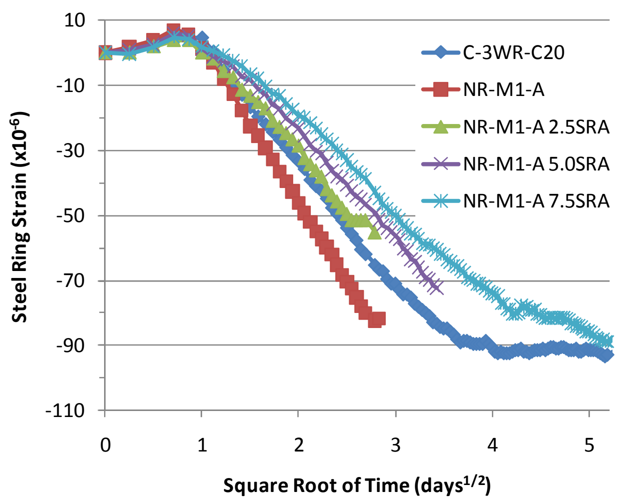


Figure 5–12. Steel strains due to concrete ring shrinkage with increasing SRA dosage

The shrinkage effects of different nano-clay admixtures were studied by testing for autogenous shrinkage, drying shrinkage, and restrained ring shrinkage. The nano-clays were Actigel (purified magnesium alumino silicate), Metamax (kaolinite clay) and Concresol (combination of kaolinite, illite, and quartz). The mix proportions of the mixtures tested are given in Table 5–5. SFC is conventional slip-form concrete, SCC is conventional self-consolidating concrete, and SCCF is SCC with 30% fly ash replacement. The nano-clays were increased by increments of 0.5% of total cementitious materials.

Table 5–5. Concrete mix proportion for testing the shrinkage effects of nano-clay

Mixture	SFC	SCC	SCCF	Actigel			Metamax			Concresol		
				1.0	1.5	2.0	1.0	1.5	2.0	1.0	1.5	2.0
Cement	353	517	362	362	362	362	362	362	362	362	362	362
Fly ash	0	0	155	155	155	155	155	155	155	155	155	155
Water	151	207	207	207	207	207	207	207	207	207	207	207
Clay	0	0	0	5.2	7.8	10.4	5.2	7.8	10.4	5.2	7.8	10.4
Gravel	897	904	904	904	904	904	904	904	904	904	904	904
Sand	886	794	794	794	794	794	794	794	794	794	794	794
Plasticizer	3.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0

Figure 5–13 shows the shrinkage development of concrete mixes without any nano-clay. The results show that the mortars exhibit swelling during the very early age. SCC and SCCF have about 37% higher autogenous shrinkage compared to SFC. The autogenous shrinkage of SCC and SCCF are similar.

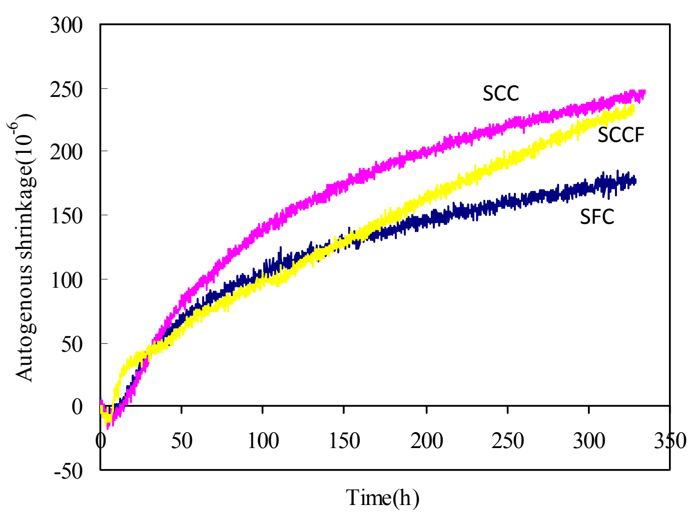


Figure 5–13. Autogenous shrinkage of SCC, SFC, and SCCF

Figure 5–14 shows the effects of different types of nano-clays on autogenous shrinkage of SCCF. It was observed that the initial swelling of mixes did not occur in mixes with nano-clay. Actigel and Metamax slightly increased shrinkage, while Concresol decreased autogenous shrinkage of SCCF.

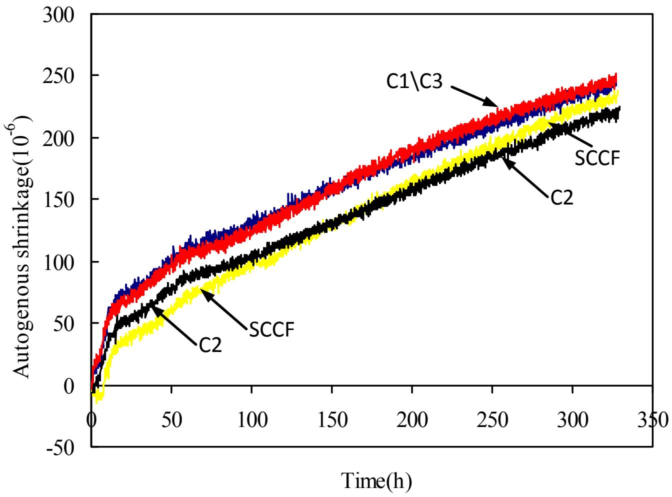


Figure 5–14. Autogenous shrinkage of SCCF with 2% addition of different nano-clay types (C1: Actigel; C2: Concresol; C3: Metamax)

The drying shrinkage of SFC was less than the shrinkage of SCC and SCCF, as shown in Figure 5–15. This was despite SFC having similar weight loss compared to SCC. The lower shrinkage was due to the smaller amount of cement used in the mixture. SCC and SCCF had similar drying shrinkage, although there was a much higher mass loss for SCCF, the mix with fly ash replacement.

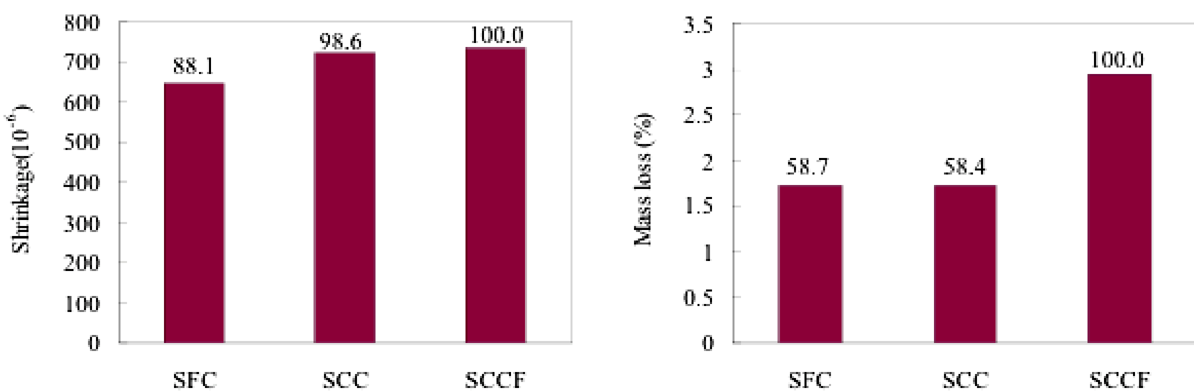


Figure 5–15. Drying shrinkage and mass loss of mixes without nano-clay

The use of 2% Actigel and Concresol increased drying shrinkage, while the addition of Metamax decreased shrinkage, as shown in Figure 5–16. Increasing the amount of Actigel in concrete increased drying shrinkage. For the case of Metamax, increasing amounts reduced drying shrinkage.

When the mixes were tested for restrained shrinkage, SFC had the highest rate of shrinkage, followed by SCCF and SCCF with Actigel, with the least rate from SCCF with Metamax (Figure 5–18). SFC had the earliest cracking time. SCCF had the longest time to cracking. Adding Actigel and Metamax in SCCF resulted in earlier cracking times.

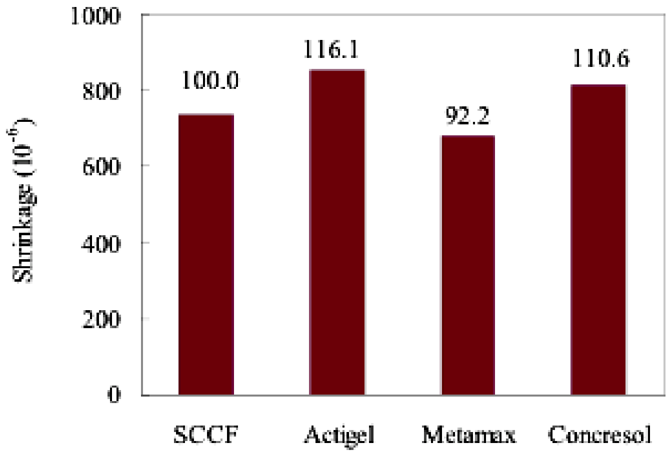
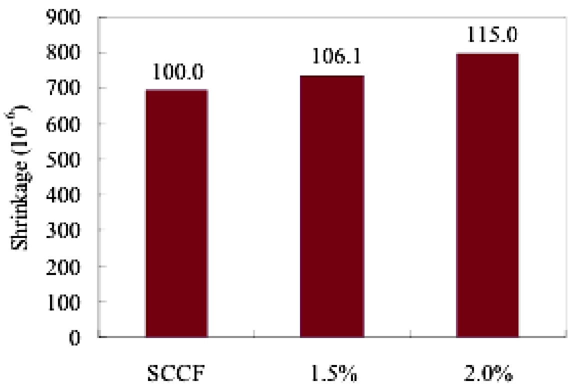
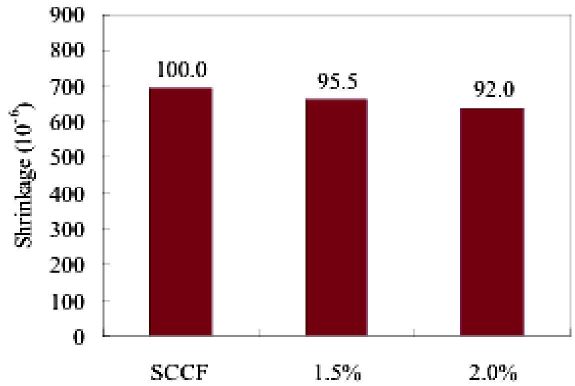


Figure 5–16. Drying shrinkage of SCCF with 2% of different nano-clay types



Actigel, 24 days



Metamax, 24 days

Figure 5–17. Drying shrinkage of SCCF with increasing Actigel and Metamax

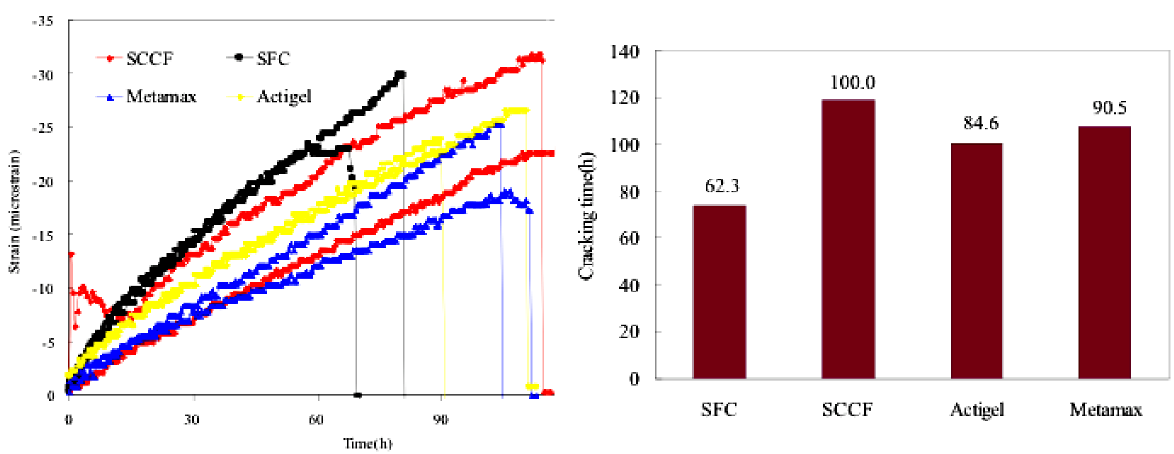


Figure 5–18. Restrained ring shrinkage strain and cracking times of SFC and SCCF with nano-clay

6. FIELD INVESTIGATION OF SFSCC

The previous sections focused on the development of a mix proportioning method and investigation of fresh and hardened concrete properties in the lab. The next step in the process is the application of the developed SFSCC mixes in the field. Field applications allow the evaluation of the early-age and long-term performance of the new SCC under different loading and environmental conditions. In this part, the feasibility of a paving method was first tested and is discussed in Section 6.1. Having concluded its feasibility, two other field tests were conducted. The first test was conducted on a bike path—a low traffic pavement, and the second test was conducted on a city road—a heavier traffic pavement.

6.1 Trial Paving at Ames City Yard

In August 2006, a field trial was conducted in Ames, IA, to determine the feasibility of casting pavements in the field. The trial tested the process of loading concrete to the paver, paver function, concrete performance, and field quality control.

Manatts Inc. provided all concrete materials and mixing facilities, while the city of Ames provided the paving site, manpower, and the paver. The location was at Ames City yard, as indicated in Figure 6–1. The paver used in the field trail was an 8 ft wide asphalt paver shown in Figure 6–2. The asphalt paver was modified by attaching 4 in. high by 4.5 ft long skids to both sides. The mixture proportions used in the field trial are given in Table 6–1.

Figure 6–1. Field trial location

Figure 6–2. Asphalt paver used for slip-form paving

Comparing the IA DOT C3 pavement concrete and the SFSCC, the differences included a decreased amount of coarse aggregate and additional fly ash, viscosity-modifying admixture (VMA), and super-plasticizer (SP).

Table 6–1. Mix proportions of SFSCC for 2006 field trail and C3 (pcy)

	Cement	Fly ash	Water	Sand	C. Agg.	VMA	SP
SFSCC-field 1	596	265	285	1341	1364	2.5	100
C3	595	-	295	1340	1686	-	-

During field trial, the concrete was dumped into the paver and extruded out while consolidating under its self-weight. Figure 6–3 shows the SFSCC pavement after paving. The surface was smooth and the edge was sharp and vertical. The field trial showed that a modified asphalt paver can be used to pave with SFSCC and that the SFSCC can self-consolidate within the modified paver and maintain its shape after extrusion.

After field paving, the following engineering properties of the mixture used were examined:

- Time of setting (ASTM C403)
- Heat of cement hydration
- Strength development(ASTM C39)
- Freeze-thaw resistance(ASTM C666)

(a) Pavement surface

(b) Pavement edge

Figure 6–3. SFSCC pavement of the first field trial

Figure 6–4 gives the time of setting results of both the SFSCC and C3 mixes. The result show that the initial set of SFSCC was 25 minutes later, while the final set was 30 minutes earlier. The later initial set of SFSCC may be due to the use of chemical admixtures, while the earlier final set may be due to the greater amount of cementitious materials. The heat of cement hydration of SFSCC was slightly lower than that of C3, as shown in Figure 6–5. The low value was likely due to the use of fly ash in the mix.

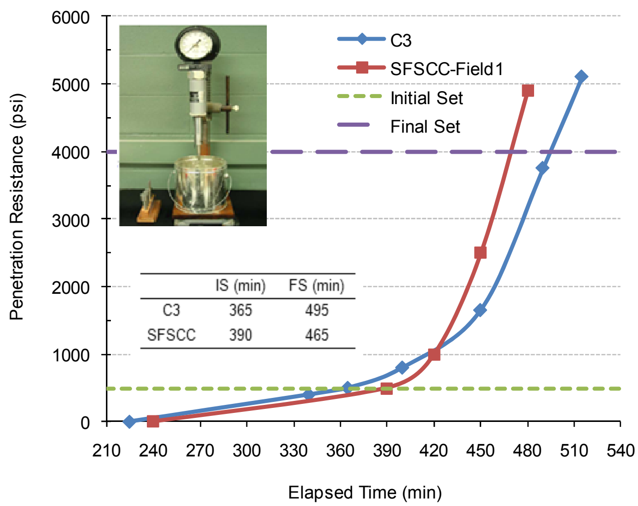


Figure 6–4. Time of setting results

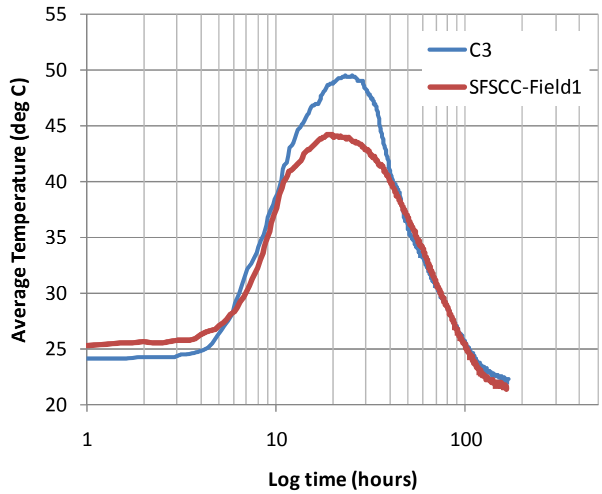


Figure 6–5. Hydration plots using a semi-adiabatic calorimetry test

SFSCC samples with different air contents (0%, 3%, and 6%) were tested for strength development, as shown in Figure 6–6. The compressive strength of SFSCC with 6% air content was comparable with the C3 mixture. It is also shown that the compressive strength of the SFSCC mixes increased with decreasing air content.

Freeze-thaw resistance results show that the SFSCC used in the first field trial had a similar durability freeze-thaw compared to the C3 concrete (Figure 6–7). In both mixtures, C3 and SFSCC, the relative dynamic modulus of elasticity remained the same until 200 cycles and dropped thereafter. C3 was slightly more durable than SFSCC at 300 freeze-thaw cycles. Both mixes had a durability factor greater than 80%.

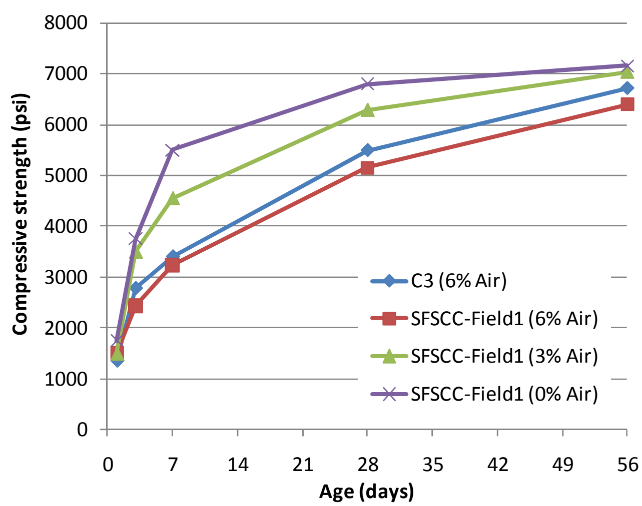


Figure 6–6. Strength development of SFSCC and C3

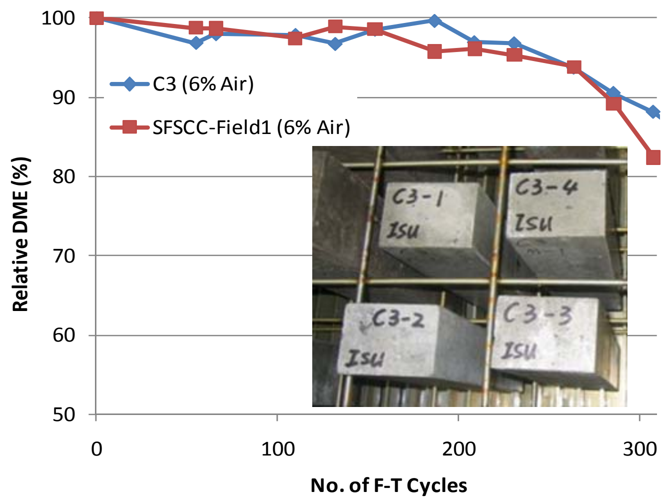


Figure 6–7. Freeze-thaw results of SFSCC for first field trial

6.2 Bike Path at South 4th Street, Ames, IA

6.2.1 General Description

The field application of SFSCC was performed in Ames, IA, on the morning of July 25, 2008. The PCC bike path was 8 feet wide and 5 in. thick. It was located at South 4th Street (S4TH), Ames, IA (Figure 6–8). Two SFSCC mixes (S4TH-M1 and S4TH-M2, 4 cubic yards each) were selected for the field trial. The paving started at Hazel Avenue and proceeded toward the east for a total length of about 60 feet. The new bike path was placed on an old asphalt pavement. The weather was overcast with an ambient temperature of 68ºF and calm wind.

Figure 6–8. Location map of the SFSCC bike path, South 4th Street (Google Maps 2008)

6.2.2 Mix Proportions

The mixture proportions of the two SFSCC mixes used for the test site are given in Tables 6–2 and 6–3. S4TH-M1 had a water-to-binder ratio (w/b) of 0.35 and it contained Navitas 33, a rheology controlling admixture. S4TH-M2 had a w/b of 0.39 and it contained Actigel 208, a self-dispersing thixotrope and anti-settling agent. UltraFiber 500 was also used in the both mixes. After concrete arrived at the field site, a small amount (200 ml) of HRWR (Glenium 7700) was added to S4TH-M1 to increase the concrete flowability.

Table 6–2. Concrete mix proportions for Ames field test, South 4th Street

	Cement	Fly ash	Water	Fine agg	Coarse agg	AEA	Others
	Ash grove	Lafarge type C			Limestone	Euclid AEA 92	
	(lb/yrd3)	(lb/yrd3)	(lb/yrd3)	(lb/yrd3)	(lb/yrd3)	(oz/yrd3)	(Table 6-3)
S4TH-M1	594.6	248.5	294.6	1306.7	1373.3	6.3	1 & 2
S4TH-M2	559.8	242.6	309.8	1226.2	1449.7	6.0	1 & 3

Note: Aggregates are in SSD condition

Table 6–3. Additives used for Ames field test, South 4th Street

Others			
1	UltraFiber 500	1.5	lb/yrd^3
2	Navitas 33	67.4	oz/yrd^3
3	Actigel 208	3.5	lb/yrd^3

6.2.3 Concrete Production

Two trucks of SFSCC mixtures were supplied by the Manatts Ready Mixed Concrete Plant. Each truck had four cubic yards of concrete with a given mix proportions (mixes S4TH-M1 or S4TH-M2). To produce a mixture, all concrete materials were batched at the ready mix plant and mixed in a ready mix truck. The fibers, Navitas and Actigel, were loaded in the mixer first, followed by the aggregates, AEA, water, and cementitious mateirals. After 5 minutes of batching and mixing, the concrete mixture was delivered to the test site. It took approximately 15 to 20 minutes to transport the concrete from the ready mix plant to the test site.

6.2.4 Paving Equipment

The paving equipment and manpower for the field test were provided by the Ames City Public Works. The paver, as shown in the Figure 6–9, was a modified asphalt paver. A 5 in. high skid was attached on each side of the paver to hold the concrete mixture during the slip-form paving. A dump truck was used to load the concrete mixture into the paver and to tow the paver forward.

Figure 6–9. Modified asphalt paver for slip-form paving

6.2.5 Field Operations and Tests

Unrodded slump tests were performed soon after concrete arrived at the site. The slump test for SFSCC was similar to ASTM C143, but without rodding the mixture. Air content of the concrete was measured according to ASTM C231.

About 10 minutes after the first concrete truck arrived, the slump of the concrete mixture (S4TH-M1) was measured. The first slump measurement was 5.5 in., and the concrete after the slump test showed a tilted cone shape (Figure 6–10). This slump value and the shape of the concrete mixture did not meet the criteria established for SFSCC. Therefore, 200 ml of HRWR was added into the mixture to increase the concrete flowability. After remixing the mixture for about 1 to 2 minutes, the concrete slump was measured again. The second measurement barely reached 6 in., the minimum slump requirement for SFSCC (Figure 6–11). Therefore, the paving was processed even though the shape of the mixture was still not desirable. The air content of the final concrete mixture was 8.5%.

Figure 6–10. Initial slump of S4TH-M1 (30 min after start of mixing)

Figure 6–11. Slump of S4TH-M1 after addition of HRWR (40 min after start of mixing)

During paving, the concrete mixture was first transferred to the dump truck and then loaded by the dump truck to the asphalt paver (Figure 6–12). As the dump truck towed the paver forward, the concrete slab was extruded out without any vibration/consolidation. The resulting slab made with S4TH-M1 without any finishing is shown in Figure 6–13. It was observed that the middle section of the pavement had concrete with good consolidation and smooth surface, while the concrete near to the sides, particularly at the ends of the pavement, seemed less consolidated and had some entrapped air voids shown on the surface. This was probably because (1) the concrete mixture was a little too dry, (2) the concrete mixture was not uniformly loaded to the paver, and (3) the amount of concrete mixture (4 cubic yards) was not enough to produce a constant pressure to consolidate the concrete at the end of the paving section. As a result, hand-finishing was applied to the pavement.

Figure 6–12. Concrete was first transported into a dump truck and then loaded into the paver

Figure 6–13. S4TH-M1 slab before finishing

About 15 minutes after the first section of the pavement was finished, the second concrete truck arrived at the test site. The slump test was performed immediately for this concrete mixture (S4TH-M2). The slump value was 7 in. (Figure 6–14). More importantly, the shape of the concrete mixture after the slump test was a symmetric cone, indicating that concrete had a good self-consolidating ability. Therefore, the mixture was used for paving without adjustment. The unfinished slab for S4TH-M2 is shown in Figure 6–15. This second section of the pavement was paved slowly and smoothly. The concrete (S4TH-M2) showed a much better consolidation and smoother surface than S4TH-M1; although, the edge of the pavement slightly slumped. Less effort was therefore required for the pavement finishing. The air content of S4TH-M2 was 8.75%.

Figure 6–14. Slump of S4TH-M2

Figure 6–15. S4TH-M2 slab before finishing

The test pavement was finished using a float and trowels (Figure 6–16). It was then grooved for joints every 9 feet and broomed for surface texture (Figures 6–17 and 6–18). Curing was done by placing wet burlap on the pavement and covering it with a plastic sheet, as shown in Figure 6–19. Figure 6–34 shows the pavement after curing.

Figure 6–16. Finishing of pavement, South 4th Street

Figure 6–17. Cutting of joint, South 4th Street

Figure 6–18. Brooming for surface texture, South 4th Street

Figure 6–19. Curing of concrete, South 4th Street

An I-Button was embedded in a cylinder of each concrete mix to monitor the change in temperature of the concrete as it matured. The concrete cylinders were placed at the eastern end of the bike path. S4TH-M1 and S4TH-M2 were subjected to the same conditions. While the samples with the temperature probes where in plastic cylinders and the bike path was covered with moist burlap and plastic sheet, both were subjected to the same environmental temperature. The temperature readings of the two mixtures for the first 48 hours are plotted in Figure 6–20. Also included is the average ambient air temperature. The time-temperature factors for both mixtures are given in Table 6–4. The time-temperature factor was solved using

$$M = \Sigma(Ta\text{-}To)\Delta t, \qquad (4)$$

where M is the time-temperature factor, Ta is the average temperature during the time increment Δt, and To is the base temperature equal to –10ºC. The time-temperature factors for the two mixtures were similar for the 12, 24, and 48 hours of hydration. However, the recorded peak temperature of S4TH-M2 was slightly higher at 8 hours.

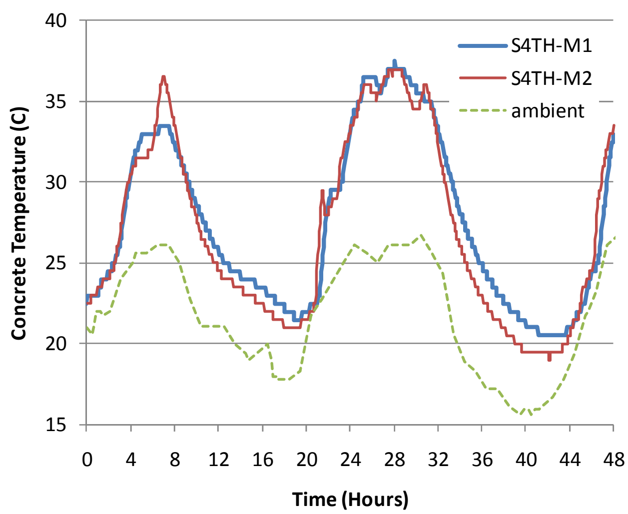


Figure 6–20. Concrete temperature during the first 48 hours

Table 6–4. Time temperature factors

Time (Hrs)	Time-temperature factor (ºC-hr)	
	S4TH-M1	S4TH-M2
12	468	467
24	883	878
48	1798	1775

6.3 City Road at North Riverside Drive

6.3.1 General Description

The second field application of SFSCC for a pavement was made at mid-day of September 11, 2008. The pavement was located at North Riverside Drive (NR), Ames, IA (Figure 6–21). The section of the road paved with SFSCC was previously an old deteriorated asphalt pavement (Figure 6–22). The asphalt layer was removed and replaced with concrete (Figure 6–23). The test SFSCC pavement was 165 ft long, 13 ft wide, and 5 in. thick, and it was on the eastern side of the road. The concrete slab on the western side had the same dimensions as the SFSCC slab but was a conventional mixture and only a day older than the SFSCC.

Figure 6–21. Location map of the test pavement, North Riverside Drive (Google Maps 2008)

The concrete was supplied by the Manatts Ready Mixed Concrete Plant, and the paving operation was handled by the Ames City Public Works. A single concrete mixture was initially planned to be used, but on-site modification had resulted in three different mixtures. The ambient temperature was 73ºF. The weather was overcast during the paving, but it started to rain before the end of the paving and rained very heavily about one hour after paving.

Figure 6–22. Asphalt pavement that was replaced

Figure 6–23. Slab made from conventional concrete mixture (right) and SCC base (left)

6.3.2 Mix Proportions

Based on the experience of using SFSCC for the bike path on South 4th Street, it was decided that the concrete mixture given in Tables 6–2 and 6–3 would be used for the present application. The chosen mixture performed well for the bike path in terms of consolidation and flowability, which would be suitable for the current demonstration. Unlike the bike path, the width of the present pavement prohibited the use of the previous modified paver. The benefit of using the paver was that it set up a head in the hopper, thereby facilitating consolidation of the mixture.

The mixture in Table 6–5 had a w/b of 0.39 and contained Actigel 208, a self-dispersing thixotrope and anti-settling agent, and UltraFiber 500 (Table 6–6). During the construction of the pavement, on-site testing was conducted resulting in modifications of the delivered concrete. The modifications resulted in three mixtures shown in Table 6–7. From the base mixture in Table 6–2, NR-M1-A resulted from adding 10 gallons of water and 500 ml of HRWR (Glenium 7700), NR-M2-A resulted from adding 20 gallons of water and 1,000 ml of HRWR, and NR-M3-A resulted from adding 15 gallons of water and 1,500 ml of HRWR.

Table 6–5. Concrete mix proportions for Ames field test, North Riverside Drive

Cement Ash grove (lb/yrd3)	Fly ash Lafarge type C (lb/yrd3)	Water (lb/yrd3)	Fine agg (lb/yrd3)	Coarse agg Limestone (lb/yrd3)	AEA Euclid AEA 92 (oz/yrd3)	Others	w/b
559.8	242.6	309.8	1226.2	1449.7	6.0	1 &3 in Table 6–3	0.39

Note: Aggregates are in SSD condition

Table 6–6. Additives used for Ames field test, North Riverside Drive

Others			
1	UltraFiber 500	1.5	lb/yrd^3
2	Actigel 208	3.5	lb/yrd^3

Table 6–7. Final concrete mix proportions after on-site modifications, North Riverside Drive

	Cement Ash grove (lb/yrd^3)	Fly ash Lafarge type C (lb/yrd^3)	Water (lb/yrd^3)	Fine agg (lb/yrd^3)	Coarse agg Limestone (lb/yrd^3)	AEA Euclid AEA 92 (oz/yrd^3)	Others	w/b
NR-M1-A	559.8	242.6	318.1	1226.2	1449.7	6.0	1 &3 in Table 6–3	0.40
NR-M2-A	559.8	242.6	325.0	1226.2	1449.7	6.0	1 &3 in Table 6–3	0.41
NR-M3-A	559.8	242.6	321.2	1226.2	1449.7	6.0	1 &3 in Table 6–3	0.40

Note: Aggregates are in SSD condition

The concrete mixture used for the western side of the road is given in Table 6–8. The mixture had a w/b of 0.43. Compared to the SFSCC mixture, the mixture had less cementitious material, more aggregates, and higher w/b.

Table 6–8. Concrete mix proportions for western slab, North Riverside Drive (conventional mixture/not SCC)

	Cement	Fly ash	Water	Fine agg	Coarse agg	AEA	WR	w/b
	Ash grove	Lafarge type C			Limestone	Euclid AEA 92	Brett WR 91	
	(lb/yrd^3)	(lb/yrd^3)	(lb/yrd^3)	(lb/yrd^3)	(lb/yrd^3)	(oz/yrd^3)	(oz/yrd^3)	
C-3WR-C20	457	114	246	1375	1698	2.86	13.71	0.43

Note: Aggregates are in SSD condition

6.3.3 Concrete Production

Concrete materials were batched at the ready mix plant and mixed in a ready mix truck. Thirty two cubic yards of concrete were prepared in batches of 10 and 11 cubic yards per truck. For each batch, fiber was first loaded together with Actigel into the truck before all other materials. After 5 minutes of batching and mixing, the concrete mixture was delivered to the test site. Each batch was prepared and delivered one after the other without gaps. It took approximately 15 to 20 minutes to transport the concrete from the Manatts Ready Mix Plant to the test site.

6.3.4 Paving Equipment

The paving equipment and manpower for the field test was provided by the Ames City Public Works. A slip-form paver that was 13 feet wide was not available for the present operation. The concrete was placed with the mixer truck chute and spreader and was leveled using a roller screed shown in Figure 6–24. No vibrators were used throughout the concrete placement.

Figure 6–24. Roller screed for leveling of poured concrete

6.3.5 Field Operations and Tests

Prior to placing the delivered concrete, an unrodded slump test was performed to determine the concrete's ability to consolidate without vibration. The unrodded slump test is similar to ASTM C143, but the slump cone is filled without rodding the concrete. Air content of the concrete was also measured according to ASTM C231.

The unrodded slump test showed that the concrete in the first truck was too stiff to consolidate without rodding. The concrete was extremely tilted when the slump cone was lifted. Because of this, modifications had to be made to the mixture before the concrete could be placed without vibration. To improve the flowability of the concrete, 500 ml of HRWR and 10 gallons of water were added, making NR-M1-A. The mixture was retested for slump. The slump was 6 in. but was still tilted. The air content of the concrete mixture was 6.6%.

During the placement of concrete from the first truck, the second and third trucks had already arrived. This posed the problem of the concrete getting stiffer the longer it had to wait.

Once the first truck had emptied its contents and driven out, the second truck backed into the road. The concrete from the truck was initially inspected and was seen to be clearly too stiff to self-consolidate. Thus, 1,000 ml of HRWR and 20 gallons of water were added into the mixer, making NR-M2-A. After thorough mixing, the slump was measured as 6 in. and had a good shape (Figure 6–27) and was ready for placement. The air content of NR-M2-A was 7.5%.

The third batch also required modification, so 1,500 ml of HRWR and 15 gallons of water were added, which produced NR-M3-A. The slump before placement was 6¼ in. The air content was 9%.

Figure 6–25. Initial slump of NR-M1-A

Figure 6–26. Slump of NR-M1-A after addition of HRWR and water

Figure 6–27. Slump of NR-M2-A

Figure 6–28. Slump of NR-M3-A

The pavement was finished using floats and trowels (Figure 6–29). It was then broomed for surface texture (Figure 6–30), after which a coat of curing compound was applied (Figure 6–31). The placement of concrete finished after 2 hours. Due to the heavy rain in the late afternoon, the fresh pavement was covered with plastic. Appendix B shows the sequence of all field operations performed in the field SFSCC trial.

Figure 6–29. Finishing of pavement, North Riverside Drive

Figure 6–30. Brooming for surface texture, North Riverside Drive

Figure 6–31. Application of curing compound, North Riverside Drive

6.4 Field SFSCC Performance Monitoring

6.4.1 South 4th Street SFSCC Field Sample Collection

Twelve 4 by 8 in. cylinders were cast for each concrete mix at the field site—3 were rodded and 9 were unrodded. The cylinders were cured at the field site until testing.

Six cores were taken from the bike path pavement. From the western end, three cores were taken from the second panel for the first mixture and three cores from the fourth panel for the second mixture (Figures 6–32 and 6–33). Seven–day splitting strengths (ASTM C496) and rapid chloride permeability (ASTM C 1202) of the core samples were tested. The visual inspection of the pavement will be performed throughout a year, and visible concrete deterioration will be recorded.

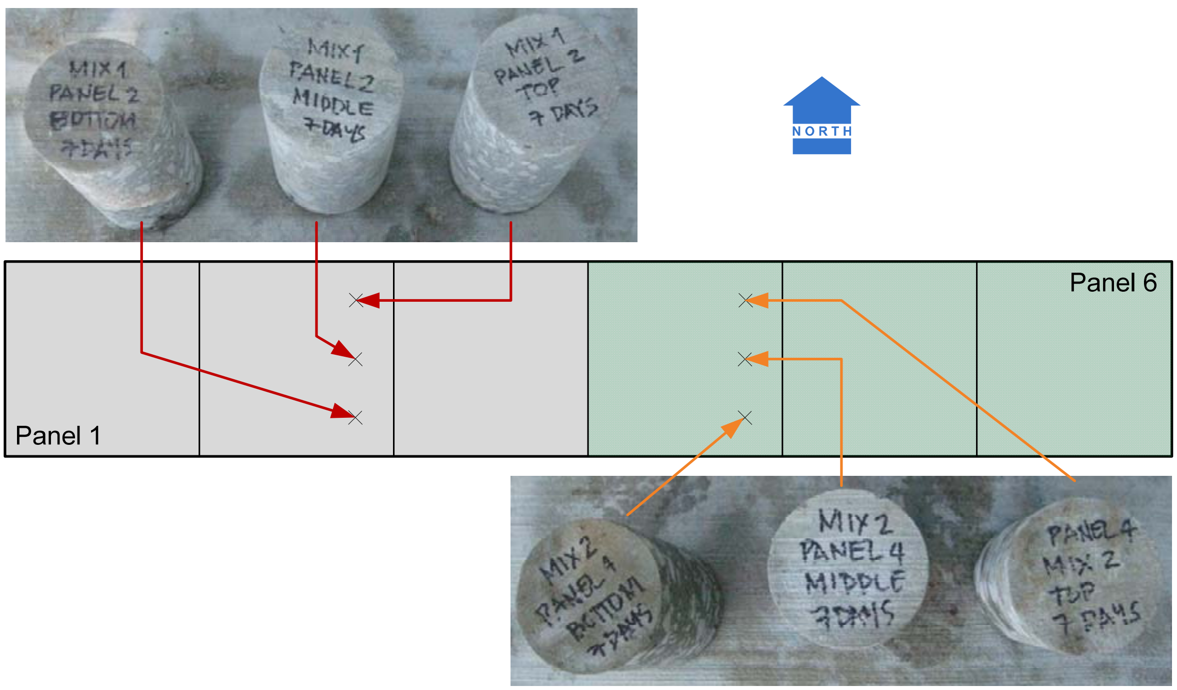


Figure 6–32. Locations of core samples on the pavement, South 4th Street

S4TH-M1 – Top | S4TH-M1 – Middle | S4TH-M1 – Bottom

S4TH-M2 – Top | S4TH-M2 – Middle | S4TH-M2 - Bottom

Figure 6–33. Core Samples from the SFSCC Bike Path, South 4th Street

6.4.2 South 4th Street SFSCC Hardened Concrete Properties

After seven days of curing, the burlap and plastic cover were removed, as shown in Figure 6–34. The pavement was inspected, and it was observed that no joints or other parts had cracked. However, burlap markings were visible. Three core samples from each mixture were taken. The cores and cylinders were then taken to the laboratory to test for hardened properties. The diameter of the cores was 3.9 in., and the heights (pavement thickness) are given in Table 6–9. The pavement was much thicker than the target 5 in. The thickness ranged from 5.8 to 6.2 in.

Figure 6–34. SFSCC bike path after 7 days of curing, South 4th Street

Table 6–9. Height of cores or pavement thickness, South 4th Street

		Height/pavement thickness (inch)
S4TH -M1	Top	6.2
	Middle	5.8
	Bottom	6.0
S4TH -M2	Top	6.0
	Middle	6.1
	Bottom	5.9

The 7-day compressive strengths of the rodded and unrodded concrete cylinders are given in Figure 6–35. The results were the averages of two samples. The strength of S4TH-M1 was higher compared to S4TH-M2 by 760 to 960 psi for the unrodded and the rodded samples, respectively, which was due to the lower w/b. It is interesting to note here that the rodded samples for both mixtures had lower strengths compared to their unrodded counterparts.

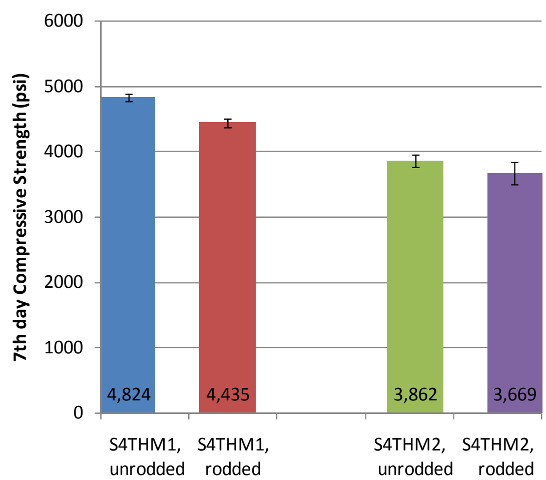


Figure 6–35. Seventh day compressive strength of rodded and unrodded samples, South 4th Street

Because of the aspect ratio of the core samples, their strengths were determined using the splitting tensile strength test following ASTM C496. Two tests were conducted for each type of sample, S4TH-M1 and S4TH-M2, cylinder and core. The results are shown in 6–36. The spitting strengths of the samples for this test were similar.

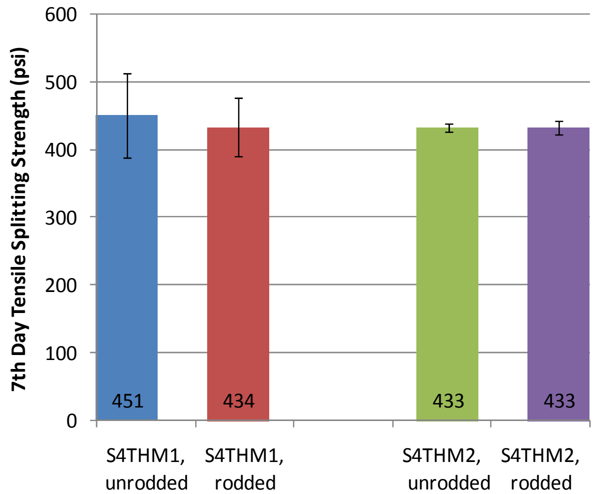


Figure 6-36. Seventh day tensile splitting strength of rodded and unrodded samples, South 4th Street

Other data determined from the 7-day samples were unit weight, compaction factor, and chloride ion permeability, given in Table 6–10. The compaction factor is the ratio of the unit weight of concrete placed in a mold by dropping it from a height of 12 in. to the unit weight of concrete test specimens made following ASTM C31.

The unit weights and the compaction factors are averages of three cores and cylinders, respectively. S4TH-M1 has a slightly higher unit weight but similar compaction factor compared to S4TH-M2. The chloride ion permeability is the average of two tests. A large difference is seen in permeability of the two mixtures. S4TH-M1 had moderate permeability, while S4TH-M2 had high permeability.

Table 6–10. Chloride ion permeability, unit weight, and compaction factor of S4TH-M1 and S4TH-M2 at 7 Days

	Unit weight (pcf)	Compaction factor (%)	Chloride ion permeability (Coulombs)
Sample / Mixture	Core	Cylinder	Core
S4TH-M1	138.6	99.2	3323
S4TH-M2	137.0	99.3	6911

The compressive strength, porosity, and chloride ion permeability of the two mixtures were determined at their 28th day (Table 6–11). The results obtained were similar to the typical values obtained in the lab tests conducted. The S4TH-M1 had a slightly better hardened properties compared to S4TH-M2 (as expected) because of its lower w/b.

Table 6–11. Strength, porosity, and chloride ion permeability of S4TH-M1 and S4TH-M2 at 28 Days

Mixture	Compressive strength (psi)	Porosity (%)	Chloride ion permeability (Coulombs)
S4TH-M1	6298	14.8	2332
S4TH-M2	5072	16.6	6322

Unrodded cylinder samples had also been cured in the same conditions as the actual pavement and were tested for their compressive strength on their 56th day. The development of compressive strength for the two mixtures is shown in Figure 6–37. While S4TH-M1 had strength similar to the average strength obtained in the laboratory, S4TH-M2 had a much lower strength compared to the average.

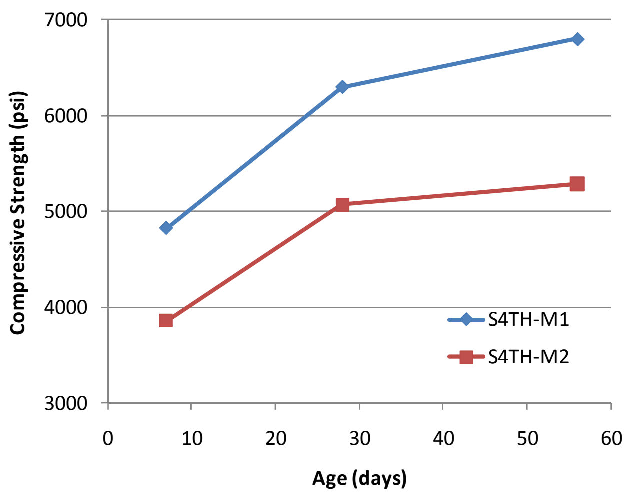


Figure 6–37. Compressive strength development of unrodded samples, South 4th Street

6.4.3 South 4th Street SFSCCField Performance Timeline

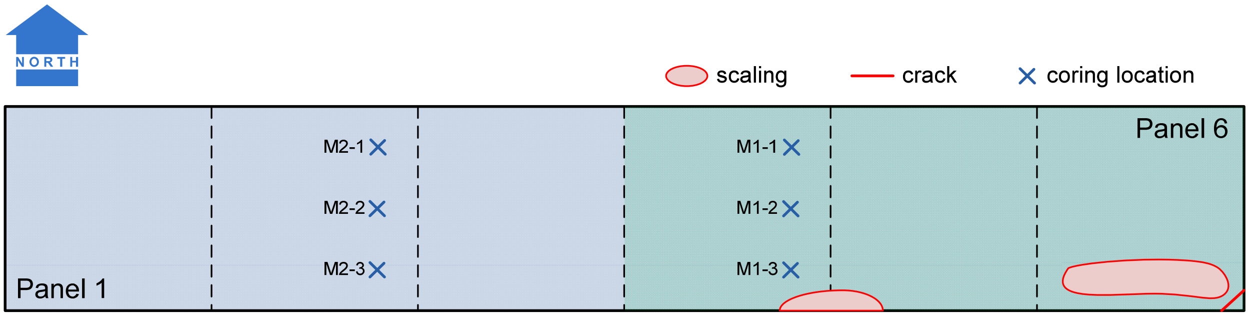
July 25, 2008—Construction of Bike Path; two mix proportions were cast.

August 1, 2008—Curing by wet burlap and plastic cover was ended. Core samples were taken from each mix type. The concrete was tested for compression, tensile splitting, RCP, and porosity.

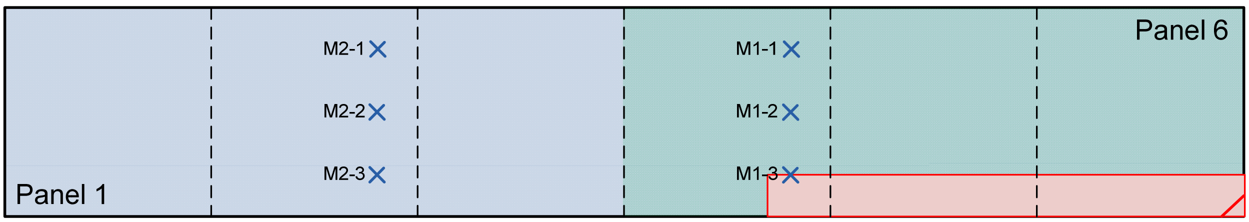
March 2009—Small areas of scaling as well as a small corner crack were found in the panels where S4TH-M2 was cast (Figures 6–38a and 6–39).

October 2009—The area of scaling was extended to the southern side of the S4TH-M2 (Figure 6–38b). There were no additional cracks.

April 2011—No additional pavement distress (neither increased scaling nor cracks) was observed (Figure 6–40).



(a) March 2009: light scaling and small corner crack observed



(b) October 2009: scaling area enlarged but degree of scaling kept the same

Figure 6–38. Observations of field SFSCC at South 4th Street

Figure 6–39. Scaling of SFSCC at South 4th Street in March 2009

Figure 6–40. Condition of SFSCC pavement at South 4th Street on April 2011

6.4.4 North Riverside SFSCC Field Sample Collection

Twenty 4 by 8 in. concrete cylinders were prepared—2 rodded and 2 unrodded for NR-M1-A and NR-M2-A and 3 rodded and 9 unrodded for NR-M3-A. The cylinders are being cured outdoors at ISU until testing to have similar conditions as the pavement. Twelve cores were taken from the hardened concrete (Figure 6–41), 3 for each mixture, including cores from the conventional mixture pavement. The core locations are shown in Figure 6–42. The core samples collected and their heights are shown in Figure 6–43 and Table 6–12. It should be noted that the heights of the cores (pavement thickness) for the SCC slab were sufficient in the middle of the road, but were less than 5 in. long on other parts.

From the cylinders of NR-M1-A and NR-M2-A, the compaction factors and 7-day compressive strengths were determined. From the cylinders of NR-M3-A, the compaction factors; 7-, 28- and 56-day compressive strength (ASTM C39); 7-day tensile splitting strength (ASTM C496); 28-day rapid chloride ion permeability (ASTM C 1202); and 28-day porosity were determined (ASTM C642). The cores were used for determining the unit weight, 7-day tensile splitting strength, and rapid chloride permeability of the mixtures.

Figure 6–41. SFSCC slab after 3 days of curing, North Riverside Drive

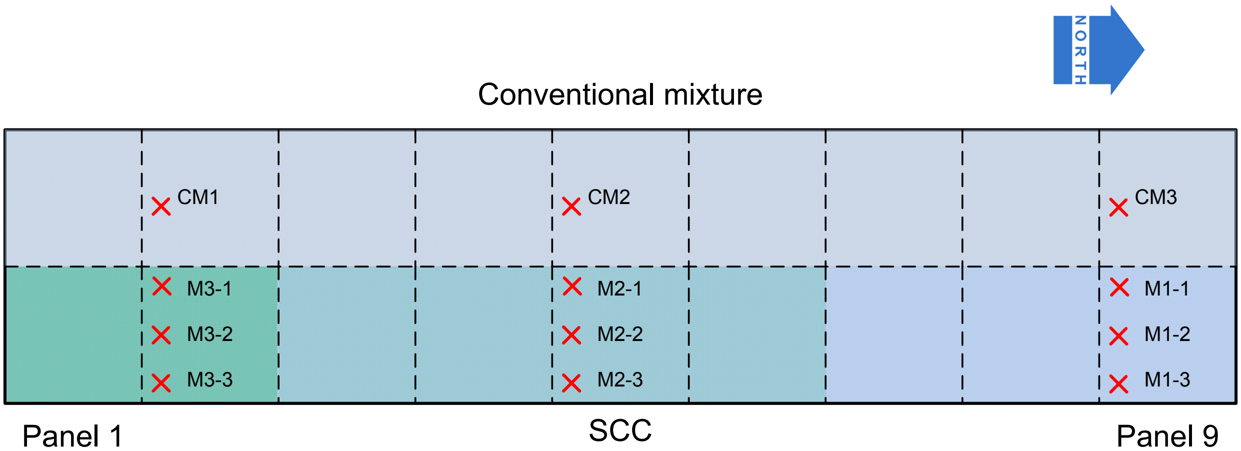


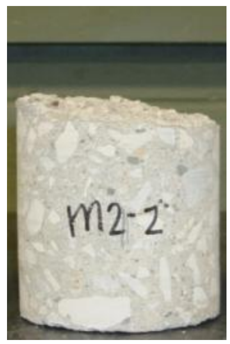
Figure 6–42. Locations of core samples on the pavement, North Riverside Drive

M1-1

M1-2

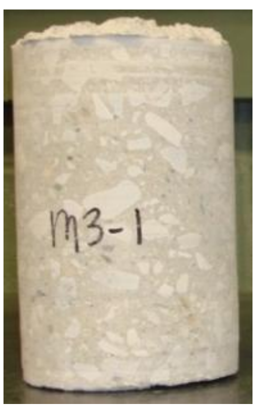
M1-3

M2-1



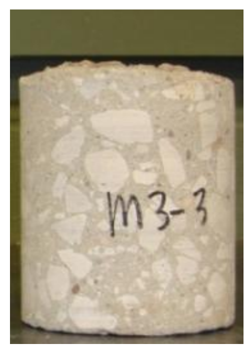
M2-2

M2-3



M3-1

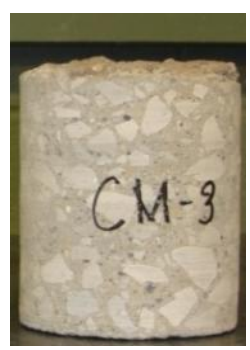
M3-2



M3-3

CM1

CM2



CM3

Figure 6–43. Core samples, North Riverside Drive

Table 6–12. Height of cores or pavement thickness, North Riverside Drive

	Height/pavement thickness (inch)		
	1	**2**	**3**
M1	5.00	3.50	3.75
M2	5.00	4.00	4.50
M3	5.75	4.75	4.25
CM	5.00	4.75	4.25

6.4.5 North Riverside Drive SFSCC Hardened Concrete Properties

The 7-day compressive strength of the concrete is given in Figure 6–44. The results are the average of two cylinder samples. The 7-day compressive strengths of the three mixtures are significantly different from one another. The compressive strength is in the 5000 to 6000 psi range for NR-M1-A, 4000 to 5000 psi range for NR-M2-A, and 3000 to 4000 for NR-M3-A. The decrease in strength is likely due to the addition of water. It is interesting to note that, similar to the bike path field test, the compressive strength of the unrodded samples is slightly higher than the compressive strength of the rodded samples.

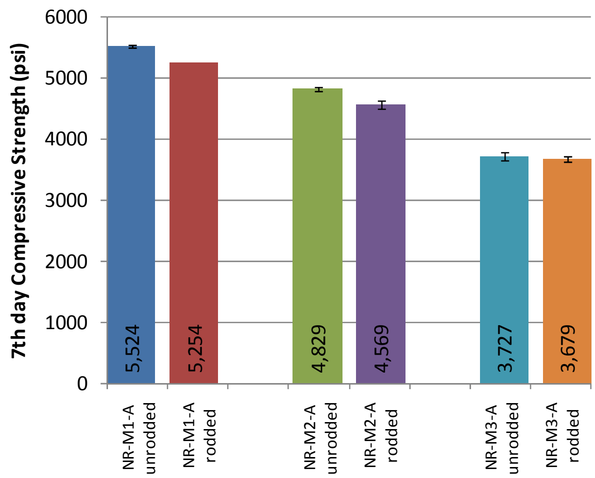


Figure 6-44. Seventh day compressive strength of rodded and unrodded samples, North Riverside Drive

Because of the aspect ratio of the core samples, their strengths were determined using the splitting tensile strength test following ASTM C496. Two tests were conducted for each type of sample. The results are shown in Figure 6–45. The tensile splitting strengths of the SFSCC samples were comparable to the conventional mix sample, with the strength of NR-M1-A as the highest.

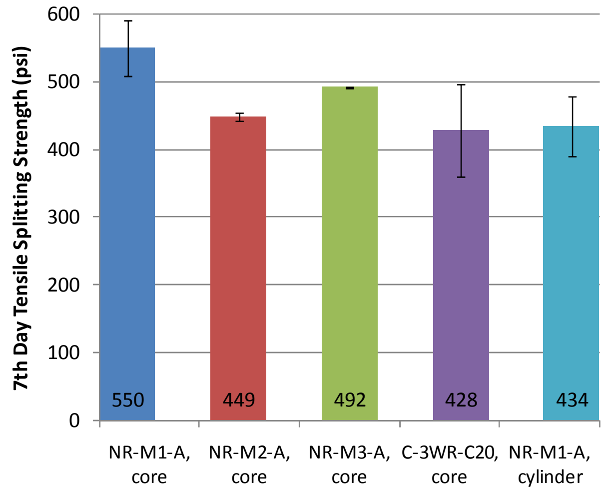


Figure 6–45. Seventh day tensile splitting strength of rodded and unrodded samples, North Riverside Drive

Other data determined from the 7-day samples were unit weight, compaction factor, and chloride ion permeability, given in Table 6–13. The compaction factor is the ratio of the unit weight of concrete placed in a mold by dropping it from a height of 12 in. to the unit weight of concrete test specimens made following ASTM C31.

The unit weights and the compaction factors are averages of two cores and cylinders, respectively. The unit weights of the SFSCC samples were slightly lower compared to the conventional mix sample. The compaction factors of the SFSCC samples were all greater than 98%. The chloride ion permeabilities of the SFSCC samples were much higher compared to the conventional mix sample. For NR-M3-A, chloride ion permeability was too high for the testing equipment to record.

Table 6–13. Chloride ion permeability, unit weight, and compaction factor, North Riverside Drive

	Unit weight (pcf)	Compaction factor (%)	Chloride ion permeability (Coulombs, 7th day)
Mixture \ Sample	Core	Cylinder	Core
NR-M1-A	141.6	100.0	5924
NR-M2-A	141.8	99.9	5658
NR-M3-A	133.9	98.0	High
C-3WR-C20	144.6	N.A	3990

During sample collection, only NR-M3-A had enough samples that could be cured and allowed to mature up to 56 days. The compressive strength, chloride ion permeability, and porosity are given in Table 6–14. The results of the development of strength are shown in Figure 6–46. The results show that the concrete had significantly increased in strength by 56 days. Though the strength was slightly lower than that achieved in the laboratory, it still had attained anadequate strength for its service.

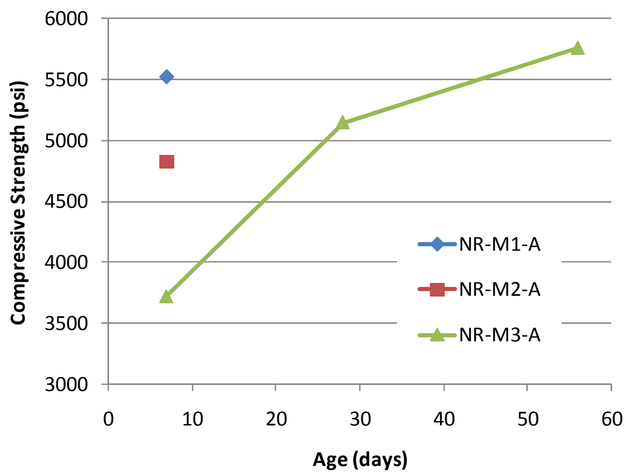


Figure 6–46. Compressive strength development of unrodded samples, North Riverside Drive

Table 6–14. Strength, porosity, and chloride ion permeability of NR-M3-A at 28 days

Mixture	Compressive strength (psi)	Porosity (%)	Chloride ion permeability (Coulombs)
NR-M3-A	5148	16.0	3250

6.4.6 North Riverside SFSCC Field Performance Timeline

September 11, 2008—Construction of City Road; three mix proportions were cast.

September 24, 2008—Core samples were taken from each mix type. The concrete was tested for compression, tensile splitting, RCP, and porosity.

October 2008—A transverse crack was found at panel 1 of the SFSCC pavement (Figures 6–47a and 6–48). The distress was most likely caused by early loading and a base weakened by water seepage.

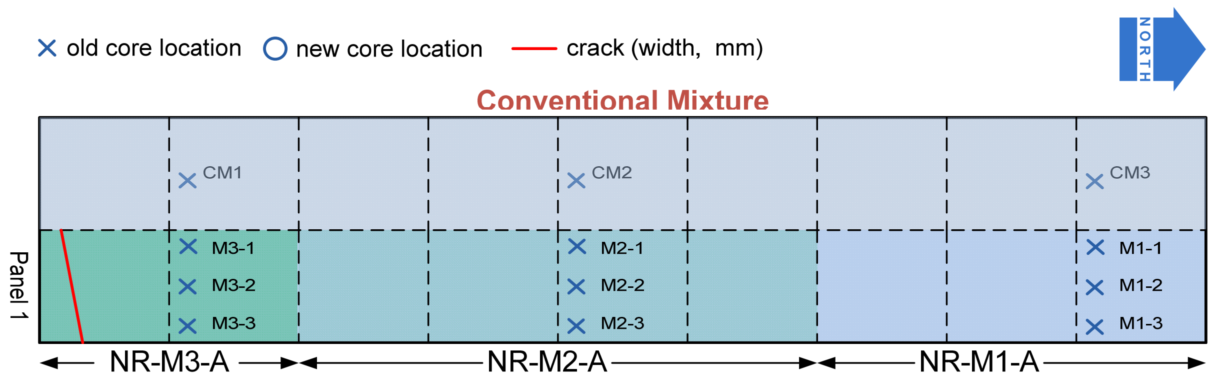
March 2009—Additional cracks were found at panels 2 to 4 (Figures 6–47b and 6–49). To prevent the propagation of the cracks, cores were taken at the ends of cracks. Five cores were drilled. Cores a, d, and e had completely cracked through the thickness. Cores b and c had cracks that started from the top. It was suspected that the cracking was caused by shrinkage. This initiated the shrinkage study discussed in Section 5.4.

April 2010—Additional cracks were developed at panels 5 and 6 (Figures 6–47c and 6–50). A core was taken at the end of the crack at panel 6. Coring showed that the crack started from the bottom. This indicated that the crack was due to pavement loading. Though the crack was in the middle of the road, the wheel paths left on the snow were consistent with the location of the cracks. It can also be noted that the thickness of the pavement was only 4 in.—1 in. thinner than designed.

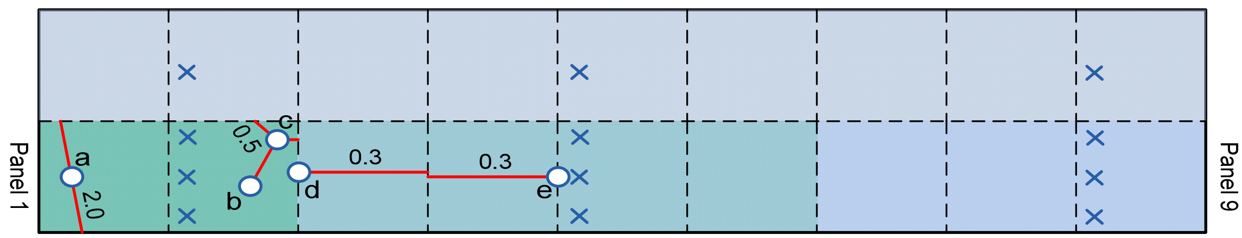
October 2010—Corner cracks were formed on panels 1and 2 (Figure 6–47d). The conventional pavement concrete had also cracked at the corner of its southernmost panel. The corner cracks were likely due to loading.

November 2010—The full eastern side of panel 1 had cracked, and another corner crack in panel 2 had developed (Figure 6–47e). These were seen as loading related.

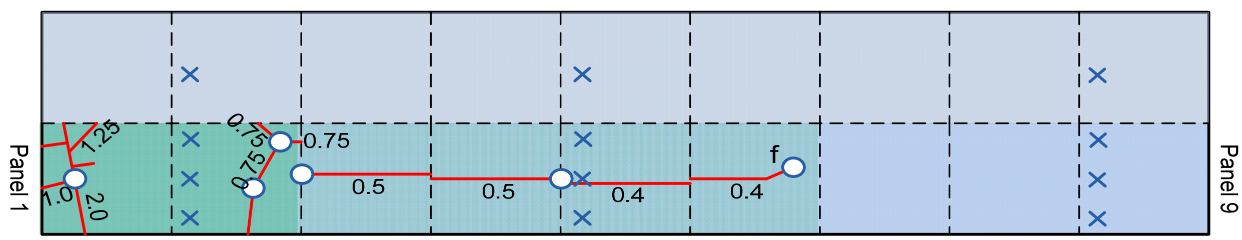
April 2011—No additional pavement distress (Figure 6–51).



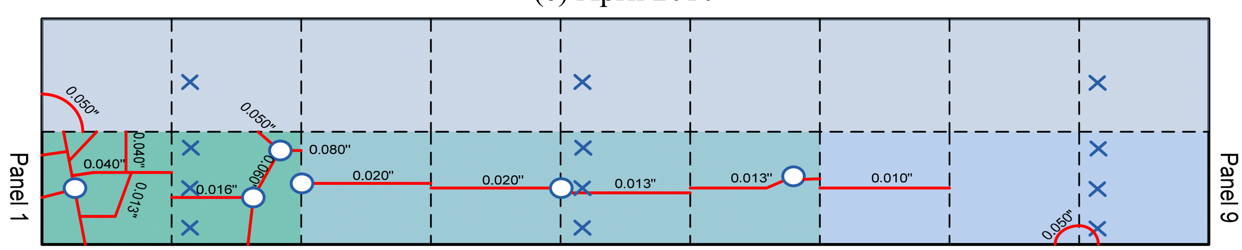
(a) October 2008



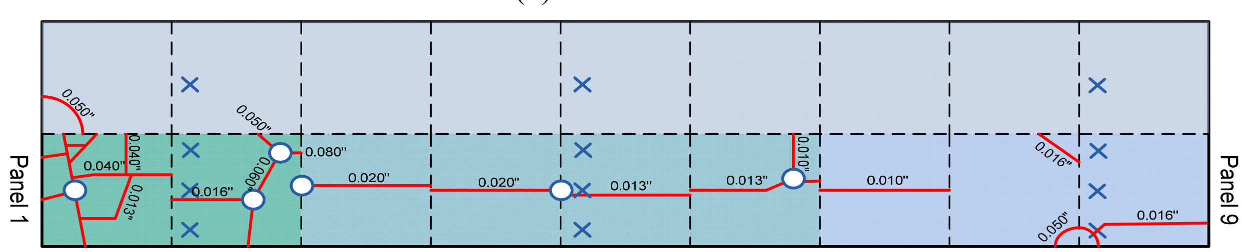
(b) March 2009



(c) April 2010



(d) October 2010



(e) November 2010

Figure 6–47. North Riverside Drive SFSCC pavement crack evolution

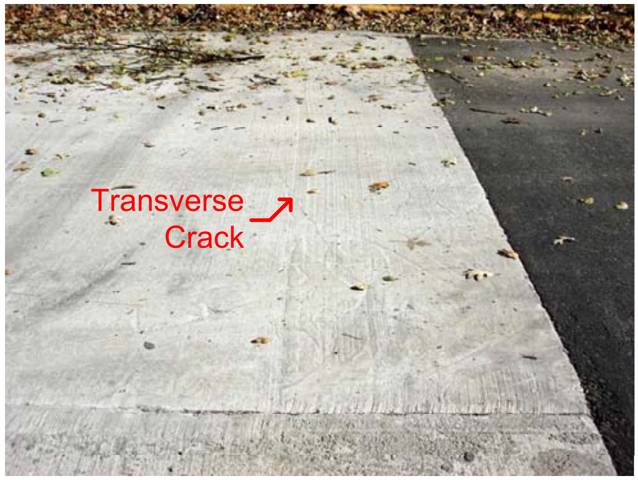


Figure 6–48. Transverse crack at North Riverside Drive SFSCC pavement located at NR-M3-A mix as of October 2008

Core a

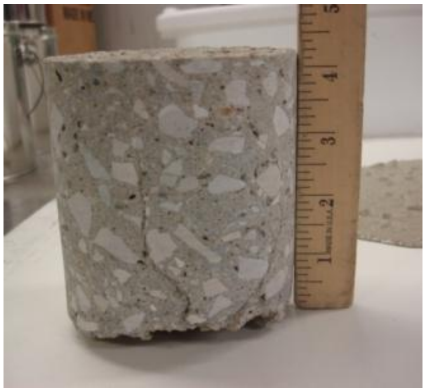
Core b

Core c

Core d

Core e

Figure 6–49. North Riverside Drive pavement cracks and core samples taken at cracks as of March 2009



Core

Tracks on snow show vehicle path/loading
(taken on February 2010)

Figure 6-50. North Riverside Drive pavement cracks and core sample as of April 2010

Figure 6–51. SFSCC pavement at North Riverside Drive as of April 2011

6.5 Comparison between South 4th Street Bike Path and North Riverside Drive

The two SFSCC pavements, South 4th Street bike path (S4TH) and North Riverside Drive (NR), had similar mix proportions but had very different performance. S4TH had one mix with a water-to-binder ratio of 0.35 (S4TH-M1) and the other with a w/b of 0.39 (S4TH-M2). On the North Riverside Drive, the first mix (NR-M1-A) was similar to S4TH-M2, while NR-M2-A and NR-M3-A were different from NR-M1-A due to addition of extra water and HRWR. Consequently, the compressive strength of S4TH-M1 was highest among the mixtures (24% higher than S4TH-M2), while S4TH-M2 and NR-M3-A were similar.

The dimensions of the two pavements were very different. The width and length of S4TH pavement was smaller than of NR, while S4TH pavement was thicker than NR. There was also more variation in thickness in NR pavement compared to S4TH pavement. These differences in geometry had a significant effect on the shrinkage behavior of the pavements. Shrinkage due to concrete drying was greater when the drying surface-to-volume ratio was higher. For a pavement of constant width, this ratio was equal to the pavement width-to-thickness ratio (b_w/h). The as-built b_w/h of NR pavement was much greater than the b_w/h of S4TH, which could lead to higher shrinkage. The as-built dimensions of the pavements are given in Table 6–15. The larger width and greater variations in thickness of NR pavement compared to S4TH pavement also contributed to larger restraint from shrinkage, and consequently larger shrinkage stress. The variation in thickness led to greater restraint because of the anchoring effect of thicker portions of the pavement. As shown in Table 6–12 and Figure 6–43, NR can be thick at the sides and thin at the center. The thinner sections in NR also produced lesser resistance to shrinkage stress.

The bases of the two pavements were also structurally different. The SFSCC at S4TH was placed on an existing asphalt bike path, which had some deterioration, while the SFSCC at NR was placed on compacted gravel on soil, where an original asphalt pavement had been removed. The wheel prints of concrete trucks were observed on the base before SFSCC was placed, which could be the cause of the significantly uneven thickness of the SFSCC slab as measured from the core samples. Because of the poor weather on the day of SFSCC paving at NR, some rain was accumulated in the southern location of the last panel (panel 1).

The S4TH pavement also had better curing compared to NR. S4TH pavement was cured with wet burlap completely covered with a plastic sheet for seven days. NR pavement was applied with curing compound and a plastic sheet, but unfortunately was rained on for several hours after placement. Rain water seeped through the plastic sheets. The plastic sheet was removed within three days. The longer curing of S4TH may significantly decrease drying shrinkage and improve cracking resistance to drying shrinkage.

The traffic loads were also significantly different. NR is a city road and carries traffic loads from cars to trucks, while the heaviest loads from the bike path are the small snow plows during winter. The thinner NR with much heavier loads makes the pavement more susceptible to cracking.

Table 6–15. Comparison of SFSCC field pavements

Condition	South 4th Street	North Riverside Drive
Dimensions	10 by 8 ft by (t=5.8 to 6.2 in.)	18 by 13 ft by (t=3.5 to 5.75 in.)
Placement	With pressure	No pressure
Base	asphalt	gravel
Curing	7 days wet with cover	Curing compound
w/b	0.35 and 0.39	0.39 to 0.41
f'c (psi)	6298 (S4TH-M1) 5072 (S4TH-M2)	5148 (NR-M3-A)

7. COST AND CARBON FOOTPRINT ANALYSIS

7.1 Cost Analysis

The cost of production and construction using SFSCC and conventional pavement concrete was studied. The parameters considered in the cost calculation were (1) concrete materials, (2) concrete mixing and transportation, (3) formwork for conventional pavement concrete, (4) concrete casting, and (4) finishing. The analysis did not include overhead and profit costs. The mobilization cost was also excluded because the application so far had been city streets and bike paths that were constructed with the help of the local public works. The concrete mix proportions analyzed are those given in Table 3–3. The unit costs of materials used in the calculations are given in Table 7–1.

Table 7–1. Unit cost of concrete materials ($)

Cement (per ton)	105.00	AEA(per gal)	9.60
Fly ash (per ton)	42.00	HRWR (per gal)	51.20
Slag (per ton)	95.00	RMA (per gal)	9.60
Limestone dust (per ton)	8.00	VMA(per gal)	9.60
Water (per cu.yd.)	0.56	Thixotrope (per ton)	41.85
Fine aggregate (per ton)	11.60	Fiber (per ton)	108.00
Coarse aggregate (per ton)	16.00		

Based on the given unit costs, the total material costs of the SFSCC and conventional pavement concrete were calculated and are given in Table 7–2. The material cost of SFSCC is equal to or greater than that of the conventional pavement concrete. The main contributors to the higher cost in SFSCC are the use of more cementitious materials, admixtures, and fiber. Figure 7–1 shows the cost of cementitious materials in SFSCC, quality management concrete (QMC), and conventional pavement concrete (QMC, C3, and C-3WR-C20). It can be seen that while the cost of cement in SFSCC can be lower than the cost of cement in conventional pavement concrete, the total cost of cementitious materials in SFSCC can exceed the cost for conventional concrete due to the addition of supplementary cementitious materials. The use of admixtures in SFSCC also increases its cost. The costs added by the admixtures to the different mixes are shown in Figure 7–2. The addition of HRWR contributes most to the additional cost in SFSCC. Other significant costs are the costs of thixotrope and fiber.

Table 7–2. Material cost of SFSCC and conventional concrete ($/cy)

Ames 0.35	66.66	SFSCC-BFS	70.37
Ames 0.39 (S4TH-M2)	59.19	SFSCC-LD	62.35
Guthrie	53.07	SFSCC-field1	96.31
Ottumwa	55.47	S4TH-M1	67.30
Webster	74.11	NR-M1-A	65.17
Alma Center	56.58	QMC	48.13
SFSCC-Control	54.64	C3	52.82
SFSCC-Max-Agg	66.97	C-3WR-C20	53.73

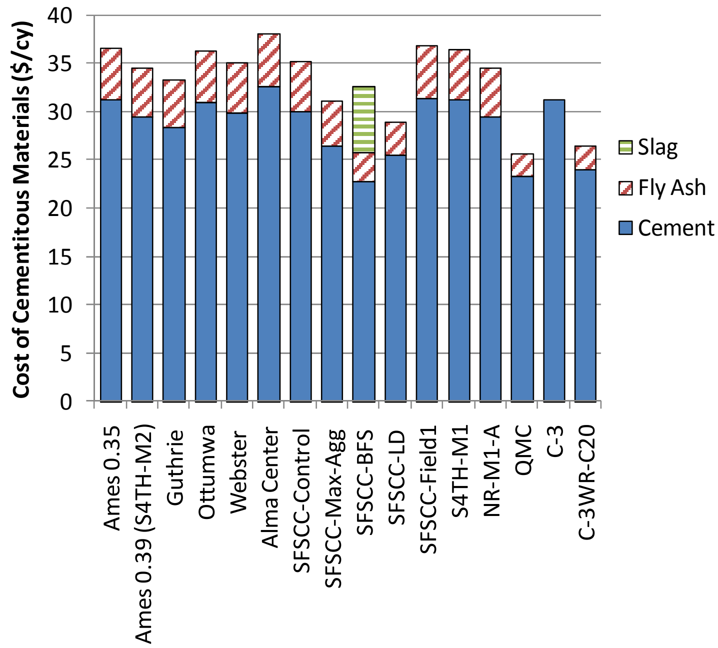


Figure 7–1. Comparative cost of cementitious materials in SFSCC and conventional pavement concrete

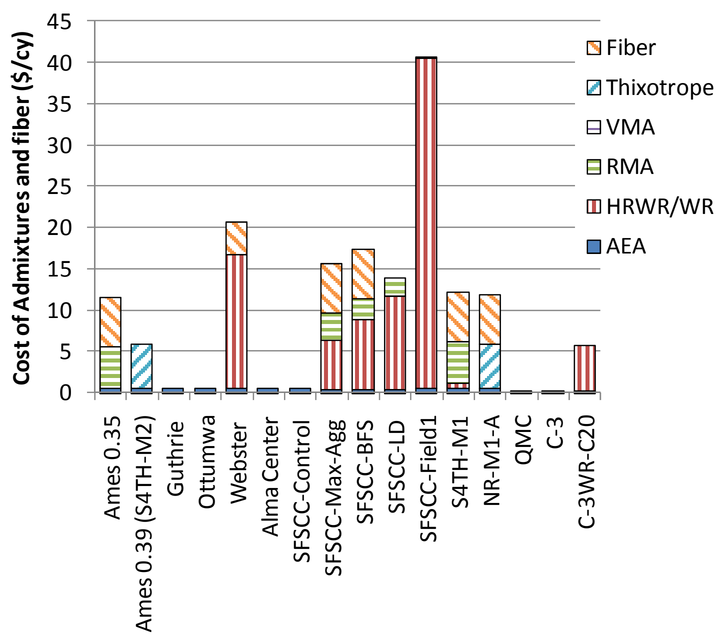


Figure 7–2. Comparative cost of admixtures and fiber in SFSCC and conventional pavement concrete

In estimating the cost of production and placement of concrete, several assumptions were made. The cost of concrete included (1) the cost of batch plant labor at $25.00 per hour and (2) the cost of the driver, concrete mixer, fuel, and oil at $68.00 per hour. Transportation costs included the cost of operating and maintaining the concrete truck and the cost of truck loading and travel distance. The average truck load was 4 cubic yards. The length of haul from the mix plant to the construction site was 3.2 mi, which was the average truck travel distance during the construction of the three SFSCC field tests. Unit cost computations were based on published rates (Page 1999; Williams 1996) and 2010 costs.

The cost of placement included four parts: (1) the cost of formwork, (2) the labor cost to place the concrete, (3) the consolidation cost, and (4) the cost of using the paver. The cost of placement was divided in this manner because SFSCC did not require formwork or external vibration for consolidation but required paving equipment.

The consolidation cost included the cost of using and maintaining a vibrator for five years and labor needed for operating the equipment. It was assumed that the formwork held 6 in. thick pavement and was 12 ft wide. For the purpose of this estimate, it was assumed that a truck was used to pull the paver for SFSCC paving, and the cost included loading the paver and casting the pavement. Based on these assumptions, the unit costs were derived (Table 7–3).

Table 7–3. Construction process unit costs of SFSCC and conventional concrete ($/cy)

Cost of mixing	3.81
Cost of transporting	17.00
Cost of placement	
Consolidation by vibration with operator	7.00
Formwork with labor	4.38
Labor for handling and spreading	9.50
Paver with operator	11.90
Paver with vibrator and operator	12.14
Finishing and Curing	32.62
Finishing and Curing (SCC)	30.38

It was assumed that the costs of mixing, transportation, and curing for SFSCC and conventional pavement concrete were the same. However, conventional fixed-form concrete placement requires consolidation or vibration, formwork, and additional labor for the spreading of the concrete in forms. SFSCC requires a paver and operators, but it requires less labor for finishing. As a result, the total estimated mixing and placement cost for conventional fixed form, conventional slip-form, and SFSCC construction methods are $74.31 per cy, $65.57, and $63.09 per cy, respectively. Table 7–4 provides a comparison of the breakdown costs of these three different construction methods. The material cost of SFSCC can be comparable to or up to 80% higher than that of conventional concrete, depending on the mix design. Although material cost can be high, SFSCC incurs lower construction process cost than conventional fixed and slip-form paving.

Table 7–4. Estimated construction cost of different paving methods ($/cy)

Item	Fixed form (C3)	Fixed form (C-3WR-C20)	Slip-form (C3)	Slip-form (QMC)	SFSCC
Cementitious	31.24	26.39	31.24	25.59	28.81 to 38.06
Aggregates and water	21.36	21.64	21.36	22.33	18.02 to 20.37
Admixtures	0.23	5.70	0.23	0.21	0.44 to 40.68
Materials sub-total	52.83	53.73	52.83	48.13	53.07 to 96.31
Cost of mixing	3.81	3.81	3.81	3.81	3.81
Cost of transporting	17.00	17.00	17.00	17.00	17.00
Cost of placement					
Consolidation by vibration w/operator	7.00	7.00			
Formwork with labor	4.38	4.38			
Labor for handling and spreading	9.50	9.50			
Paver			12.14	12.14	11.90
Finishing and curing	32.62	32.62	32.62	32.62	30.38
Construction process sub-total	74.31	74.31	65.57	65.57	63.09
Total	127.14	128.04	118.40	113.7	116.16 to 212.47

Using the information provided in Table 7–4, the total costs for each concrete mix studied are given in Figure 7–3. It is noted that for a given construction method, such as SFSCC paving, the cost for construction is constant, while the total costs vary with the concrete material costs. Figure 7–3 indicates that the total costs, the sum of material and construction costs, of SFSCC mixes are comparable to those of conventional fixed form and slip-form pavement concrete. The present cost analysis does not include the cost saving that resulted from accelerated construction provided by the SCC slip-form paving method.

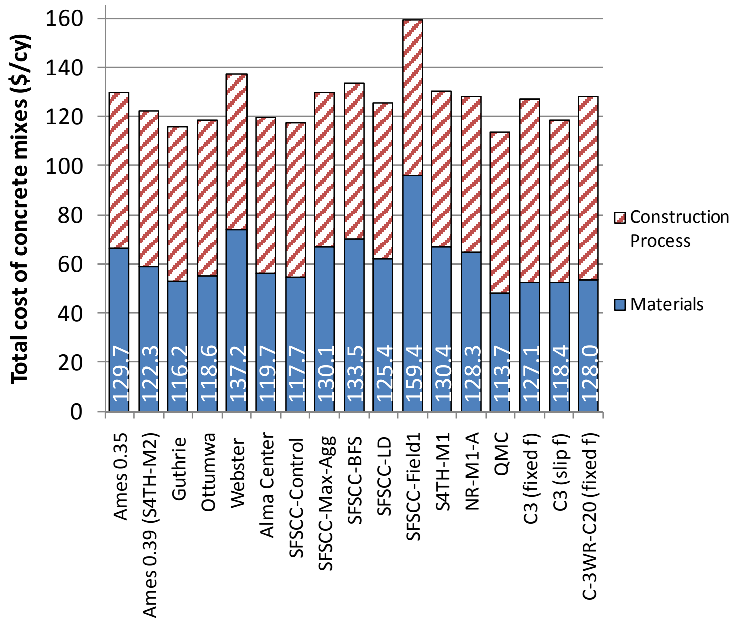


Figure 7–3. Total estimated cost of SFSCC and conventional pavement concrete, excluding overhead and profit ($/cy).

7.2 Carbon Footprint Analysis

The carbon footprint in mass of carbon dioxide (CO_2) per cubic yard of concrete (lb CO_2/cy) was estimated for SFSCC and conventional pavement concrete. Similar to the cost estimate, the calculations were made for the construction of a city road. The estimated carbon footprint for each unit material and paving procedure considered are listed in Table 7–5.

The amounts of CO_2 produced in the production of cement, slag, and aggregates were estimated based on the report of Marceau et al. (2007). No distinction was made for the production of fine or coarse aggregates. The estimated value was also adopted for limestone dust. The CO_2 produced from the production of each material was calculated from Marceau et al. (2007) report by

$$CO_2 \text{ per unit material} = \frac{CO_2 \text{ emmision from production}}{\text{Mass of material in mixture}} \tag{5}$$

The CO_2 produced during the capture, refining, and transport of fly ash were considered in the work of Flower and Sanjayan (2007). However, calculations made in the present study were based on the report of Marceau et al. (2007), which did not consider the CO_2 resulting from fly ash production since it is an industrial waste. Though most concrete mixtures used in this study had admixtures, the CO_2 contributions were in the order of 10^{-6} lb CO_2/cy and therefore were not considered in the analysis.

The CO_2 from batching was due to plant operations. Transport CO_2 was from the delivery and return trips of mixers. Consolidation CO_2 was estimated based on the operation of a 1.6 kW vibrator. A variable width 250 hp slip-form paver was assumed for conventional slip-form paving. It was assumed that 15% of the energy used by the paver was used for an array of vibrators. For SFSCC, the paver was pulled by a 250 hp truck.

Table 7–5. Estimated pounds of CO_2 per unit material or operation

Materials		Mixing and placing	
Cement (lb)	0.90603	Batching (cy)	2.97
Fly ash (lb)	0.01690	Transport (cy)	10.7
Slag (lb)	0.02100	Consolidation (cy)	0.25
Aggregates (lb)	0.00023	Paver (cy)	1.05

In the calculation of the CO_2 per cubic yard of concrete, the amount of CO_2 produced from each material as given in Table 7–5 was multiplied by the quantity of the material used in each concrete mix as given in Table 3-3. It was assumed that the CO_2 productions from concrete mixing and transportation were the same for all different concrete mixes. During concrete placement, SFSCC and conventional slip-form construction generated CO_2 through the use of a paver, while conventional fixed form (hand placed) concrete construction generated CO_2 from the use of a vibrator (Table 7–6). The total pounds of CO_2 per cubic yard of concrete for the different mixes are given in Figure 7–4.

Figure 7–4 indicates that CO_2 production from concrete construction was minimal compared with that from materials used in the concrete mixes. The carbon footprint of SFSCC was comparable to that of conventional pavement concrete (QMC, C3, and C-3WR-C20), despite having a higher cementitious content. SFSCC construction may reduce approximately 0.74 lb CO_2 per cubic yard when compared with conventional concrete slip-form paving due to the elimination of vibrators.

Table 7–6. Estimated construction CO_2 of SFSCC and conventional concrete ($/cy)

Item	Fixed form (C3)	Fixed form (C-3WR-C20)	Slip-form (C3)	Slip-form (QMC)	SFSCC
Cementitious	539.09	414.05	539.09	401.37	395.25 to 560.83
Aggregates	0.70	0.71	0.70	0.73	0.61 to 0.68
Materials sub-total	539.79	414.76	539.79	402.10	395.92 to 561.44
Batching	2.97	2.97	2.97	2.97	2.97
Transport	10.7	10.7	10.7	10.7	10.7
Consolidation	0.25	0.25			
Paver			4.92	4.92	4.18
Construction process sub-total	13.92	13.92	18.59	18.59	17.85
Total	553.71	428.68	558.38	420.69	413.77 to 579.29

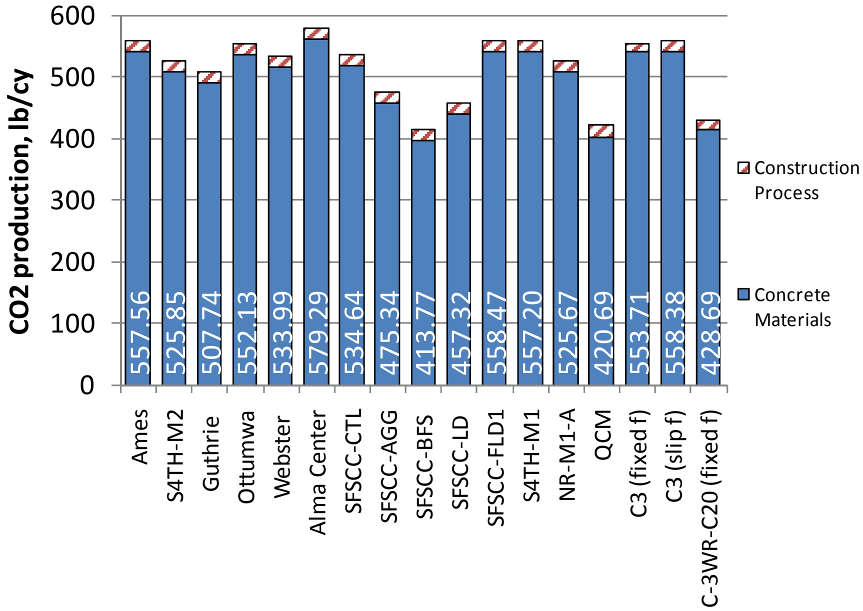


Figure 7–4. Estimated pounds of CO_2 per cubic yard of SFSCC and conventional pavement concrete

8. SFSCC GUIDE FOR DESIGN AND CONSTRUCTION

8.1 Basic SFSCC Properties

SFSCC was originally conceptualized as a mixture that will be used for slip-form paving. Hence, the foremost properties that were considered are the following:

1. Self-consolidating ability. The concrete mixture should flow into forms without the aid of an external vibrator and follow the shape of the form. Pressure may be applied to the concrete from its own weight during paving or preparation of samples. Consolidation pressure from paving comes from the concrete pile upstream of the paver, which is at least 18 in. high. Pressure from preparation of samples is made by placing the slump cone above the molds and letting concrete fall 12 in. into the form. SFSCC should not segregate when molded. Voids should not form when the concrete fills the formwork.
2. Shape holding ability. When the concrete mixture comes out of the moving form, it should maintain the shape of the form with little or no edge slump. The edge slump can be assessed using the modified slump test and designing for sufficient green strength. The SFSCC should have a good shape, and the remaining height should be at least the thickness of the pavement to be cast.

Other properties that were considered in the design and construction with SFSCC are the following:

1. Green strength. Green strength as defined here is the amount of weight an unsupported cylinder of concrete can carry without collapsing. Sufficient green strength for paving can be achieved with the proportioning of fine materials and use of admixtures. Green strength has a positive effect on shape stability. However, excessive green strength reduces flowability and has a negative impact on self-consolidation.
2. Hardened concrete performance. SFSCC should have comparable performance to pavement concrete. The hardened properties of concrete include strength development, freeze-thaw durability, rapid chloride ion permeability, porosity, and scaling resistance to deicing chemicals.

8.2 Testing of Fresh Concrete Properties

The different testing methods for proportioning and quality control of SFSCC are discussed in Chapter 2 and Appendix A. The tests are discussed here based on their application and evaluation.

1. Flow table tests. Mortar that will be part of an SFSCC mixture should have an initial flow of 10% (4.4±0.2 in. in diameter at zero flow table drops). The final flow should be 138% (9.5±0.2 in. in diameter) at 16 to 18 drops. These initial and final flows requirements have been used to develop SFSCC with a good balance of shape stability and flowability.
2. Rheometer tests. The rheology test and properties of SFSCC are discussed in detail in Section 4.2. The loading history should be considered in four stages:
    a. Preshear. A low-speed motion of the impeller performed to remove any local restraints created during placement of concrete in the sample container.

b. Rest. A stage where there is no motion in the impeller. The concrete is allowed to come to rest from the preshear; ready for the shear loading.
c. Increasing load. The impeller/vane/plate motion is started and gradually increased.
d. Decreasing load. The impeller is brought to rest from the peak loading. The rate of decrease in shear rate is the same as the rate of increase in shear rate in the previous step.

The loading history for a Brookfield rheometer for pastes and mortars is given in Figure 4–1 and Figure 4–12, respectively, and the loading history for an IBB rheometer for concrete is given in Figure 4–9.

The yield stress with the IBB rheometer is related to IBB-yield torque, while viscosity is related to IBB-slope. The IBB-yield torque for SFSCC ranges from 3 to 5 N-m, and the IBB-slope ranges from 3 to 7.5 N-m-s. SFSCC generally has a lower IBB-slope compared to conventional pavement concrete due to the lesser coarse aggregate content.

3. Modified slump tests. The slump and spread of an unrodded slump test should be determined to measure flowability of SFSCC. The slump should be within 6 to 8 in. and the spread should be within 11 to 13 in.. It should have a symmetric cone shape. The correct geometry of the slump indicates a good balance between flowability and self-consolidation. In also indicates uniform distribution of materials.
4. Mini-paver test. As the mini-paver (Figure A-5) moves forward, SFSCC should move to the horizontal part of the paver and follow the shape of the form without making voids. The surface should be smooth and the sides should have little to no edge slump.
5. Compaction factor test. Good self-consolidating concrete should have a compaction factor close to or equal to 1.
6. Green strength test. The test measures the amount of compressive load molded fresh concrete can carry until collapse. SFSCC is molded into a cylinder and the load is from dry sand that is slowly poured in the vessel on top of the fresh concrete. The green strength (Method B) of freshly mixed concrete is optimum at 1.3 to 2.5 kPa for a flow diameter of 41%–47%. The maximum green strength (Method A) of freshly mixed and molded SFSCC without compromising compaction factor is 4 kPa (Wang et al. 2005).

8.3 Mix Proportioning

SFSCC is composed of cementitious materials, aggregates, and water. Admixtures may be included to improve self-consolidation and modify green strength. The objective of mix proportioning is to properly combine these materials to produce concrete that meets requirements for self-consolidation, shape stability, economy, strength, and durability.

8.3.1 SFSCC Mixture Materials

1. Cementitious materials. All cementitious materials suitable for conventional SCC can be used for SFSCC. The used cementitious materials include Type I cement, as described in ASTM C150, and supplementary cementitious materials (SCM) that meet ASTM C618 and ASTM C989 requirements. To improve concrete flowability, fly ash can be used up to 40% of portland cement, and use of only Type I cement is encouraged.
2. Aggregates. Aggregate gradation greatly influences flowability, compactability, and shape holding ability of SFSCC. Aggregates used for SFSSC are recommended to meet

requirements of ASTM C33. Aggregates may be natural or manufactured, and they should be hard, dense, durable, and free of deleterious substances.

3. Admixtures. Commonly used admixtures in SFSCC include air entraining agents, water reducing agents, viscosity modifying agents, and shrinkage reducing admixtures.
   a. Air entraining agents are required for freeze-thaw resistance. The entrained air can also benefit flowability of the concrete.
   b. Water reducing agents are used for improving concrete flowability without increasing water-to-cementitious material ratio.
   c. Viscosity modifying agents are recommended for SFSCC to improve concrete segregation resistance and shape-holding ability.
   d. Thixotropes can increase concrete green strength while maintaining flowability when flow is initiated.
   e. Shrinkage reducing admixture reduces drying shrinkage and the stresses developed when restraints are present. The reduction in restrained shrinkage reduces the risk of cracking. It may also reduce compressive creep and carbonation.

8.3.2 SFSCC Mix Proportioning Method

The proportioning of SFSCC is discussed in detail in Chapter 3. The steps and criteria recommended for proportioning a suitable SFSCC mixture are divided into three parts: (1) design of mortar, (2) design of coarse aggregate content, and (3) SFSCC mix proportion verification. The SFSCC mix proportioning flow chart is given in Figure 3–4. The key points in the mix proportioning steps are as follows:

1. Design of mortar. Two mix design parameters will be determined in this step: water-to-binder ratio and fine aggregate content. The water-to-binder ratio should be chosen based on the concrete strength and durability requirements, which is similar to those required by conventional pavement concrete. The amount of fine aggregates should be selected based on the results from modified flow test, using the flow table as designated in ASTM C230. The criteria for accepting the mortar are an initial flow of 10% and a flow diameter of 9.5±0.2 in. after 16-18 drops. Initial flow is measured when the mold is removed. A good starting fine aggregate content is 50% of the total mortar volume.
2. Design of coarse aggregate content. The mix design parameter to be determined in this step is the coarse aggregate content. The coarse aggregate content should be determined based on the results of modified (unrodded) slump test and compaction factor test. The criteria for accepting the concrete mixture are a slump of 7±1 in., spread of 12±1 in., having a regular cone shape after the slump test, and having compaction factor of 98% or higher. A recommended starting coarse aggregate content for SFSCC is 40%–45% volume fraction.
3. SFSCC mix proportion verification. Mini-paver test should be used to verify the overall performance of fresh SFSCC. The freshly extruded concrete slab from the mini-paver should have visually good rectangular shape, minimal edge slump (≤8% of slab thickness), and a good surface finish (≤15% surface defect by the surface area). The cross section of the hardened concrete slab should have no visible segregation and no honeycombs.

8.3.3 Alternative Approach to SFSCC Mix Proportion

The SFSCC mix proportioning development may be started with a conventional SCC mix proportion, modified by gradually adding different fine materials, such as fly ash, nano-clay, and cement, until the concrete reaches a shape stable condition. Figure 2–1 shows the effects of different fine materials and water-to-fine material ratio on flowability and shape stability of concrete pastes, where the paste flow was measured by the flow drop table as described in ASTM C230.

8.4 Effects of Concrete Materials on SFSCC Performance

When proportioning SFSCC, the type of materials and their proportions affect its fresh state properties. The effects of some fine materials on the rheological behavior of pastes are listed in Table 8–1.

Table 8–1. Effects of different fine materials addition on paste materials (from Table 2–1)

Material	Viscosity	Yield stress
Slag	Increase	Increase
Fly ash	Decrease	Decrease
Limestone dust	No change	Increase
Gypsum	Increase	Increase
Actigel	Increase	Increase

Nano-clay materials may be added to modify the flowability and green strength of SFSCC. Dosage generally ranges from 1% to 2% by weight of cementitious materials. Microfibers added in SFSCC reduce flowability but improve shape stability. The gradation, texture, and shape of aggregates affect the self-consolidation behavior of SFSCC. A higher compaction factor of plain coarse aggregates results in better SFSCC self-consolidation. When using high-range water reducers, naphthalene-based plasticizer generally provides a positive effect on concrete flowability under the influence of external compaction energy compared to polycarboxylate-based plasticizers.

8.5 Production and Construction

1. Concrete production and paving equipment. Batching of concrete should be accurate, consistent, and reliable. Variations in batching, measurement of moisture in aggregates, and water in measuring and mixing equipment affect the consistency in flowability and shape-holding ability of the final concrete. For the field application of SFSCC, mixing and delivery should comply with ASTM C94. To produce a mixture, solid additives are added first, followed by aggregate, water and liquid admixtures, and cementitious materials.
   The timing of delivery and casting of SFSCC has a significant effect on the performance of fresh SFSCC. Standby time of delivery trucks should be such that there is no loss of flowability. Due to the absence of mechanical consolidation, stiffening of SFSCC will affect its flowability and filling ability.

When SFSCC is mixed and the concrete truck arrives at the construction site, the suitability of the mixture should be determined by the modified slump test. The slump, spread and shape of the concrete are measured. Practical measures may be taken at the field site to ensure that concrete mixture meets the criteria, such as addition of admixtures. There should be no modification to the mixture after the concrete has been placed in the paver. Air content of the concrete is measured according to ASTM C231 Method B to check for potential freeze-thaw durability. When a scale is available on site, the compaction factor should also be determined.

2. Finishing, texturing, and jointing. To improve pavement surface appearance, minimal hand finishing may be applied to SFSCC surfaces using bull floats. Texturing and jointing of SFSCC pavement can be conducted using the same methods as those for conventional slip-form concrete pavement.
3. Curing and Maintenance. Proper attention to curing should be made to minimize the risk of uncontrolled shrinkage cracking. Although all curing methods for conventional concrete pavements, such as use of wet burlap, plastic sheet, and curing compound, can be applied to SFSCC, moist curing is desirable. Since the hardened SFSCC has been shown to have similar mechanical properties to conventional pavement concrete, the maintenance would also be the same.
4. Field sample preparation. Cylinders and beams made from representative samples of fresh SFSCC should conform to ASTM C31 but not rodded or vibrated. Samples should be cured in the same conditions as field concrete pavement.

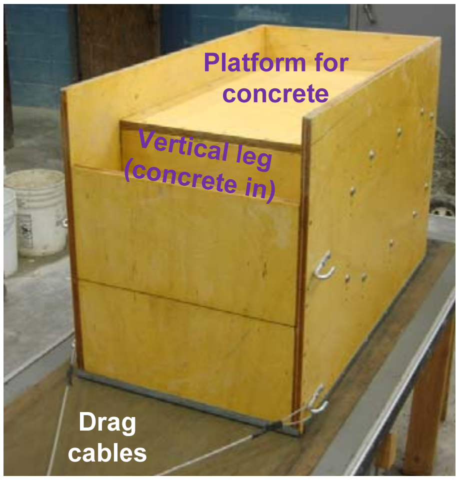
8.6 Recommendations on Paving Equipment for SFSCC Applications

Two types of slip-form paver had been used for the project. The first was the lab-scale mini-paver, and the second was the modified asphalt paver used in two field tests. The mini-paver is composed of several compartments: (1) vertical leg/chute, (2) horizontal leg/form (3) top platform for concrete, and (4) weight chamber (Figure 8–1). Among these four parts, the vertical leg and the horizontal form are responsible for aiding concrete consolidation and shaping the concrete. The vertical leg holds the concrete to a height of 18 in. This produces a pressure of 1.2 psi at the top of the concrete slab. The corner of the form may also cause a slight redistribution. The 29-inch horizontal leg shapes the concrete. The slow-moving form lets the concrete fill the form, rest, and gain green strength due to its static state.

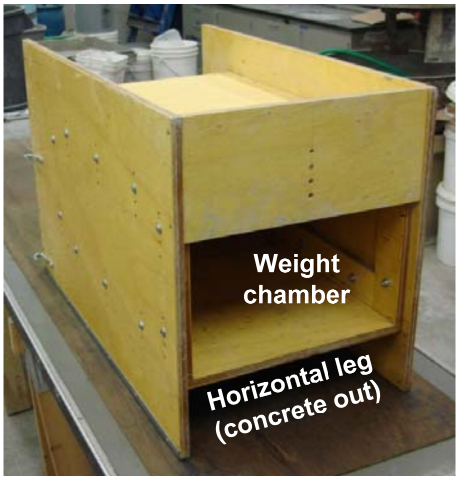
It is recommended that field pavers should have the same characteristics as the mini-paver to be able to use SFSCC for field application. For the case of the modified asphalt paver, the vertical leg is not present. The consolidation pressure can be obtained by piling concrete in front of the paver and maintaining this height. The horizontal leg is simulated by adding skid. The possible improvements on the field paver are as follows:

1. Length of skids. The skids should be lengthened when paving needs to be faster. The present mini-paver has a horizontal length of 29 in. and moves forward at a speed of 1 ft per minute. This means that the concrete should be inside the form for at least 2.4 minutes before extrusion from the form.
2. Level of skids. The skids used have a tendency to dig into a soft base. This would result in thinner pavement. The elevation of the skids should be maintained by support, suspension, or wider skids.

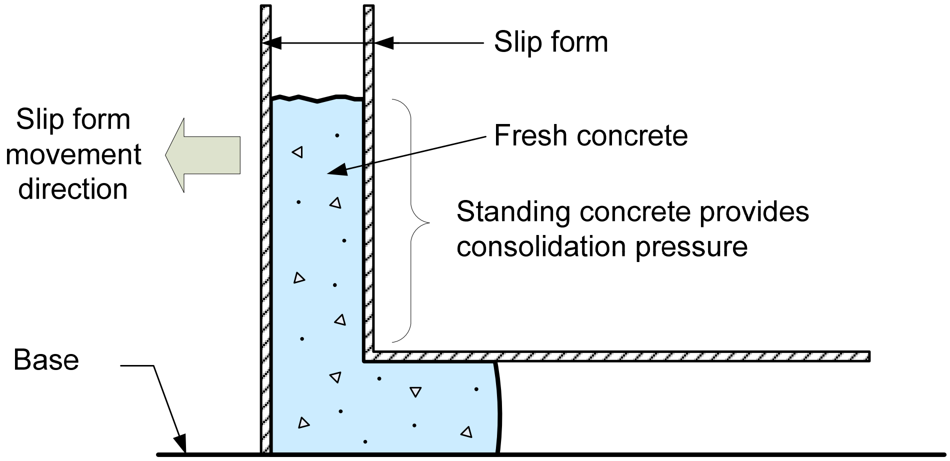
3. Length of top cover of horizontal leg. The top portion of the horizontal leg can be extended to the length of the skids. This will improve the finish and shape of the concrete.
4. Vertical level mark. To be able to maintain a consistent pressure on the concrete, a vertical level mark should be provided, the pressure sensor should be placed, or a funnel-shaped chute should be used.
5. Spreading of concrete along the width of the paver. Aside from a constant vertical pressure, it should be ensured that the concrete has a constant pressure along the width.



(a) Front of mini-paver



(b) Rear of mini-paver



(c) Section of paver with concrete passing though the vertical and horizontal leg

Figure 8–1. Mini-paver compartments and schematic diagram of paver cross section

9. CONCLUSIONS AND RECOMMENDATIONS

9.1 Project Overview

A new type of self-consolidating concrete (SCC)—semi-flowable SCC (SFSCC)—has been developed in this project for slip-form paving. The project consists of two Phases: (I) feasibility study and (II) in-depth mix proportioning and performance study as well as field applications. The following tasks have been completed in the Phase II study:

1. Studying effects of materials and mix proportions on SFSCC properties
2. Developing a mix proportioning procedure for functional SFSCC
3. Characterizing fresh SFSCC properties
4. Evaluating general engineering properties of hardened SFSCC
5. Developing quality control tests for both laboratory and field applications
6. Conducting field applications of SFSCC
7. Monitoring field performance of SFSCC
8. Analyzing carbon footprint and cost of SFSCC
9. Establishing guidelines for proportioning, testing, production, and construction of SFSCC

Fifteen SFSCC mixtures made with materials from five different sources in Iowa and Wisconsin have been designed and evaluated in the laboratory, and three field SFSCC applications have been conducted.

9.2 Conclusions

The following are major observations and findings from the Phase II study:

- The proposed SFSCC mix proportioning procedure is a performance-based procedure, which consists of three major steps: (1) to design SFSCC mortar mix proportion for specified flowability, (2) to determine coarse aggregate content in SFSCC based on required flowability and compactability, and (3) to verify the initial SFSCC mix proportions with a mini-paver test that simulates field slip-form paving. The performance criteria for a potential SFSCC mix are that (1) the mortar must have an initial flow of 10% and a final flow of 9.5±0.2 in. after 16-18 drops on a standard flow table; (2) the amount of coarse aggregates in SFSCC should let the concrete have unrodded slump of 7±1 in., slump spread of 12±1 in., symmetric slump cone shape, and a compaction factor larger than 95%; and (3) the results of the mini-paver test should show a smooth pavement with the correct shape, and the hardened properties of the concrete should meet service and durability requirements. Adjustments can be made by altering mix proportions and using admixtures to meet the mix design criteria.
- The newly developed SFSCC mix proportioning procedure has been verified by performance tests of SFSCC designed and cast with different sources of cementitious materials and aggregates from Iowa and Wisconsin. The experimental test results from both laboratory and field studies have shown that well-proportioned SFSCC mixes not only meet the criteria for flowability, consolidation, and shape-holding ability but also show adequate properties in the hardened concrete.

- The in-depth study on the fresh concrete properties of SFSCC has showed that SFSCC generally has a lower viscosity when compared with conventional concrete due to smaller volume of coarse aggregates. The required force for SFSCC to flow is shown to be inversely proportional to its slump. Addition of fines and nano-clay materials has significant effects on flowability and shape-holding ability of SFSCC. Increasing the nano-clay (Actigel) content of a cement-based material considerably increases its yield stress, viscosity, and thixotropy. (Thixotropy is a time-dependent behavior in which viscosity of a material decreases with time under shearing but recovers to its original value when the shearing ceases.) A high value of thixotropy of a cement-based material indicates a quick viscosity recovery, and it controls timely shape-holding ability. Differently, addition of water reducer and air entraining agent reduce thixotropy of cement-based materials.
- The compressive strength and rate of the strength development of SFSCC tend to be higher than those of conventional concrete due to the lower water-to-binder ratio. The elastic modulus of SFSCC is lower due to its low coarse aggregate content. The porosity and rapid chloride ion permeability of SFSCC are noticeably higher than those of conventional pavement concrete at 28 days, but they become comparable at the later ages, probably due to the extensive use of supplementary materials. The heat of cementitious material hydration of SFSCC is comparable to or lower than that of conventional pavement concrete. The freeze-thaw durability of SFSCC is also comparable to that of conventional concrete, which is primarily dependent upon durability of the aggregates used. Scaling resistance to deicing chemicals varies with SFSCC mixes, and addition of nano-clay Actigel generally provides SFSCC with a better scaling resistance to deicing chemicals.
- Under a lab drying condition (T=23ºC±2ºC and RH=50%±4%), compressive strength of SFSCC is similar to or slightly higher than that of conventional concrete, while shrinkage of SFSCC is noticeably higher than that of conventional concrete at a given age. Addition of some nano-clay materials (Actigel and Metamax) in SFSCC slightly increases autogenous shrinkage, while another nano-clay material (Concresol) decreases autogenous shrinkage. With 2% addition (by weight of cementitious materials), Actigel and Concresol increase drying shrinkage, while Metamax decreases drying shrinkage of SFSCC. Drying shrinkage increases with increasing amount of Actigel in the concrete; while it decreases with increasing amount of Metamax. Shrinkage reducing agent effectively reduces shrinkage of SFSCC.
- The field applications show that SFSCC can successfully be prepared in a commercial batching plant. SFSCC that passes the proposed criteria for the modified slump test is suitable for field paving. The paving equipment should have sufficient uniformly distributed concrete in front of the form for proper consolidation, and the horizontal form should be sufficiently long for the concrete to follow and attain green strength to hold its shape. SFSCC requires minimal finishing. Texturing, jointing, and curing of SFSCC pavements can be done using the same methods as those for conventional slip-form concrete pavement. To facilitate cement hydration and prevent shrinkage cracking, proper curing of SFSCC is essential for quality SFSCC products. The field applications of SFSCC have demonstrated that, although having high shrinkage, well-proportioned and well-constructed SFSCC in a bike path constructed in Ames, IA, has not shown any shrinkage cracks after approximately 3 years of field service, while another street

pavement at North Riverside Drive, Ames, IA, made with different mix proportions and under different construction conditions showed random cracking. The results suggest that not only the mix proportioning method but also construction practice are important to produce durable SFSCC pavements.

- A comparison analysis shows that the material cost of SFSCC is equal to or greater than that of conventional pavement concrete. The main contributors to the higher cost in SFSCC are the use of more cementitious materials and admixtures/additives. The total costs, the sum of material and construction costs, of SFSCC mixes are comparable to those of conventional fixed form and slip-form pavement concrete. CO_2 production from concrete construction is minimal compared with that from materials used in the concrete mixes. Despite having a higher cementitious content, the carbon footprint of SFSCC is comparable to that of conventional pavement concrete (Iowa DOT C3 and C-3WR-C20 mixes).

9.3 Recommendations

The following are recommendations from the Phase II study:

- While it has been shown that SFSCC can significantly benefit the pavement construction process and has a positive environmental impact compared to current slip-form construction, a paver specifically designed for SFSCC is recommended for it to be fully utilized. A paver for SFSCC should allow the concrete to consolidate under its own weight, uniformly distribute the concrete through the width of the paver, and have a horizontal leg that will mold and hold the concrete for a sufficient amount of time for its green strength to develop. Once a paver has been developed, the construction procedures using the paver can be made and tested.
- More admixtures may be studied for SFSCC applications. The admixtures should maintain or increase yield stress to promote shape-holding ability; however, at the same time, they should be able to decrease viscosity to promote better flow during the extrusion process.
- Currently, fine materials used to improve concrete flowability are cementitious materials. The use of limestone dust was tested during this research. Along these lines, other inert fine materials may be explored to be used as a replacement to cementitious materials. This may lead to reduction in SFSCC cost and cracking potential due to drying shrinkage. While the use of shrinkage-reducing admixture was studied, other mitigation measures such as self-curing may be studied.
- Among five SFSCC mixes tested for scaling resistance to deicing chemicals, some SFSCC showed a comparable or higher resistance to that of conventional pavement concrete, while others displayed a lower resistance. The lab test results seemed not consistent with those of field concrete. More studies should be conducted on the potential factors affecting SFSCC scaling resistance (e.g., effects of fines and nano-clay additions). Other characteristics of SFSCC, such as thermal expansion, alkali-silica reaction, and sulfate resistance, may be explored.

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APPENDIX A: TEST METHODS USED FOR SFSCC MIXTURE CHARACTERIZATION

Modified Slump Test

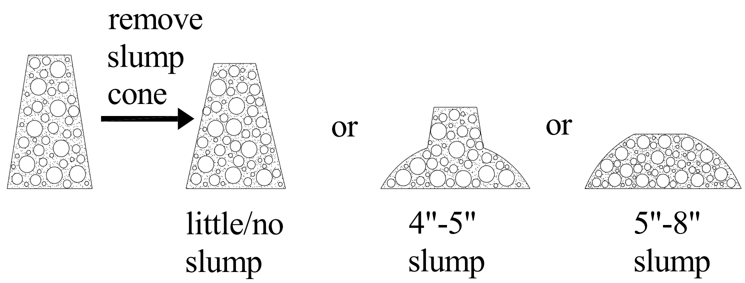
Flowability of concrete is commonly measured by a standard slump cone test (ASTM 143). For conventional concrete, the standard test requires the concrete sample to be placed with three layers and rodded 25 times for each layer. The test measures the slump of the concrete right after the slump cone mold is removed. For conventional SCC, a modified slump cone test is often used, where no rodding, tamping, or any vibration is allowed for the sample preparation. The test provides two measurements: slump and spread (or slump flow). Conventional SCC generally has a slump spread ranging from 20 to 32 in. (50 to 80 cm). With such a large spread, conventional SCC can flow well and self-consolidate, but it shapes like a big pancake after the slump cone mold is removed and has no timely shape-holding ability. It, therefore, requires formwork for construction.

For SFSCC, the modified slump cone test that is used for conventional SCC can also be applied. The test is able to provide three parameters: slump, spread, and shape of the mixture right after the slump cone mold is removed. The measurements of the concrete slump and spread are related to the concrete flowability, while the shape of the mixture after the slump cone removal provides an insight into the concrete compactability.

When a fresh concrete mixture is placed into the slump cone from a constant height without any rodding, tamping, or vibration, the following observations can be made and explained:

- If a concrete mixture has good compactability or it is well compacted, the shape or deformation of the mixture after the slump cone is removed should be plastically isotropic, as shown in Figure A–1a. The mixture has a uniform aggregate particle distribution and good cohesion.
- If a concrete mixture does not have good compactability or it is not well compacted, the shape or deformation of the mixture after the slump cone is removed may be irregular due to the weak zones in the fresh concrete, as shown in Figure A–1b.

The flow behavior of SFSCC is generally between those of conventional pavement concrete and SCC mixtures. That is, a SFSCC mixture often has certain slump and spread values so as to be able to flow. It should also have a good cone shape, as shown in Figure A–1a, after the slump cone is removed, thus ensuring a good self-consolidating ability. The criteria of these three slump cone test parameters—slump, spread, and shape—have to be met together for SFSCC mix design.



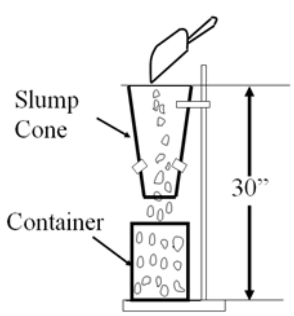
(a) well compacted

(b) poorly compacted

Figure A–1. Slump cone shape versus concrete compactability

Compaction Factor Tests

A modified compaction factor test method was used to evaluate the self-consolidating ability or compactability of a concrete mixture (Figure A–2). In this test, an inverse slump cone is placed above a 4 by 8 in. (10 by 20 cm) cylinder. Freshly mixed concrete is filled in the slump cone and falls into the container under its own weight. The unit weight of the concrete cylinder is then measured and compared with that of concrete cylinder prepared with three layers and rodded 25 times for each layer. The compaction factor of the concrete is expressed by the ratio of the unit weights of the unrodded and rodded concrete.



$$CF = \frac{UW\ (\text{un-compacted})}{UW\ (\text{compacted})}$$

CF – compaction factor
UW – unit weight

(a) Un-compacted concrete (b) Compacted concrete

Figure A–2. Compaction factor test setup

“Green” Strength Tests

A simple test was initially developed to assess the “green” strength of fresh concrete. Figure A–3 illustrates the Method A test procedure for the concrete green strength measurement.

In this test, a plastic cylinder mold (4 by 4 in. [10 by10 cm] without bottom) was used for concrete casting. During the casting, a concrete mixture was placed into the cylinder mold at a given height (6 in. [15 cm]) with no additional consolidation applied. Immediately after the cylinder was filled up, the plastic mold was removed, and the shape of the concrete sample was examined. If a mixture demonstrated little or no deformation after the mold was removed, the mixture was considered to have good shape-holding ability, and the green strength test of the sample was then pursued. A large plastic cylinder was placed on the top of the fresh concrete sample. A small amount of sand was then slowly but continuously poured into the large plastic cylinder until the sample collapsed. The maximum amount of the sand applied during the test divided by the loading area of the sample defined the green strength of the concrete.

(a) Test setup: slump cone placed on top of a plastic mold without the bottom

(b) Casting: mold is filled with fresh concrete without rodding or vibration

(c) Demolding: after plastic mold is removed; some concrete holds its shape

(d) Loading: a big cylinder is placed on top of fresh concrete sample; sand is gradually loaded into cylinder until sample fails

Figure A–3. Test procedure for concrete green strength measurement, Method A

In the later course of the SFSCC development, the above green strength test method was further modified (Method B). A standard drop table was used and the shape stability of the tested materials was evaluated after compaction. As shown in Figure A–4, in the modified test, a 4 by 8 in. cylinder was loosely filled up with fresh concrete. This cylinder was then placed on the drop table and subjected to 25 drops. After the compaction, the cylinder was turned over and demolded. A vertical force was applied to the cylinder until the specimen collapsed. The maximum load was used to calculate the green strength of the tested cylinder.

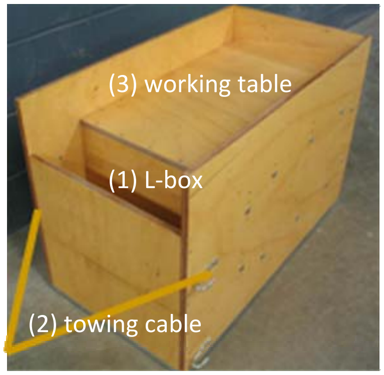
(a) Drop table (b) After 25 drops (c) After loading

Figure A–4. Device and samples used for modified green strength measurement, Method B

Mini-Paver Tests

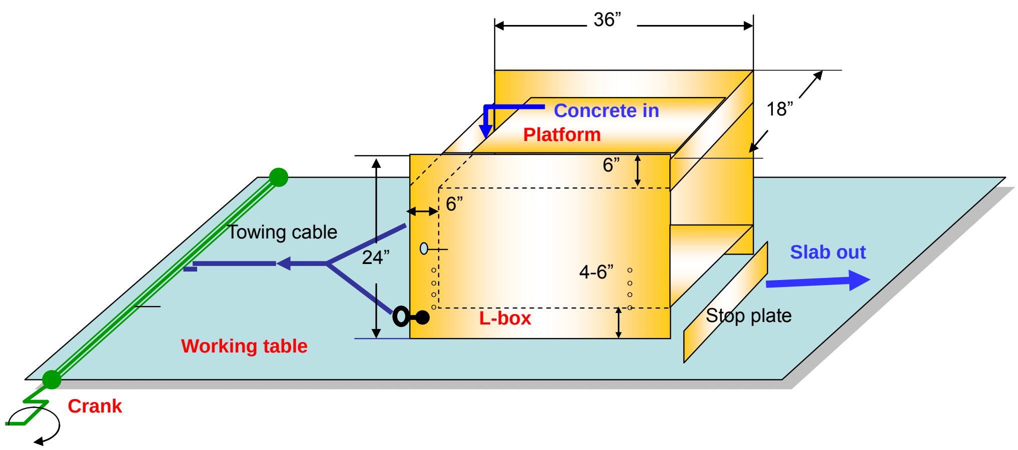
A mini-paver was developed to simulate field paving using SFSCC in laboratory. As shown in Figure A–5, the system consists of three parts: (1) an L-box with a platform on top, (2) a towing system (a towing cable and a crank), and (3) a working table. The L-box was 18 in. (46 cm) wide, 24 in. (60 cm) long, 18 in. (46 cm) high, and 3 to 6 in. (7.5 to 15 cm) thick. It could pave an18 in. (46 cm) wide, 3 to 6 in. (7.5 to 15 cm) thick, and 48 in. (122 cm) long slab in the lab using two cubic feet of concrete mixture.

Before the paving test, approximately 200 pounds of weights were placed in the back chamber of the paver (Figure A–5[b]). A stop plate was positioned at the end of the horizontal leg of the L-box. Freshly mixed concrete was stored on the platform. To begin paving, the concrete was pushed from the platform into the vertical leg of the L-box up to a certain height, which generated a pressure to consolidate the concrete. After that, the crank system was turned and it pulled the mini-paver forward at a designed speed (3 to 5 ft/min). As the mini-paver moved forward, it extruded the concrete slab out of the horizontal leg of the L-box.



(a) front view

(b) back view



(c) sketch

Figure A–5. Mini-paver system

APPENDIX B: SEQUENCE OF FIELD OPERATIONS FOR SFSCC CONSTRUCTION

Construction of Bike Path at South 4th Street

No	Item	Time
	S4TH-M1	
1	Adding of UltraFiber 500 and Navitas 33	7:30 am
2	Mixing of other concrete materials	7:36 am
3	Arrival at the site	7:50 am
4	Slump test	8:00 am
5	Slump test with HRWR	8:10 am
6	Start of paving	8:20 am
7	End of paving	8:22 am
Time from the concrete arrived at the site to start of paving		30 minutes
	S4TH-M2	
8	Arrival at the site	8:56 am
9	Testing of slump	8:57 am
10	Start of paving	9:11 am
11	End of paving	9:18 am
Time from the concrete arrived at the site to start of paving		15 minutes
12	Brooming	10.03 am

Construction of City Road at North Riverside Drive

No	Item	Time
	NR-M1-A	
1	Mixing of concrete materials	11:41 am
2	Arrival at the site	12:00 pm
3	Slump test	12:00 pm
4	Start of paving	12:17 pm
5	End of paving	12:38 pm
Time from the concrete arrived at the site to start of paving		17 minutes
	NR-M2-A	
6	Mixing of concrete materials	11:55 am
7	Arrival at the site	12:15 pm
8	Slump test	12:55 pm
9	Start of paving	1:02 pm
10	End of paving	1:30 pm
Time from the concrete arrived at the site to start of paving		47 minutes
	NR-M3-A	
11	Mixing of concrete materials	12:09 pm
12	Arrival at the site	12:35 pm
13	Slump test	1:35 pm
14	Start of paving	1:37 pm
15	End of paving	1:45 pm

Time from the concrete arrived at the site to start of paving		62 minutes
16	Start of surface finishing	12:38 pm
17	Start of curing compound spray	1:30 pm