PROPOSAL

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

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A. PHASE II PROPOSAL SUMMARY

1. Project Objective

The objective of this research is to develop a new type of concrete that can self-consolidate (without vibration) and hold its shape right after slip-form paving. Different from the conventional self-consolidating concrete (SCC), which has very high flowability and requires formwork for construction, this new type of self-consolidating concrete for slip-form paving (SF SCC) will have sufficient flowability (a slump of approximate 8”) for self-consolidation but be stiff enough to hold its shape right after paving, thus not requiring formwork for construction.

2. Project Background

The overall Self-Consolidating Concrete—Applications for Slip-Form Paving project is a collaborative, multi-phase, and multi-sponsored program. The project is being performed through collaboration between the National Concrete Pavement Technology Center (CP Tech Center) at Iowa State University (ISU) and the Center for Advanced Cement-Based Materials (ACBM) at Northwestern University (NU). (Note: The CP Tech Center was known as the Center for Portland Cement Concrete Pavement Technology, or PCC Center, at the time of Phase I; the new name is used here throughout for consistency.)

Five state departments of transportation (Iowa DOT, Kansas DOT, Nebraska DOR, New York State DOT, and Washington State DOT), industry (W. R. Grace and Active Minerals Company), the FHWA, and the CP Tech Center participated in the Phase I study, TPF-5(098). Phase I, completed in November 2005, demonstrated the feasibility of designing a new type of SF SCC that can not only self-consolidate but also have timely shape-holding ability. As summarized in the Appendix, the results from the Phase I study clearly show that the development of such a SF SCC for field application is feasible. The complete Phase I report can be found at the CP Tech Center’s website, www.cptechcenter.org.

3. Phase II Overview

Based on the promising results of Phase I, additional study is proposed to refine the mix design of SCC for slip-form paving and apply the new SF SCC in the field. Proposed sponsorship for Phase II is through a combination of funding from the CP Tech Center Cooperative Agreement with the FHWA, FHWA and state DOTs through a pooled fund, and private industry contributions. Interested state DOTs will be asked to obligate funds at the beginning of Phase II for funding from Fiscal Year 2006, 2007, and/or 2008. See Sections C and D for more detail on the proposed plan, budget, and funding.

Representatives from the FHWA, state DOTs, the cement and concrete paving/equipment industries, and other organizations sponsoring the study will serve as Technical Advisory Committee (TAC) members. A paver manufacturer and a contractor will be invited to join the TAC to help guide the field application of the new SF SCC technology. The TAC will provide input on the project direction and ongoing research activities. This group will also help ensure a smooth transition between Tasks 1, 2, and 3.

Task 1. Mix Design Refinement and Field Trial Testing

As described in Section C, Task 1 is designed to minimize the gap between the laboratory study and field application. In this task, the SF SCC mix proportions obtained from Phase I will be further modified, and the engineering properties of selected concrete mixes will be further evaluated. A small scale of field trial tests will then be conducted, and the field test results will be used for the Task 2 study. The estimated duration for Task 1 is 15 months.

Task 2. Field Investigation

As described in Section C, Task 2 subtasks include (1) selecting paving equipment for SF SCC application, (2) determining construction time and location, (3) performing various field tests to characterize SF SCC performance, (4) analyzing field test data and establishing primary guidelines for construction of SF SCC, and (5) preparing an interim report. The estimated duration for Task 2 is one year (12 months).

Task 3. Performance Monitoring and Technology Transfer

As described in Section C, Task 3 will focus on the evaluation of the in-service performance of field demonstration sites. The pavement performance characteristics will be monitored at 1, 3, and 5 year intervals. The evaluation will include pavement surface condition (such as smoothness, cracking, and surface defects). Effects of deicing chemicals on the SF SCC pavement in particular will be studied. Field demonstrations, short courses, workshops, publications, and videos will be conducted for the new SF SCC technology to assist in implementation nationally. The estimated duration for Task 3 is 5 years.

B. PROBLEM STATEMENT AND RESEARCH BACKGROUND

Slip-form paving has been extensively used worldwide by the paving industry since its development in Iowa in the 1940s. Slip-form pavement concrete generally has a slump less than 2 inches, which ensures the shape stability of the fresh concrete that keeps the fresh concrete in a rectangular shape right after it is extruded from the paver. Because of the low slump of the mixture, a great deal of vibration is necessary to move entrapped air and consolidate the concrete. Over-consolidation of pavements has been noted visually in finished pavements. Longitudinal trails, called vibrator trails, observed in the surface of the concrete pavements run parallel to each other, with spacing similar to that of the vibrators on the pavers. Cores taken from vibrator trails of some pavements have revealed that in many instances the hardened concrete contains less than 3% air, rather than 6%-7% as designed, thus significantly reducing concrete freeze-thaw durability.

Today's concrete research and practice have shown that material selection and mix design of concrete can be tailored to provide good compaction without the need for vibration. This approach is based on the principles of self-consolidating concrete (SCC) widely used in precast and cast-in-place construction. SCC has generated tremendous industrial interest since its initial introduction in Japan in 1990. Due to its excellent flowability and stability (segregation resistance), SCC has been used for many different applications, including bridge decks, precast bridge members, and pavement repairs. SCC can be cast and self-compacted in small dimension and/or heavily reinforced formwork without vibration. Use of SCC technology also increases the speed of the construction, improves the quality of the concrete (without segregation and loss of air), and reduces the cost of labor and energy caused by vibration and/or noise.

A challenge in developing SCC for slip-form paving (SF SCC) is that the new SF SCC needs to possess not only excellent self-compactibility and stability before extrusion but also sufficient "green" strength right after extrusion while the concrete is still in a plastic (green) state. Such green strength will ensure that the fresh concrete can sustain its self-weight, or hold the slab in shape, without having support from any formwork. To obtain self-compactibility, a concrete mixture needs to overcome the shear strength resulting primarily from particle friction and cohesion. In order to hold the slab in shape, the fresh concrete must gain enough shear strength. A key challenge is achieving the necessary concrete properties related to shear strength at each of these appropriate times.

At a high shear rate (such as during mixing), concrete microstructure is disturbed, and its yield stress and viscosity are reduced. Thus, the concrete becomes flowable and self-compactible. When at a low or zero shear rate, concrete microstructure can be re-built, green strength will develop, and the concrete will become less deformable. The extrusion process, even at low pressure, will help concrete consolidation, while rearrangement of solid particles for packing will lead to green strength development.

Based on the promising results from Phase I (see Appendix), the research team believes that a desirable balance between compactibility and green strength or shape-holding ability of a concrete mixture may be achieved by carefully balancing concrete materials and mix design. The new SF SCC will (1) be workable enough for machine placement, (2) be self-compacting with minimum segregation, (3) hold shape after extrusion from a paver, and (4) have performance properties (strength and durability) compatible to current pavement concrete.

C. PHASE II WORK PLAN

Although significant achievements have been made in Phase I (see Appendix), more research on SF SCC is needed to bring the laboratory research results into concrete field practice. Phase II provides the transition between the laboratory research and field application of the new SF SCC technology. The TAC will meet to provide input on the project direction and ongoing research activities. This section provides the proposed work plan for Phase II.

Task 1. Mix Design Refinement and Field Trial Testing

Subtask 1.1. Further Study SF SCC Materials and Mix Proportions

Several promising mixture proportions have been identified in Phase I. Systematical study on various material and mix-design variables is still needed. These variables include different type, size, and gradation of aggregate, different type and proportion of cementitious materials (portland cement, fly ash, slag, silica fume, and clay), and different type and amount of chemical admixtures (water reducer, VMA (voids in mineral aggregate), and superplasticizer).

In Subtask 1.1, the research team will select a rational minimum number of mixes to study these variables. Screening tests will be performed to find out how these designed parameters influence flow ability, self-consolidating ability, shape-holding ability, and hardened strength of these mixes. Selected mixes will be further tested in Subtask 1.2 for proper setting, air structure, and strength development.

Subtask 1.2. Conduct Quality Control Tests for Selected SF SCC Mixtures

In addition to slump and green strength, set time, heat of cement hydration, or maturity, entrained and entrapped air content, and 1-day and 3-day compressive strength of the concrete made with selected SF SCC mixes will be tested in Subtask 1.2. These test results will provide engineers with basic information on fresh concrete performance and on the time for saw cutting and/or the time for pavement to open to traffic. Some concrete mix proportions may be further modified based on these test results before the mixes are further tested in Subtask 1.3.

Subtask 1.3. Investigate Engineering Properties and Durability of SF SCC Candidates

Based on the test data obtained from Subtasks 1.1 and 1.2, two to three potential SF SCC mix proportions will be chosen for some preliminary durability tests, such as drying free and/or restraint shrinkage measurement, scaling, and freezing-thawing tests. The damaging effect of deicing chemicals on the SF SCC mixes will be considered in the scaling test. The purpose of the durability study is to prevent severe premature (within 1-2 years) deterioration after the new SF SCC is applied to field in Tasks 2 and 3. Due to the limited time, other engineering property and durability tests, such as elastic modulus, Poisson ratios, thermal coefficient, sulfate attack, alkali-silica reaction (ASR), etc., will be studied in the future.

Subtask 1.4. Conduct Field Paving Trial Tests Using SF SCC

During Phase I, the research team and TAC members recognized and discussed the scale problem related to the lab simulation conducted with the mini-paver. Although the current mini-paver can pave a slab with a thickness varying from 3” to 6”, the lab paving situation is still very different from that of 8”-12” thick concrete paving in the field. Depending on mix design, the SF SCC shape-holding ability may be significantly affected by the pavement geometry (such as height). Therefore, mini-field tests are proposed before the SF SCC is applied to full-scale field paving. One or two field trial tests will be performed for paving of curb, bike-trail, or whitetopping using the newly developed SF SCC.

Participating state DOTs will have representatives serve as project TAC members and participate in the coordination of work for the field sites. The research team will work closely with the TAC members to select contractors and field sites and to conduct field tests. Constructability and consistency of the field SF SCC will be evaluated. Deicing chemicals will be applied to the SF SCC structures as a part of the trial tests. Additional mix design modifications and lab tests may be necessary. Task 2 will proceed once the field trial tests are determined to be successful.

Task 1.5. Develop SF SCC Mix Design Methodology and Acceptance Criteria

While identifying a few of the promising SF SCC mix proportions, the research team will also explore a methodology for SF SCC mix design. ACBM has developed a rheological model that makes possible the close control of SCC properties while the construction project suffers changes of raw materials and climatic conditions. The model is based on paste rheology criteria, which includes minimum apparent viscosity, minimum flow, and optimum flow-viscosity ratio to achieve SCC with satisfactory segregation resistance and deformability. This model will be further extended as a tool for mix design, choice of materials, and quality control of SF SCC.

Because the previously developed mix design criteria for conventional SCC cannot be directly applied to the new SF SCC, these existing criteria for conventional SCC will be modified and new criteria for SF SCC mix design will be established according to the preliminary information obtained from Subtasks 1.1-1.4. To achieve this, the optimal combination of yield stress and viscosity for SF SCC will be determined. The yield stress and viscosity of concrete determined by a rheometer may be related to the simple slump and compaction tests.

Subtask 1.6. Further Study the “Green” Strength, Shape-holding Ability, and Compactibility of SF SCC

Phase I showed that the desired properties of SF SCC can only be accomplished if the parameters of green strength and flowability are located within a certain range. For most of the tested mixtures, these two parameters follow a trend that shows a decrease in green strength with an increase in flowability. However, some of the tested mixtures do not follow this trend and they have higher green strength for a given flowability. An important objective of the Phase II Task 1 research is to understand the factors that govern the relationship between green strength and flowability of fresh concrete.

The researchers will continue finding appropriate ways to characterize the compactibility and flowability of fresh concrete. The flow drop table tests used by ACBM in Phase I can be further employed to conduct reliable and repeatable tests on concrete with small size aggregates. To investigate concrete with the large size limestone aggregates, a new, large-scale, drop table test will be devised. This test will allow a rapid assessment of the flowability of any concrete mixture in the laboratory or the field.

Phase I study has indicated that pressure has significant influence on concrete shape-holding ability. In Phase II Task 1, emphasis will be placed on the development of a laboratory compactibility test to investigate the pressure effect.

Research has revealed that the distance between aggregate surfaces dominates concrete particle packing, which has considerable influence on the concrete flow properties. Factors such as aggregate size, shape, content, gradation, and coarse aggregate/total aggregate ratio affect the spacing between aggregate particles in concrete. Green strength of SCC provided by internal friction and cohesion also significantly depends on the aggregate (or paste) volume and particle arrangement/orientation.

In Subtask 1.6, the internal friction and cohesion of SF SCC aggregate particles will be studied using a direct shear test based on the concept of soil mechanics, and the aggregate packing characteristics will be studied using X-ray CT scanning. X-ray CT scanning equipment is available at the Center for Nondestructive Evaluation (CNDE) at ISU. By using this technology, particle packing characteristics of current pavement concrete and newly developed SCC mixes will be further studied, and their effects on flowability, stability, and green strength of concrete will be analyzed.

Subtask 1.7. Complete Test Data Analyses and Prepare Task 1 Report

At the end of Task 1, all test data will be systematically analyzed, and an interim report will be prepared to summarize all work done in this phase. The report will be sent to all TAC members for review and comments before it is finalized. Revisions to the work plan for Tasks 2 and 3 may also be proposed.

Task 2. Phase Field Investigation of SF SCC Paving

Subtask 2.1. Select/Modify Paving Equipment for SF SCC Applications

Based on the experience from the trial SF SCC paving in Task 1 and input from the TAC, paving contractor, equipment manufacturer, and ready mix supplier, the researchers will select one or two pavers and evaluate their suitability (such as paving speed and extrusion pressure) for SF SCC paving. The current paving equipment with turn-off vibrators may be tried first. Suggestions on modification of the pavers will then be proposed based on the evaluation results. The need for surface finishing as well as the time required for finishing, texturing, curing, and saw cutting will also be considered.

Subtask 2.2. Determine Construction Times and Locations

It is preferred that a pavement site in Iowa and one or two sites in other states will be selected for the SF SCC application. The SF SCC will be used in the construction of a concrete pavement section and possibly an overlay application. Pavement length, width, and thickness as well as possibility for deicer applications will be considered in the field site selection. SF SCC mix design may be modified based on the locally available materials and the pavement environmental conditions.

Subtask 2.3. Perform Field Tests to Characterize SF SCC Performance

General concrete quality tests, such as slump (slump spread), air content, unit weight compressive/flexural strength, and maturity of concrete, will be performed at SF SCC paving sites. Visual observation of the shape-holding ability and surface condition of the pavement will be examined. Cores will be taken from the SF SCC pavement to test the concrete strength, air system, and rapid chloride permeability.

Moisture and temperature profile in the pavement may be also monitored. Deicing chemical will also be applied to the pavement. The investigation sites before, during, and after paving will be videotaped for analysis in Subtask 2.4. Regular visual inspection of the tested pavements will be performed, and possible cracking, faulting, and joint opening will be monitored.

Subtask 2.4. Analyze Field Test Data and Establish Primary Guidelines for SF SCC Paving

The data collected from Subtask 2.3 will be used to identify the new developed SF SCC and paving equipment. The measured concrete properties, problems, and possible causes will be evaluated. This information will be used to further improve the mixture design and/or to modify the paving equipment and paving procedure.

Guidelines including mixing method (time and procedure) for SF SCC will be specified. Necessary modification of the paver will be made. Specifications for paving conditions including paver speed, paving thickness, and joint spacing will also be decided according to Subtask 2.1. TAC members will review and approve the developed guidelines.

Subtask 2.5. Prepare Task 2 Report

An interim report will be prepared at the end of Task 2.

Task 3. Performance Monitoring and Technology Transfer

Subtask 3.1. Field Performance Monitoring of SF SCC Pavement

In-service performance of the field demonstration sites will be monitored and documented at 1, 3, and 5 years. The pavement performance characteristics to be monitored and/or evaluated will include pavement surface condition (such as smoothness, cracking, and surface defects). Non-destructive evaluation (NDE) methods such as laser scan and falling weight deflectometer (FWD) may be used in addition to visual examination. Cores may be taken from selected areas for strength and air void analysis of the concrete in service and the results will be compared with those obtained from Subtask 2.3.

Subtask 3.2. Technology Transfer

A technology transfer program will be developed to provide the participants with the results of the overall study and assist the state DOTs in the mix design of SF SCC using their local materials. Tech transfer efforts will include field paving demonstrations, short courses, workshops, tech brief publications, and short videos. The TAC and other interested stakeholders will be invited to the demonstrations and workshops.

Subtask 3.3. Prepare Final Report for Entire Project

A final report documenting the entire project and its conclusions will be prepared.

D. RESEARCH TEAM, PROJECT SCHEDULE, AND BUDGET

1. Research Team

A collaborative research team from the National Concrete Pavement Technology Center (CP Tech Center) at Iowa State University (ISU) and the Center for Advanced Cement Based Materials (ACBM) at Northwestern University (NU) has been formed to conduct this research.

The CP Tech Center will lead this project. ISU team members Kejin Wang, David White, Bob Steffes, and Jim Grove have significant relevant experience in concrete materials, pavement system design, and construction.

ACBM is a national leader in development of SCC and concrete extrusion technology. NU team members, including Surendra P. Shah, will provide the study with input and analysis related to testing, modeling, and mix design of SCC.

The ISU and NU levels of involvement in each task are indicated in Table 2.

Table 2. Research Tasks and Team Involvement

Task 1	**ISU**	**NU**
1.1. Further study SF SCC materials and mix proportions	XXX	XXX
1.2. Conduct quality control tests for selected SF SCC mixtures	XXX	XXX
1.3. Investigate engineering properties and durability of SF SCC candidates	XXX	XX
1.4. Conduct field paving trial tests using SF SCC	XXX	XX
1.5. Develop SF SCC mix design methodology and acceptance criteria	XX	XXX
1.6. Further study the green strength, shape-holding ability, and compactibility of SF SCC	XXX	XXX
1.7. Complete test data analysis and prepare Phase II report	XXX	X
Task 2		
1.1. Select/modify paving equipment for SF SCC applications	XXX	XX
1.2. Determine construction times and locations	XXX	X
1.3. Perform field tests to characterize SF SCC performance	XXX	XX
1.4. Analyze field test data and establish primary guidelines for SF SCC paving	XXX	XXX
1.5. Prepare Phase III-A interim report	XXX	XXX
Task 3		
1.1. Field performance monitoring	XXX	X
1.2. Technology transfer	XXX	XX
1.3. Prepare final report for entire project	XXX	XXX

Notes: XXX = heavily involved; XX = moderately involved; X = involved.

The TAC will consist of experts from state DOTs, FHWA, and the concrete industry. The committee will keep the project well grounded in an industrial perspective.

2. Anticipated Project Schedule and Budget

The anticipated project schedule and budget are summarized below. An itemized budget is provided in Table 3.

Task	Total
Pooled fund TAC member travel (funded from pooled fund only)	$25,000
Task 1. Mix Design Refinement and Field Trial Testing (15 months)	$200,000
Task 2. Field Investigation (12 months)	$200,000
Task 3. Performance Monitoring and Technology Transfer (5 years)	$85,000
Total	**$510,000**

Table 3. Itemized Budget

Task	ISU	NU	Subtotal
Pooled fund TAC member travel for meeting and/or field trials			25,000
Task 1			
1.1. Further study SF SCC materials and mix proportions	30,000	25,000	55,000
1.2. Conduct quality control tests for selected SF SCC mixtures	6,000	3,000	9,000
1.3. Investigate engineering properties and durability of SF SCC candidates	16,000	8,000	24,000
1.4. Conduct field paving trial tests using SF SCC	22,000	5,000	27,000
1.5. Develop SF SCC mix design methodology and acceptance criteria	8,000	10,000	18,000
1.6. Further study the green strength, shape-holding ability, and compactibility of SF SCC	30,000	25,000	55,000
1.7. Complete test data analysis and prepare Task 1 interim report	8,000	4,000	12,000
Task 1 Subtotal	**120,000**	**80,000**	**200,000**
Task 2			
2.1. Select/modify paving equipment for SF SCC applications	10,000	5,000	15,000
2.2. Determine construction times and locations	5,000	2,000	30,000
2.3. Perform field tests to characterize SF SCC performance	100,000	25,000	20,000
2.4. Analyze field test data and establish primary guidelines for SF SCC paving	30,000	15,000	60,000
2.5. Prepare Task 2 interim report	5,000	3,000	13,000
Task 2 Subtotal	**150,000**	**50,000**	**200,000**
Task 3			
3.1. Field performance monitoring	35,000	10,000	45,000
3.2. Technology transfer	25,000	5,000	30,000
3.3. Prepare final report for entire project	5,000	5,000	10,000
Task 3 Subtotal	**60,000**	**20,000**	**85,000**
TOTAL			**$510,000**

3. Estimated Level of Funding Required

The funding breakdown is proposed as the following:

CP Tech Center Cooperative Agreement with FHWA	$210,000
FHWA pooled funding	$100,000
State DOT pooled funding (5 @ $30,000 each)	$150,000
Industry	$ 50,000
Total	$510,000

In addition to research funding support from the CP Tech Center, FHWA, and state DOTs, this project may need materials support from fly ash, slag, and cement organizations and field test support from the paving industry.

E. ANTICIPATED PROJECT IMPACT AND IMPLEMENTATION

1. Project Deliverables

- Demonstration projects for the implementation of pavement system design and construction using SF SCC
- Assessment of the need to modify existing paving equipment to fit the new paving technology (in consultation with construction equipment manufacturers)
- Recommendations concerning specifications for design and construction of SF SCC
- Final report and project summary at the end of the project
- Project video and website
- Performance reports documenting the long-term properties, especially durability, of the new SF SCC demonstration projects at 1, 3, and 5 years

2. Intended Users of Results

This research is intended to be of interest and benefit to state and local transportation agencies and the concrete paving materials, construction, and equipment industries. The research results will be useful for slip-form paving but also for slip-form construction of pipes, tanks, towers, silos, and high-rise buildings. A specification should be developed from the results to address pavement structure design, material design, and construction of SF SCC. Construction equipment will be simplified based on the new paving technology.

3. Implementation Plan

- DOTs may conduct demonstration projects for the implementation of pavement system design and construction using SF SCC.
- DOTs and construction equipment companies may work together to modify existing pavers to fit the new paving technology.
- DOTs involved in this project may take a lead in the development of new specifications for design and construction of SF SCC.

4. Anticipated Benefits

This new technology may have revolutionary impacts on the environment, construction costs, and pavement sustainability. The potential benefits of this new type of SF SCC include the following:

- Better pavement performance
- Reduced construction costs
- Elimination of vibrator trails in concrete pavement
- More uniform air void system
- Improved uniformity of concrete pavements by reducing the problems resulting from inconsistent vibration of concrete such as segregation and air loss
- Improved pavement smoothness by minimizing hand surface finishing requirements
- Elimination of heavy formwork required by the use of conventional SCC
- Reduced construction machine energy and noise that are consumed and generated by vibrators
- Solutions to consolidating thin concrete pavement sections (such as ultrathin overlays, two-lift, and curb paving) where regular vibration is difficult to apply properly

APPENDIX. SUMMARY OF PHASE I FEASIBILITY STUDY

The research team completed the following major tasks as part of Phase I:

- Formed a technical advisory committee for the project and collected input on the new technology
- Investigated essential material components and potential mix proportions of SF SCC
- Developed test methods for characterization of the new SF SCC
- Simulated the slip-form paving process in a laboratory test

The preliminary research results indicate the following:

- New SF SCC can self-consolidate and can hold its shape right after paving.
- The strength of the SF SCC is comparable to the strength of standard pavement concrete.

The major findings work performed at the CP Tech Center/ISU and ACBM/NU are summarized below.

1. Work Conducted at the CP Tech Center/ISU

The research team members at the CP Tech Center first investigated the effects of materials on concrete flowability, consolidation, and shape-holding ability. The investigation focused on the effects of supplementary cementitious materials (SCMs) (such as slag, fly ash, limestone dust, gypsum, and Acti-gel) and aggregate gradation on flow behavior of pastes and concrete. The flow properties of pastes were evaluated by a Brookfield rheometer, and the flow properties of concrete were assessed primarily by a standard slump cone test.

Slag replacement increased both yield stress and viscosity, while fly ash replacement decreased yield stress but increased the viscosity of paste, which increased the flowability of the paste. The quality of coarse aggregate gradation could be evaluated with the difference between loose and compacted bulk density of the aggregate, which provided a good indication of the energy needed for the aggregate to be well packed and had a close relationship with concrete compaction factor. Concrete mixtures made with different materials and mix proportions displayed different slump, spread, and shape after slump cone tests. Some concrete mixtures may have a similar slump value but different spread values and shape stability. Proper balance among slump, spread, and shape might provide the concrete with proper ability to self-compact and hold shape.

Conventional pavement concrete mixtures had a low slump and very little spread. This concrete showed good shape-holding ability but little flowability without vibration; therefore, vibration is necessary for consolidation. On the other hand, conventional SCC had very high slump and large spread values. This concrete flowed well but had no timely shape-holding ability, therefore requiring formwork for construction. The researchers found out that the flow behavior of the new SF SCC is between these two extreme concrete mixtures (i.e., conventional pavement concrete and SCC mixtures). The shape of the concrete after the slump cone test could also provide valuable information on the shape-holding ability of the concrete. Several mixtures tested at ISU had similar slump, but only a few mixtures kept a regular short cone shape after the slump cone was removed. The researchers identified that the potential new SF SCC mixtures might have a slump value of approximately 7”-8” and a spread value of approximately 13”-15” with a regular short cone shape after the slump cone was removed.

After identifying the features of the potential SF SCC mixtures, the researchers at ISU then developed a simple test method to evaluate the “green” strength of the concrete mixtures. In this simple test, a fresh concrete cylinder sample was cast in a plastic mold without a bottom. Right after casting, the plastic mold was removed, and the sample was loaded slowly with sand until it collapsed. The total amount of sand applied in the test divided by the loading area of the sample defined the green strength of the concrete. Researchers found that the green strength generally decreased with concrete compaction factor. Although it had low green strength, the newly developed SF SCC did self-consolidate and hold its shape very well right after casting and de-molding. Addition of Acti-gel into the SF SCC mixture significantly increased the concrete green strength. Adopting this simple test method, ACBM researchers further evaluated the green strength of various concrete mixtures. It was also found that the 7-day compressive strength of the new SF SCC cylinder samples was approximately 5500 psi, comparable with that of conventional pavement concrete. No visible honeycombing or segregation was observed from the digital images of the cross section of the hardened SF SCC cylinder samples.

Encouraged by the initial success, the project research team was eager to find out whether or not this new SF SCC was applicable to field paving. To address this question, the CP Tech Center team members developed a simple mini-paver for paving SF SCC segments in the laboratory. See Figure 1.

Figure 1. Mini-paver

In April 2005, the first trial of the mini-paver test was conducted at ISU’s PCC Pavement and Materials Research Laboratory. To start paving, fresh concrete was first pushed from a platform into the vertical leg of the box up to a certain height, which generated a pressure to consolidate the concrete. Then, the mini-paver was pulled forward by a crank system at a designed speed (3-5 ft/min). As the mini-paver moved forward, it extruded a 4.5-foot concrete pavement slab out of the horizontal leg of the box. See Figure 2. Videos of the mini-paver test are available at www.cptechcenter.org/research/scc/.

Figure 2. SF SCC pavement slab produced using mini-paver

With no additional consolidation applied during the test, the SF SCC not only flowed and consolidated well but also held the shape of the slab very well, especially at edge. The 9-day compressive strength of the 2” cylinders cored from the slab was 4900 psi and the splitting tensile strength was 420 psi.

After receiving the brief presentations and reviewing the videotape of the mini-paver test on May 6, 2005, all TAC members agreed that the initial work presented by the research team had demonstrated a promising approach to further development of SF SCC for field applications. Various suggestions were provided by the participants on further study of SF SCC. These suggestions were divided into two categories: (1) for immediate action and (2) for Phase II study.

The immediate action items suggested by the TAC members included the following:

- Conduct a mini-paver test with different sizes of dowel bars in the slab.
- Perform a mini-paver test using one or two ACBM mix proportions.
- Conduct some engineering property tests (such as set time, heat of cement hydration, and strength development) for the newly developed SF SCC.
- Summarize the Phase I study.
- Develop a proposal for Phase II study.

The research team has taken actions on all these suggested items. The recent mini-paver tests indicated that the SF SCC had comparable set time, heat evolution, and strength development to conventional pavement concrete. It also had a very good bond with simulated dowel bars. The selected ACBM mixture demonstrated excellent consolidation and shape-holding ability. Using a copy of the mini-paver equipment, ACBM is simulating the slip-form paving process at its lab for more concrete mixes.

2. Work Conducted at ACBM/NU

ACBM researchers conducted a focused, systematical investigation on the effects of mineral and chemical additives (clay, fly ash, and superplasticizer) on the flowability of fresh concrete mixtures. Specifically, the following parameters were examined:

- Type and content of plasticizer
- Paste content
- Type and content of clay
- Fly ash addition

The investigations were conducted by adapting the mixture proportion of a conventional self-consolidation concrete. It was then examined how the flowability of this concrete could be manipulated to combine the good flow properties with the shape stability required for concrete used for slip-form paving. An important aspect in the evaluation of the results was achieving an understanding of the relationship between green strength and flowability of the fresh concrete. The ultimate goal of the investigations was to find the optimum combination of these two parameters to achieve a self-consolidating and at the same time shape-stable material.

To investigate the influence of the type of plasticizer on the flowability and green strength of fresh concrete, the flowability of a conventional SCC mix design with a polycarboxylate-based plasticizer in different amounts was compared with the same concrete mixture containing naphtaline-based plasticizer. It was found that the concrete containing naphtaline-based plasticizer exhibited a larger flow diameter on the drop table than the one containing polycarboxylate-based plasticizer. This indicates that naphtaline-based plasticizers have a positive effect on the flowability of concrete under the influence of external compaction energy.

The use of different clays, commonly used in standard SCC, was investigated in this study. Experiments concerning the influence of different fine materials on the flowability of fresh concrete showed that all tested clays, especially Acti-Gel, were effective in reducing the flowability of the concrete. This was likely due to the finer particle size of the clays compared to that of fly ash and cement powder. The research team then conducted a more systematic investigation of the different clays. The results of this investigation are summarized in Table 1.

Table 1. Influence of Clay Type on Flowability of Fresh Concrete

Clay Type	Most beneficial additive amount (per cement weight)	Comments
Acti-Gel	1%-2%	1% represents best compromise between flow and green strength
Metakaolinite	1.5%	Increased flow by maintaining green strength of comparable plain concrete mixture
Kaolinite	1.5%	Significant increase in green strength with only minimal reduction of flow when compared to plain concrete

With respect to flowability only, the replacement is most beneficial for the amount of 10% of original cement weight. This, however, has a detrimental effect on the green strength and the shape stability of the fresh concrete. Although no green strength could be measured, the concrete did show certain shape retention. Future work will be done to improve the shape stability of this particular mixture.

The analysis of the relationship between green strength and flowability for all tested mixtures showed that the majority of the mixtures followed one main trend: green strength increased with a decrease in flow diameter after 25 drops on the drop table. An important finding is that certain mixtures were not part of this trend. These mixtures showed a higher green strength (corresponding to a better shape stability) for a given flowability than other mixtures. These mixtures are potential candidates to be recommended for use in low compaction energy concrete.

The researchers have found that it is necessary to have a high content of fine materials present in the fresh concrete to achieve a good balance between flowability and form stability in fresh state. There are two main parameters: (1) addition of fine particles and (2) modification of the type of plasticizer. Both modifications have led to significant improvement of the flowability of the fresh concrete.

3. Phase I Conclusions

The Phase I research results have demonstrated that it is feasible to engineer the materials present in the fresh concrete so as to achieve a good balance between flowability and form stability in fresh state. More detailed research activities conducted by the CP Tech Center and ACBM are presented in the Phase I report, which can be found at the CP Tech Center’s website, www.cptechcenter.org. The report also includes the results from X-ray computed tomography (X-ray CT) tests performed at ISU, which monitored aggregate segregation and void distribution in selected SF SCC cylinder samples.

Because the new concrete may require a minimum of compaction energy (such as a static pressure) to achieve a maximum density, the designations of “Minimally Compacted Concrete (MCC)” and “Minimal Compaction Energy Concrete (MCEC)” have been proposed. The term “SF SCC” is currently used until the new designation is finalized.