DEVELOPMENT OF PERFORMANCE PROPERTIES OF TERNARY MIXES

Pooled Fund Project

Problem Statement
February 2005

PROJECT TITLE

Development of Performance Properties of Ternary Mixes

PROBLEM STATEMENT

Supplementary cementitious materials, such as fly ash, ground granulated blast-furnace slag, and silica fume, have become common parts of modern concrete practice (*1, 2*). The blending of two or three cementitious materials to optimize durability, strength, or economics provides owners, engineers, materials suppliers, and contractors with substantial advantages over mixtures containing only portland cement. However, these advances in concrete technology and engineering have not been adequately captured in the specification of concrete. Usage is often curtailed because of prescriptive concerns or historical comparisons about how such materials should perform. In addition, supplementary cementitious materials can exhibit significant variation in chemical and physical properties, both within a given source and, more commonly, between sources. Hence, current literature contains contradictory reports concerning the "optimal use" of supplementary cementitious materials. Users need specific guidance to assist them in defining the performance requirements for a concrete application and the selection of optimal proportions of the cementitious materials needed to produce the required durable concrete. The selection process is complicated by the fact that blended cements are currently available in selected regions (*3*). Both portland and blended cements have already been optimized by the manufacturer to provide specific properties (i.e., setting time, shrinkage, strength gain). The addition of supplementary cementitious materials (as binary, ternary, or even more complex mixtures) can alter these properties, and, hence, has the potential to impact the overall performance of the concrete. Research is needed to identify and quantify the major factors that govern the performance of mixtures containing supplementary cementitious materials. The focus of the research should be directed at ensuring that the use of these various materials always has a positive impact on the overall durability of the concrete.

PROJECT GOALS

The goal of this project is to provide the quantitative information needed to make sound engineering judgments pertaining to the selection and use of supplementary cementitious materials in conjunction with portland or blended cement. This will lead to a more effective utilization of supplementary materials and/or blended cements enhancing the life-cycle performance and cost of transportation pavements and structures. The efforts of this project will be directed at producing test results that support the following specific goals:

- Provide quantitative guidance for ternary mixtures that can be used to enhance the performance of structural and pavement concrete
- Provide a solution to the cold weather issues that are currently restricting the use of blended cements and/or supplementary cementitious materials
- Identify how to best use ternary mixes when rapid strength gain is needed
- Develop performance-based specifications for concrete used in transportation pavements and structures

BACKGROUND

Engineers for state departments of transportation (DOT) throughout the United States have used fly ash and ground granulated blast-furnace slag (slag cement) as a partial replacement for portland cement in concrete production for many years. However, the main thrust of their usage has been to comply with the Resource Conservation and Recovery Act (RCRA) mandate for the use of by-product materials in federally funded projects. Few attempts have been made to optimize the use of fly ash or slag cement to produce concrete mixtures that meet specific performance objectives. Instead, the strategy has always been to produce concrete mixtures that exhibit performance similar to mixtures employing only portland cement. With the growing availability of slag cement and silica fume, and the limited supply of fly ash in some markets, the selection of materials for any given job has become more complicated.

Supplementary cementitious materials (SCMs) have the potential to dramatically improve the overall performance and lower the long-term (life-cycle) cost of concrete. However, this assumes that the various materials have been used properly. Some believe that the introduction of fly ash and slag cement, as a cement replacement in concrete, has resulted in the following problems:

- Rapid slump loss
- Unstable air content or inability to retain air
- Uncontrolled cracking with late season paving
- Unfriendly or hard to work mixtures
- Inability to predict workability and set time in early or late season construction
- Scaling in mixtures containing high dosages of SCMs

Closer inspection of the list and the technical literature suggests that the root issues appear to be related to constructability, ambient weather problems, proportioning of cementitious materials, and materials variability problems. However, some detailed discussion with appropriate materials vendors is needed to clarify the reasons for the real or perceived problems and to design solutions that optimize multiple cementitious systems for transportation concrete.

There are currently several ongoing research projects in this area. The Pennsylvania DOT and an industrial consortium have been working with Pennsylvania State University on optimizing performance in bridge deck concrete, using both binary and ternary blends of SCM (*4*). The Texas DOT has conducted detailed studies on optimizing fly ash and portland cement combinations for selected performance characteristics (*5*). On a national level, the FHWA initiated a major project (Task 64) that will help simplify job-specific mix design when multiple sources of materials are available. Also, the NCHRP has two projects that are currently in progress that deal with SCMs. The first project is entitled "Supplementary Cementitious Materials to Enhance Durability of Concrete Bridge Decks (project 18-08A)." The second project is entitled "Improved Specifications and Protocols for Acceptance Tests on Processing Additions in Cement Manufacturing (project 18-11)."

RESEARCH PLAN (PROJECT DESCRIPTION)

The purpose of this research project is to make a comprehensive study of how SCMs can be used to improve the performance of concrete mixtures. This is an enormous task because the study must incorporate both portland cements and blended cements. In addition, it is desirable to include several samples of each type of supplementary cementitious materials (fly ash, slag, and silica fume in this instance) so that the material variability issue can also be addressed. Several different sources of portland cement and blended cement also need to be included in the experimental program. This causes the experimental matrix to grow rapidly, and, hence, the proposed project will be conducted in three different phases. In addition, a brief literature study will be conducted to close some of the knowledge gaps that exist in the research plan. The literature study will include making contact with state DOTs that have already utilized ternary mixtures in field work (for example, Ohio DOT, New York DOT, Pennsylvania DOT, Iowa DOT) to discuss practical concerns about field applications. The effort expended in the three different phases will not be uniform. Most of the effort (and monetary resources) will be directed at Phases 2 and 3. The thrust of this project is to get to the field concrete studies. Phase 1 will simply serve as a filter to identify materials combinations that will not perform adequately.

The first phase will consist of laboratory experiments that study the influence of various proportions of cement, slag, silica fume, and fly ash on specific properties of mortar specimens. The Phase 1 testing program will use a wide range of different materials and many different dosage levels. Test results will be evaluated to locate potential optimums in the various test responses. Chemical admixtures (water reducers) will be included in this phase of the study to compare how setting and strength gain behavior of the mixtures varies with chemical admixture dosage and SCM dosage. All of the materials used in the study will be subjected to bulk chemical and physical testing in accordance with the appropriate ASTM or AASHTO specifications. In addition, X-ray diffraction and thermal analysis will be used to determine the minerals present in the bulk samples and selected paste specimens. Glass content of the various SCMs and blended cements will also be estimated using X-ray diffraction.

The second phase will use the information obtained from Phase 1 to select a reasonable range of materials and dosages for use in laboratory concrete mixtures. Again, the thrust of the experimentation is to replicate optimum mixtures that were obtained from Phase 1 of the laboratory study. The materials used in both phases will be identical so that the mortar test results can be directly compared to the test results obtained from concrete test specimens. This comparison is needed so that the research project provides information pertaining to the selection of appropriate quality control tests. It would be very desirable to find out that quality control testing could be conducted on mortar specimens rather than on full-scale concrete specimens.

The third phase will be a field demonstration phase where contractors and states will have on-site technical support for using ternary mixes. The PCC Center's mobile research laboratory will participate in at least one project for each participant state.

Phase 1: Laboratory Study on Mortar

Presently, it is anticipated that the lab testing will evaluate binary mixtures (i.e., slag and cement, fly ash, and cement) that range from 0 to 75% replacement. Binary mixtures of silica fume and cement will also be made, but the maximum dosage of silica fume will be limited to about 15%. Ternary mixtures (slag, fly ash, and cement; slag, silica fume, and cement, etc.) would be evaluated over a similar range of replacement, although higher replacements may be necessary for statistical reasons. The mixtures would be evaluated as mortar specimens because this eliminates the impact of coarse aggregate on the mixtures and it also reduces the overall cost of the study. Currently, it is anticipated that important properties would include those summarized in Table B.1.

Phase 2: Laboratory Study on Concrete

Phase 2 will use the information obtained from Phase 1 to select a reasonable range of materials and SCM dosages for use in laboratory concrete mixtures. Researchers will attempt to keep the various concrete mixtures reasonably close to regions of interest that were identified in Phase 1 (i.e., optimum mixtures) without being overly restrictive. Since the purpose of this project is to evaluate cementitious materials combinations, only a single source of coarse and fine aggregates will be included in the study. The concrete mixtures would be evaluated for slump, slump loss, bleeding, setting time, strength gain (both compressive and flexural), shrinkage (plastic and drying shrinkage), and durability (freeze-thaw durability or the determination of hardened air-void parameters, Cl permeability, and scaling). For completeness, a limited number of concrete mixtures will be subjected to ASR and sulfate resistance testing (see Table B.2).

Table B.1. Mortar properties that need to be measured for Phase 1

Property	Primary variables	Secondary variables	Test method(s)
Workability	SCM dosage Water content Admixture dosage	Temperature Fineness	Flow test (ASTM C 1437)
Compatibility	SCM dosage Cement type	Temperature Fineness	Penetration test (ASTM C 359 and modified C 359)
Setting Time	SCM dosage Admixture dosage	Temperature Fineness	Penetration test (ASTM C 403)
Strength Development	SCM dosage Fineness	Temperature	Cube strength (ASTM C 109) Heat signature
Shrinkage	SCM dosage Cement type	Water content Fineness	Mortar bar test (ASTM C 157)
ASR Resistance	SCM dosage Cement alkali content	SCM alkali content	Mortar bar test (ASTM C 441)
Sulfate Resistance	SCM dosage Cement type	SCM type	Mortar bar test (ASTM C 1012)

Table B.2. Concrete properties that need to be measured for Phase 2

Property	Primary variables	Secondary variables	Test method(s)
Workability & Compatibility	SCM dosage Water content Admixture dosage	Temperature Fineness	Slump test (ASTM C 143) Slump loss
Bleeding	SCM dosage Water content Admixture dosage	Temperature Fineness	ASTM C 232
Setting Time	SCM dosage Admixture dosage	Temperature Fineness	Penetration test (ASTM C 403)
Strength Development	SCM dosage Admixture dosage	Temperature Fineness	Compressive strength Flexural strength Heat signature
Shrinkage	SCM dosage Cement type	Water content Fineness	Concrete prism (ASTM C 157)
Durability	SCM dosage Cement type	Water content	Freeze-thaw or C 457 Cl penetration (C 1202) Surface scaling
ASR Resistance	SCM dosage	SCM type	Concrete Prism (ASTM C 1293)
Sulfate Resistance	SCM dosage Cement type	SCM type	Concrete Prism (USBR test method)

Phase 3: Field Demonstrations
This phase of the project is intended to provide states and contractors with the use and field management of ternary mixes. The PCC Center will provide its state-of-the-art 44-foot long mobile laboratory equipped for on-site cement and concrete testing. The mobile lab will be made available for up to two weeks in each of the participating states to demonstrate the tests and procedures available for field management of ternary mixes. Contractors will be provided with a list of potential mix designs that encompass the optimum properties identified in Phases1 and 2 and the materials available in the local market. The contractors would be able to make minor adjustments in a selected mix design to better meet the needs of their equipment and crew.

RESEARCH TEAM

The research team is proposed to be a collaboration between Iowa State University and Pennsylvania State University.

E. Thomas Cackler, Project Manager
Mr. Tom Cackler is the director of the Center for Portland Cement Concrete Pavement Technology (PCC Center) at Iowa State University. He brings to the project over 25 years of experience as a transportation engineer and research administrator at the Iowa DOT. Most recently, he served as chief engineer and director of the Iowa DOT Highway Division, where he was responsible for the overall management and direction, development, and delivery of an annual $500 million highway improvement program, as well as managing an annual $170 million operations budget. Mr. Cackler currently serves on the TRB Construction Management Committee (A2F05) and has served on the AASHTO Standing Committee on Highways,

AASHTO Subcommittee on Construction, and joint industry quality improvement committees with the Associated General Contractors of Iowa, Asphalt Paving Association of Iowa, and Iowa Concrete Paving Association. He is a registered professional engineer in the State of Iowa.

Paul Tikalsky, Principal Investigator

Dr. Paul J. Tikalsky is an associate professor of civil and environmental engineering at Pennsylvania State University, with a joint appointment with the Pennsylvania Transportation Institute, where he is Director of the Infrastructure Testing and Evaluation Laboratory. Dr. Tikalsky teaches courses in construction materials and concrete materials and behavior. His research is in the area of the development and implementation of higher durability concrete materials and structures. He has completed projects with NCHRP to evaluate new portland cement criteria for highway specifications and the Pennsylvania Department of Transportation to define HPC criteria for concrete in the transportation infrastructure. His current research includes a showcase with industry and state highway departments to demonstrate the durability of concrete bridges and structures. Dr. Tikalsky is a Fellow of the American Concrete Institute and currently serves as a Director of the Institute. He chairs the Educational Activities Committee and serves as a member to ACI Committees 201, 232, E701 and the Concrete Research Council. In addition, he serves on the Basic Research Committee and the Concrete Durability Committee of the Transportation Research Board and on the ASTM C-9 on Concrete and Aggregates. He has published more than 50 articles on concrete and structural durability. He received his B.S. in Civil Engineering from the University of Wisconsin at Madison and his M.S. and Ph.D. in Structural and Materials Engineering from the University of Texas at Austin. He is a registered professional engineer in the State of California.

Vernon Schaefer, ISU Research Manager/Co-Principal Investigator

Dr. Vernon R. Schaefer is a professor of civil engineering and holder of the James M. Hoover Chair in Geotechnical Engineering at Iowa State University and associate director for research for the Center for Portland Cement Concrete Pavement Technology (PCC Center) at ISU. In the Civil, Construction & Environmental Engineering Department, Dr. Schaefer is the division leader for the Geotechnical and Materials Engineering Division. Dr. Schaefer teaches classes in geotechnical engineering. His research is broad based in the soil and materials engineering areas. His current research includes long-life foundations for pavements and improving PCC mix consistency through mixing improvements. Dr. Schaefer received his B.S. in Civil Engineering from South Dakota State University, his M.S. in Geotechnical Engineering from Iowa State University and his Ph.D. in Civil Engineering from Virginia Tech. He is a registered professional engineer in the State of South Dakota.

Kejin Wang, Co-Principal Investigator

Dr. Kejin Wang is an assistant professor at Iowa State Univeresity and a research engineer at the PCC Center. She received her Ph. D. from the University of California at Berkeley in 1994 and then worked at the Center for Advanced Cement-Based Materials, Northwestern University, as a research associate and the Director of Educational Program. Her research interests include microstructure and properties of concrete, supplementary cementitious materials (slag, fly ash, and cement-kiln dust), concrete durability (frost action, alkali-silica reaction, and steel corrosion), pavement distresses and repairs. Since joining the PCC Center/ISU in 2000, she has been a leading investigator in various projects, including development of non-clinker cement using fly ash and cement-kiln dust, pavement curing materials and techniques, blended cement, damage of de-icing chemicals on concrete, concrete mixing optimization, and self-consolidating concrete for slip-form paving projects.

Scott Schlorholtz, Research Advisor
Dr. Scott Schlorholtz is a scientist at the Material Analysis and Research Laboratory (MARL) at ISU. His major research interests are in the area of portland cement, PCC materials, fly ash and coal combustion byproducts, and the characterization of inorganic cement binders. Dr. Schlorholtz has actively investigated the physical and chemical properties of supplementary cementitious materials and their influence on the fundamental properties of portland cement pastes, mortars, and concretes. He has also attempted to broaden the use of modern analytical techniques, such as x-ray methods, thermal analysis, and scanning electron microanalytical techniques, for the routine characterization of construction materials.

RESEARCH FACILITIES

PCC Research Lab, Iowa State University
The Portland Cement Concrete Pavement and Materials Research Laboratory (PCC Research Lab) at Iowa State University is supported by the Center for Portland Cement Concrete Pavement Technology (PCC Center) and the Iowa State University Department of Civil, Construction and Environmental Engineering (CCEE). Housed at the CCEE Department, Room 138 of the Town Engineering Building, the PCC Research Lab has a total working space of approximately 2,300 square feet. New in 2002, this facility brings a vast array of concrete pavement testing equipment into one comprehensive lab with major spaces for mixing optimization and high-speed testing, concrete processing and manufacturing research, fresh concrete property management, and durability-related experiments.

MARL, Iowa State University
The Materials Analysis and Research Laboratory (MARL) is also housed in the CCEE Department at Iowa State University. The lab is equipped with state-of-the-art equipment for low-vacuum scanning microscopy; energy dispersive x-ray spectrometry; image acquisition, processing, and analysis; light microscopy; x-ray diffraction; x-ray fluorescence; and thermal analysis. MARL is conducting several projects regarding the durability of concrete, including research into the characterization of concrete microstructure, the factors that determine it, and the influence of that structure on concrete durability. For the last few years, the Iowa DOT has supported research at MARL examining the pore structure of concrete as it affects its durability. Sample preparation, image acquisition, and image analysis techniques continue to undergo development in order to obtain quick and accurate information about the air-void structure. MARL also contains a pozzolan testing lab that routinely conducts performance tests on supplementary cementitious materials. MARL participates in the Cement and Concrete Reference Laboratory (CCRL) pozzolan proficiency sample testing program and the CCRL laboratory inspection program.

PCC Center's Mobile Concrete Lab
The Center for PCC Pavement Technology has a fully equipped, 44 foot by 8.5 foot trailer to take to the job site to test samples of plastic concrete during the most critical phase of a

pavement's life (the first hour) and after the concrete has hardened. The $130,000 trailer was donated to Iowa State University by concrete industry sponsors, and can be driven to concrete road construction sites throughout the United States. The mobile lab is fully outfitted with a comprehensive range of high-tech equipment. Some of the equipment had to be custom built or modified to provide optimum results in the mobile lab's unusual lab-in-the-field environment. The ability to test materials at the actual job site can help provide detailed data necessary to conducting research to make a difference.

Infrastructure Testing and Evaluation Laboratory (InTEL), Penn State
The Infrastructure Testing and Evaluation Laboratory at Penn State is a combined College of Engineering and Pennsylvania Transportation Institute (PTI) facility for testing materials and structural component of the nation's infrastructure (highways, airports, railways, pipelines, and buildings). The laboratory is equipped for the full range of AASHTO and ASTM testing for construction materials, as well as customized evaluation of new and innovative materials and structural elements. The 56,000 square foot laboratory has more than 40,000 square feet of experimental laboratories for full-scale and bench top testing. The lab is equipped with data acquisition equipment, automated environmental chambers, a 10,000 square foot high bay structural testing facility, and state of the art equipment for characterizing the chemical, physical, behavioral, and electrical properties of construction materials.

The laboratory is equipped for testing fresh and hardened properties of cementitious systems and concrete. This includes the physical, chemical, strength, and durability characteristics of portland cements, pozzolans, aggregates, pastes, grouts, mortar, concrete, and reinforcing steel and strand. In addition, the laboratory is equipped to conduct detailed corrosion studies, pH and select ion concentration testing for hardened materials, and environmental exposure studies.

Among the capabilities of the InTEL concrete materials lab is equipment for both a high shear vertical-axis paddle mixer and a 9 cu ft concrete drum mixer, as well as a progressive cavitating pump, 2-ft and 8-ft diameter autoclave facilities, cellular foam generator, abrasion testing machines, multiple MTS load systems, 700,000 compression testing machines, curing rooms, freeze-thaw and environmental chamber test facilities, petrographic evaluation services, and ACI certified technicians. For fresh concrete testing and mixture characterization, the laboratory maintains slump cones, a Kelly ball, a fixed penetrometer, pressure-type and volumetric air meters, unit weight containers, a Blaine air meter, a bleed-test apparatus, flow tables, digital batching scales, indoor aggregate and cement handling facilities, volumetric admixture dispensers, and wet curing facilities.

Other PTI Facilities, Penn State
Penn State provides a number of other excellent field facilities and experimental laboratories for evaluating new, proposed, or re-engineered transportation materials and structures. PTI has test track facilities for in-situ field durability testing of pavement materials; tire/pavement phenomena; the effects of crashes and impacts on barriers and vehicles; and bridge loadings, design, construction, monitoring and evaluation.

ESTIMATED PROJECT DURATION

Phase 1 and 2 of the project are expected to take 36 months to complete. An additional 24 months for phase 3 (field implementation) is expected, for a total project duration of 5 years.

BUDGET AND SPONSORSHIP

Proposed Project Funding

The total project budget is estimated at $1.8 million. A partnership for funding this research is proposed between state DOTs, industry, FHWA, and the PCC Center at Iowa State University. The state and federal sponsorship is targeted at two-thirds of the necessary funds and will be administered through the pooled-fund process. The PCC Center will work with industry to provide the balance of the needed funding.

Funding by Phase

Phase 1: 18 months $500,000
Phase 2: 18 months $500,000 (36 month total for Phases 1 & 2)
Phase 3: 24 months $800,000 (5 years total for all phases)
Phase 1 will begin as soon as funding is available.

Sponsorship Goals

State DOTs and FHWA 2/3 of funding: 12 states @ $15,000 per year for 5 years: $75,000
Industry and PCC Center 1/3 of funding

Summary of Requirements for Project Sponsors

- Financial support: $75,000 from each state participant
- Technical Advisory Committee (TAC) participation
- State DOTs are also asked to work with principal investigators on field implementation

DELIVERABLES

The following products will be submitted as indicated:

1. Yearly progress report that summarizes test results and status of research (yearly)
2. Final report that documents the results of the entire study
3. Field demonstration projects in each participating state
4. Software decision support tool
5. Proposed specifications for using ternary mixes

Note: Actual dates for reports will be a function of the start time of the project.

IMPLEMENTATION

Implementation of the project results will be conducted through presentations at technical meetings (e.g., TRB and ACI meetings) and/or symposia and in journal papers. The field demonstration projects will also be a hands-on implementation of the project results.

PROJECT ADMINISTRATION

The Iowa DOT, through the PCC Center at Iowa State University, will serve as the lead state and handle administrative duties for the project. Each participating entity may provide an individual to serve on the technical advisory committee that will provide direction to the project. The TAC will organize the specifics of the cooperative work tasks and oversee the accomplishment of these tasks. The PCC Center, under direction of the TAC, will provide administrative management and be the lead research institution on the project.

CONTACT FOR FURTHER INFORMATION

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