Self-Consolidating Concrete (SCC) for Infrastructure Elements
Summary Report

Prepared By:

Missouri University of Science and Technology

Final Report Prepared for Missouri Department of Transportation

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FINAL Report

TRyy1103

Self-Consolidating Concrete (SCC) for Infrastructure Elements

Prepared for
Missouri Department of Transportation
Construction and Materials

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The investigation was conducted in cooperation with the U. S. Department of Transportation, Federal Highway Administration.

16. Abstract

Because of its unique nature, self-consolidating concrete (SCC) has the potential to significantly reduce costs associated with transportation-related infrastructure, benefiting both MoDOT and the residents of Missouri. SCC is a highly flowable, nonsegregating concrete that can be placed without any mechanical consolidation, and thus has the following advantages over conventional concrete including decreased labor and equipment costs during concrete placement, decreased potential for and costs to repair honeycombing and voids, increased production rates of precast and cast-in-place elements, and improved finish and appearance of cast and free concrete surfaces.

However, concerns exist over the structural implications of SCC in cast-in-place and precast elements. Specifically, higher paste contents, higher fines contents, and the use of smaller, rounded aggregates may significantly alter the creep, shrinkage, bond, and shear strength of SCC mixes as compared to traditional concrete mixes with the same compressive strength. These concerns increase for mixtures that use untested aggregate types and various supplementary cementitious materials.

The objective of this research was to determine the structural implications of using SCC mixes compared to traditional concrete mixes. This study focused on the hardened properties of SCC mixes containing Missouri aggregates and developed guidelines on its use in infrastructure elements for MoDOT. Consequently, to achieve the benefits and potential savings with SCC, this study undertook seven tasks including the following: Task 1: Literature Review; Task 2: Mix Development; Task 3: Bond and Development of Prestressing Strand and Mild Steel; Task 4: Hardened Properties of SCC Mixes; Task 5: Shear Properties of SCC Mixes; Task 6: Recommendations and Specifications for SCC Implementation; and Task 7: Value to MoDOT and Stakeholders to Implementing SCC. Within these studies, locally available materials were used that were representative of MoDOT produced concrete. The final report consists of a summary report and five technical reports. The findings, conclusions and recommendations of the study can be referenced within these reporting components.

17. Key Words Self-consolidating concrete (SCC), High-strength Self-consolidating concrete (HS-SCC), SCC Mix Design Survey, Bond and Development of Prestressing Strand and Mild Steel, Shear Characteristics of SCC, Fresh and Hardened Properties of SCC, and Durability of SCC.		18. Distribution Statement No restrictions. This document is available to the public through National Technical Information Center, Springfield, Virginia 22161	
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EXECUTIVE SUMMARY

This research project entitled, ***Self-Consolidating Concrete for Infrastructure Elements***, is separated into seven major task which include Task 1: Literature Review; Task 2: Mix Development; Task 3: Bond and Development of Prestressing Strand and Mild Steel; Task 4: Hardened Properties of SCC Mixes; Task 5: Shear Properties of SCC Mixes; Task 6: Recommendations and Specifications for SCC Implementation; and Task 7: Value to MoDOT and Stakeholders to Implementing SCC. Within these studies, locally available materials were used that were representative of MoDOT produced concrete including benchmark mix designs.

After thorough mechanical property, shear, bond, transfer, and durability testing, it is recommended that SCC be implemented in precast and prestressing applications within the State of Missouri. With SCC showing comparable results for hardened mechanical properties, insignificant variations in shrinkage, creep, abrasion, shear, bond, transfer and development and slightly higher performance for durability, SCC appears to be a viable option to decrease the cost of labor and time consumption during concrete placement. This performance was observed in both normal and high strength SCC, with high strength SCC performing at a slightly higher margin over high strength conventional concrete than SCC performed over conventional concrete. The following advantages over conventional concrete exist:

- *Decreased labor and equipment costs during concrete placement.* Limited “hard” data exists to date in the traditional sense from bid documents involving SCC concrete due to its innovative nature; however, through laboratory experience at Missouri S&T, 40 to 60% less labor was needed to fabricate and place concrete when comparing SCC elements to the conventional concrete elements, which required more personnel to consolidate the conventional concrete elements and produce standard quality control / quality assurance (QC/QA) specimens. As more SCC is implemented, historic cost trends will provide more quantitative financial data. However, it should be noted as SCC involves some new testing standards (i.e. QC/QA tests), there may be a “learning curve” for field and plant engineers / inspectors as they gain experience with new fresh concrete property testing protocols such as Slump Flow ASTM C 1611, J-Ring ASTM C 1621, L-Box (non-ASTM), and Column Segregation ASTM C 161.
- *Improved quality through the decreased potential for and costs to repair honeycombing and voids.* Due to SCC’s flowability, when properly formulated, there holds a great potential to decrease voids, anomalies and other defects that may occur during the placement of conventional concrete. This decreased potential should translate to an increase in the service life of the bridge or structure particularly as high-strength SCC is implemented with its improved durability performance.
- *Increased production rates of precast and cast-in-place elements.* In terms of both precast and cast-in-place elements, SCC offers the unique opportunity to expedite construction due to its unique characteristics. This increased rate of production translates into reduced construction time. This will open infrastructure systems in less time and help the traveling public in Missouri with reduced travel delays and congestion.
- *Improved finish and appearance of cast and free concrete surfaces.* While not a physical cost issue, improved finish and appearance of concrete elements provides an enhanced visual perspective of infrastructure elements for the riding public and will likely translate to a higher perceived level of quality.

FINAL SUMMARY REPORT

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Self-Consolidating Concrete (SCC) for Infrastructure Elements

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1. REPORT ORGANIZATION

The following report is organized as follows: Section 1 presents the report organization and acknowledgements. The project work plan is presented in Section 2 to familiarize the reader with the overall objectives, project tasks, and scope of the research study. Following the report work plan, the summary findings, conclusions, and recommendations are presented task by task in Section 3. Detailed Technical Reports A through E are attached following this summary report which provides the detailed specifics undertaken in this research investigation. The Summary Report is designed to provide the reader with the project highlights in terms of findings, conclusions, and recommendations, while Reports A through E provide the detailed approach, experimental procedures and processes, results, findings, and recommendations.

1.1 PROJECT ACKNOWLEDGEMENTS

The authors wish to acknowledge the leveraged funding to make this extensive study possible; first and foremost from the **Missouri Department of Transportation** (MoDOT), many thanks for not only the financial support, but also the many insightful comments particularly from the members of the Technical Advisory Group (TAG), namely Ms. Jennifer Harper, Mr. Gregory Sanders, and Mr. Brett Trautman.

In addition, the authors would like to thank the **National University Transportation Center** (NUTC): **Center for Transportation Infrastructure and Safety** (CTIS) housed at the Missouri University of Science and Technology (Missouri S&T), which provided valuable match funding from the United States Department of Transportation through RITA and the UTC Program.

The researchers would like to thank the **Precast/Prestressed Concrete Institute** (PCI) for providing an extremely valuable Daniel P. Jenny Student Fellowship for Ms. Krista Porterfield. This was the first PCI Fellowship received by Missouri S&T and the project investigators, which allowed for important and more in-depth bond related contributions to the project.

Finally, the project team would like to thank the **Missouri University of Science and Technology** for their valuable contribution in multiple forms: first, in the awarding of five Chancellor’s Fellowships to the graduate students working on this project. These individuals represented the very best of the best Missouri S&T graduate students. Secondly, the project team would like to thank the tireless staff of the **Department of Civil, Architectural and Environmental Engineering** and the **Center for Infrastructure Engineering Studies** at Missouri S&T. Their assistance both inside and out of the various laboratories assisted immensely.

2. PROJECT WORK PLAN

Because of its unique nature, self-consolidating concrete (SCC) has the potential to significantly reduce costs associated with transportation-related infrastructure, benefiting both MoDOT and the residents of Missouri. SCC is a highly flowable, nonsegregating concrete that can be placed without any mechanical consolidation, and thus has the following advantages over conventional concrete:

- decreased labor and equipment costs during concrete placement,
- decreased potential for and costs to repair honeycombing and voids,
- increased production rates of precast and cast-in-place elements, and
- improved finish and appearance of cast and free concrete surfaces.

However, concerns exist over the structural implications of SCC in cast-in-place and precast elements. Specifically, higher paste contents, higher fines contents, and the use of smaller, rounded aggregates may significantly alter the creep, shrinkage, bond, and shear strength of SCC mixes as compared to traditional concrete mixes with the same compressive strength. These concerns increase for mixtures that use untested aggregate types and various supplementary cementitious materials. Consequently, to achieve the benefits and potential savings with SCC, guidelines are needed for its proper application in bridges, roadways, culverts, retaining walls, and other transportation-related infrastructure components.

2.1 PROJECT TASKS

The ***objective*** of this research was to determine the structural implications of using SCC mixes compared to traditional concrete mixes. This study focused on the hardened properties of SCC mixes containing Missouri aggregates and developed guidelines on its use in infrastructure elements for MoDOT.

The ***proposed research plan*** included seven (7) tasks necessary to reach this goal, as well as the task durations and level of effort. The research tasks consisted of the following:

2.1.1 Task 1: Literature Review

The purpose of this task was to conduct a comprehensive and critical literature review of past experiences and previous research on SCC, with particular attention to the impact that these findings may have on the research plan. Specifically, the literature review focused on studies involving the hardened properties of SCC that affect structural performance (*e.g.*, bond, shear, prestress losses) and durability (*e.g.*, freeze-thaw resistance, permeability), particularly the role of local aggregates and sensitivity in the mix designs. Sensitivity involves the impact that relatively small changes in the mix design have on the performance of the material, which is critical for a construction material such as concrete. Furthermore, to establish a solid background for the study, the investigators also reviewed literature on SCC related to fresh properties, workability, stability, admixtures, and mix design methods.

2.1.2 Task 2: Mix Development

The aim of this task was to determine a set number of SCC and non-SCC mix designs to use during the subsequent research. The non-SCC mixes served as controls during the research. Concrete properties, particularly at higher strengths, are very dependent on aggregate type, so comparison mixes are necessary to allow an unbiased assessment of SCC mixes containing Missouri aggregates. This task involved three (3) subtasks.

Subtask 2a: Survey Missouri Precast Suppliers. The investigators surveyed Missouri precast suppliers to obtain representative SCC mix designs currently in use throughout the state, particularly in large metropolitan areas such as St. Louis and Kansas City. All proprietary information on mix designs was treated as confidential and not released to anyone outside the project team.

Subtask 2b: Survey MoDOT and MoDOT Contractors. The investigators surveyed MoDOT and MoDOT contractors on potential SCC mix designs used in infrastructure applications. These sources offered a valuable resource on past experiences with SCC.

Subtask 2c: Select SCC Mixes for Testing. The goal of Subtask 2c was to arrive at four (4) mix designs to form the basis of the subsequent research. These four (4) mix designs, based on the survey results, consisted of SCC and non-SCC versions of both a typical concrete (target compressive strength of 4,000 to 6,000 psi) and a high-strength concrete (target compressive strength of 8,000 to 10,000 psi). The final mix design choices and target strength levels were approved by MoDOT prior to the start of test specimen construction.

2.1.3 Task 3: Bond and Development of Prestressing Strand and Mild Steel

The issue to be addressed under this task was whether SCC enhances or compromises the bond between concrete and reinforcing steel, both prestressing strand and mild steel. Excessive bleeding and lack of stability in SCC can comprise the integrity of the concrete-steel bond, particularly in regard to the top bar effect (greater reduction in bond for upper levels of reinforcement). This task involved two (2) subtasks, with one subtask addressing prestressing strand and the other addressing mild steel. Details regarding the test methods to be investigated are summarized in **Table 1**. Many of the test methods are standard AASHTO/ACI/ASTM/PCI test methods. The reader may be referred to Section 5 of this Summary Report for their affiliated website for additional details on testing and standards on the aforementioned methods.

TABLE 1: CONCRETE TEST METHODS AND PROTOCOLS

PROPERTY	TEST METHOD	TEST TITLE/DESCRIPTION	TASK
FRESH CONCRETE PROPERTY TESTS			
Unit Weight	ASTM C 138	Standard Test Method for Density (Unit Weight).	MSTR
Air Content	ASTM C 173	Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method.	MSTR
Slump	ASTM C 143	Standard Test Method for Slump of Hydraulic-Cement Concrete (non-SCC mixes).	MSTR
Slump Flow	ASTM C 1611	Standard Test Method for Slump Flow of Self-Consolidating Concrete (SCC mixes).	MSTR
J-Ring	ASTM C 1621	Standard Test Method for Passing Ability of Self-Consolidating Concrete by J-Ring (SCC mixes).	MSTR
L-Box	Non-ASTM	Determines the slump flow of the concrete (SCC mixes).	MSTR
Column Segregation	ASTM C 1610	Standard Test Method for Static Segregation of Self-Consolidating Concrete Using Column Technique.	MSTR
HARDENED MECHANICAL PROPERTY TESTS			
Compressive Strength	ASTM C 39	Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.	4
Splitting Tensile Strength	ASTM C 496	Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens.	4
Flexural Strength	ASTM C 78	Standard Test Method for Flexural Strength of Concrete.	4
Modulus of Elasticity	ASTM C 469	Standard Test Method for Static Modulus of Elasticity.	4
Creep/Shrinkage	ASTMC 512	Standard Test Method for Creep of Concrete in Compression.	4
DURABILITY TESTS			
Chloride Permeability	ASTM C 1202	Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration.	4
Chloride Permeability	AASHTO T 259	Standard Method of Test for Resistance of Concrete to Chloride Ion Penetration	4
Rapid Freeze Thaw Resistance	ASTM C 666	Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing.	4
Wear Resistance	ASTM C 944	Standard Test Method for Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method.	4
PT STRAND BOND TESTS			
Mustafa Pullout Test	Non-ASTM	Current PCI recommended test method.	3
NASP Bond Test	Non-ASTM	Currently undergoing due diligence testing by PCI as new standard.	3
PT STRAND PERFORMANCE (COMPONENT AND FULL-SCALE TESTING)			
Strand End-Slip	Non-ASTM	Property related to both transfer length and development length.	3
Transfer Length	Non-ASTM	Test to determine required length for full prestress transfer.	3
Development Length	Non-ASTM	Test to determine required length for yielding of strand in flexure.	3
MILD STEEL BOND AND DEVELOPMENT			
Direct Pull-out Tests	RILEM 7-II-128	A comparative test that evaluates direct bond strength while minimizing the effect of confining pressures as in previous direct pull-out test methods, see Fig. 1.	3
4-Point Loading Beam Splice Test Specimens	Non-ASTM	See Fig. 2.	3
SHEAR			
Small Scale Beam Tests	Non-ASTM	Small scale tests will be undertaken to examine the components that contribute to the concrete's ability to provide shear resistance. This includes V_c (compression), V_a (aggregate interlock), V_d (dowel action).	5
Full Scale Beam Tests	Non-ASTM	Larger scale tests will examine global behavior in shear including global contribution from the concrete, V_c. Prestressed concrete (PC) members will be studied.	5

Table Notes:

Non-ASTM – refers to a test method that is not a standard ASTM test. The test is either a generally accepted research practice test or standard undertaken at Missouri S&T for similar studies. Detailed reports A-E provide specifics undertaken.

MSTR = refers to a Missouri S&T recommended test for this project.

Subtask 3a: Prestressing Strand Transfer Length, End Slip, and Development Length. This subtask investigated three (3) interrelated issues with regard to prestressing strand performance in concrete, both SCC and non-SCC mixes, namely transfer length, end slip, and development length.

To evaluate bonding characteristics of prestressing strand, there are currently three (3) testing protocols available: the Moustafa Bond Test, the Post-Tensioning Institute (PTI) Bond Test, and the North American Strand Producers (NASP) Bond Test.[1] Based on a review of the literature and the current MoDOT requirements, the investigators performed both the Moustafa (also referred to as the Large Block Pullout Test [LBPT]) and NASP bond tests to evaluate the comparative bond behavior between SCC and non-SCC mixes. The NASP bond test, an updated version of the PCI bond test, is currently undergoing due diligence review by the Precast/Prestressed Concrete Institute (PCI), and will most likely develop into the industry standard.[2, 3]

To evaluate strand end slip and transfer length, the investigators constructed and instrumented rectangular beams. The rectangular beams contained either two or four 1/2-inch-diameter strands, with the four-strand beams having two strands at the top and bottom of the section. The four-strand beams were used to evaluate the top bar effect, as top strands are often used to control release stresses for heavily pretensioned sections. The instrumentation included both depth micrometers to measure strand end slip and demountable mechanical strain gauges (DEMEC gauges) to measure changes in concrete surface strains.

To evaluate development length, the investigators constructed and instrumented a series of pretensioned rectangular beams of varying lengths. The beam lengths were based on calculated development lengths from both AASHTO LRFD and ACI 318. Since development length involves adequate stress transfer to insure yielding of the strand, the beams were tested in flexure to failure. Data recorded during the tests included load, deflection, concrete surface strains, strand end slip, and strain in the strands.

Subtask 3b: Mild Steel Bond and Development.

This subtask investigated development length of mild steel in both SCC and non-SCC mixes, using both direct pull-out tests and beam splice tests. Although there are a variety of bond and development length testing protocols available, a direct pull-out test offers several advantages, including test specimens that are easy to construct and a testing method that is relatively simple to perform. The downside is a lack of direct comparison with actual structures and the development of compressive and confinement stresses generated due to the reaction plate.

However, modifications suggested in RILEM 7-II-1282 reduce some of these problems and result in a simplified test that offers relative comparisons between concrete or reinforcement types. **Figure 1** is a schematic of the test specimen based on the RILEM specifications. Bond between the reinforcing bar and the concrete only occurs in the upper half of the concrete block, through the addition of a PVC tube in the lower portion, significantly reducing the effect of any confinement pressure generated as a result of friction between the specimen and the reaction plate.

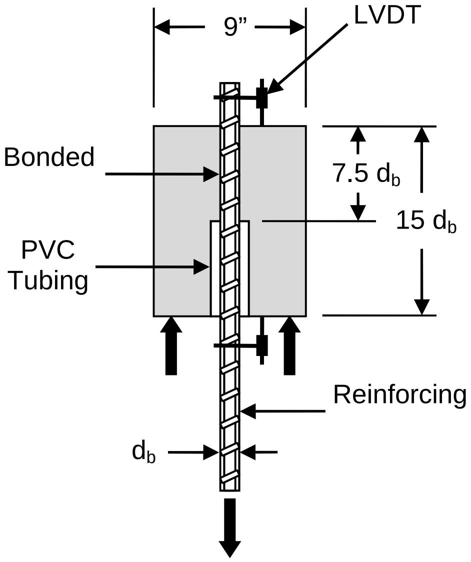

FIGURE 1: DIRECT PULLOUT TEST SETUP.

The investigators constructed and instrumented several direct pullout specimens for testing as shown in **Fig. 1**. The variables included bar size and concrete type. Data recorded during the test included load and free end slip at each end of the reinforcing bar.

Although there are a variety of bond and development length testing protocols available, the beam splice specimen shown in **Fig. 2** is generally regarded as the most realistic test method.[1, 4] Current AASHTO LRFD and ACI 318 design provisions for development length and splice length are based primarily on data from this type of test setup.[4]

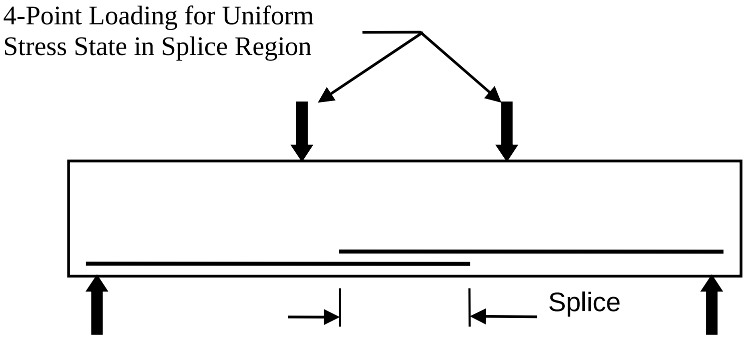

FIGURE 2: BEAM SPLICE TEST SETUP.

The investigators constructed and instrumented rectangular beams for splice specimen testing as shown in **Fig. 2.** The variables included lap length and lap position. To evaluate the top bar effect, several beams were cast upside-down with at least 12 inches of concrete below the bars. Specimen instrumentation consisted of strain gauges placed at the start of each lap. Data recorded during the tests included load and deflection of the specimen as it was tested to flexural or bond failure.

2.1.4 Task 4: Hardened Properties of SCC Mixes

The objective of the proposed research is to determine the structural implications of using SCC mixes compared to traditional concrete mixes. As such, the investigators focused on the hardened properties of SCC mixes as compared to "identical" non-SCC mixes. Task 4 involved three (3) subtasks.

Subtask 4a: Test Matrix. **Table 1** represents the test matrix for this research study based on MoDOT's RFP and the opinions of the investigators. Broadly speaking, the tests are classified into four (4) categories: fresh concrete properties (*e.g.*, slump), hardened mechanical properties (*e.g.*, compressive strength), durability (*e.g.*, freeze-thaw resistance), and structural performance (*e.g.*, bond, shear strength).

Subtask 4b: Test Results. This subtask was critical to a successful research program and involved more than simply compiling the test results. In reality, this subtask involved adapting the test matrix as necessary during the course of testing. In other words, if a particular property turned out to be critical to the overall performance of SCC, more or different tests may be warranted, and the testing plan adapted accordingly.

Subtask 4c: Conclusions & Recommendations. The investigators developed conclusions and recommendations based on the test results. In addition to evaluating the different SCC mixes for performance, these conclusions and recommendations formed the basis of the draft specifications developed as part of Task 6. The investigators also made recommendations on the design of precast/prestressed girders constructed with SCC, including suggested revisions to Section 700 of MoDOT's EPG.

2.1.5 Task 5: Shear Properties of SCC Mixes

The issue to be addressed under this task was to determine whether the current AASHTO *LRFD Bridge Design Specifications* for shear are appropriate for SCC. Higher paste contents, higher fines contents, and the use of smaller, rounded aggregates may significantly alter the shear strength of SCC mixes as compared to traditional concrete mixes with the same compressive strength. As a result, the following three (3) factors were studied based on MoDOT's RFP and the opinions of the investigators:

1. Shear contribution from aggregate interlock (interface shear transfer), including the influence of concrete strength and aggregate type, size, and shape,
2. Shear contribution from concrete (overall), including moderate to high-strength mix designs, and
3. Shear contribution from steel (stirrups and longitudinal steel).

This task involved two (2) subtasks (see **Table 1**) based on the type of test recommended to study different aspects of each issue, with one subtask based on small scale element and beam tests and the other based on mid-to-full scale beam tests.

Subtask 5a: Small Scale Element and Beam Tests. This subtask consisted of small scale element and beam tests. The element tests primarily investigated the complex phenomenon of aggregate interlock (or interface shear transfer). The beam tests, on the other hand, were used to investigate a large variety of variables before moving onto full scale beam tests.

After diagonal cracking and up to the ultimate limit state, aggregate interlock provides a substantial portion of the concrete contribution to shear resistance.[5] In fact, the Modified Compression Field Theory (MCFT) shear design provisions in the current AASHTO *LRFD Bridge Design Specifications* include aggregate interlock as a design parameter to determine the allowable shear stress on the crack plane.[6] The accepted test method to study the effects of aggregate interlock is referred to as a push-off test and is shown in **Figure 3**.[7]

The investigators constructed and instrumented push-off specimens as shown in **Figure 3** to study the impact of SCC mix designs on aggregate interlock. The variables included: concrete strength and aggregate type, size, shape and content level. Aggregate type and proportioning is a significant variable in the design of SCC mixes, which typically use low volumes of coarse aggregate and high paste volumes to maximize flowability. Furthermore, for high-strength concrete, the effect of aggregate interlock is significantly reduced as the aggregate fractures and results in a smoother crack surface. Specimen instrumentation consisted of strain gauges, linear variable displacement transducers (LVDTs) and DEMEC gauges. Data recorded during the tests also included normal and shear forces from the start of loading to failure.

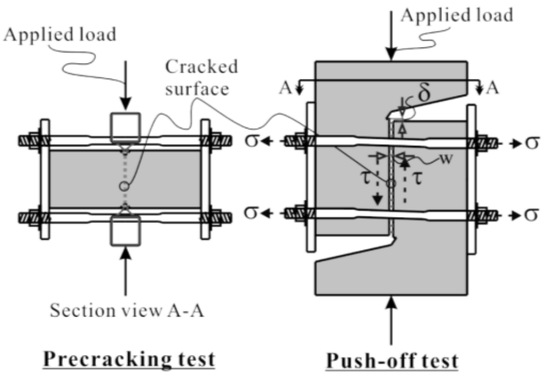

FIGURE 3: TEST FIXTURE FOR EVALUATING AGGREGATE INTERLOCK.

The small scale beam tests of this subtask will be used to investigate a large variety of variables before moving onto full scale beam tests. The investigators will construct and instrument a series of rectangular beams to study shear in SCC mixes. The purpose of these tests is to begin to quantify the different contributions to shear strength in an SCC beam. The variables will include: dimensions of the beam cross section, concrete strength, and amount of transverse reinforcement. Specimen instrumentation will consist of strain gauges, DEMEC gauges, and LVDTs. Data recorded during the tests will also include load and deflection of the specimen as it is tested to shear failure.

Subtask 5b: Mid-to-Full Scale Beam Tests. This subtask involved mid-to-full scale beam tests to study the global behavior of shear in SCC beams and evaluate the contributions from the concrete and transverse reinforcement. The investigators constructed and instrumented a limited number of rectangular full-scale beams as a final evaluation of the shear behavior of SCC. The results from Subtask 5a were used to determine the variables to study in the full-scale beam tests. Specimen instrumentation consisted of strain gauges, DEMEC gauges, and LVDTs. Data recorded during the tests included load and deflection of the specimen as it was tested to shear failure.

2.1.6 Task 6: Recommendations and Specifications for SCC Implementation

Based on the results of Tasks 1 through 5, the investigators developed recommendations for the use of SCC in infrastructure elements, including suggested revisions to Section 700 of MoDOT’s EPG. Based on these recommendations and the results of this research study, the investigators also developed a suggested MoDOT specification for the use of SCC in transportation-related infrastructure.

2.1.7 Task 7: Value to MoDOT and Stakeholders to Implementing SCC

The issue to be addressed under this task was to quantify the value of this research effort. Contained within this “Value to MoDOT” task was both quantitative and qualitative values to MoDOT. Overall, this task provided a basis for whether or not SCC should be implemented by MoDOT if the technology shows promise based upon the results from Project Tasks 1-5.

3. TASK SUMMARIES: CONCLUSIONS AND RECOMMENDATIONS

The following sub-sections summarize the major findings and conclusions as it relates to Project Tasks 1 through 7 as applicable. Prior to the summary, each sub-section refers to the specific Technical Report A through E where the detailed approach, experimental procedures and processes, results, findings, and recommendations may be referenced for much greater detail. Within each finding and conclusion a report designation (i.e. Report "A") is provided as a reference to the reader such that the detailed report may easily be referenced to gain an improved understanding of how this particular finding or conclusion was established.

3.1 TASK 1: LITERATURE REVIEW

Detailed Technical Reports A through E each provide a thorough literature review related to the topic of study at hand. The reader is referred to the detailed technical reports for the specific literature review on SCC. The more notable general observations include the following:

TECHNICAL REPORT A:

- National SCC studies have produced guidelines for developing fresh property test programs to develop robust mix designs and reliable QA/QC programs.
- There exist standardized test procedures for testing "fresh" or plastic SCC.
- Research on strand bond in SCC has shown conflicting results, where some mixes have resulted in increased transfer and development lengths compared to conventional concrete while others have shown the opposite effect.
- Research on bond of mild steel in SCC have shown conflicting results, where some mixes have resulted in increased development lengths compared to conventional concrete while others have shown the opposite effect.
- Research on creep and shrinkage of SCC generally indicates increased values due to higher paste and fine contents and lower coarse aggregate contents.
- Research on material properties of SCC generally indicates comparable values compared with conventional concrete.
- Research on durability of SCC generally indicates comparable or improved performance compared with conventional concrete.
- Research on shear strength of SCC has shown conflicting results, where some mixes have resulted in decreased shear strength compared to conventional concrete while others have shown either comparable or increased capacity.

3.2 TASK 2: MIX DEVELOPMENT

The aim of this task was to determine a set number of SCC and non-SCC mix designs to use during the subsequent research. The non-SCC mixes served as controls during the research. Concrete properties, particularly at higher strengths, are very dependent on aggregate type, so comparison mixes were necessary to allow an unbiased assessment of SCC mixes containing Missouri aggregates. This task involved three (3) subtasks.

Subtask 2a: Survey Missouri Precast Suppliers. The survey results of Missouri precast suppliers are presented in Section 3 of Technical Report A.

Subtask 2b: Survey MoDOT and MoDOT Contractors. The survey results from MoDOT, MoDOT contractors, and the national level DOT survey is presented in Section 3 of Technical Report A.

Subtask 2c: Select SCC Mixes for Testing. The final selected four (4) mix designs, based on the survey results and MoDOT input are presented in Section 3 and 4 of Technical Report A. This consisted of SCC and non-SCC versions of both a typical concrete (compressive strength of 4,000 to 6,000 psi) and a high-strength concrete (compressive strength of 8,000 to 10,000 psi). The findings and conclusions from this task are as follows:

TECHNICAL REPORT A:

- *SCC Precast Producer Survey:* Positive results were gathered from the Missouri precast concrete suppliers; 6 out of the 13 solicited precast suppliers replied with valuable responses, several even provided multiple mix designs in use at their facilities. Results of the survey that are not confidential are reported in Technical Report A, Section 3.1.
- *SCC Ready-Mix Producer Survey:* No ready mix concrete suppliers in Missouri replied to survey solicitations. It is known from the personal experience of the project Principal Investigator that some ready mix producers in Missouri have made SCC, but it remains unknown to what extent or level of sophistication.
- *National DOT Survey:* SCC was used in all applications, not only aesthetic or low stress drainage structures; reportedly, the most common use for SCC is in structural beams and girders.
- *National DOT Survey:* Aggregates used for SCC seem to be as diverse as the local geology; river gravel and limestone are used approximately equally, and other materials such as granite, trap rock, and quartz are used to a lesser extent, as would be typical of conventional concrete.

- *National DOT Survey:* As was reflected in the precast survey responses, the most common nominal maximum aggregate size was 3/4 in. (19 mm) with 1/2 in. (13mm) also commonly reported.
- *National DOT Survey:* The majority of AASHTO survey respondents' reports less than 25% of all projects utilize SCC with first use occurring within the last 7 years; few respondents report a majority of projects using SCC with more than 10 years of experience.

3.3 TASK 3: BOND AND DEVELOPMENT OF PRESTRESSING STRAND AND MILD STEEL

- ***Subtask 3a: Prestressing Strand Transfer Length, End Slip, and Development Length.*** Based on the work undertaken, several conclusions can be drawn regarding the applicability of the NASP test in mortar and LBPT bond tests, the bond performance of SCC compared to conventional concrete, and the feasibility of using concrete strength and pullout test results to predict transfer lengths. The conclusions and recommendations from this subtask are as follows:

TECHNICAL REPORT B, CONCLUSIONS:

- Based on the linear relationship found between the LBPT and NASP pullout values and the similar coefficients of variation between the two tests for a given strand type, either the LBPT or NASP test are equally valid approaches to evaluating bond performance of prestressing strand. However, the limits set on passing may need some refinement, as two of the strand sources passed the proposed NASP standard but did not pass the LBPT requirements.
- Proportioning for the mortar mixes did appear to have an effect on NASP in mortar pullout values, and it is hypothesized that a decreased amount of sand could detrimentally affect mechanical interlocking and lead to lower pullout values.
- While first slips are not required to be monitored in the NASP test, strands with high 0.1 in. (2.54 mm) pullout loads sometimes had the lowest 0.001 in. (0.025 mm) pullout loads, which could indicate a problem with adhesion of the strand.
- The NASP test in concrete revealed that the high strength concretes had lower first slip values than the normal strength concretes. This could be due to the inclusion of fly ash in the high strength mixes, or the increase in total cementitious content, as these were the only major differences between the normal and high strength mixes.
- SCC and conventional concrete were comparable in terms of bond performance, showing few statistical differences between measured transfer lengths or pullout loads between the two types of concrete.

- Increases in concrete strength generally resulted in shorter, although not always statistically different, transfer lengths, especially if the live end values were removed from the averages. Also, top strands only seemed to show statistically significant increases in transfer length at later ages. The "live end" is the end directly adjacent to where the strand is first released.
- Transfer lengths of bottom strands tended to increase from 1 to 28 days, with most of the increase occurring between 1 and 4 days. Also, the transfer lengths in normal strength mixes appeared to increase more than those in high strength mixes, and transfer lengths in conventional concrete increased more than transfer lengths in SCC. However, no consistent trends were noted for change in top strand transfer lengths over time.
- The AASHTO transfer length equation was generally conservative for all mixes for both top and bottom strands, even when compared to live end transfer lengths. The ACI equations were generally conservative except when compared to live end transfer lengths or the top strands in the normal strength conventional concrete.
- The linear potentiometers were found to be unreliable, and the steel ruler measurements were determined to be imprecise; the transfer lengths determined from the DEMEC readings and 95% Average Mean Strain Method were found to be the most consistent and reliable.
- Due to the fact that increased concrete strength resulted in decreased transfer lengths and increased NASP in concrete pullout loads, concrete strength does have an effect on bond and the equation for transfer length should be a function of concrete strength.
- Transfer length does appear to be related to the square root of concrete compressive strength, as noted by Ramirez and Russell (2008) and others.
- The proposed transfer length equation from Ramirez and Russell (2008) was slightly less conservative than the AASHTO equation, but still mostly conservative when compared to the measured transfer lengths, although the proposed equation was not conservative when compared to the live end transfer lengths.
- Development length specimens tested at embedment lengths of 80% of the development length calculated from the AASHTO and ACI equations still failed in flexure, so the current AASHTO and ACI equations for development length are conservative.
- SCC and conventional concrete appeared to exhibit comparable flexural behavior.
- Ramirez and Russell's proposed development length equation (2008) appeared to be less conservative than the AASHTO and ACI equation but still conservative in three out of the four cases because in this test program, even the development length tests completed at an embedment length of 58 in. (1,473 mm), which is 80% of the development length calculated from the current AASHTO equation and shorter than any of the development lengths calculated by the proposed

equation, failed in flexure, showing the strand could be fully developed. However, the proposed equation did predict one development length greater than the AASHTO and ACI value for one mix, showing the proposed development length equation may be over-conservative in some cases.

TECHNICAL REPORT B, RECOMMENDATIONS:

- Because differences in bond quality have been shown to vary greatly depending on the source, a standard bond test should be recommended and performed to ensure strand bond quality before the strand is used in production.
- The NASP test in concrete should not necessarily be a required test for strand bond because the tests showed pullout strength is mostly a function of concrete compressive strength; however the NASP test in concrete still could be useful for identifying possible effects of mix additions or proportioning on bond.
- The pullout limits for both the NASP test in mortar and LBPT need refinement. Additional research should be conducted with NASP and LBPT specimens and corresponding transfer length specimens to see if the NASP minimum value should be raised and the LBPT minimum value should be lowered. Specifically, strands with NASP pullout values between 12,000 and 18,000 lb (53 and 80 kN) and LBPT pullout values between 30.0 and 36.0 kips (133 and 160 kN) should be targeted.
- The pullout value at first slip, or 0.001 in. (0.025 mm) of displacement, should also be reported for the NASP test because low first slip values could indicate problems with adhesion of strand.
- Additional studies should be completed to investigate the effect of mortar mix proportioning on the pullout values from the NASP test in mortar, and limits should be set for proportioning in addition to strength and flow.
- More research should be conducted to determine if the contours of the load vs. displacement curves for the NASP test in mortar specimens can also be indicators of bond quality. Strand types that show plateaus or drop-offs in load at 0.1 in. (2.54 mm) instead of continuing to increase may not have acceptable bond quality, even if they pass a minimum load limit.
- The potentiometer and plate method for measuring end slip should be reinvestigated to see if other plate/potentiometer bonding methods or other less violent release methods could yield useable data. However, the steel ruler method should be abandoned, and end slips should be measured with a more precise means, such as a caliper.
- The current AASHTO and ACI transfer length and development length equations are adequate and conservative for use with conventional concrete as well as SCC.

- The proposed transfer length equation from Ramirez and Russell (2008) should potentially be reinvestigated because the equation was not conservative for live end transfer lengths.
- The proposed development length equation from Ramirez and Russell (2008) should also potentially be reinvestigated because the equation might result in overly conservative values in some cases.

Subtask 3b: Mild Steel Bond and Development. Two test methods were used for bond strength comparisons. The first was a direct pull-out test based on the RILEM 7-II-128 "RC6: Bond test for reinforcing steel. 1. Pull-out test" (RILEM, 1994). Although not directly related to the behavior of a reinforced concrete beam in flexure, the test does provide a realistic comparison of bond between types of concrete. The second test method consisted of a full-scale beam splice test specimen subjected to a four-point loading until failure of the splice. This test method is a non-ASTM test procedure that is generally accepted as the most realistic test method for both development and splice length. The conclusions and recommendations from this subtask are as follows:

TECHNICAL REPORT C, CONCLUSIONS:

- Direct Pull-out Testing. Analysis of the test data indicates that the normal strength SCC mix design has higher bond strength and the high strength SCC mix design has lower bond strength than their respective control mix designs for both bar sizes. Statistical analysis indicates that only the #6 (#19) reinforcing bar, high strength SCC mix design specimens did not perform equally with the control.
- Beam Splice Testing. Analysis of the test data indicates that both SCC mix designs exhibited improved bond performance under realistic stress states relative to their respective control mix designs when the splice was cast at the bottom of the specimen. Only the high strength SCC mix design exhibited improved bond performance when the splice was cast at the top of the specimen. However, statistical analysis indicates that all four mix designs performed equally. These findings, along with the findings from the direct pull-out tests, indicate that using SCC is feasible in terms of bond and development of reinforcing steel.

TECHNICAL REPORT C, RECOMMENDATIONS:

There have been numerous studies conducted to determine the bond performance of SCC. However, additional studies are needed to establish a database of results that can eventually be used for comparison as well as for future AASHTO/ACI design code changes. Also important for design would be to explore whether or not certain AASHTO/ACI code distinctions, such as confinement, bar size, or bar coating factors, used for conventional concrete designs also apply to SCC, or if they need to be developed specifically for SCC. Below is a list of recommendations for testable variables related to SCC concrete bond behavior:

- Perform tests with a larger variation in bar sizes based on AASHTO and/or ACI 318 code distinctions for bar size effect on development length.
- Conduct tests determining the effect of different admixtures on the bond performance of SCC.
- Conduct tests determining the effect of various aggregate percentages and types on the bond performance of SCC.
- Perform tests with aggregates from different sources.
- Perform bond test on more specimen types mentioned in ACI 408.

3.4 Task 4: Hardened Properties of SCC Mixes

The objective of the proposed research was to determine the structural implications of using SCC mixes compared to traditional concrete mixes. The mechanical and durability performance of the baseline mixes and the SCC mixes are presented in multiple sections of the technical reports. Section 3 of Technical Report D reports the mechanical property results in terms of shrinkage, creep and abrasion resistance. Section 3 of Technical Report E reports the mechanical property results in terms of compressive strength, modulus of elasticity, modulus of rupture, and splitting tensile strength. Section 5 of Technical Report E reports the durability property results including rapid freezing and thawing, electrical indication to resist chloride penetration, ponding testing performance, and concrete resistivity. Section 5 of Technical Report A reports the mechanical property results as they relate to the various mix designs used for shear related studies. Technical Reports B and C also present hardened property results for their respective testing. The conclusions from this task are as follows:

TECHNICAL REPORT D, CONCLUSIONS:

- Shrinkage behavior results all indicated shrinkage levels at a microstrain of approximately 780 or lower as would be expected for conventional concrete shrinkage. The higher strength mixes tended to track better to various shrinkage models where the lower strength mixes tended to be over predicted by current models. It should be noted that many of the shrinkage models have not been specifically calibrated for SCC mixes in particular where the mix constituents vary from conventional concrete (i.e. lower coarse aggregate contents).
- Creep behavior results showed that the conventional concrete variation outperformed SCC in terms of creep behavior. This would be expected due to the lower coarse aggregate content in the SCC mixes. For normal strength concrete, these results are supported by every prediction model

that was analyzed. Every model predicts that the normal strength conventional concrete would have a lower creep coefficient than normal strength SCC after 126 days being loaded. The models were not as consistent when predicting the creep behavior of high strength concrete due to their calibration. The overall creep coefficients were approximately at or lower than the values which would be expected for conventional concrete.

- Abrasion resistance results of the locally produced Missouri mixes are very consistent with other national findings. The abrasion resistance of concrete is primarily dependent on compressive strength. For both criteria (mass loss and depth of abrasion), the abrasion resistance of concrete increased as the compressive strength of the specimens increased, with the exception of mass loss properties for the high strength conventional concrete relative to the high strength SCC; where, for the high strength mixes SCC and HSC exhibited similar performance. When comparing the conventional strength concrete mixes with the same design strength, the SCC mix generally showed a lower resistance to wear. This is most likely due to the decreased amount of coarse aggregate in the SCC mixes. Based on observations during and after testing, the majority of mass loss due to abrasion was from the cement paste, as opposed to the aggregate. Generally, for each test, cycle 1 shows the greatest amount of mass loss. The general decrease in measured mass loss for each subsequent cycle indicates that as the depth of wear increases, the aggregate begins to dominate the response. This would explain why the SCC mixes showed a slight decrease in abrasion resistance relative to their conventional concrete equivalents for subsequent cycles.

TECHNICAL REPORT E, CONCLUSIONS:

- The normal strength SCC mix in this investigation outperformed the conventional normal strength concrete in nearly every aspect tested. This finding is important for determining the plausibility of using SCC instead of conventional concrete. The normal strength SCC mix achieved a higher 28-day compressive strength than the normal strength conventional concrete mix. With the w/cm ratio being equal, as well as the type of aggregate and cement, it is believed that the high amount of HRWR used to provide SCC with its flowable characteristics accounts for the higher strength. The HRWR allows more water to be effective in the hydration process. This characteristic in turn hydrates more of the Portland cement, creating a denser overall microstructure, thus improving the compressive strength of the concrete. The normal strength SCC mix showed a comparable modulus of elasticity to the C6-58L mix. However, both mixes fell below the recommended ACI coefficient used to estimate this property. This was attributed to the aggregate characteristics. The normal strength conventional concrete mix showed a higher modulus of rupture when compared to the SCC mix and exceeded the recommended ACI coefficient used to estimate the modulus of rupture. However, in regards of the ACI coefficient, the SCC mix only fell slightly below the recommended value of 7.5. Both concrete mixes showed comparable splitting-tensile strength, while both mixes fell below the recommended ACI coefficient used to estimate the splitting-tensile strength.

- The normal strength SCC mix showed very comparable durability behavior and even exceeded the performance of the normal strength conventional concrete mix in some aspects. Both concretes performed poorly for resistance to freeze-thaw. This result is most likely due to the aggregate source incorporated into the specimens. Jefferson City Dolomitic Limestone is known for its poor durability performance, and resistance to freeze-thaw for concrete is very dependent on the aggregate's performance. Both concrete mixes showed very similar performance with the Rapid Chloride Permeability Testing (RCT). This result was further supported by similar performance in the ponding test. While the RCT classified both concrete mixes as moderate permeability, both mixes reached negligible corrosion risk at a relatively shallow depth in the ponding test. Both mixes also performed almost identical in the area of concrete resistivity, indicating a low rate of corrosion.
- The high strength SCC mix outperformed the conventional high strength concrete in nearly every aspect tested. The high strength SCC mix achieved a much higher 28-day compressive strength than the high strength conventional concrete mix. This increase in strength can most likely be attributed to the high dosage of HRWR used to produce the SCC. The HRWR allows more water to be effective in the hydration process. This characteristic in turn hydrates more of the Portland cement, creating a denser overall microstructure, thus improving the compressive strength of the concrete. This was also noted in the normal strength SCC mix but not to the degree observed in the high strength investigation. It could be concluded that the HRWR has a larger effect on strength gain at lower w/cm ratios. The HRWR allows the majority of water to be used in hydration, allowing for a much denser paste. When this aspect is combined with the lower w/cm ratio necessary to achieve high strengths, it appears that SCC will achieve higher compressive strengths than an equivalent conventional concrete mix.
- The high strength SCC mix showed a lower modulus of elasticity (MOE) than the high strength conventional concrete mix. This result was attributed to the decreased amount of coarse aggregate present in the SCC mix. Both of the mixes were considerably lower than the recommended ACI coefficient used to estimate the modulus of elasticity. Both mixes showed comparable modulus of rupture and exceeded the recommended ACI coefficient. Both mixes also showed comparable splitting-tensile strength as well, while both mixes fell short of the recommended ACI coefficient used to estimate this property. As with any HSC project (SCC or non-SCC), particularly those

involving long-span HSC members, a performance-based approach where important design parameters such as MOE should be specified with mix design property characterization before member fabrication for conformance to ensure expected design behavior; for example, in the case of MOE, a required minimum MOE will ensure serviceability requirements will be satisfied. This performance-based approach may be considered even more critical for SCC mix designs since the survey results indicated that the coarse aggregate content will vary more depending on the particular producer.

- The high strength SCC mix significantly outperformed the high strength conventional concrete mix in every durability test except resistance to freezing and thawing. During the freeze-thaw test, the S10-48L showed noticeably poorer performance when compared to the high strength conventional concrete mix. Neither mix contained an air entraining admixture. It is possible that the high strength conventional concrete mix entrapped more air during the mixing process than the high strength SCC mix, improving its performance relative to the SCC mix. In all other durability aspects the high strength SCC mix showed improved performance compared to the high strength conventional concrete mix. In both the RCT and ponding test, the high strength SCC mix showed greater resistance to chloride penetration. The high strength conventional concrete mix was classified as highly permeable by the RCT while the high strength SCC mix was classified as moderate. This classification was further supported by the ponding test. While both mixes performed well, the high strength SCC mix achieved negligible corrosion risk at a third of the depth that the high strength conventional concrete mix achieved negligible corrosion risk. This increase in performance is most likely due to the denser microstructure achieved by SCC. The high strength SCC mix also outperformed the high strength conventional concrete mix in concrete resistivity, most likely due to the denser microstructure.

3.5 TASK 5: SHEAR PROPERTIES OF SCC MIXES

The shear characterization results of locally available SCC and non-SCC mixes are presented in Technical Report A. The conclusions and recommendations from this task are as follows:

TECHNICAL REPORT A, CONCLUSIONS:

- The increased rate and higher ultimate strength development of SCC compared to CC observed by other researchers was also observed in this investigation.
- The decreased MOE for SCC compared to CC noted by others was not exhibited by the concrete batch proportions tested in this study.

- Researchers have reported conflicting results regarding the relative tensile strength of SCC to CC; this study observed improved tensile strength of SCC with respect to CC.
- The concrete batch proportions containing river gravel exhibited improved hardened mechanical properties of increased compressive strength, increased modulus of elasticity (MOE), and increased splitting tensile strength (STS) despite their decreased surface roughness compared to limestone aggregates tested.
- Vertical push-off specimen fabrication was effective in resembling actual member fabrication and adequately controlled geometrical tolerances for superior stress propagation and improved test results.
- Software imaging of post-failure cross-sections indicate segregation was not a significant issue and that tested specimen closely match calculated material proportions.
- The precrack test result analysis indicated that initial crack widths are highly controllable by increasing the initial clamping force.
- Precrack results exhibited a positive correlation to the concrete compressive strength, tensile strength, and test variations in initial clamping force.
- Push-off test results indicate decreasing aggregate interlock with increasing concrete compressive strength, a trend noted by other researchers and supported by theory.
- For the concrete batch proportions tested, river gravel exhibited superior aggregate interlock capability when compared to the limestone; this was the variable that had the largest effect on shear resistance of the concrete specimen and variables tested within this study.
- Despite other researchers' findings and theoretical conflict, the SCC did not appear to resist shear through aggregate interlock in a distinguishable manner from CC; the effect of coarse aggregate (C.A.) percentage was not detectable for the tests performed in this investigation.
- The E-value that other researchers have proposed and relied on for push-off analysis was discussed and discarded as the highly sensitive analysis tool it has been proposed to be. The E-value does examine shear and normal stress, crack width, and crack opening; however, it effectively averages and smears important incremental information.
- The increased rate of strength gain for SCC relative to CC was also noted for the shear beams; increased SCC strength at the time of release may be important to elastic prestress loss as well as losses over time.
- The tested shear beams exhibited similar flexural stiffness in the elastic range, this is supported by the relative ratio of concrete to steel as well as the consistent MOE of SCC and CC discussed above.

- SCC shear beams demonstrate increased deflections at increased shear strengths over comparable CC beams in this study. Other researchers have seen mixed results when comparing shear strength of SCC and CC beams.
- The beams of this study were tested once on each end. All secondary tests had increased shear strength and deflections over the virgin test indicating increased ductility.
- At failure, the SCC beams displayed crushing in their top fibers, the CC beams failed explosively in a shear plane extending from support to load point, away from developing flexural shear cracks.

TECHNICAL REPORT A, RECOMMENDATIONS:

- From the investigation undertaken it is evident that it would be advisable to undertake additional research in the subject of SCC shear behavior. There are limited test results for the full range of hardened mechanical and shear tests available to characterize SCC.
- It is recommended that an SCC be designed and developed following the guidelines from the NCHRP report 628 to become familiar with the issues and sensitivities of fresh SCC. Subsequent to SCC batch proportioning, it would be useful to conduct a QA/QC study across numerous Missouri precast and possibly ready-mix suppliers to ensure that adequate control of the material is ensured with the fast and simple fresh tests of slump-flow and J-ring. This process would familiarize all parties involved with the concerns of creating robust SCC, as well as help to establish practical and acceptable limits on the filling capacity and stability of subsequently developed SCC batch proportions.
- No concerns were identified in this investigation with regard to hardened mechanical testing of SCC relative to CC. Strength development and tensile strength was identified to be improved for SCC over similar CC. MOE was consistent between SCC and CC; other researchers have noted decreased MOE for SCC, but have also seen that the lower bound predictive models are still conservative.
- Additional shear testing of SCC would be useful. Push-off tests conducted throughout this investigation proved to be economical and quick, once familiar with the fabrication and testing procedures. Additional push-off testing, with some standardization and improvements to the test suggested by the authors, would be useful in refining the results of this study as well as investigating additional variables. Push-off testing would be most useful for lower strength concrete batch proportions where the impact of aggregate interlock is greater than at higher strengths. Variables that could be investigated could include maximum aggregate size, C.A. gradation, C.A. surface roughness and angularity, C.A. hardness, mineral and chemical

admixtures, as well as the variables tested in this investigation. A broad push-off test program may identify additional or compounding effects that have not been previously identified. It would also be valuable to conduct additional shear beam testing. It was identified that SCC shear beams have been tested in third point loading, but not commonly with distributed loading. Larger scale and more practical geometries of beams and girders should be tested in shear to compare to trends identified in this study. A beam with web-shear cracking may exhibit completely different behavior from the rectangular beams tested in this study that produced flexural-shear cracks and failed in a plane away from these developing cracks. Therefore, a full-scale beam test(s) with complete stress-strain instrumentation is recommended as part of an implementation program.

3.6 TASK 6: RECOMMENDATIONS AND SPECIFICATIONS FOR SCC IMPLEMENTATION

Based on the results of Tasks 1 through 5, the investigators recommend implementation of SCC in the construction of precast/prestressed, transportation-related infrastructure in the State of Missouri. To accomplish this, the following requirements are recommended for incorporation into MoDOT's standard specifications or job specific provisions.

SELF-CONSOLIDATING CONCRETE FOR PRECAST PRODUCTS

1.0 Description. Self-Consolidating Concrete (SCC) is a specially designed concrete that enables the concrete to flow under the influence of its own weight and does not require mechanical vibration for consolidation. All material, proportioning, mixing and transporting of concrete shall be in accordance with Sec 501, except as specified herein.

2.0 Materials. All material shall be in accordance with Division 1000, Material Details, except as noted herein.

2.1 Aggregate. Fine and coarse aggregate shall be in accordance with Sec 1005, except that the requirements for gradation will not apply.

2.1.1 Gradation. The contractor shall submit the target gradation and allowable gradation range of each fraction of each aggregate source used in the mix design. During production, the contractor shall be within the allowable gradation range for each aggregate that was submitted.

2.1.2 Maximum Coarse Aggregate Size. Minimum requirement for coarse aggregate passing ¾-inch sieve shall be 100 percent.

2.1.3 Minimum Coarse Aggregate Content. Minimum coarse aggregate content shall be 48 percent by weight of total aggregate content.

2.2 Admixture. All chemical admixtures shall be in accordance with Sec 1054, except as noted herein.

2.2.1 High Range Water Reducer. The polycarboxylate based high range water reducer shall be in accordance with AASHTO M 194, Type F or G.

2.2.2 Viscosity Modifier. The viscosity-modifying admixture shall be evaluated according to the test methods and mix design proportions referenced in AASHTO M 194.

2.2.3 Combination. The self-consolidating admixture system shall consist of either a polycarboxylate based high range water-reducing admixture or a polycarboxylate based high range water reducer combined with a separate viscosity-modifying admixture.

3.0 Concrete Mix Design. At least 120 days prior to using SCC, the contractor shall submit a mix design for approval to Construction and Materials. The SCC mix shall be designed by absolute volume methods or an optimized mix design method such as Shilstone or other recognized optimization method.

3.1 Required Information. The mix design shall contain the following information:

(a) Source, type and specific gravity of Portland cement

(b) Source, type (class, grade, etc.) and specific gravity of supplementary materials, if used

(c) Source, name, type and amount of admixture

(d) Source, type (formation, etc.), ledge number if applicable, and gradation of the aggregate

(e) Specific gravity and absorption of each fraction in accordance with AASHTO T 85 for coarse aggregate and AASHTO T 84 for fine aggregate, including raw data

(f) Unit weight of each fraction in accordance with AASHTO T 19

(h) The design air content and target slump flow (also referred to as slump spread)

(i) Batch weights of Portland cement and supplemental cementitious materials

(j) Batch weights of coarse, intermediate and fine aggregates

(k) Batch weight of water

(l) Compressive strength at release, 28 days, and 56 days

3.2 Supplementary Cementitious Materials. The SCC mix may use fly ash, GGBFS, metakaolin, or silica fume. Ternary mixes will be allowed for SCC. Ternary mixes are mixes that contain a combination of Portland cement and two supplementary cementitious materials. The amount of supplementary cementitious material content shall be limited to the following requirements:

Supplementary Cementitious Material (SCM)	
SCM	**Maximum Percent of Total Cementitious Material**
Fly Ash (Class C)	25 %
Ground Granulated Blast Furnace Slag (GGBFS)	30 %
Metakaolin	15%
Silica Fume	8 %
Ternary Combinations	40 %

3.3 Water Amount. The water/cementitious materials ratio shall meet the following requirements:

Water/Cementitious Materials Ratio	
Minimum	**Maximum**
0.27	0.37

3.4 Minimum Cementitious Amount. The total amount of cementitious materials shall not be below 700 pounds per cubic yard.

3.5 Slump Flow. The slump flow (or slump spread) test shall be performed in accordance with ASTM C 1611. The visual stability index rating shall be a maximum of 1. The slump flow shall meet the following requirements:

Slump Flow (inches)	
Minimum	***Maximum***
20	30

3.6 Passing Ability. Passing ability shall be performed in accordance with ASTM C 1621. The test value shall not be less than the slump flow by more than 2 inches.

3.7 Segregation Resistance. Resistance to segregation shall be performed in accordance with ASTM C 1610. The test value shall not exceed 10 percent.

3.8 Air Content. Air content shall be performed in accordance with AASHTO T 152. The minimum air content shall be as shown on the contract documents.

3.9 Compressive Strength. Compressive strength shall be performed in accordance with AASHTO T 22. Concrete shall have tendon release and 28-day minimum compressive strengths as shown on the contract documents.

4.0 Batching Sequence Plan. The contractor shall submit a Batching Sequence Plan outlining how the SCC mix will be batched and mixed. The Batching Sequence Plan shall be submitted to the MoDOT Resident Engineer for approval.

5.0 Trial Batch. A trial batch shall be done at least 90 days prior to SCC being used to ensure the mix is in accordance with this special provision. The SCC mix design shall not be used until all of the specified criteria have been met. The trial batch shall be at least 3 cubic yards. The MoDOT personnel shall be present during the trial batch. The SCC mix shall be tested for air content, slump flow, visual stability index, passing ability, compressive strength and strand bond (NASP test).

5.1 Control Mix. The control mix shall be the Class A-1 concrete mix currently being used by the producer for MoDOT work.

5.2 Strand Bond. Strand bond shall be evaluated in accordance with the North American Strand Producers (NASP) test method as prescribed in National Cooperative Highway Research (NCHRP) Report 603: Transfer, Development, and Splice Length in High-Strength Concrete, except as noted herein.

5.2.1 NASP Test in Mortar. Minimum acceptance criteria for strand bond in mortar: average of six specimens shall be greater than or equal to 16,000 lb. with no individual test result less than 14,000 lb.

5.2.2 Additional Testing. Additional strand bond testing will be required when a different manufacturer or strand configuration is used or if a different manufacturer or type of admixture is used.

6.0 Production. SCC mix shall not be used until the concrete mix, the Batching Sequence Plan, and the trial batch have been approved. The SCC mix shall not vary from the mix design submitted for approval. Any changes in material sources, aggregate gradations, or material content shall require a new SCC mix be resubmitted for approval. Changes to the water content and chemical admixture dosages will be allowed to handle changes in environmental conditions.

6.1 Forms. SCC mixes generate higher fluid pressures than conventional concrete mixes. Forms shall be mortar-tight and capable of supporting the additional pressure.

6.2 Reinforcement. Reinforcement and other critical components shall be tightly secured in the form to prevent these items from shifting during concrete placement.

7.0 Quality Control. Because the quality of freshly mixed SCC may fluctuate at the beginning of daily production, the contractor shall conduct air test, slump flow, visual stability index, and passing ability for every truck until consistent and compliant results are obtained. Subsequently, all testing shall be conducted in accordance with MoDOT specifications.

7.1 Slump Flow Requirement. During production, the slump flow shall be within +/- 2 inches of the target slump flow designated by the contractor and shall not exceed 30 inches. Sections 3.5 through 3.8 discuss slump flow, passing ability, segregation resistance and air content mix design requirements. Sampling and testing frequency for SCC should conform to current MoDOT requirements for conventional concrete.

3.7 TASK 7: VALUE TO MODOT AND STAKEHOLDERS TO IMPLEMENTING SCC

The use of self-consolidating concrete provides distinct value to the Missouri Department of Transportation through multiple avenues. Because of its unique nature, self-consolidating concrete (SCC) has the potential to significantly reduce costs associated with transportation-related infrastructure, benefiting both MoDOT and the residents of Missouri. SCC is a highly flowable, nonsegregating concrete that can be placed without any mechanical consolidation, and thus has the following advantages over conventional concrete:

- *Decreased labor and equipment costs during concrete placement.* Limited “hard” data exists to date in the traditional sense from bid documents involving SCC concrete due to its innovative nature; however, through laboratory experience at Missouri S&T, 40 to 60% less labor was needed to fabricate and place concrete when comparing SCC elements to the conventional concrete elements, which required more personnel to consolidate the conventional concrete elements and produce standard quality control / quality assurance (QC/QA) specimens. A similar trend was noted in November 2011 during fabrication of a cast-in-place SCC arch element in a MoDOT Hybrid Composite Beam in Mountain Grove, Missouri. Once concrete placement started, fabrication times were completed in significantly less time based upon contractor commentary. As more SCC is implemented, historic cost trends will provide more quantitative financial data. However, it should be noted as SCC involves some new testing standards (i.e. QC/QA tests), there may be a “learning curve” for field and plant engineers / inspectors as they gain experience with new fresh concrete property testing protocols such as Slump Flow ASTM C 1611, J-Ring ASTM C 1621, L-Box (non-ASTM), and Column Segregation ASTM C 161.

- *Improved quality through the decreased potential for and costs to repair honeycombing and voids*. Due to SCC’s flowability, when properly formulated, there holds a great potential to decrease voids, anomalies and other defects that may occur during the placement of conventional concrete. This decreased potential should translate to an increase in the service life of the bridge or structure particularly as high-strength SCC is implemented with its improved durability performance.
- *Increased production rates of precast and cast-in-place elements.* In terms of both precast and cast-in-place elements, SCC offers the unique opportunity to expedite construction due to its unique characteristics. This increased rate of production translates into reduced construction time. This will open infrastructure systems in less time and help the traveling public in Missouri with reduced travel delays and congestion.
- *Improved finish and appearance of cast and free concrete surfaces*. While not a physical cost issue, improved finish and appearance of concrete elements provides an enhanced visual perspective of infrastructure elements for the riding public and will likely translate to a higher perceived level of quality.

3.8 OVERALL PROJECT RECOMMENDATIONS

After thorough mechanical property, shear, bond, transfer, and durability testing, it is recommended that SCC be implemented in precast and prestressing applications within the State of Missouri. With SCC showing comparable results for hardened mechanical properties, insignificant variations in shrinkage, creep, abrasion, shear, bond, transfer and development and slightly higher performance for durability, SCC appears to be a viable option to decrease the cost of labor and time consumption during concrete placement. This performance was observed in both normal and high strength SCC, with high strength SCC performing at a slightly higher margin over high strength conventional concrete than SCC performed over conventional concrete.

4. REFERENCES

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5. TESTING STANDARDS

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4. PCI – Prestressed/Precast Concrete Institute: http://www.pci.org