Self-Consolidating Concrete (SCC) and High-Volume Fly Ash Concrete (HVFAC) for Infrastructure Elements: Implementation

Summary Report

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Final Report Prepared for Missouri Department of Transportation

June 2016 Project TR201236 Report cmr16-011

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. cmr 16-011	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Self-Consolidating Concrete (SCC) and High-Volume Fly Ash Concrete (HVFAC) for Infrastructure Elements: Implementation. Summary Report.		**5. Report Date** March 2016 Published: June 2016 **6. Performing Organization Code**
7. Author(s) John J. Myers, Ph.D., P.E. http://orcid.org/0000-0001-5269-8218, Eli S. Hernandez, Hayder Alghazali, Alexander Griffin, Kaylea Smith		**8. Performing Organization Report No.**
9. Performing Organization Name and Address Missouri University of Science and Technology Department of Civil, Architectural, and Environmental Engineering 325 Civil Engineering Rolla, MO 65409		**10. Work Unit No.** **11. Contract or Grant No.** MoDOT project #TRyy1236 NUTC project # 00040350 USDOT contract # DTRT06-G-0014
12. Sponsoring Agency Name and Address Missouri Department of Transportation (SPR) http://dx.doi.org/10.13039/100007251 Construction and Materials Division P.O. Box 270 Jefferson City, MO 65102 Center for Transportation Infrastructure and Safety/NUTC program Missouri University of Science and Technology 220 Engineering Research Lab Rolla, MO 65409		**13. Type of Report and Period Covered** Final report (October 2012-March 2016) **14. Sponsoring Agency Code**

15. Supplementary Notes

Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration. MoDOT research reports are available in the Innovation Library at http://www.modot.org/services/or/byDate.htm. This set of reports is available at https://library.modot.mo.gov/RDT/reports/TR201236/.

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: 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 (CIP) elements, and improved finish and appearance of cast and free concrete surfaces. In addition to SCC, innovative materials, such as high-volume fly ash concrete (HVFAC), also provide a significant potential to produce more cost effective mix designs for CIP concrete. Since the 1930's, fly ash – a pozzolanic material – has been used as a partial replacement of portland cement in concrete to improve the material's strength and durability, while also limiting the amount of early heat generation. From an environmental perspective, replacing cement with fly ash reduces the concrete's overall carbon footprint and diverts an industrial by-product from the solid waste stream (currently, about 40 percent of fly ash is reclaimed for beneficial reuse and 60 percent is disposed of in landfills).

The objective of this research was to provide an implementation test bed and showcase for the use of sustainable and extended service life concrete. In this implementation study for Missouri Bridge A7957, a level of 50% fly ash to cement proportions was utilized as well as normal strength self-consolidating concrete (NS-SCC) and high-strength self-consolidating concrete (HS-SCC) in its primary carrying elements to showcase the use of these innovative materials. This study focused on monitoring the serviceability and structural performance, both short-term and long-term, of the bridge in an attempt to investigate the in-situ behavior of the NS-SCC, HS-SCC and also the HVFAC mixtures.

Consequently, to compare and demonstrate the potential benefits and savings of using NS-SCC, HS-SCC and HVFAC in the first Missouri DOT large-scale bridge structure, this study undertook ten tasks including the following: Task 1: Pre-Construction Planning and Construction Coordination; Task 2: Development of Bridge Instrumentation Plan & Load Testing Plan (Bridge A7957); Task 3: Mix Design and Quality Control Procedures/Quality Assurance – Trial Mixes; Task 4: Shear Testing and Evaluation of HS-SCC Precast NU Girders; Task 5: Precast-Prestressed Plant Specimen Fabrication and Instrumentation; Task 6: Field Cast-In-Place Elements and Instrumentation; Task 7: Hardened Properties of Plant and Field Produced Concrete; Task 8: Bridge Load Testing and Monitoring/Evaluation of Experimental Load Testing Results; Task 9: Reporting/Technology Transfer; Task 10: Value to MoDOT and Stakeholders to Implementing SCC/HVFAC. The final report consists of a summary report and four technical reports. The findings, conclusions and recommendations of the study can be referenced within these reporting components.

17. Key Words		18. Distribution Statement	
Cast in place concrete; Cost effectiveness; Durability; High strength concrete; Mix design; Portland cement concrete; Precast concrete; Self compacting concrete		No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.	
19. Security Classif. (of this report)	**20. Security Classif. (of this page)**	**21. No. of Pages**	**22. Price**
Unclassified.	Unclassified.	44	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

FINAL REPORT

TRyy1236

Self-Consolidating Concrete (SCC) and High-Volume Fly Ash Concrete (HVFAC) for Infrastructure Elements: Implementation

Prepared for
Missouri Department of Transportation
Construction and Materials

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March 2016

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Self-Consolidating Concrete (SCC) and High-Volume Fly Ash Concrete (HVFAC) for Infrastructure Elements: Implementation		5. Report Date March 31, 2016 6. Performing Organization Code
7. Author(s) Dr. John J. Myers, P.E., Eli S. Hernandez, Hayder Alghazali, Alex Griffin, and Kaylea Smith		8. Performing Organization Report No.
9.Performing Organization Name and Address Missouri University of Science and Technology 325 Butler Carlton Hall; 1401 North Pine Street Rolla, MO 65409		10. Work Unit No. 11.Contract or Grant No.
12.Sponsoring Agency Name and Address Missouri Department of Transportation Research, Development and Technology P.O. Box 270-Jefferson City, MO 65102		13. Type of Report and Period Covered Final Report 14.Sponsoring Agency Code
15. Supplement Notes		

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Self-consolidating concrete (SCC), High-strength Self-consolidating concrete (HS-SCC), HS-SCC Prestress Losses, HS-SCC Shear Strength, High-Volume Fly Ash Concrete (HVFAC), Live Load Test, Girder Distribution Factors, GDF, Lateral Distribution Factors, LDF.	No restrictions. This document is available to the public through National Technical Information Center, Springfield, Virginia 22161

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

Form DOT F 1700.7 (0698)

EXECUTIVE SUMMARY

This research project entitled, Self-Consolidating Concrete (SCC) and High-Volume Fly Ash Concrete (HVFAC) for Infrastructure Elements: Implementation, is separated into ten major tasks which include: Task 1: Pre-Construction Planning and Construction Coordination; Task 2: Development of Bridge Instrumentation Plan & Load Testing Plan (Bridge A7957); Task 3: Mix Design and Quality Control Procedures/Quality Assurance – Trial Mixes; Task 4: Shear Testing and Evaluation of HS-SCC Precast NU Girders; Task 5: Precast-Prestressed Plant Specimen Fabrication and Instrumentation; Task 6: Field Cast-In-Place Elements and Instrumentation; Task 7: Hardened Properties of Plant and Field Produced Concrete; Task 8: Bridge Load Testing and Monitoring/Evaluation of Experimental Load Testing Results; Task 9: Reporting/Technology Transfer; Task 10; Value to MoDOT and Stakeholders to Implementing SCC/HVFAC. Within these studies, locally available materials, representative of MoDOT benchmark design concrete mixtures, were employed.

After thorough inspection, QC/QA of trial mixes, shear testing and evaluation of HS-SCC precast NU large-scale girder specimens, and in-service evaluation of the Bridge A7957's superstructure, it is recommended that the NS-SCC and HS-SCC be widely implemented in precast-prestressing applications within the State of Missouri. It is also recommended that HVFAC be implemented in cast-in-place applications.

With NS-SCC exhibiting comparable results for hardened mechanical properties, insignificant variations in shrinkage, creep, abrasion, shear strength and serviceability response, and slightly higher performance for durability, SCC demonstrated to be a viable option to decrease the cost of labor and time consumption during concrete placement. This performance was exhibited by both the NS-SCC and HS-SCC, with HS-SCC performing at a slightly higher margin over conventional concrete than NS-SCC over conventional concrete. The following advantages over conventional concrete were observed:

- *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 C1621, 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.
- *Improved flexural behavior of HS-SCC.* HS-SCC brings to SCC's main attributes an enhanced flexural performance achieved as a consequence of increasing the SCC's compressive strength. This stronger flexural feature brings the possibility to reduce the number of main carrying members and interior supports of bridge super structures.

The following summarizes the benefits of using fly ash to replace a significant portion of the cement in concrete:

- *From an environmental perspective*, replacing cement with fly ash reduces concrete's overall carbon footprint and diverts an industrial by-product from the solid waste stream (currently, about 40 percent of fly ash is reclaimed for beneficial reuse and 60 percent is disposed of in landfills). These values align with both MoDOT's Mission of being environmentally and socially responsible (MoDOT 2016) and MoDOT's Research Need for strategies to reduce energy consumption (Stone 2010). Concrete is the most widely used man-made material on earth, with nearly three tons produced annually for each man, woman, and child, and accounts for 5% of the carbon dioxide released into the atmosphere each year. On average, replacing even 50% of the cement used in concrete with fly ash will reduce the annual amount of greenhouse gas emissions by nearly 1.8 billion tons worldwide. Furthermore, this change would also eliminate more than 20 billion cubic feet of landfill space each year. In terms of energy consumption, this fly ash replacement level would save the equivalent of 6.7 trillion cubic feet of natural gas annually.
- In terms of *monetary savings*, fly ash costs approximately one-half the amount for cement.
- For the same *workability*, fly ash reduces the amount of potable mixing water by approximately 20%.
- Even more importantly, fly ash increases the *durability* of concrete beyond what can be attained with portland cement alone. Increased durability translates into increased *sustainability* by extending the useful life of the material.

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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 D 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 D 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 and Anousone Arounpradith.

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.

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 two Chancellor's Fellowships to 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:

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In addition to SCC, innovative materials such as High-Volume Fly Ash Concrete (HVFAC) also provide a significant potential to produce more cost effective mix designs for cast-in-place concrete. Since the 1930's, fly ash – a pozzolanic material – has been used as a partial replacement of portland cement in concrete to improve the material's strength and durability, while also limiting the amount of early heat generation. From an environmental perspective, replacing cement with fly ash reduces concrete's overall carbon footprint and diverts an industrial by-product from the solid waste stream (currently, about 40 percent of fly ash is reclaimed for beneficial reuse and 60 percent is disposed of in landfills). In this implementation study, a level of 50% fly ash to cement proportions was utilized.

This project aimed to implement previous research (TRyy1103 and TRyy1110) undertaken at Missouri S&T and elsewhere on SCC and HVFAC (Myers et al. 2012, Volz et al. 2012) into an implementation project.

The main ***objective*** of this research was to provide an implementation test bed and showcase for the use of SCC and HVFA concrete. This study investigated the in-situ performance of both SCC and HVFAC in Missouri bridges including to monitor the serviceability and structural performance both short-term and long-term of the concrete members in the structure i.e., monitor deflections of prestressed girders from casting

through service conditions, perform condition survey, monitor any signs of distress, etc. The project also provided assistance to the contractor, inspector, and designer during all phases of construction.

The ***proposed research plan*** included ten (10) 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. TASK 1: PRE-CONSTRUCTION PLANNING AND CONSTRUCTION COORDINATION

The construction of Bridge A7957 in Osage County, Missouri was done according to current MoDOT practice. At the discretion of MoDOT the following meetings were held and attended by the Missouri S&T research team.

a) A partnering workshop to facilitate getting the contractor, subcontractors, researchers and MoDOT working as a team.
b) A pre-construction meeting after the contract was let, to clarify any details specific to the construction of the bridge and bridge components.
c) A pre-fabrication meeting prior to fabrication of the pre-tensioned girders to discuss issues including level of instrumentation, staging of instrumentation, and fabrication-related issues.
d) A pre-deck / pre-substructure construction meeting prior to formwork placement to discuss issues including level of instrumentation, staging of instrumentation, and casting & placement of concrete issues.

The contract documents / special project provisions detailed the roles of the researchers, who acted as consultants to assist the contractor, subcontractors and MoDOT personnel in procedures that were necessary to consistently obtain the characteristics in bridge construction. Also included in the contract documents / special project provisions were the modifications to current construction specifications that were inherent with the use of high performance concrete.

The researchers and MoDOT Resident Engineer were on site as needed during concrete casting, instrumentation, materials testing, etc. Digital images were taken during all stages of the construction process.

After construction of the implementation bridge, final instrumentation drawings were submitted to MoDOT detailing the exact locations of instrumentation on the bridge as part of the Interim Project Report.

2.2. TASK 2: DEVELOPMENT OF BRIDGE INSTRUMENTATION PLAN & LOAD TESTING PLAN (BRIDGE A7957)

The aim of this task was to develop an efficient, effective instrumentation and load testing plan as follows:

2.2.1. Subtask 2a: Instrumentation

The overall monitoring plan for the proposed research study was consistent with the instrumentation guidelines for bridges satisfying the minimum requirement of the basic instrumentation program recommended by FHWA. These guidelines were developed in part with previous research / instrumentation work conducted by the PI and may be referenced in the FHWA publication entitled *"Implementation Program on High Performance Concrete - Guidelines for Instrumentation of Bridges"*. Additional instrumentation was selected as detailed below.

The basic instrumentation program consisted of the measurement of temperatures, strains, and deflections. Thermocouples were used to monitor the effects of the heat of hydration, temperature / thermal gradients, the number of freeze-thaw cycles the bridge is subjected to during the monitoring period, and to perform temperature related modifications for other recorded measurements. The early-age temperature effects were monitored through the use of match curing technology. Early-age and later-age strains were monitored to determine prestress losses from elastic shortening, creep, shrinkage, and relaxation of tendons. Measurements of deflections were recorded to monitor the change in camber with time and the systems overall structural performance with the prestressing strands. In addition, the transfer and development length of the tendons were

investigated. Furthermore, instrumentation was selected to monitor the durability performance of the deck. This consisted of a chloride-monitoring device to document the application of roadway salts and chloride penetration. The project team worked with a research group from Oklahoma State University to secure a novel corrosion detection/chloride sensor. The project research program monitored the short and long-term mechanical and material performance of the concrete including both the fresh and hardened concrete properties. Concrete properties including compressive strength gain with time, elastic modulus, tensile strength, creep, shrinkage, permeability, freeze-thaw resistance, scaling resistance, and abrasion resistance were considered.

2.2.2. Subtask 2b: Monitoring of Concrete In-Place

The monitoring of concrete included the following:

2.2.2.1. Temperature Rise

On selected members, thermocouples were embedded to monitor the heat development of the concrete during early ages. This included the beams and deck. Data was recorded automatically during the initial 24 to 48 hours after placement, followed by manual readings at later ages.

2.2.2.2. Performance of Precast Girders, Deck and Sub-Structure Elements

2.2.2.2.1. <u>Implementation Planned</u>

For the structural behavior of the precast / prestressed beams it was desirable to log data on performance at all stages of the construction progress. The performance with time for the beams was important at each stage of significant progress within the structure. In addition, both the deck and some of the sub-structure elements using innovative and traditional concrete were instrumented. Typical instrumentation considered in this project included:

2.2.2.2.2. <u>Deflections</u>

- This included utilizing an high precision laser based systems such as and automated TOTAL STATION™ (ATS) and/or a field precision surveying technique

used by Yang and Myers on previous bridge instrumentation projects including ones for MoDOT.

2.2.2.2.3. Timing and Deflection Measurements

- at transfer;
- approximately nine months following completion;
- after three years if arrangements can be made for a longer-term monitoring study (not within the scope of this project).

2.2.2.2.4. Strains in Concrete

- Gauges on Steel Reinforcing Bars – Strain gauges were mounted on mild steel bars at Missouri S&T and the bars were then installed in the deck and/or pier caps. These bars were tied in position before the concrete was cast and connecting wires were brought out the element to the DAS.
- Vibrating Wire Gauges in Concrete – placed in cluster locations in specific precast beam elements, deck, and sub-structure elements. Brought lead wires out together with color coding tags to identify gage type and location that feed into two DAS.

2.2.2.2.5. Stages when Cylinders were Needed

- at transfer (for prestressed-precast concrete);
- at 7 days (for cast-in-place concrete);
- at 28 days;
- at 56 days;
- at time slab was cast;
- at completion of entire bridge;
- at first part of load test 1 (April 2014);
- at second part of live load test 1 (August 2014);
- after three years if arrangements can be made (not within the scope of this project).

2.2.2.2.6. Data Acquisition System (DAS)

In order for data collection from the sensors, a data acquisition system (DAS) was used both at the precast plant and at the bridge site. The research team required access to a power source at the precast plant to supply power to the DAS system during fabrication and monitoring of the girders. At the jobsite, the researchers required assistance from the contractor (a cherry picker) to permanently mount the DAS to the interior bridge bents. It was arranged to have two DAS that required mounting and connections from the embedded sensors within the bridge components.

2.2.3. Subtask 2c: Long-Term Monitoring of Concrete In-Place

Adequate evaluation of long-term durability of Bridge A7957 will require 20 to 30 years of exposure to the environment. Monitoring, therefore, is recommended to continue during this 20 to 30-year period (similar concept as long-term pavement evaluations). Data collection and evaluation after the end of this 40-month research study should be done annually and methods must be consistent with this study to ensure a continuous behavior history. The specific sub-tasks related to Work Activity are as follows:

- Subtask 2c.1: Concrete compressive strengths: f'_c (girders, slab, and sub-structure elements under investigation), f'_{ci} (girders);
- Subtask 2c.2: Concrete tensile strength: ft and/or fr;
- Subtask 2c.3: Concrete modulus of elasticity: Ec;
- Subtask 2c.4: Chloride concentration evaluation on concrete representative of the structure;
- Subtask 2c.5: Concrete freeze-thaw of conventional concrete (deck slab) in cooperation with MoDOT;
- Subtask 2c.6: Concrete abrasion resistance for concrete representative of the structure subjected to wearing;
- Subtask 2c.7: Coefficient Thermal Expansion (CTE) for HS-SCC, HVFAC, and conventional concrete mixes;

- Subtask 2c.8: Measurement of creep and shrinkage characteristics, along with other needed information, to determine the estimated losses in prestress due to creep and shrinkage;
- Subtask 2c.9: Measurement of girder strains over time to assess the effects of creep, shrinkage, and temperature at the girder ends near the diaphragms at the intermediate bents;
- Subtask 2c.10: Measurements of deflection over time to verify the accuracy of camber calculations done with known parameters and with the variables determined in Task 2c.1, 2c.3, and 2c.7;
- Subtask 2c.11: Measurements of thermal gradients and girder strains induced;
- Subtask 2c.12: Level of continuity (both M- and M+) provided at the intermediate bents.

2.3. TASK 3: MIX DESIGN AND QUALITY CONTROL PROCEDURES / QUALITY ASSURANCE – TRIAL MIXES

The development and production of the mix design used on Bridge A7957 components was the ultimate responsibility of the precast fabricator (precast components) and ready-mix producer (CIP concrete). However, the Missouri S&T research team provided expertise in the development of the SCC and HVFAC mix designs. This included technical advice on the development and production of the mix designs as needed in conjunction with satisfying the specification requirements. Missouri S&T researchers evaluated the final mix designs for all classes of concrete used in the project as these characteristics were needed for modeling and assessment of the bridge.

2.4. TASK 4: SHEAR TESTING AND EVALUATION OF HS-SCC PRECAST NU GIRDERS

The aim of this task was to validate the shear capacity of two full-scale NU bridge girders using the high-strength self-consolidating concrete (HS-SCC) mix design used within the bridge girders. The researchers studied the shear response using both mild steel

bars and welded wire mesh as the primary reinforcing steel. Two test girders were tested in shear. Previous laboratory tests were conducted on mid-scale rectangular beams.

2.5. TASK 5: PRECAST-PRESTRESSED PLANT SPECIMEN FABRICATION AND INSTRUMENTATION

The issue addressed under this task involved the instrumentation and fabrication of the prestressed-precast girders. This task involved the placement of instrumentation and assemblage of the data acquisition system (DAS) as described in Task 2. The research team worked closely with the fabricator to ensure that research related activities did not impede the fabricators schedule as described in Task 1.

2.6. TASK 6: FIELD CAST-IN-PLACE ELEMENTS AND INSTRUMENTATION

The issue addressed under this task involved the instrumentation and construction of the site cast-in-place (CIP) concrete to be investigated. This task involved the placement of instrumentation and assemblage / mounting of the data acquisition system (DAS) as described in Task 2. The research team worked closely with the fabricator to ensure that research related activities did not impede the fabricators schedule through pre-construction meeting and instrumentation planning as described in Task 1.

2.7. TASK 7: HARDENED PROPERTIES OF PRECAST PLANT AND READY MIX PRODUCED CONCRETE

The issue addressed under this task was to determine the hardened properties of the precast plant and ready mix produced concrete. Test data was evaluated between the traditional MoDOT concrete mixes and the specialty concretes including, NS-SCC, HS-SCC and HVFA concrete. Hardened mechanical and material properties were required not only for benchmarking purposes, but also required for analytical studies and bridge modeling.

2.8. TASK 8: BRIDGE LOAD TESTING AND MONITORING / EVALUATION OF EXPERIMENTAL LOAD TESTING RESULTS

2.8.1. Sub-Task 8a: Bridge Load Testing and Monitoring

The instrumentation outlined in Task 2 above allowed the researchers and MoDOT designers to follow the behavior of Bridge A7957 through all the significant steps in the construction history of the bridge. The deflections with time under a constant loading for the prestressed / precast beams were important data recorded with the instrumentation as outlined. The composite structure was completed by adding the cast-in-place deck to the prestressed / precast beams, and deflection changes in this structure under its own load with time was recorded. The applied load deflection for the bridge was measured as load/deflection response after it was completed.

Deflections under applied loading were compared to the analysis predictions. Because the flexural stiffness of the completed bridge is an important consideration in bridge design, these measured and predicted values were very important in the later stages of the project. As part of this work activity, it was therefore desirable to perform a live load test. Vehicles of known loads and traffic control were required to perform a live load test. These vehicles and traffic control were requested from the MoDOT Area Engineer for the proposed live load test. The live load test was executed after all construction had been completed. A second part of the first series of load tests was conducted approximately 8 months after construction had been completed.

In summary, the completed bridge utilizing NS-SCC, HS-SCC and HVFAC presented a unique opportunity to study all stages of performance, both experimentally and analytically. As outlined above, the serviceability was evaluated in terms of long-term deflection over the time period of the research project. Shrinkage and creep were essentially completed by the end of a one-year period.

Prior experience with the bridge testing for deflections under applied test loads had shown that temperature effects were to be separated from applied load deflections. This was done in both the experimental program and in the analysis.

2.8.2. Sub-Task 8b: Evaluation of Experimental Load Testing Results

The instrumentation plan of Task 2 showed the staging of the readings for deflection over the entire history of the project. The time history of events was extremely important as previously outlined in the discussion of the instrumentation plan. Because of the shrinkage and creep properties of concrete with time, the evaluation of the experimental results obtained through two plus years of monitoring was a very significant part of this project.

As described in Task 8a, the evaluation of the experimental results taken over one year of testing and monitoring involved the comparison of the test results from those using a sophisticated analysis program which takes time effects of material properties into account.

The concrete strain instrumentation was designed to use vibrating wire strain gauges that are known to last for multiple years for obtaining reliable data. With these data available, it was possible to verify whether predicted concrete strains from analysis were valid. Perhaps more importantly, it was possible to evaluate the losses of prestress with time to compare with the values now incorporated into design codes for bridges.

Calculation of prestress losses with time is the objective in many of the design expressions which attempt to pull together the losses from elastic shortening, shrinkage and creep of concrete plus relaxation of the prestressed steel. This project allowed an evaluation of the current expressions, but interaction among these various sources of loss almost defies an exact solution to the loss of prestress problem. The fact that deflections are being measured with time means that the analysis procedure used for predicting the deflection with time could be evaluated, which is perhaps more important than loss of prestress.

Temperature gradients have received much discussion in the literature in recent years and some suggested assumptions for temperature distribution over the depth of a member have been made. The instrumentation includes thermocouples, which could allow an evaluation of temperature gradient to be made for high performance concrete. The objective, of course, is to improve design assumptions for bridges in Missouri that utilize SCC and HVFAC. Test measurements for deflection answered the question as to

whether the higher modulus of elasticity (more stiffness of material) for SCC is sufficient to offset this reduction of the cross-sectional moment of inertia (less cross-section stiffness).

2.9. TASK 9: REPORTING / TECHNOLOGY TRANSFER

Developments, findings and recommendations from this study were reported in several mechanisms as reported under the Project Deliverable section below. Some of these include Quarterly Progress Reports, Interim Report, Final Reports, Technical Summary, Technical Presentations, and subsequent Technical Publications. The Interim Report was submitted for review at approximately midpoint of the project after construction had been completed.

2.10. TASK 10: VALUE TO MODOT AND STAKEHOLDERS TO IMPLEMENTING SCC/HVFAC

The issue 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. The quantitative cost analysis comparisons were undertaken in this task by obtaining cost estimates from precast fabricators and ready-mixed concrete (RMC) producers to examine both the short- and long-term benefits. While it was expected that the initial bids costs for new material usage in the field may be comparable to traditional mix designs, the fabricator and producer were surveyed after the completion of the job to gain insight into future projects involving these materials.

3. TASK SUMMARIES: CONCLUSIONS AND RECOMMENDATIONS

The following sub-sections summarize the major findings and conclusions as it relates to Project Tasks 1 through 10. Prior to the summary, each sub-section refers to the specific Technical Report A through D 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: PRE-CONSTRUCTION PLANNING AND CONSTRUCTION COORDINATION

The objective of this task was to conduct a series of meetings among the members of the working team to coordinate and clarify details about to the construction of the bridge and its components. The following meetings were held and attended by the Missouri S&T research team:

a) A partnering workshop to facilitate getting the contractor, subcontractors, researchers and MoDOT working as a team.
b) A pre-construction meeting after the contract was let, to clarify any details specific to the construction of the bridge and bridge components.
c) A pre-fabrication meeting prior to fabrication of the pre-tensioned girders to discuss issues including level of instrumentation, staging of instrumentation, and fabrication-related issues.
d) A pre-deck / pre-substructure construction meeting prior to formwork placement to discuss issues including level of instrumentation, staging of instrumentation, and casting & placement of concrete.

3.2. TASK 2: DEVELOPMENT OF BRIDGE INSTRUMENTATION PLAN & LOAD TESTING PLAN (BRIDGE A7957)

The aim of this task was to develop an efficient, effective instrumentation and load testing plan.

3.2.1. Subtask 2a: Instrumentation

The details of the type of measurement instruments and instrumentation plan implemented on Bridge A7957 are presented in Sections 4 and 5.2 of Technical Report A, and Section 3 of Technical Report D.

3.2.2. Subtask 2b: Monitoring of Concrete In-Place

The monitoring program carried out on Bridge 7957 is reported in Sections 5.3-5.5 of Technical Report A. Results are presented in Section 6 and 7 of Technical Report A.

3.2.3. Subtask 2c: Long-Term Monitoring of Concrete In-Place

The long-term monitoring program executed on Bridge A7957 is presented in Sections 3, 5.3-5.5 of Technical Report A.

Results are presented in Section 6 and 7 of Technical Report A. Conclusions from these tasks are as follows:

Technical Report A, Conclusions

- The instrumentation phase of Bridge A7957 was conducted effectively. The different measurement systems installed on the bridge's superstructure were used to monitor and compare the spans' response in the short and long-term when their different structural components are exposed to similar environmental conditions.
- Maturity studies were performed on the different concrete mixtures utilized in Bridge A7957. These studies were used to compare the differences among the mechanical properties development including: creep, shrinkage, thermal gradients, time dependent behavior and serviceability in the long term.

- High-volume fly ash concrete, a sustainable material, was employed at a 50% replacement level within one of the bridge's interior supports. Coupled with the use of SCC, Bridge A7957 is expected to have a longer service life than traditional prestressed and reinforced concrete structures.
- Raising the level of replacement fly ash from 20% to 50% reduced the heat generated by 24-43%.
- There was a negligible difference in the setting time of the HVFAC versus the CC mix with 20% fly ash replacement.
- The measured elastic shortening losses for the HSC, HS-SCC, and NS-SCC averaged 19.13 ksi, 20.866 ksi, and 17.43 ksi, respectively. For all the girders, the measured elastic shortening losses were higher than predicted using gross section and measured or predicted MOE.
- The average ratio of measured to predicted losses by these methods were between 1.21 and 1.67 for HSC. Ratios were between 1.35 and 1.43 for HS-SCC. For the NS-SCC, the ratios of measured to predicted losses were between 1.23 and 1.42. The reasons of the difference between measured and predicted elastic shortening losses might be due to restraint against shortening of the girders prior to the release and this caused losses to appear artificially high. The other reason was that the differences between the actual MOE and the values determined from companion specimen tests.
- The total prestress losses averaged 38.65 ksi, 48.85 ksi, and 43.24 ksi for the HSC, HS-SCC, and NS-SCC girders, respectively.
- For all the girders, elastic shortening losses accounted for the largest component of the total measured loss.
- For most girders, the measured total prestress losses were greater than predicted using the AASHTO LRFD and the PCI Handbook methods. Unconservative results were obtained for the NS-SCC and HS-SCC. Reasons might be attributed to the higher paste volume and difference in the mixes content compare to the HSC.

3.3. TASK 3: MIX DESIGN AND QUALITY CONTROL PROCEDURES / QUALITY ASSURANCE – TRIAL MIXES

This task aimed at providing technical advice on the development and production of the mix designs as needed in conjunction with the specification requirements. Missouri S&T researchers evaluated the final mix designs for all classes of concrete to be used in the project as these characteristics were needed for modeling and assessment of the bridge. Details about the trial mix designs conducted on the HVFAC, NS-SCC, and HS-SCC mixtures are provided in Section 5.1 of Report A. Results are presented in Section 6.1.1 of Report A. Conclusions and findings from this task are as follows:

Technical Report A, Conclusions

- The HVFAC modulus of elasticity of the trial mix was overestimated by the ACI and AASHTO empirical models. After a complete analysis of these results, the HVFAC mix design used in the trial mix was recommended to be implemented in the construction of the interior support Bent 3.
- The modulus of elasticity of the HS-SCC trial mix closely matches the Martinez et al. equation of ACI 363R 2010 while the equation suggested by Tomosawa et al. in ACI 363R 2010 provides a lower bound estimate. The ACI 318 2011 equation overestimated the modulus of elasticity.
- The modulus of elasticity of the 8,000 psi (55.2 MPa) NS-SCC trial mix was accurately estimated by both the Tomosawa et al. and Martinez et al. prediction equations in ACI 363R 2010. Both of these curves intersected at roughly 8,000 psi.

3.4. TASK 4: SHEAR TESTING AND EVALUATION OF HS-SCC PRECAST NU GIRDERS

The objective of this task was to validate the shear capacity of two full-scale NU bridge girders using the high-strength self-consolidating concrete (HS-SCC) mix design used within the bridge girders. The researchers studied the shear response using both mild

steel bars and welded wire mesh as the primary reinforcing steel. Two test girders were tested in shear. Previous laboratory tests were conducted on mid-scale rectangular beams.

The girders' design and fabrication details are described in Section 3 of Report B. Test results and analysis with comparisons to the ACI 318 code, and AASHTO's LRFD Bridge Design Specifications are presented in Section 4 of Report B. The conclusions, findings and recommendations from this task are the following:

Technical Report B, Conclusions

- Shear crack widths obtained during test 1 conducted on the welded-wire shear reinforced girder (TG1-T1) were 23% of those obtained during test 1 of the mild-steel bar shear reinforced girder (TG2-T1), a result of the spacing of shear reinforcement. A recommendation based on this observation is provided in the subsequent section.
- The shear resistance provided by the uncracked concrete in the presence of transverse reinforcement increased by 48% and 23% in test girders 1 and 2, respectively. In these tests, the shear reinforcement limited both the formation and widths of the cracks.
- The concrete contribution to shear not in the presence of transverse reinforcement exceeded the factored shear capacity predicted by ACI 318 (2011). The average load at failure exceeded the nominal predicted capacity by a factor of 1.02 when the actual concrete compressive strength was used. This value increased to 1.04 when the ACI 318 maximum limit on f'_c of 10,000 psi (68.9 MPa) is included.
- The shear load at failure exceeded both the nominal and the factored shear resistance predicted by the 2012 AASHTO LRFD Bridge Design Specifications for the concrete contribution to shear without web reinforcement. The size effect parameter included in the AASHTO provisions led to more conservative estimates than ACI 318 (2011).
- Response 2000 predicted the shear capacity of the NU test girders to a reasonable degree of accuracy. However, the level of conservativeness is greatly affected by

the input tensile strength of concrete, which can vary significantly for a given compressive strength.

- ATENA Engineering v5.0.3 showed a general decrease in the shear capacity as the coarse aggregate content reduces to zero. However, there were mixed results when the aggregate size was increased to 1 in. (25.4 mm). Based on the analysis, the presence of aggregate (rather than the size) influenced the results. The predicted crack patterns aligned with the tested observations when shear reinforcement is placed at 12 in. (305 mm) on center.
- Based on the constructed shear database, the shear strength ratio of the HS-SCC tests girders was similar to the shear strength ratios of other specimens, specifically when analyzed with the 2012 AASHTO LRFD specifications. The test results appear to be on the lower end of the data points when compared with the 2011 ACI 318 estimations; however this trend occurs from the size effect not accounted for in the ACI 318 provisions. Based on the data collected, there were no distinguishable trends of the shear strength ratio with respect to the coarse aggregate content as other factors contribute more heavily to the shear capacity of prestressed concrete members.

Technical Report B, Recommendations

The results and testing observations of the NU girders were recorded and documented. Based on the results obtained:

- The high strength self-consolidating concrete mix investigated is a viable alternative for precast prestressed concrete elements.
- When designing HS-SCC elements in shear, the transverse reinforcement should be designed to minimize the spacing.
- By reducing the spacing of web reinforcement, the diagonal shear crack widths are minimized such that the interface shear transfer mechanism of the shear carried by the concrete is maximized even when cracks propagate through the aggregate. The shear test observations containing web reinforcement support this recommendation.

3.5. TASK 5: PRECAST-PRESTRESSED PLANT SPECIMEN FABRICATION AND INSTRUMENTATION

The issue addressed under this task involved the instrumentation and fabrication of the prestressed-precast girders. This task involved the placement of instrumentation and assemblage of the data acquisition system (DAS) as described in Task 2. The research team worked closely with the fabricator to ensure that research related activities did not impede the fabricators schedule as described in Task 1.

Details of the precast-prestressed specimen fabrication, instrumentation and data collection of the implemented girders on Bridge A7957 are presented in Sections 5.2 and 5.4 of Technical Report A, and Section 3 of Technical Report D.

3.6. TASK 6: FIELD CAST-IN-PLACE ELEMENTS AND INSTRUMENTATION

This task involved the instrumentation and construction of the site cast-in-place (CIP) concrete to be investigated. This task involved the placement of instrumentation and assemblage / mounting of the data acquisition system (DAS) as described in Task 2. The research team worked closely with the fabricator to ensure that research related activities did not impede the fabricators schedule through the pre-construction meeting and instrumentation planning as described in Task 1.

Details of the field cast-in-place elements and instrumentation are presented in Sections 5.2 and 5.3 of Technical Report A, and Section 3 of Technical Report D.

3.7. TASK 7: HARDENED PROPERTIES OF PLANT AND FIELD PRODUCED CONCRETE

The issue addressed under this task was to determine the hardened properties of the plant and produced concrete. Test data was evaluated between the traditional MoDOT concrete mixes and the specialty concretes including NS-SCC, HS-SCC and HVFA concrete. Hardened mechanical and material properties were required not only for benchmarking purposes, but also required for analytical studies and bridge modeling.

Details about how the hardened properties of the plant and produced concrete were obtained are summarized in Sections 5.4 and 5.5 of Technical Report A. Results are

presented in Section 6.1.2-6.1.6 of Technical Report A. Conclusions from this task are as follows:

Technical Report A, Conclusions

- The specified 28-day compressive strength of 3,000 psi (20.7 MPa) was exceeded at 7 days by both concrete mixtures employed to cast the abutments and bents 2 and 3. This early strength gain is related to the portland cement replacement by Class C fly ash which has been reported to perform well at early age strength gains due to cementitious activity given by their higher calcium content (Naik et al. 2003).
- The HVFAC mixture developed a larger compressive strength than the control mixture (MoDOT Class B with 20% fly ash replacement) used to cast the abutments and bent 2.
- The HVFAC mixture showed a 28-day compressive strength of 5970 psi (41.2 MPa) that approximately doubled the specified design compressive strength of 3,000 psi (20.7 MPa).
- By raising the level of fly ash from 20% to 50%, a reduction of the heat of hydration was achieved on the order of 25-40%.
- A negligible difference between the setting time of HVFAC and conventional concrete (MoDOT's Class B Mixture) was observed.
- The 28-day target compressive strength was reached by all of the instrumented girders after 7 days except for span 3's girder 4 (S3-G4) that exceeded the design strength at 14 days. This was caused by adding a slightly larger amount of air-entraining admixture during the batch of this girder's concrete mixture (NS-SCC). In addition, a reduction of the S3-G4's compressive strength and modulus of elasticity was observed with respect to the rest of the precast, prestressed girders. As reported by (Khayat and Mitchell 2009), slight variations of the mixture proportions adversely affect the mechanical properties of the concrete mixture. These results implied that it is critical to follow a strict control when

proportioning SCC to avoid this type of mechanical properties variation that might adversely impact the in-service response of the bridge superstructure.

- The ACI 318 2011 empirical equation used to predict the splitting tensile strength provided the best prediction for NS-SCC specimens, while the ACI 363R 2010 equation overestimated this mechanical property.
- The splitting tensile strength of the HS-SCC mix was overestimated by both the ACI 318 2011 and ACI 363R 2010 prediction equations. Post-test cross section images revealed that the aggregate failed before the interfacial bond zone between the paste and aggregate.

In addition, an evaluation, aiming at examining the effects of high replacement levels of fly ash at later ages of durability testing, was conducted. Currently, American Society for Testing and Materials (ASTM) set test methods to determine concrete suitability for certain applications. With the implementation of fly-ash, standards recommendation of using 28-day properties of such concrete may not always be beneficial due to delay in hydration causing a delay in the attainment of certain concrete properties. The emphasis of this evaluation was to determine the appropriate age at which to test HVFAC for different durability aspects. Properties assessed within this complimentary task included: slump, air content, density, temperature, modulus of elasticity, compressive strength, abrasion resistance, freeze-thaw durability, and chloride ion penetration resistance. The study was carried out in two phases. In Phase 1, the compressive strength and durability characteristics of replacing cement with fly-ash at many replacement levels (0, 35, 50, 60, and 70%) was investigated. Phase II assessed the accelerated curing method [for temperatures of 100°F (37.8°C) 130°F (54.4° C) and 160°F (71.7°C)]. Once each characteristic was evaluated, recommendations were made to amend ASTM standards to allow later age testing according to the durability aspects under evaluation. Report C presents detailed information about the laboratory work carried out. Results are presented in Section 4 of Report C. The findings, conclusions and recommendations obtained from this evaluation are as follows:

Technical Report C, Conclusions

- All concrete mixes reached a slump between 7 and 7 ¾ inches (177.80-196.85 mm). Concrete temperature at every level of fly-ash replacement was higher than room temperature. Then as fly-ash was added the difference in temperature increased suggesting that fly-ash immediately generates higher heat than conventional concrete followed by a slower rate of heat generation in turn delaying hydration.
- Air content decreased as fly-ash was added up to 50% before leveling out. Fly-ash acts as a filler packing air voids and decreasing air content. Mass and density across all mix designs were constant with HVFAC weighing slightly greater.
- Past research has shown there is a delay in the hydration of HVFAC and this causes a delay in compressive strength gain. Although there is a delay in compressive strength, it has been discovered that there is an age where HVFAC is actually stronger than conventional concrete. In the area of compressive strength, for Phase I, the findings showed that by 56 days, mixtures up to 60% HVFAC were comparable, if not greater, in compressive strength to the conventional mix. In fact, the 35% and 50% HVFAC mixtures showed results comparable to that of the conventional mix at 28 days. The largest compressive strength gain was seen between 28 and 56 days considering HVFAC, and conventional concrete leveled off beginning at 28 days. All mixes gained a structural compressive strength of at least 2900 psi at some age except for 70% replacement mixes in Phase II. Although at a specific age each mix showed comparable results to the conventional mix, the 70% HVFAC never reached the compressive strength of any other mix at the respective age nor gained compressive strength similar to that of conventional concrete at 28 days.
- Phase II specimens exhibited increased compressive strength from conventional curing methods within the first 3 days. Post 3 days, there was a decrease in compressive strength from Phase I to Phase II. Within Phase II, the largest compressive strength gain was between 3 and 7 days at which point the compressive strengths generally plateaued. As the curing temperature increased,

specimens plateaued earlier. As the specimens cured, water was wicked away from the surface leaving little water for HVFAC mixes to hydrate with.

- All concrete exhibited higher stiffness than predicted by ACI Eq. (2.1) once the specimens gained 3,000 psi (20.68 MPa). Even for HVFAC the findings proved to be linear.
- Between 3,000 and 6,000 psi (20.68 MPa and 41.37 MPa) HVFAC gains stiffness per unit strength which exceeds the conventional mix. 70% HVFAC performs best within this range.
- Post 6,000 psi (41.37 MPa) HVFAC mixes tend to cease to increase in stiffness per unit strength while the conventional mix continues to gain stiffness. When considering mixes above 50% replacement, the MOE gained at 28 days is the stiffness expected at 120 days whereas the conventional and 35% HVFAC continues to gain stiffness as they age. At 28 days HVFAC shows a slightly increased MOE over the conventional even though HVFAC compressive strength is lower at this age.
- The maturity method is useful in estimating the concrete compressive strength at any age where the temperature history is recorded by non-destructive means. This method can also be used to estimate compressive strength at different curing temperatures as well. Knowing the concrete compressive strength at specific times is beneficial when determining a construction schedule. However, there are some disadvantages. The concrete must be cured in an environment where hydration can occur. This method does not take into account the effect of early-age heat generation on long-term compressive strength and must be accompanied by another means of indication of concrete compressive strength.
- Mortar cubes were made and tested to determine the datum temperatures and activation energy. Hydration of concrete can occur if cured at a temperature lower than the datum temperature. The datum temperature increased as the fly-ash increased. Using Nurse-Saul’s equation, the maturity is computed and plotted against the compressive strength of the moist cured specimens. Using this plot, the concrete compressive strength can be estimated at any time the temperature history of the in-place concrete is known. Inversely, the age of concrete at which a

specific concrete compressive strength is required, such as formwork removal, can also be estimated based on the data and plots.

- Maturity results agree that HVFA concrete takes longer to hydrate in turn gaining compressive strength at a slower rate. Results showed that 70% HVFAC would take roughly 6 times longer to gain compressive strength than the conventional mix. Bridge A7957 specified target compressive strength for 50% HVFAC of 3,000 psi (20.7 MPa). If 70% HVFA concrete had been used, over 25 days would have had to pass before 70% HVFAC reached the target, whereas 50% HVFA concrete gains adequate compressive strength by day 4. In applications where time is a factor, it is not recommended to replace cement by fly-ash past 50%.
- The maturity method also gave an indication about placing concrete in a variety of temperatures. As the temperature increased, the time to specific compressive strengths decreased. As the fly-ash increased the temperature during hydration was reduced. Again, 70% HVFAC is not recommended in application where early strength gain is necessary due to the delay in strength gain. Replacement levels of 35% to 60% perform similar between 65°F (18°C) and 95°F (35°C). Flash set is a concern when placing conventional concrete in temperatures above 80°F (27°C).
- During Phase I there was a correlation between compressive strength and mass loss. There was also a correlation between age and mass loss because the specimens gained compressive strength as they aged. As the specimens aged and gained compressive strength the mass loss decreased. Optimum replacement level was 50%. There was a decreased mass loss up to 50% and a decrease beyond 50%.
- By 56 days, 70% HVFAC performed better than the conventional at 28 days and by 90 days 70% HVFAC performed similar to the conventional at 90 days and beyond. 35% and 50% HVFAC outperformed the conventional concrete at all ages.
- A significant decrease in mass loss was consistently seen up to 120 days of age at all levels of fly-ash replacement.
- Phase II specimens incurred issues with the surface layer being soft (high mass loss of the first trials). Standard deviation was above the allotted deviation set

forth by ASTM C994-12. To compare results effectively, the first trial was omitted for Phase I and Phase II. By omitting trial one, all standard deviations and coefficients of variance fell within the acceptable range. No correlation between percentage of fly ash and mass loss was found during Phase II.

- Specimens cured at 100°F (37.8°C) performed best of phase II specimens, while specimens cured at the other two temperatures varied in performance. All specimens in Phase II performed worse than their Phase I counterparts.
- No admixtures other than fly-ash were used in this study. All specimens performed poorly in terms of durability factor (DF) during freeze-thaw testing as expected from the lack of air-entrainment. A slight increase in DF was seen with an increase in age and compressive strength. The compressive strength affected the conventional mix much greater than the HVFAC mixes. Replacement up to 50% showed an increase in DF until 120 days where conventional concrete shot past HVFAC mixes. At rates above 50%, a steep decrease in DF occurred. The 70% HVFAC performed the worse not showing a DF (<10) until 120 days. By 120 days, 60% HVFAC outperformed the conventional concrete at 28 days. Beginning at 28 days, the 35% and 50% HVFAC performed greater than the conventional concrete. Standard deviations of data met requirements set forth by ASTM C666-03 Procedure A.
- Overall, between 28 and 56 days in ages, for the 35 and 50% HVFAC, there was a significant increase in DF prior to leveling off between 56 and 90 days. Fly-ash levels greater than 50% showed similar results at each age of testing until 120 days where a significant increase occurred. DF for the conventional concrete increased up to 120 days.
- Phase II specimens performed worse than Phase I in terms of the freeze-thaw test. Data for this phase rarely fell within the acceptable range of standard deviation. Many Phase II specimens failed before completing one set of 36 freeze-thaw cycles. However, these specimens didn’t necessarily fail due to falling below 60% initial relative dynamic modulus (RDM) rather they failed due to insubstantial surface area required for testing.

- A majority of Phase II specimens did not improve in terms of DF from 14 to 28 days. Lack of improvement could be caused from the lack of compressive strength gain during this 14 to 28 days period. During Phase II, 70% HVFAC never achieved a DF. 160°F curing temperature proved to be detrimental to all Phase II specimens.
- In terms of freeze-thaw resistance, phase II 14-day conventional concrete cured at 100°F (37.8°C) and 130°F (54.4°C) outperformed Phase I specimens at 28, 56, and 90 days. Phase II 50% HVFAC specimens cured at 100°F (37.8°C) performed better at all ages. Curing temperature affected HVFA concrete greater than conventional concrete.
- Previous research showed that by incorporating fly-ash into concrete makes it less permeable. The fly-ash reacts with the CH to form denser hydration products. Fly-ash also bonds to the chloride to combat penetration.
- In both phases the %Cl decreased as the depth increased. In Phase I, HVFAC mixes up to 60% performed similar if not better than the conventional mix beginning at 28 days. There did not seem to be a correlation between age and permeability within the HVFAC mixes. However, as the conventional concrete aged the permeability decreased. The original chloride content decreased as the percent of fly-ash increased. Between ages of 28 and 120 days, each mix performed similar to itself at each location.
- Upon inspection of Phase II specimens the curing process left a porous structure. There is an increase in permeability from conventional to 35% HVFAC. Above 35% HVFAC the results remained very similar. The curing temperature and age (14 to 28 days) did not play a role in %Cl values. At both ages and all three temperatures, Phase II specimens consistently fell in the high risk zone (> 0.14% Cl). Phase I 28 day conventional concrete showed lower permeability than Phase II specimens.

Technical Report C, Recommendations

In reference to amending to the American Society for Testing Materials (ASTM) the followings modifications may be considered:

- In applications where structures will not undergo service conditioning for longer than 28 days, HVFAC is a suitable alternative to concretes without Class C fly ash replacement.
- Based on all results, the maximum recommended replacement level is 50%. In terms of compressive strength, modulus of elasticity, abrasion and freeze-thaw, the optimum replacement level was 50%.
- When considering chloride penetration, 50% HVFAC performed similar to all the other replacement levels.
- When determining target compressive strength and modulus of elasticity, 56-day testing should be considered for HVFAC. By 56 days, HVFAC performs similarly, if not better than conventional concrete. Beyond 56 the rate of compressive strength gain decreased.
- When considering durability aspects, the results varied depending on the characteristic considered. For abrasion resistance, 28 days is an adequate age to test HVFA concrete based on comparison to the conventional mix. Both of these tests showed increased performance with the inclusion of fly-ash up to 50% at 28 days although not significantly. These properties are partially reliant on the compressive strength whereas HVFAC approaches similar compressive strength to conventional concrete at 56 days.
- As the percent fly-ash increases, the effect of compressive strength decreases. Although 28 day abrasion resistance is adequate for HVFA concrete, it is recommended to use the resistance tested at 120 days of age. Concrete at all fly-ash replacement levels showed a significant decrease in mass up to 120 days.
- It should be emphasized that this work was conducted on non-air entrained HVFA concrete and the reulsts may not be representative of air entrainded HVFAC. When considering freeze-thaw resistance, the recommended age of testing is 56 days respective to 50% maximum replacement level. Above 50% fly-ash it is

necessary to wait 120 days until exposing HVFA concrete to freeze-thaw conditions. The conventional concrete consistently showed an increase DF between 28 and 120 days of age.

- Chloride permeability by RCT showed scattered results. Beyond 28 days results are unclear. There is little correlation between age and permeability. HVFAC performs similar to the conventional from 28 days on. When considering each HVFAC mix individually, they performed similar from 28 days to 120 days of age.
- HVFA concrete should not be cured at temperatures greater than 100°F (37.8°C) and low relative humidity. High temperatures are detrimental, in terms of mechanical and durability properties, to concrete and significantly affect HVFAC. Curing conventional concrete at high temperatures may cause flash or false set. Durability properties and later age strength may suffer as well. Future testing should explore curing HVFA concrete around 100°F (37.8°C) with high relative humidity so hydration continues.
- It is recommended in future studies to either omit investigation on 70% HVFAC or to include admixtures in mix designs. Future work should look at lowering the cement content and adjusting the mix constituents based on keeping a constant slump at 5 inches.
- Future studies should include investigation on reliability of the Maturity Method in the field. From lab testing the maturity method showed general trends expected based on literature review. Research should include verifying the estimation of concrete compressive strength at different temperatures.

3.8. TASK 8: BRIDGE LOAD TESTING AND MONITORING / EVALUATION OF EXPERIMENTAL LOAD TESTING RESULTS

Bridge A7957 is the first bridge superstructure implementation conducted by the Missouri Department of Transportation (MoDOT) employing self-consolidating concrete (SCC) and high-strength self-consolidating concrete (HS-SCC) in its primary supporting members. In summary, the completed bridge utilizing HS-SCC and HVFAC presented a unique opportunity to study all stages of performance, both experimentally and

analytically. As intended, the serviceability was evaluated in terms of long-time deflection over the time period of the research project.

During the field load test, embedded vibrating wire strain gauges (VWSGs) recorded strain variations at instrumented sections. In addition, an automated total station (ATS) measured the girders' vertical deflection at critical sections. Based on field results, the precast, prestressed girders' response of the different spans was compared, and lateral load distribution factors were obtained from field measurements and using the AASHTO LRFD Bridge Design Specifications.

3.8.1. Sub-Task 8a: Bridge Load Testing and Monitoring

The objective of this task was to perform several series of load tests on Bridge A7957 to establish its baseline response and to compare the spans' behavior (in particular the first and third spans which have similar geometry and materials' mechanical properties). To fulfill this goal, a field load test strategy was planned and carried out to evaluate the bridge's response under different static load test configurations.

During the field load test, embedded vibrating wire strain gauges (VWSGs) recorded strain variations at instrumented sections. In addition, an automated total station (ATS) measured the girders' vertical deflection at selected locations.

3.8.2. Sub-Task 8b: Evaluation of Experimental Load Testing Results

The purpose of this task consisted of evaluating the experimental data recorded during the bridge load testing and the different monitoring stages of the bridge. This task also aimed at improving design assumptions for bridges in Missouri that utilize SCC and HVFAC. Test measurements for deflection answered the question as to whether the higher modulus of elasticity (more stiffness of material) for SCC was sufficient to offset this reduction of the cross-sectional moment of inertia (less cross-section stiffness). Based on field results, the precast, prestressed girders' response of the different spans was compared, and lateral load distribution factors were obtained from field measurements and using the AASSHTO LRFD Bridge Design Specifications.

The findings and conclusions from these two subtasks are given in the following:

Technical Report D, Conclusions

- The first full-scale structure implementation of high-strength self-consolidating concrete (HS-SCC) and high-volume fly ash concrete (HVFAC) has been executed on the structure of Bridge A7957 through the Missouri Department of Transportation (MoDOT).
- The instrumentation phase of the project has been effectively accomplished and was employed to record the bridge response during the first series of live load tests conducted on the bridge superstructure during April and August 2014.
- The first series of diagnostic load tests conducted on Bridge A7957 served to evaluate the initial in-service response and the lateral load distribution of the bridge superstructure PC/PS primary supporting members.
- The structural response of the normal-strength self-consolidating concrete (NS-SCC) and conventional concrete (CC) PC/PS girders was similar, suggesting that the structural performance of the NS-SCC and HS-SCC PC/PS girders should not prevent its implementation in future infrastructure projects.
- Load distribution factors are critical in the design of new bridges and in the serviceability assessment of existing bridge structures.
- Load distribution factors (LDFs) were estimated from field measurements, and girder distribution factors (GDFs) were obtained using the AASHTO LRFD Bridge Design Specification (AASHTO 2012) approach. The AASHTO LRFD GDFs resulted in larger and more conservative values compared to the experimental LDFs.
- Differences between GDFs and LDFs may be related to several causes. The AASHTO LRFD equations were developed to be applied to a wide variety of type of bridges with a variable range of span lengths, girders spacing, and stiffness. LDFs, obtained from field tests, implicitly consider in-situ conditions such as unintended support restraints, skew angle, contribution of secondary members, and multiple presence factors, which may contribute to improve the bridge's in-service structural performance.

- More research needs to be conducted to evaluate differences between the GDFs and LDFs and the range of applicability of each approach specifically for in-service assessments of existing structures.

3.9. TASK 9: REPORTING / TECHNOLOGY TRANSFER

Developments, findings and recommendations from this study were transferred in several mechanisms including Quarterly Progress Reports, an Interim Report, Conference & Journal Publications and this Final Report.

3.10. TASK 10: VALUE TO MODOT AND STAKEHOLDERS TO IMPLEMENTING SCC/HVFAC

Consistent with previous work undertaken by the research team (Myers et al. 2012, Volz et al. 2012) 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.
- *Improved flexural behavior of HS-SCC*. HS-SCC brings to SCC's main attributes an enhanced flexural performance achieved as a consequence of increasing the SCC's compressive strength. This stronger flexural feature brings the possibility to reduce the number of main carrying members and interior supports of bridge super structures.

High-volume fly ash concrete (HVFAC) has demonstrated to be a potential alternative to traditional concrete mixtures, and to be significantly more sustainable. By

nearly doubling the use of reclaimed fly ash in concrete, HVFAC aligns well with MoDOT's green initiative on recycling. Since the 1930's, fly ash – a pozzolanic material – has been used as a partial replacement of portland cement in concrete to improve the material's strength and durability, while also limiting the amount of early heat generation and cracking of concrete. HVFAC has the following advantages over conventional concrete:

- From an environmental perspective, replacing cement with fly ash reduces concrete's overall carbon footprint and diverts an industrial by-product from the solid waste stream (currently, about 40 percent of fly ash is reclaimed for beneficial reuse and 60 percent is disposed of in landfills). These values align with both MoDOT's Mission of being environmentally and socially responsible (MoDOT 2016) and MoDOT's Research Need for strategies to reduce energy consumption (Stone 2010).
- Concrete is the most widely used man-made material on earth, with nearly three tons produced annually for each man, woman, and child, and accouns for 5% of the carbon dioxide released into the atmosphere each year. On average, replacing even 50% of the cement used in concrete with fly ash will reduce the annual amount of greenhouse gas emissions by nearly 1.8 billion tons worldwide. Furthermore, this change would also eliminate more than 20 billion cubic feet of landfill space each year. In terms of energy consumption, this fly ash replacement level would save the equivalent of 6.7 trillion cubic feet of natural gas annually.
- There are additional benefits of using fly ash to replace a significant portion of the cement in concrete. In terms of monetary savings, fly ash costs approximately one-half the amount for cement. For the same workability, fly ash reduces the amount of potable mixing water by approximately 20%. Even more importantly, fly ash increases the durability of concrete beyond what can be attained with portland cement alone. Increased durability translates into increased sustainability by extending the useful life of the material.

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