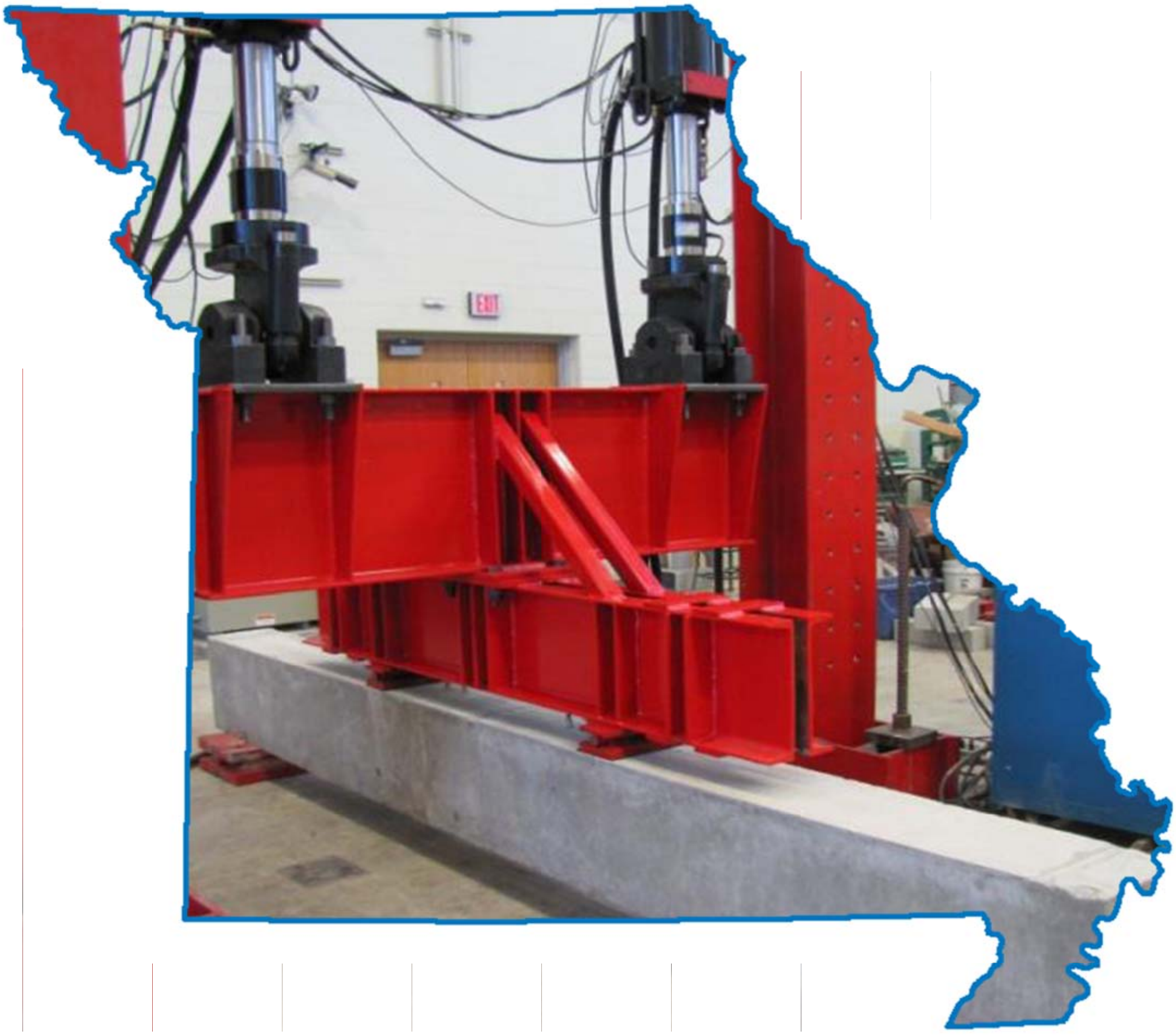
Development and Evaluation of High-Volume Fly Ash (HVFA) Concrete Mixes



Prepared By
Jeffery S. Volz, S.E., P.E., Ph.D.
John J. Myers, P.E., Ph.D.
David N. Richardson, P.E., Ph.D.
Missouri University of Science and Technology

MoDOT
Final Report Prepared for Missouri Department of Transportation
January 2013 Project TRyy1110 Report cmr 13-008

FINAL Report

TRyy1110

Design and Evaluation of High-Volume Fly Ash (HVFA) Concrete Mixes

Prepared for
Missouri Department of Transportation
Construction and Materials

By

Jeffery S. Volz, SE, PE, PhD (Principal Investigator)
John J. Myers, PE, PhD (Co-Principal Investigator)
David N. Richardson, PE, PhD (Co-Principal Investigator)
Mahdi Arezoumandi
Karl Beckemeier
Drew Davis
Kyle Holman
Trevor Looney
Brian Tucker

Missouri University of Science and Technology, Rolla, Missouri

October 2012

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. cmr 13-008	2. Government Accession No.	3. Recipient's Catalog No. TRyy1110
4. Title and Subtitle Design and Evaluation of High-Volume Fly Ash (HVFA) Concrete Mixes		5. Report Date October 31, 2012 6. Performing Organization Code
7. Author(s) Jeffery S. Volz, PE, PhD, John J. Myers, PE, PhD, David N. Richardson, PE, PhD, Mahdi Arezoumandi, Karl Beckemeier, Drew Davis, Kyle Holman, Trevor Looney, and Brian Tucker		8. Performing Organization Report No.
9. Performing Organization Name and Address Missouri University of Science and Technology 331 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 Construction and Materials P. O. Box 270, Jefferson City, MO 65102		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code
15. Supplementary Notes The investigation was conducted in cooperation with the U. S. Department of Transportation, Federal Highway Administration.		

16. Abstract

Concrete is the world's most consumed man-made material. Unfortunately, the production of portland cement, the active ingredient in concrete, generates a significant amount of carbon dioxide. For each pound of cement produced, approximately one pound of carbon dioxide is released into the atmosphere. With cement production reaching nearly 6 billion tons per year worldwide, the sustainability of concrete is a very real concern.

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).

Traditional specifications limit the amount of fly ash to 25 or 30 percent cement replacement. Recent studies, including those by the investigators, have shown that higher cement replacement percentages – even up to 75 percent – can result in excellent concrete in terms of both strength and durability. Referred to as high-volume fly ash (HVFA) concrete, this material offers a viable alternative to traditional portland cement concrete and is significantly more sustainable. By nearly doubling the use of reclaimed fly ash in concrete, HVFA concrete aligns well with MoDOT's green initiative on recycling.

However, HVFA concrete is not without its problems. At all replacement rates, fly ash generally slows down the setting time and hardening rates of concrete at early ages, especially under cold weather conditions, and when less reactive fly ashes are used. Furthermore, with industrial by-products, some variability in physical and chemical characteristics will normally occur, not only between power plants but also within the same plant. Consequently, to achieve the benefits of HVFA concrete, guidelines are needed for its proper application in bridges, roadways, culverts, retaining walls, and other transportation-related infrastructure components.

The objective of this research was to design, test, and evaluate HVFA concrete mixtures. The study focused on the hardened properties of HVFA concrete containing aggregates and fly ash indigenous to the state of Missouri and developed guidelines on its use in infrastructure elements for MoDOT.

17. Key Words Cement, Concrete, Flexural Behavior, Fly Ash, High-Volume Fly Ash Concrete, Mix Design, Mix Optimization, Reinforcing Bond, Reinforced Concrete, Shear Behavior, Sustainability.	18. Distribution Statement No restrictions. This document is available to the public through National Technical Information Center, Springfield, Virginia 22161

19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages 817	22. Price

Form DOT F 1700.7 (06/98)

EXECUTIVE SUMMARY

On behalf of the Missouri Department of Transportation (MoDOT), Missouri University of Science and Technology (Missouri S&T) completed a research study on high-volume fly ash (HVFA) concrete using fly ashes and aggregates indigenous to the State of Missouri. The report, entitled *Design and Evaluation of High-Volume Fly Ash (HVFA) Concrete Mixes*, consists of a summary report followed by five detailed technical reports. Taken together, these reports document the background, detailed approaches, experimental procedures and processes, results, findings, conclusions, and recommendations of the study.

The research work plan included eight tasks consisting of the following: (1) Task 1: Literature Review, (2) Task 2: Mix Development, (3) Task 3: Hardened Properties of HVFA Concrete Mixes, (4) Task 4: Bond and Development of Mild Steel, (5) Task 5: Full Scale Specimen Tests, (6) Task 6: AASHTO & ACI Code Comparison of Test Results, (7) Task 7: Recommendations & Specifications for Implementing HVFA Concrete, and (8) Task 8: Value to MoDOT and Stakeholders to Implementing HVFA Concrete.

Based on the results of Tasks 1 through 6, the researchers recommend the implementation of HVFA concrete in the construction of transportation-related infrastructure in the State of Missouri. However, the investigators also recommend initially limiting the fly ash replacement levels to 50% and avoiding applications subjected to direct deicing chemicals, such as bridge decks and pavements, due to potential scaling issues.

To alleviate any potential construction delays due to low early-age strength gains, the researchers recommend two approaches: (1) lowering the water-cementitious materials (*w/cm*) ratio compared to equivalent conventional concrete mixes or (2) adding powder activators such as gypsum, lime, and rapid-set cement. In general, the gypsum and lime powder activators offer the greatest benefits to early-age strength gain, with recommended dosages of 4% gypsum and 10% lime as a function of the amount of fly ash. At the recommended initial levels of 50% fly ash replacement, lowering the *w/cm* ratio is also a very viable approach to any early-age strength gain issues, particularly since the high amount of fly ash will significantly improve workability even without water-reducing admixtures.

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.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the many individuals and organizations that made this research project possible. First and foremost, the authors wish to extend a very sincere thank you to the Missouri Department of Transportation (MoDOT). In addition to their financial support, the authors appreciate MoDOT’s vision and commitment to recycling and using innovative materials in the construction and maintenance of Missouri’s transportation network. In particular, the success of this project would not have been possible without the guidance and many insightful comments from MoDOT’s Technical Advisory Group, namely Mr. Andrew Hanks, Mr. John Donahue, Ms. Jennifer Harper, Mr. Sam Marshall, Mr. Brett Trautman, and Mr. John Wenzlick. The authors also appreciate the assistance of Mr. Steven Jackson for testing many of the durability specimens. Special thanks also to Mr. Bill Stone for his unwavering support of the project.

The authors would also like to thank the National University Transportation Center (NUTC): Center for Transportation Infrastructure and Safety (CTIS) housed at 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. This match funding allowed for more extensive testing and research on the many factors critical to success of the project.

The authors would also like to thank the many companies that provided material contributions necessary for the successful completion of this project, including the Ameren Corporation, Ash Grove Cement Co., BASF Corporation, Buzzi Unicem USA, Continental Cement Co., LLC, Holcim (US) Inc., Kansas City Power and Light Co., and Lafarge North America Inc. Special thanks to Mr. Charles Henderson and Mr. Roger Zipprich of the Ameren Corporation and Mr. Dave Rylance of Lafarge North America Inc. for providing all of the fly ash necessary for this research project.

Finally, the authors would like to thank Missouri S&T for their valuable contributions to the research. The university awarded four Chancellor’s Fellowships to graduate students working on this project. These individuals represent some of the finest graduate students at Missouri S&T. The authors also appreciate the tireless staff of the Department of Civil, Architectural, and Environmental Engineering and the Center for Infrastructure Engineering Studies. Their assistance both inside and out of the various laboratories was invaluable to the successful completion of this project.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1. INTRODUCTION

1.1. REPORT ORGANIZATION

The following report documents a research project on high-volume fly ash (HVFA) concrete performed by Missouri University of Science and Technology (Missouri S&T) on behalf of the Missouri Department of Transportation (MoDOT). The report consists of a Summary Report followed by five detailed technical reports. Section 1 of the Summary Report presents the report organization and background for the study. 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 project 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 the 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 Technical Reports A through E provide the background, detailed approaches, experimental procedures and processes, results, findings, conclusions, and recommendations.

1.2. BACKGROUND

Concrete is the world's most consumed man-made material. Unfortunately, the production of portland cement, the active ingredient in concrete, generates a significant amount of carbon dioxide. For each pound of cement produced, approximately one pound of carbon dioxide is released into the atmosphere. With cement production reaching nearly 6 billion tons per year worldwide, the sustainability of concrete is a very real concern.

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).

Traditional specifications limit the amount of fly ash to 25 or 30 percent cement replacement. Recent studies, including those by the investigators, have shown that higher cement replacement percentages – even up to 75 percent – can result in excellent concrete in terms of both strength and durability. Referred to as HVFA concrete, this material offers a viable alternative to traditional portland cement concrete and is significantly more sustainable. By nearly doubling the use of reclaimed fly ash in concrete, HVFA concrete aligns well with MoDOT's green initiative on recycling ("MoDOT Keeps Billions of Pounds of Waste from Landfills," MoDOT News Release, September 20, 2010).

However, HVFA concrete is not without its problems. At all replacement rates, fly ash generally slows down the setting time and hardening rates of concrete at early ages, especially under cold weather conditions, and when less reactive fly ashes are used. Furthermore, with industrial by-products, some variability in physical and chemical characteristics will normally occur, not only between power plants but also within the same plant. Consequently, to achieve the benefits of HVFA concrete, guidelines are needed for its proper application in bridges, roadways, culverts, retaining walls, and other transportation-related infrastructure components.

2. PROJECT WORK PLAN

As with most research projects, the project work plan evolved during the course of the study as results became available. The work plan described below reflects the work as completed on the project.

The ***objective*** of the research was to design, test, and evaluate HVFA concrete mixtures. The study focused on the hardened properties of HVFA concrete containing aggregates and fly ash indigenous to the state of Missouri and developed guidelines on its use in infrastructure elements for MoDOT. The ***project work plan*** included eight (8) tasks necessary to reach this goal and consisted of the following:

1. Task 1: Literature Review
2. Task 2: Mix Development
3. Task 3: Hardened Properties of HVFA Concrete Mixes
4. Task 4: Bond and Development of Mild Steel
5. Task 5: Full Scale Specimen Tests
6. Task 6: AASHTO & ACI Code Comparison of Test Results
7. Task 7: Recommendations & Specifications for Implementing HVFA Concrete
8. Task 8: Value to MoDOT and Stakeholders to Implementing HVFA Concrete

The following sections discuss each of these individual tasks.

2.1. 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 HVFA concrete, with particular attention to the impact that these findings may have on the work plan. Specifically, the literature review focused on studies involving the hardened properties of HVFA concrete that affect structural performance (e.g., compressive strength, bond, shear strength) and durability (e.g., freeze-thaw resistance, permeability), particularly the role of local aggregates and fly ash sources. Furthermore, to establish a solid background for the study, the investigators also reviewed literature on HVFA concrete related to fresh properties, admixtures, and mix design methods.

2.2. TASK 2: MIX DEVELOPMENT

The aim of this task was to develop several HVFA concrete mix designs that maximized the percentage of fly ash yet still fulfill typical construction needs, such as early strength development. These mix designs will then serve as the basis for the subsequent research. One (1) traditional concrete mix design served as a control 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 HVFA concrete mixes containing Missouri aggregates. This task involved three (3) subtasks.

2.2.1. Subtask 2a: Characterize Missouri Fly Ash Sources. The investigators obtained fly ash samples from a variety of coal-fired power plants in Missouri, including Ameren's Labadie, Meramec, and Rush Island plants and Kansas City Power & Light's LaCygne, and Nearman plants (the Iatan plant had a shutdown during the course of the project). All of these plants produce an ASTM C 618 (AASHTO M 295) Class C fly ash.

However, studies have shown that the pozzolanic and cementitious quality of fly ash can vary significantly between sources and even within the same plant.

As a result, in addition to the traditional oxide analyses, the investigators performed x-ray diffraction (XRD) and scanning electron microscopy (SEM) techniques to characterize the mineralogical composition of the different fly ash sources. This step was necessary in order to characterize the amount and composition of the glassy phases, as well as the amount of calcium silicates and calcium aluminates present in the fly ash. Both of these factors have a significant influence on the pozzolanic and cementitious properties of the fly ash, and the maximum percentages that can be successfully used in the HVFA concrete mixes.

2.2.2. Subtask 2b: Establish Maximum Fly Ash Replacement Percentages. The Class C fly ash produced in Missouri has significant potential for HVFA concrete mixtures. In a previous study for the Ameren Corporation, the investigators successfully developed a 75 percent fly ash concrete with a 28-day compressive strength of 4,250 psi. More importantly, the concrete reached 910 psi in one (1) day and 2,880 psi in seven (7) days, which is conducive to a traditional construction environment. To reach these early strength gains, the investigators added gypsum, calcium hydroxide, and calcium sulfoaluminate cements to the fly ash and Type I portland cement mixture. This part of the study used paste mixes to arrive at the optimum combinations and percentages of several additives to maximize the percentage of fly ash. The primary criteria at this stage of the research was set time and rate of strength gain. The results from this subtask formed the basis of Subtask 2c.

2.2.3. Subtask 2c: Develop HVFA Concrete Mixes. Based on the results of Subtask 2b, the investigators developed several HVFA concrete mix designs that maximized the percentage of fly ash yet still fulfill typical construction needs, such as early strength development. The results of Subtask 2b determined whether each of the Missouri fly ash sources required a different formulation to maximize the fly ash percentage yet still achieve similar set times and strength gains. Consequently, the number of HVFA concrete mix designs depended on the results of Subtask 2b. Subtask 2c also evaluated the impact of Missouri aggregates on the properties of HVFA concrete. The primary criteria at this stage of the research was set time and rate of strength gain. The final mix design choices and target strength levels were approved by MoDOT prior to the start of test specimen construction.

2.3. TASK 3: HARDENED PROPERTIES OF HVFA CONCRETE MIXES

The objective of the proposed research was to design, test, and evaluate HVFA concrete mixtures containing aggregates and fly ash indigenous to the state of Missouri. As such, in Task 3, the investigators focused on the hardened properties of HVFA concrete as compared to traditional concrete mixes. Task 3 involved three (3) subtasks.

2.3.1. Subtask 3a: Test Matrix. **Table 1** represents the test matrix for this research study based on MoDOT's requirements and the opinions of the investigators. Broadly speaking, the tests are classified into four (4) main categories: fresh concrete properties (*e.g.*, slump), hardened mechanical properties (*e.g.*, compressive strength, shrinkage), durability (*e.g.*, freeze-thaw resistance), and structural performance (*e.g.*, bond, shear strength).

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 231	Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method.	MSTR
Slump	ASTM C 143	Standard Test Method for Slump of Hydraulic-Cement Concrete.	MSTR
Time of Set	ASTM C 403	Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance.	MSTR
Miniature Slump Test	Non-ASTM	A method to study rheological properties of cement pastes.	MSTR
Calorimetry	Non-ASTM	A method to study rate of set and strength gain based on heat evolution of paste, mortar, and concrete mixtures.	MSTR
HARDENED MECHANICAL PROPERTY TESTS			
Compressive Strength	ASTM C 39	Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.	3
Splitting Tensile Strength	ASTM C 496	Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens.	3
Flexural Strength	ASTM C 78	Standard Test Method for Flexural Strength of Concrete.	3
Modulus of Elasticity	ASTM C 469	Standard Test Method for Static Modulus of Elasticity.	3
Creep/Shrinkage	ASTMC 512	Standard Test Method for Creep of Concrete in Compression.	3
DURABILITY TESTS			
Chloride Permeability	ASTM C 1202	Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration.	3
Chloride Permeability	ASTM C 1543	Standard Test Method for Determining the Penetration of Chloride Ion into Concrete by Ponding.	3
Concrete Resistivity	Non-ASTM	A method to determine the ability of concrete to protect steel from corroding.	3
Rapid Freeze Thaw Resistance	ASTM C 666	Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing.	3
Scaling Resistance	ASTM C 672	Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals	3
Wear Resistance	ASTM C 944	Standard Test Method for Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method.	3
MILD STEEL BOND AND DEVELOPMENT TESTS			
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.	4
4-Point Loading Beam Splice Test Specimens	Non-ASTM	Generally regarded as the most realistic test method for development length and splice length, see Fig. 2.	4
FULL SCALE SPECIMEN TESTS			
Shear Test Specimens	Non-ASTM	Full-scale tests to study the shear behavior of HVFA concrete beams and evaluate the contributions from the concrete, V_c, and transverse (shear) reinforcement, V_s, see Fig. 3.	5
Flexural Test Specimens	Non-ASTM	Full-scale tests to study the flexural behavior of HVFA concrete beams, see Fig. 3.	5

Table Notes:

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

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

2.3.2. Subtask 3b: 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 HVFA concrete, more or different tests may have been warranted, and the testing plan was adapted accordingly.

2.3.2. Subtask 3c: Conclusions & Recommendations. The investigators developed conclusions and recommendations based on the test results. In addition to evaluating the different HVFA concrete mixes for performance, these conclusions and recommendations formed the basis of the draft specifications developed as part of Task 7.

2.4. TASK 4: BOND AND DEVELOPMENT OF MILD STEEL

The issue to be addressed under this task was to determine whether the current AASHTO LRFD Bridge Design Specifications[1] for development length are appropriate for HVFA concrete. In other words, does HVFA concrete enhance, compromise, or not affect the relationship between development length and compressive strength as previously formulated for conventional portland cement concrete. Although the design equations are currently valid for fly ash replacement rates up to 35 percent, the micro- and macro-structure of the cementitious system may well change with significantly higher fly ash percentages. This task involved two (2) subtasks. Details regarding the test methods to be investigated are summarized in **Table 1**.

2.4.1. Subtask 4a: Direct Pull-out 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-128[2] 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.

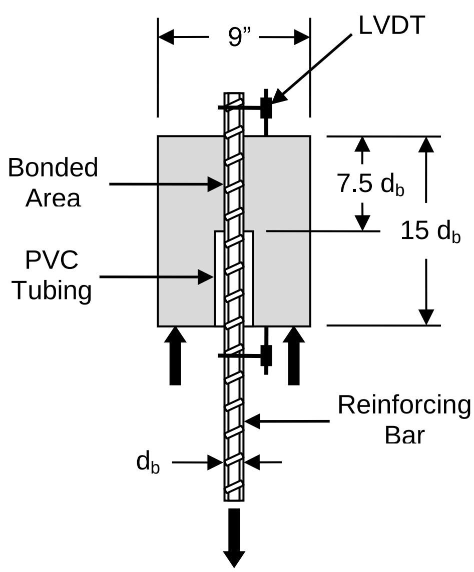


Figure 1 – Direct Pull-out Test Setup

The investigators constructed and instrumented several direct pull-out specimens for testing as shown in **Fig. 1**. The variables included bar size and concrete type (HVFA or conventional concrete). Data recorded during the test included load and bar slip.

2.4.2. Subtask 4b: Mild Steel Bond and Development. This subtask investigated development length of mild steel in both HVFA concrete and conventional concrete mixes. 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.[3, 4] Current ACI 318 design provisions for development length and splice length are based primarily on data from this type of test setup.[4]

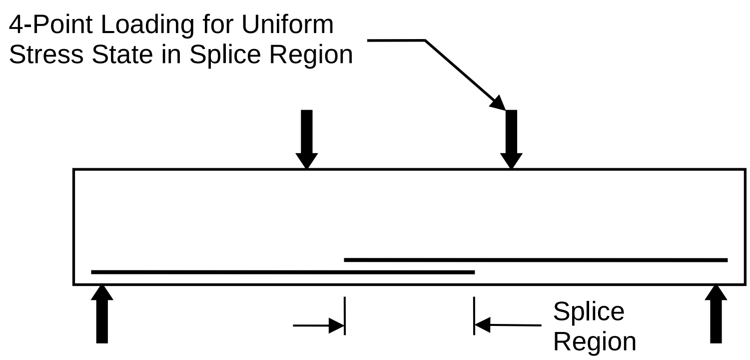


Figure 2 – Beam Splice Test Setup

The investigators constructed and instrumented rectangular beams for splice specimen testing as shown in **Fig. 2**. The variables included bar size, lap length, and concrete type (HVFA or conventional concrete). 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.

2.5. TASK 5: FULL SCALE SPECIMEN TESTS

This task involved testing of full-scale specimens to demonstrate the potential of HVFA concrete construction. The specimens were constructed with HVFA concrete from the local Ready Mix Concrete plant to confirm the ability to successfully transfer the mix designs from the laboratory to the field. The testing also included control specimens constructed from conventional concrete. The full-scale tests consisted of beam specimens for both shear and flexural testing. This task involved two (2) subtasks. Details regarding the test methods to be investigated are summarized in **Table 1**.

At the beginning of the research project, there was a possibility of a MoDOT pilot project using HVFA concrete that the research team could monitor and evaluate as part of this research study. Unfortunately, due to timing issues, this aspect did not occur.

2.5.1. Subtask 5a: Full-Scale Beam Shear Tests. This subtask involved full-scale beam tests to study the shear behavior of HVFA concrete beams and evaluate the contributions from the concrete and transverse (shear) reinforcement. The investigators constructed, instrumented, and tested rectangular beams in the configuration shown in **Fig. 3**, which applies a uniform shear over a significant portion of the beam. The variables included amount of transverse (shear) reinforcement and concrete type (HVFA or conventional concrete). Specimen instrumentation consisted of strain gauges, demountable mechanical strain gauges (DEMEC gauges), and linear variable displacement transducers (LVDTs). Data recorded during the tests also included load and deflection of the specimen as it was tested to shear failure.

2.5.2. Subtask 5b: Full-Scale Beam Flexural Tests. This subtask involved full-scale beam tests to study the flexural behavior of HVFA concrete beams. The investigators constructed, instrumented, and tested rectangular beams in the configuration shown in **Fig. 3**, which applies a uniform moment over a significant portion of the beam. The variables included amount of longitudinal (flexural) reinforcement and concrete type (HVFA or conventional concrete). Specimen instrumentation consisted of strain gauges, DEMEC gauges, and LVDTs. Data recorded during the tests also included load and deflection of the specimen as it was tested to flexural failure.

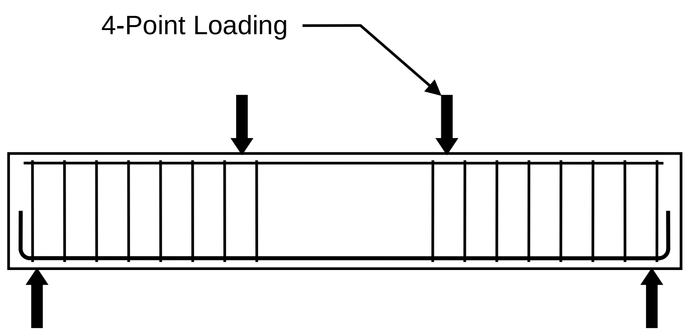


Figure 3 – Full Scale Beam Test Setup

2.6. TASK 6: AASHTO & ACI CODE COMPARISON OF TEST RESULTS

The purpose of this task was to compare the test results from Tasks 3, 4, and 5 with the design provisions and relationships in the current AASHTO LRFD Bridge Design Specifications. Although the design equations are currently valid for fly ash replacement rates up to 35 percent, the micro- and macro-structure of the cementitious system may well change with significantly higher fly ash percentages. The comparisons ranged from relatively simple relationships – such as modulus of elasticity based on compressive strength – to complex design relationships – such as bond, development length, and shear strength. As necessary, the investigators also compared the test results with prediction equations and relationships from other publications, such as the various

ACI committee documents and the CEB-FIP Model Code.[5] The results of this task assessed whether or not the current design provisions are applicable to HVFA concrete.

2.7. TASK 7: RECOMMENDATIONS & SPECIFICATIONS FOR IMPLEMENTING HVFA CONCRETE

Based on the results of Tasks 1 through 6, the investigators developed recommendations for the use of HVFA concrete in infrastructure elements. Based on these recommendations and the results of this research study, the investigators also developed a suggested MoDOT specification for the use of HVFA concrete in transportation-related infrastructure.

2.8. TASK 8: VALUE TO MODOT AND STAKEHOLDERS TO IMPLEMENTING HVFA CONCRETE

The issue to be addressed under this task was to quantify the benefit to MoDOT of applying the results of this research project – specifically, to determine a "value to MoDOT and the residents of Missouri" in the event that HVFA concrete is incorporated into construction of the State's transportation-related infrastructure. 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). This value aligns with both MoDOT's Tangible Result of being environmentally and socially responsible[6] and MoDOT's Research Need for strategies to reduce energy consumption.[7] The investigators determined the reduction in energy and greenhouse gas emissions and the amount of material recycled by implementing HVFA concrete.

Furthermore, increased use of fly ash has several other benefits to MoDOT and the residents of Missouri. These benefits include less need for concrete mixing water – as fly ash reduces the water demand to obtain the same level of workability – and increased concrete durability – resulting in longer life and reduced life-cycle costs. The investigators evaluated qualitative and quantitative measures for both of these benefits.

Overall, this task sought to establish a basis for whether or not HVFA concrete should be used by MoDOT, based upon the results from Tasks 1 through 6.

3. TASK SUMMARIES: FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

The following descriptions summarize the major findings, conclusions, and recommendations for project Tasks 1 through 8. Each sub-section refers to the specific Technical Report A through E where the background, detailed approach, experimental procedures and processes, results, findings, conclusions, and recommendations may be referenced for much greater detail. Report designations (*i.e.*, "Report A") are provided as a reference such that the specific detailed report located in the appendix may be consulted 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 topic specific literature reviews on HVFA concrete. However, the more notable general findings include the following:

Technical Reports A through E:

- Research on hydration of HVFA concrete has found that if not enough sulfate is present, ettringite will be unable to slow the reaction of tricalcium aluminate, which will consume the calcium in solution, slowing or stopping hydration of the silicates, resulting in retardation of set or failure to set.

- Research on hydration of HVFA concrete has shown that the reactivity of the particular fly ash combined with the amount of calcium hydroxide present is critical to optimum hydration of the HVFA concrete mixture.
- Research on plastic properties of HVFA concrete has shown increased slump, decreased rate of set, and potential air entraining issues depending on the particular fly ash used in the mixture.
- Research on hardened properties of HVFA concrete has shown decreased rate of strength gain compared with conventional concrete but that the differences are reduced over time, particularly at ages of 56 days and beyond. Flexural strength and splitting tensile strengths tended to track with concrete strength, but modulus of elasticity was found to be higher for HVFA concrete, possibly due to unreacted glassy fly ash particles acting as aggregate and increasing the rigidity of the material.
- Research on creep and shrinkage of concrete with fly ash has been studied extensively, except that the vast majority of studies have been limited to Class F fly ash and fly ash replacement levels of 50% or less.
- Research on durability of HVFA concrete has shown decreased permeability and increased freeze-thaw resistance but decreased scaling resistance compared with conventional concrete.
- Research on bond of mild steel in HVFA concrete has been very limited, with most studies performing only pull-out tests, tests on small-scale specimens, or limiting the fly ash replacement levels below 50%, which is the traditional cutoff for HVFA concrete.

- Research on shear strength of HVFA concrete has been very limited, with most studies performing tests on small-scale specimens, beams with shear span-to-depth ratios that classify the specimens as deep beams, or limiting the fly ash replacement levels to between 40% and 50%.

3.2. TASK 2: MIX DEVELOPMENT

This portion of the study involved working with cementitious paste mixtures to examine the effect of water reducer dosages, fly ash substitution rates, cement brands, fly ash sources, and powder activator types and amounts. Based on the results of the paste study, the researchers developed the concrete mixes used to study the fresh and hardened properties of HVFA concrete. The findings and conclusions from this task consist of the following:

Technical Report A:

- The position of the calorimetry curve was reflected in setting time, early strength achieved, and tendency for early stiffening, offering a valuable tool to assess different combinations of cement, fly ash, powder activators, and chemical admixtures.
- At high levels of CaO and low levels of aluminate, alkali, and aluminate/sulfate ratio, as fly ash increased, the calorimetry curves were increasingly delayed and the peaks were shorter.
- As the CaO dropped and the aluminate, alkali, and aluminate/sulfate ratio increased to more moderate levels, the curves became shorter and broader, sometimes exhibiting two peaks.

- When the CaO was low and the aluminate, alkali, and aluminate/sulfate ratio was high, the curves reversed and occurred earlier than straight portland cement curves.
- Fly ash effects on initial setting time were mixed. At 25% replacement, retardation usually occurred. At 50% replacement, both retardation and acceleration occurred. At 70% replacement, many times acceleration occurred.
- To improve early strengths, lime, rapid set cement (RSC), or gypsum by themselves were not particularly helpful. However, gypsum and lime together were effective, but lowered later strengths. Gypsum-RSC improved strengths at all ages. Gypsum by itself helped restore (retarded) the fly ash-accelerated HVFA calorimeter curve positions, as did gypsum-RSC. Gypsum-lime restored the curves almost to the zero fly ash positions. Early stiffening tendencies were alleviated by gypsum and gypsum-lime, but made worse by gypsum-RSC.
- The dosages chosen for the concrete study were 4% gypsum because it controlled the fly ash-accelerated reactions best, 10% lime because in combination with the 4% gypsum, it controlled the accelerated reactions best, and 20% RSC because it improved one day strengths best.

3.3. TASK 3: HARDENED PROPERTIES OF HVFA CONCRETE MIXES

This portion of the study involved scaling up the most promising powder activator combinations from paste to concrete and evaluating the mixtures in terms of plastic and hardened properties. The mixture matrix included two portland cement-fly ash blends and fly ash replacement at three levels (zero, 50% and 70%) with the water reducer dosage, gypsum content (4%), lime content (10%), and RSC content (20%) held constant.

Additional studies were also completed on two HVFA concrete mixtures that used 70% replacement of cement with fly ash as well as gypsum and lime as the powder activators. One mix used a relatively high total cementitious content of 756 lb/yd^3 (448 kg/m^3), and the other had a relatively low total cementitious content of 564 lb/yd^3 (335 kg/m^3). A conventional concrete mix was used as a control for comparison. The findings and conclusions from this task consist of the following:

Technical Report A (hardened properties):

- For reaction time (calorimeter curve time, setting time, stiffening time), the value varied as a function of the characteristics of the OPC and fly ash in conjunction with each other, type and level of powder activators used, dosage of WR/HRWR, and the type of test method used for evaluation.
- For compressive strength, at the 50% fly ash level, one day strengths were low no matter what powder activator was used, but 1000 psi (6.9 MPa) was reached in a number of OPC-fly ash blends, with and without powder activators. Good strengths can be achieved at 3 days. At the 70% fly ash level, concrete is weaker, but reasonable strengths can be reached at 28 days.
- For flexural strength, and with all tests conducted at 28 days, depending on the blend, the 50% fly ash mixtures were about the same strength as the OPC mixture, or somewhat below, although the weakest was still greater than 600 psi (4.1 MPa). At the 70% fly ash level, strengths dropped below the 50% fly ash level. Only one mixture achieved 550 psi (3.8 MPa).

- For splitting tensile strength, and with all tests conducted at 28 days, at the 50% fly ash level, the strengths either slightly exceeded or were a bit below the OPC strengths. The 70% fly ash level mixtures were weaker than 50% fly ash mixtures.
- For modulus of elasticity, as a general rule, the 50% fly ash values were close to, and in some cases slightly greater than the OPC strengths. As expected, the 70 % mixtures had lower modulus of elasticity values.
- For drying shrinkage, the HVFA concrete mixtures shrink less than their OPC counterparts.

Technical Report A (durability):

- For chloride resistance, in comparison to the OPC mixtures, rapid chloride permeability is lower for the 50% fly ash mixtures, but the 70% fly ash mixtures are more permeable, possibly due to the 28-day testing time as the fly ash will continue to hydrate.
- For freeze-thaw resistance, all HVFA concrete mixtures had greater durability factors than the OPC mixtures.
- For scaling resistance, all fly ash mixtures did poorly in regard to salt scaling.
- For abrasion resistance, at 50% fly ash replacement, resistance is somewhat lower. At 70% replacement, the effect is much worse, but usually tracks with compressive strength.

Technical Report D (creep and shrinkage):

- The HVFA concrete mixes that used 70% replacement of cement with fly ash showed significantly less shrinkage strain compared to the control mix.
- As expected, the HVFA concrete with the lower cementitious content had noticeably less shrinkage than the higher cementitious content mix.
- Both HVFA concrete mixes compared favorably with previous research results on shrinkage of HVFA concrete.
- Existing shrinkage models for conventional concrete overestimated the shrinkage strains for the HVFA concrete specimens.
- Both HVFA concrete mixes outperformed the conventional concrete mix in terms of creep strain, with both mixes experiencing significantly less creep strain at 126 days after loading than the conventional concrete mix.
- Creep strain data may be misleading due to the fact that HVFA concrete specimens were loaded at lower levels than conventional concrete due to their decreased compressive strengths at the time of loading. To normalize results, specific creep can be examined. The high cementitious HVFA concrete mix performed poorly in creep when taken in terms of specific creep. As the specimens got older, however, specific creep of the high cementitious HVFA concrete mix got closer to that of the conventional concrete.
- The two HVFA concrete mixes and the conventional concrete mix showed similar behavior under load, however, as the specimens aged, the advantage of the HVFA concrete mixes over the conventional mix became more apparent. This is demonstrated best by the percentage of 126 day creep. The data shows that during the

first two weeks of loading, the HVFA concrete specimens experienced a greater percentage of their ultimate creep strain than did the conventional concrete specimens. However, due to the tendency of HVFA concrete to gain strength at later ages, creep performance improved as the specimens aged.

Technical Report E (hardened properties):

- For compressive strength, both of the 70% fly ash level HVFA concretes trailed behind the conventional concrete mix in terms of rate of strength gain and 28-day strength. Minimal improvement occurred at 56 days most likely due to depletion of the available calcium hydroxide.
- For flexural strength, in all but one instance, the 70% fly ash level HVFA concretes exceeded the conventional concrete mix even though the compressive strength of the conventional concrete significantly exceeded that of the HVFA concrete mixes. Consequently, when normalized for concrete strength, the HVFA concrete mixes significantly outperformed the conventional concrete mix.
- For splitting tensile strength, the conventional concrete mix outperformed the HVFA concrete mixes.
- For modulus of elasticity, in all but one instance, the 70% fly ash level HVFA concretes exceeded the conventional concrete mix even though the compressive strength of the conventional concrete significantly exceeded that of the HVFA concrete mixes. Consequently, when normalized for concrete strength, the HVFA concrete mixes significantly outperformed the conventional concrete mix.

Technical Report E (durability):

- For chloride resistance as measured by the rapid chloride permeability test, the 70% HVFA concrete mixtures could not complete the test due to excessive voltage buildup or excessive current. However, previous research has established that the rapid chloride permeability test may not be applicable to concretes with very high fly ash replacement levels.
- For chloride resistance as measured by ponding, the 70% HVFA concrete mixtures had lower chloride levels than the conventional concrete mix.
- For freeze-thaw resistance, the 70% HVFA concrete mixtures had greater durability factors than the conventional concrete mix.
- For scaling resistance, all fly ash mixtures did poorly in regard to salt scaling.

3.4. TASK 4: BOND AND DEVELOPMENT OF MILD STEEL

The mix designs tested for bond and development consisted of two HVFA concrete mixtures that used 70% replacement of cement with fly ash, with gypsum and lime as the powder activators, and one conventional concrete mix for the control. One of the HVFA concrete mixes used a relatively high total cementitious content of 756 lb/yd^3 (448 kg/m^3), and the other HVFA concrete mix had a relatively low total cementitious content of 564 lb/yd^3 (335 kg/m^3), with the mixes denoted as HVFA-70H and HVFA-70L, respectively.

Two test methods were used for bond strength comparisons. The first was a direct pull-out test based on RILEM 7-II-128[2] "RC6: Bond test for reinforcing steel. 1. Pull-out test." The second test method consisted of full-scale beam splice test specimens subjected to a four-point loading until failure of the splice. The findings and conclusions from this task consist of the following:

Technical Report B:

- The average peak load for the #4 (#13), HVFA-70H and HVFA-70L pull-out specimens was 0.7% lower and 2.3% higher than that of the control, respectively. The average peak load for the #6 (#19), HVFA-70H and HVFA-70L pull-out specimens was 11.3% and 9.9% higher than that of the control, respectively.
- A total of nine test specimens with 3#6 (#19) longitudinal reinforcing bars spliced at midspan were constructed for the HVFA concrete bond test program – three for each concrete type. The average peak bar stress for the HVFA-70H and HVFA-70L bottom splice beam specimens was 29.5% and 15.2% higher than that of the control specimens, respectively. The peak bar stress for the HVFA-70H and HVFA-70L top splice beam specimens was 48.7% and 23.1% higher than that of the control specimens, respectively.
- Based on an analysis of the test results, particularly those for the more realistic beam splice specimens, the HVFA concrete has significantly improved bond strength compared to conventional concrete.

3.5. TASK 5: FULL SCALE SPECIMEN TESTS

The mix designs tested in the full-scale specimens for shear and flexure consisted of two HVFA concrete mixtures that used 70% replacement of cement with fly ash, with gypsum and lime as the powder activators, and two corresponding conventional concrete mixtures for the controls. One of the HVFA concrete mixes used a relatively high total cementitious content of 756 lb/yd^3 (448 kg/m^3), and the other HVFA concrete mix had a relatively low total cementitious content of 564 lb/yd^3 (335 kg/m^3), with the mixes denoted as HVFA-70H and HVFA-70L, respectively.

Most research to date has consisted only of the evaluation of the strength and durability of HVFA concrete mixtures, while only a limited number of studies have implemented full-scale testing of specimens constructed with HVFA concrete to determine its potential use in the industry. For this research, a laboratory testing program was developed to investigate the shear and flexural performance of reinforced concrete (RC) beams constructed with HVFA concrete. The experimental program consisted of 36 tests performed on full-scale RC beams. The findings and conclusions from this task consist of the following:

Technical Report C:

- In terms of crack morphology, crack progression, and load-deflection response, the behavior of the HVFA concrete and conventional concrete beams was virtually identical.
- Existing design standards (AASHTO, ACI, CSA) conservatively predicted the shear and flexural capacities of the HVFA concrete beams.
- The total cementitious content had little effect on the shear and flexural behavior of the HVFA concrete beams.
- In general, the HVFA concrete beams exceeded the code predicted shear strengths by a larger margin than the conventional concrete beams.

- Statistical data analyses – both parametric and nonparametric – showed that the HVFA concrete beams had higher normalized shear capacities than the conventional concrete beams.
- The HVFA concrete and conventional concrete test results fall within a 95% confidence interval of a nonlinear regression curve fit of a shear test database of conventional concrete specimens.
- A significant majority of the HVFA concrete test results fall at or above the nonlinear regression curve fit of the conventional concrete shear test database.

3.6. TASK 6: AASHTO & ACI CODE COMPARISON OF TEST RESULTS

The test results from Tasks 3, 4, and 5 were compared with the design provisions and relationships in the current AASHTO LRFD Bridge Design Specifications and ACI Building Code. The comparisons ranged from relatively simple relationships – such as modulus of elasticity based on compressive strength – to complex design relationships – such as bond, development length, and shear strength. In general, the current AASHTO and ACI design provisions and relationships for conventional concrete are equally applicable or conservative for HVFA concrete with fly ash replacement levels up to 70%. These provisions include mechanical properties, creep and shrinkage behavior, bond and development of reinforcing steel, and shear and flexural strength. Refer to detailed Technical Reports A through E for the in-depth comparisons and evaluations.

3.7. TASK 7: RECOMMENDATIONS & SPECIFICATIONS FOR IMPLEMENTING HVFA CONCRETE

Based on the results of Tasks 1 through 6, the investigators recommend the implementation of HVFA concrete in the construction of transportation-related infrastructure in the State of Missouri. However, the investigators also recommend initially limiting the fly ash replacement levels to 50% and avoiding applications subjected to direct deicing chemicals, such as bridge decks and pavements, due to potential scaling issues. To accomplish this, the following requirements are recommended for incorporation into MoDOT's standard specifications or job specific provisions.

HIGH-VOLUME FLY ASH CONCRETE FOR CAST-IN-PLACE CONSTRUCTION

1.0 Description. High-Volume Fly Ash (HVFA) concrete is concrete with at least 50 percent of the cement replaced with fly ash. All material, proportioning, mixing and transporting of concrete shall be in accordance with Sec 501, except as specified herein.

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

2.1 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 fly ash

(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

(g) The design air content and target slump

(h) Batch weights of Portland cement and fly ash

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

(j) Batch weight of water

(k) Compressive strength at 1-, 3-, 7-, and 28 days

2.2 Fly Ash. The fly ash shall be in accordance with Sec 1018, except as noted herein. The HVFA concrete mix shall use only Class C fly ash as the supplementary cementitious material. The amount of fly as a percentage of total cementitious material shall be as shown on the contract documents.

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

Water/Cementitious Materials Ratio	
Minimum	**Maximum**
0.30	0.40

2.4 Minimum Cementitious Material Amount. The total amount of cementitious materials shall not be below 600 pounds per cubic yard.

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

2.6 Compressive Strength. Compressive strength shall be determined in accordance with AASHTO T 22. Concrete shall have 1-, 3-, 7-, and 28-day minimum compressive strengths as shown on the contract documents.

3.0 Batching Sequence Plan. The contractor shall submit a Batching Sequence Plan outlining how the HVFA concrete mix will be batched and mixed. The Batching Sequence Plan shall be submitted to the Engineer for approval.

4.0 Trial Batch. A trial batch shall be done at least 90 days prior to HVFA concrete being used to ensure the mix is in accordance with this special provision. The HVFA concrete 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 Field Materials Engineer shall be present during the trial batch. The HVFA concrete mix shall be tested for air content, unit weight, slump, and compressive strength.

4.1 Compressive Strength. Compressive strength testing shall be conducted in accordance with AASHTO T 22. Concrete shall have 1-, 3-, 7-, and 28-day minimum compressive strengths as shown on the contract documents.

5.0 Production. HVFA concrete mix shall not be used until the concrete mix, the Batching Sequence Plan, and the trial batch have been approved. The HVFA concrete 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 HVFA concrete mix be resubmitted for approval. Changes to the water content and chemical admixture dosages will be allowed by the MoDOT Field Materials Engineer to handle changes in environmental conditions.

3.8. TASK 8: VALUE TO MODOT AND STAKEHOLDERS TO IMPLEMENTING HVFA 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 Tangible Result of being environmentally and socially responsible[6] and MoDOT's Research Need for strategies to reduce energy consumption.[7]

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 over 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.

4. REFERENCES

1. AASHTO (2010). *AASHTO LRFD Bridge Design Specifications*, 5th edition, Washington, D.C.

2. RILEM (1994). "RC5: Bond Test for Reinforcing Steel. 1. Pullout test," *RILEM Technicial Recommendations for the Testing and Use of Construction Materials, 7-II-128*, E & FN Spon, London, U.K.

3. Ramirez, J.A. and Russell, B.W. (2008). *Splice Length for Strand/Reinforcement in High-Strength Concrete*, NCHRP Project 12-60 Report, Transportation Research Board, Washington, D.C.

4. ACI Committee 408 (2003). "Bond and Development of Straight Reinforcing Bars in Tension (408R-03)," *Technical Documents*, American Concrete Institute, Farmington Hills, MI.

5. Comité Euro-Internationale du Bèton (1993). "CEB-FIP Model Code 1990," Bulletin d'Information, No. 213/214, Lausanne, Switzerland.

6. MoDOT Tangible Results – Environmentally and Socially Responsible, http://www.modot.mo.gov/about/MissionValuesTangibleResults.htm.

7. Stone, W. (2010). "Update on MoDOT's Research Activities and Needs," http://library.modot.mo.gov/RDT/Forum/y10/BillStoneLunchDiscussion.pdf.

5. TESTING STANDARDS

1. AASHTO – American Association of State Highway Transportation Officials: http://www.trasportation.org

2. ACI – American Concrete Institute: http://www.concrete.org

3. ASTM International – American Society of Testing Methods: http://www.astm.org

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

APPENDIX A

APPENDIX B

APPENDIX C

APPENDIX D

APPENDIX E