Material and Construction Optimization for Prevention of Premature Pavement Distress in PCC Pavements: Final Report

National Concrete Pavement Technology Center

Tech Center

Final Report
March 2008

Sponsored through
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Center for Transportation Research and Education

Iowa State University

About the National Concrete Pavement Technology Center

The mission of the National Concrete Pavement Technology Center is to unite key transportation stakeholders around the central goal of advancing concrete pavement technology through research, tech transfer, and technology implementation.

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16. Abstract

Mixture materials, mix design, and pavement construction are not isolated steps in the concrete paving process. Each affects the other in ways that determine overall pavement quality and long-term performance. However, equipment and procedures commonly used to test concrete materials and concrete pavements have not changed in decades, leaving gaps in our ability to understand and control the factors that determine concrete durability. The concrete paving community needs tests that will adequately characterize the materials, predict interactions, and monitor the properties of the concrete.

The overall objectives of this study are (1) to evaluate conventional and new methods for testing concrete and concrete materials to prevent material and construction problems that could lead to premature concrete pavement distress and (2) to examine and refine a suite of tests that can accurately evaluate concrete pavement properties.

The project included three phases. In Phase I, the research team contacted each of 16 participating states to gather information about concrete and concrete material tests. A preliminary suite of tests to ensure long-term pavement performance was developed. The tests were selected to provide useful and easy-to-interpret results that can be performed reasonably and routinely in terms of time, expertise, training, and cost. The tests examine concrete pavement properties in five focal areas critical to the long life and durability of concrete pavements: (1) workability, (2) strength development, (3) air system, (4) permeability, and (5) shrinkage. The tests were relevant at three stages in the concrete paving process: mix design, preconstruction verification, and construction quality control.

In Phase II, the research team conducted field testing in each participating state to evaluate the preliminary suite of tests and demonstrate the testing technologies and procedures using local materials. A Mobile Concrete Research Lab was designed and equipped to facilitate the demonstrations. This report documents the results of the 16 state projects.

Phase III refined and finalized lab and field tests based on state project test data. The results of the overall project are detailed herein. The final suite of tests is detailed in the accompanying testing guide.

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MATERIAL AND CONSTRUCTION OPTIMIZATION FOR PREVENTION OF PREMATURE PAVEMENT DISTRESS IN PCC PAVEMENTS

Final Report
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Mobile Lab Sponsors

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Iowa Concrete Pavement Association
Concrete & Aggregate Association of Louisiana
Michigan Concrete Paving Association
Concrete Paving Association of Minnesota
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Nebraska Concrete Paving Association
North Dakota Chapter, American Concrete Pavement Association
Northeast Chapter, American Concrete Pavement Association
Ohio Concrete Construction Association
South Dakota Chapter, American Concrete Pavement Association
Southeast Chapter, American Concrete Pavement Association
Wisconsin Concrete Pavement Association

INTRODUCTION

Problem Statement

The make-up of today's concrete mixtures is complicated by many variables, including multiple sources of aggregate and cements and a plethora of mineral and chemical admixtures. Concrete paving has undergone significant changes in recent years as new materials have been introduced into concrete mixtures. Supplementary cementitious materials, such as fly ash and ground granulated blast furnace slag (GGBFS), are now regularly used. In addition, many new admixtures that were not available a few years ago are now widely used. Adding to the complexity are construction variables such as weather, mix delivery times, finishing practices, modern paving equipment, and pavement opening schedules.

Mixture materials selection, mix design and proportioning, and pavement construction are not isolated steps in the concrete paving process. Each affects and is affected by the others in ways that determine the overall pavement quality and long-term performance.

Equipment and procedures commonly used to test concrete materials and concrete pavements have not changed in decades, leaving serious gaps in our ability to understand and control the factors that determine concrete durability. The concrete paving community needs tests that will adequately characterize the materials, predict interactions, and monitor the properties of the concrete.

Project Background

The project entitled "Material and Construction Optimization for Prevention of Premature Pavement Distress in PCC Pavements" (MCO) was initiated to investigate available and new testing procedures for evaluating concrete materials, mix designs, and construction practices.

In August 1998, the Federal Highway Administration (FHWA) demonstration project 119, "Implementing PCC Excellence in the Highway Project," was discontinued due to lack of funding. However, the urgent need for better testing was still present. The ten states that made up the Midwest Concrete Consortium (MC^2) recognized this shortcoming and the advantages of pooling their research resources. At their April 18, 2001 meeting, MC^2 members voted to support the pooled fund concept for research to meet those needs. With their input, Iowa State University's Center for Portland Cement Concrete Pavement Technology (PCC Center), now the National Concrete Pavement Technology Center (CP Tech Center), developed a research plan for the five-year MCO pooled fund project.

Project Objectives

The objectives for the MCO pooled fund project included the following:

- Evaluate conventional and new technologies and procedures for testing concrete and concrete materials to prevent material and construction problems that could lead to premature concrete pavement distress.

- Develop a suite of tests that provides a comprehensive method of ensuring long-term pavement performance.

Overview of Project Phases

The five-year MCO project is divided into three major phases.

Phase I

The objective in Phase I (2003–2004) was to compile practical, easy-to-use testing procedures for identifying and monitoring material and concrete properties to ensure durable pavement. Phase I involved a literature search and a survey of participating agencies and others in the portland cement concrete (PCC) paving community to gather information about best practices and solutions to common problems. Phase I also included developing standard test procedures for tests that may not have national standards.

Phase II

Phase II (2004–2006) demonstrated, evaluated, and refined the best practices and lab and field tests proposed in the Phase I suite of tests. The research team worked with participating states to demonstrate and evaluate proposed practices and tests on a current paving project in each state.

Phase III

Phase III (2006–2007) refined and finalized lab and field tests based on the shadow project test data from Phase II. A field-oriented manual that includes a description of recommended tests and troubleshooting guidance was prepared. An outline of Phase III technology transfer activities is presented in Appendix F.

Pooled Fund Partnership

The MCO project solicitation was posted on the FHWA transportation pooled fund website, ultimately resulting in a research partnership of 16 states, the FHWA, and the concrete paving industry (see Figure 1). Seventeen states are listed because Nebraska participated for the first three years only, and Oklahoma joined for the remaining two years. Thus, 16 states participated in the project at any one time.

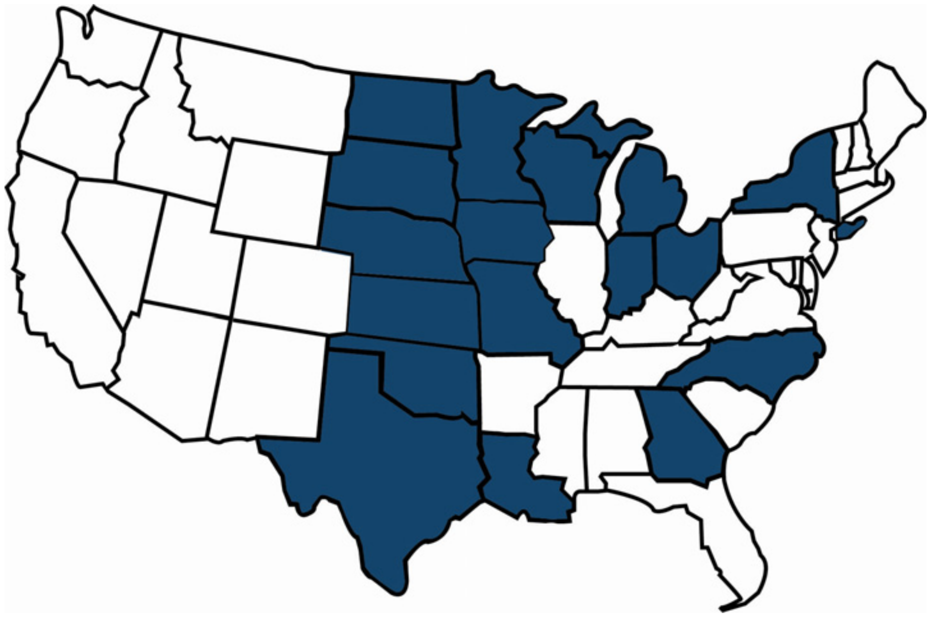

Figure 1. Map of States Participating in the MCO Project

The 17 participating state highway agencies were as follows:

- Georgia Department of Transportation
- Indiana Department of Transportation
- Iowa Department of Transportation (lead state)
- Kansas Department of Transportation
- Louisiana Department of Transportation
- Michigan Department of Transportation
- Minnesota Department of Transportation
- Missouri Department of Transportation
- Nebraska Department of Roads
- New York Department of Transportation
- North Carolina Department of Transportation
- North Dakota Department of Transportation
- Ohio Department of Transportation
- Oklahoma Department of Transportation
- South Dakota Department of Transportation
- Texas Department of Transportation
- Wisconsin Department of Transportation

The industry was represented by the American Concrete Paving Association (ACPA) and 14 state/regional paving associations:

- Indiana Chapter, ACPA
- Iowa Concrete Paving Association
- Concrete & Aggregates Association of Louisiana
- Michigan Concrete Paving Association

- Concrete Paving Association of Minnesota
- Missouri/Kansas Chapter, ACPA
- Nebraska Concrete Paving Association
- North Dakota Chapter, ACPA
- Northeast Chapter, ACPA
- Ohio Concrete Construction Association
- Oklahoma/Arkansas Chapter, ACPA
- South Dakota Chapter, ACPA
- Southeast Chapter, ACPA
- Wisconsin Concrete Pavement Association

Project Organization

The MCO project was organized by the following model: a state highway agency leading other participating states; a university research center serving as the central research team; the FHWA acting as a primary technical and administrative advisor; a technical advisory committee (TAC) composed of representatives from participating states and industry; and an executive committee providing close guidance and monitoring for the project.

Iowa Department of Transportation (Lead State)

The Iowa Department of Transportation (DOT) served as the lead state for the project. The CP Tech Center at Iowa State University initiated project development and administered the day-to-day workings of the project.

CP Tech Center, Iowa State University (formerly the PCC Center)

The CP Tech Center is a research coordination center at Iowa State University. The CP Tech Center, under the direction of the TAC, was responsible for the management and execution of the project. The center's responsibilities included the following:

- Administration of the federal appropriation and industry financial contributions
- Completion of the work tasks
- Communication with the TAC and executive committee regarding ongoing research and problems or potential problems
- Preparation of progress, interim, and final reports

Federal Highway Administration

The FHWA, Iowa Division, was active as both a technical and administrative liaison on the project TAC and executive committee. The FHWA Office of Pavement Technology also participated in the project's TAC.

Technical Advisory Committee

Each agency participating in the pooled fund study provided up to two individuals to serve on the TAC who provide direction to the project. Along with the state representatives, the committee included industry participants, as represented by an ACPA representative and two ACPA chapter representatives. The FHWA participated in the TAC, with one representative from the Office of Pavement Technology in Washington and one from the Iowa Division office.

The TAC was responsible for the following:

- Provide an overall direction for the project
- Formalize the specifics of the cooperative work tasks
- Review the work in progress
- Approve interim and final reports and other project deliverables

Executive Committee

At the first TAC meeting, an executive committee was appointed to function as the board of directors for the project. The executive committee's responsibilities included the following:

- Implement the recommendations of the TAC
- Define and approve work tasks
- Monitor progress of the project
- Track financial expenditures

A monthly conference call updated the executive committee and allowed for their input on issues that arose. See Appendix A for a list of executive committee members.

PHASE I. EXISTING STATE KNOWLEDGE AND PRELIMINARY SUITE OF TESTS

Phase I Overview

Tasks for Phase I included data collection, test development, visits to participating states, and a pilot project to evaluate the preliminary suite of tests. Data collection included a review of existing relevant literature, current state practice and state procedures, problem project information, and a compilation of published and unpublished state research. The information collected allowed the research team to develop the preliminary suite of tests for use in the mobile concrete research lab.

Test development involved identifying material and concrete tests that characterize the properties of durable concrete. Test development also included research of new tests and further developing existing tests. The tests were broken into five focal areas (workability, strength development, air system, permeability, and shrinkage) and grouped into the following three stages of construction: (1) mix design, (2) pre-construction mix verification, and (3) construction quality control. The results of the test development were incorporated into a preliminary suite of tests comprising about 40 tests.

Visits to the participating states included a half-day meeting with DOT officials, local FHWA representatives, contractors, and concrete paving association members. Information regarding state practices and procedures and published and unpublished research was collected at these meetings. Questions and concerns about the project were also addressed throughout the meetings.

The pilot project was completed in the lead state, Iowa, to evaluate the preliminary suite of tests. The project shadowed a construction project from late August to early October 2003. This project allowed the preliminary suite of tests to be refined.

Research Focus and Framework

To focus this project on the most critical research needs, experts from the concrete paving community were brought in at an early stage to help develop the scope for this research. An initial focus group meeting included industry participants (Gordon Smith, Iowa Concrete Paving Association; Jim Thompson, Ash Grove; Rob Rasmussen, Transtec; Tom VanDam, Michigan Technological University), Iowa DOT representatives (Sandra Larson and Jim Grove), and Iowa State University researchers (Jim Cable, Tom Cackler, Halil Ceylan, Dale Harrington, and Bob Guinn). The group drafted a proposal to develop a suite of laboratory and field tests so that concrete mixtures could be designed and field controlled for the parameters that relate to performance and constructability.

The group limited the scope of the research to concrete and its materials to focus the work and limit what could feasibly be accomplished within a reasonable timeframe and budget. Construction aspects that affect concrete performance were also included. The group prioritized the properties of concrete, establishing workability, strength development, air system, permeability, and shrinkage as the five focal areas that were felt to be the most critical to the long life and durability of concrete pavements.

Another primary consideration is the point in the construction process when the tests needed to be performed. This project focused on three critical stages in the construction process:

1. The first stage was during mix design development. Mix design is usually a laboratory procedure performed either before the letting or before construction during the winter months. The materials and concrete properties of several mix designs may be characterized in this stage. The drawback to this stage is that the materials used in the laboratory mix design may or may not be exactly what will be used on the job site.

2. The second stage occurred just prior to construction or on the first day of paving. This stage has been labeled as mix verification because the mix design is verified with actual project materials and plant-produced concrete. Properties of the field concrete are compared and contrasted to the properties measured in the laboratory. HIPERPAV can be used in this stage to determine saw cutting windows and potential early-age cracking issues that may arise.

3. The third stage was the quality control stage, which occurred during the construction itself. Testing at this stage included AVA, slump, air, maturity, unit weight, compressive strength, and flexural strength.

On April 9, 2003, this approach was presented to the MC^2 group for discussion, and the draft was approved as the guiding framework for the MCO pooled fund study.

Data Collection

Three specific types of information were gathered for this research:

1. Published and Unpublished Research Literature. The first research task included a thorough literature search for existing information on concrete material and concrete pavement tests. Because of the common goals with FHWA Task 64 research (Task 64 will develop a computer-based mix optimization program), this task was completed jointly with Transtec, the lead researcher for Task 64. Transtec searched national and international databases for this information. MCO project researchers contacted and visited each participating state to gather published and unpublished research documentation related to concrete materials and concrete pavement testing (the state visit requested information form is included in Appendix B.1). Effort was also made to find simple, practical research that state highway agencies conduct but that is not often reported. Emphasis was placed on research related to concrete material properties and concrete paving construction practices. A summary compilation of the state research is included in Appendix B.2.

2. State Practices. A detailed inventory of participating states' technologies and procedures for mix design, materials control, concrete testing, and field control was gathered (see Appendix B.1 for the data collection form). This information provided a baseline for

proposed testing recommendations and helped identify practices with potential for success in other states. A summary compilation of the state practices is included in Appendix B.4.

1. Problem Projects. Problem project data from participating states were collected through a web-based information reporting form (see Appendix B.5). Participating states identified past projects exhibiting some form of early pavement deterioration. Details about these projects provided researchers with specific, real-world examples of problems and the opportunity to assess the causes of concrete pavement distress to ensure that the proposed testing identifies the problems. The survey gathered information on problem projects in the last 15 years and the solutions used. The survey was intended to gather representative examples of common problems from a maximum of six projects from each state. Appendix B.6 is a compilation of the responses.

Visits to Participating States

The project monitor visited each of the participating states between fall 2003 and summer 2004, with the exception of Oklahoma, which was visited on April 28, 2006. A half-day meeting was held with each participating state's personnel involved with research, materials, and construction. This offered an opportunity for the TAC representative to invite others within the department, as well as contractors and FHWA state division representatives, to hear about the research and its goals. Representatives from the FHWA division office and state/regional concrete paving association were also invited. Table 1 summarizes the meeting dates and attendance.

Table 1. Meetings with Participating States

Participating State	Meeting Date	Meeting Attendance				
		DOT	**FHWA**	**CPA***	**Other**	**Total**
South Dakota	September 30, 2003	7	2	0	0	9
Nebraska	October 1, 2003	7	0	0	0	7
Wisconsin	October 7, 2003	5	0	0	0	5
Minnesota	October 8, 2003	4	1	2	0	7
North Dakota	October 9, 2003	12	0	1	0	13
Missouri	October 28, 2003	7	1	0	0	8
Kansas	October 29, 2003	6	0	0	0	6
Michigan	December 10, 2003	10	1	10	1	22
New York	January 9, 2004	10	0	0	0	10
Texas	January 27, 2004	8	1	0	1	10
Louisiana	January 29, 2004	17	1	0	2	20
Georgia	March 2, 2004	6	0	1	0	7
North Carolina	March 19, 2004	5	1	1	0	7
Indiana	June 8, 2004	4	0	1	0	5
Ohio	June 9, 2004	4	1	2	0	7
Iowa	August 26, 2004	9	1	1	0	11
Oklahoma	April 28, 2006	5	1	1	1	8
Total						**162**

* Concrete paving association.

The visits to participating states served the following purposes:

- Present an overview and update of the project to the participating states
- Solicit details on past projects exhibiting premature pavement distress
- Collect information on current state technologies and practices for materials and construction testing
- Gather related state research, especially unpublished research

In addition, several state visits involved a field trip to a nearby project. The meeting and site visits provided the research team with critical information and insights into the concerns and priorities of each state.

Coordinated Research

The MCO project research team was closely monitoring ongoing related research and incorporated findings when possible. The following projects are examples of complementary research.

FHWA Task 64

The purpose of FHWA Task 64, "Software to Identify Rapid Optimization of Available Inputs," is to create computer-based guidelines for optimizing paving concrete. Task 64 involves the development of a computerized knowledge base that will be populated by data from numerous sources. Research efforts are also focused on computer-based guidelines that will work independently.

The result was a comprehensive software package that can assist in the optimization of concrete pavement, concrete overlays, and patching and repair jobs throughout the United States. The knowledge base serves as an initial subset of materials to be further investigated, and computer guidelines will the further refine the materials identifying the optimal mix for the job.

The software can be used in three modes. The planning mode allows decisions about the mix to be made in advance. The second mode will allow the user to determine the project mix based on the available job specific materials. The third mode will allow the user to complete a sensitivity analysis to asses the impact of changes in the mix and how they affect the behavior and performance of the concrete pavement.

FHWA Task 4

The purpose of FHWA Task 4, "Tests or Standards to Identify Compatible Combinations of Individually Acceptable Concrete Materials," was to evaluate incompatibility issues related to hydraulic cements in combination with other common admixtures and identify combinations of materials that lead to premature deterioration in concrete pavements.

This research developed a protocol to detect the potential for uncontrolled stiffening and setting due to material incompatibility. The first step in the protocol, during the pre-construction stage, is to review the chemistry of reactive materials, including the cement, supplementary cementitious material (SCM), and chemical admixtures. The next step is to select the tests to determine whether any of the following three problems may occur: (1) stiffening, (2) air void system, and (3) cracking. Tests are proposed for each problem and guidelines are given in order to vary several parameters and assess the risk of problems and potential solutions. The output of the pre-construction stage is a guideline for actions to take if temperatures change, materials change, or problems occur.

The last step of the protocol occurs in the construction stage. During the construction stage, the chemistry of the reactive materials must be monitored, including the cement, SCM, and chemical admixtures. Field testing includes slump loss, setting time, air content, air void analyzer (AVA), and HIPERPAV™. It is noted that, if significant changes or problems occur during the construction stage, the user should implement actions determined during the pre-construction stage and, if problems persist, refer the materials back to laboratory testing.

Material and Mix Optimization Procedures for PCC Pavements

This Iowa State University project consisted of a field study and a laboratory study. The purpose of the field study was to document the uniformity of raw materials delivered to a construction site and the uniformity of fresh concrete that is produced under normal field conditions. The purpose of the laboratory study was to evaluate new mix control technology and to evaluate mix problems that may occur when using SCMs. The field results showed that the concrete being placed generally was of good quality and had good to excellent workability.

Phase I Key Findings

This section presents the key findings of the data collection, divided into three categories: published and unpublished state research, state construction practices, and problem projects identified by individual state DOTs.

State Research

State research showed research in the five focal areas of strength development, air system, permeability, shrinkage, and workability. Due to the wide range of research projects given to the research team, the remaining research was divided into the following categories: durability, overlays, joints, high-performance concrete, aggregate, and pavement design. The remaining projects were placed in a category labeled other. A complete list of state research by focal group can be found in Appendix B.2.

Strength Development

The strength development focal area includes 38 projects completed by local DOTs. The majority of the research in strength development is due to the addition of SCMs and their impact on early-age strength and research on maturity technology. Other research projects include curing methods, investigation of low early-age strengths, and flexural strength.

Air System

The air void system focal area produced 11 research projects focused on image analysis of the air void system, air void analyzer results, plastic versus hardened air, and durability of concrete related to the air void system

Permeability

The permeability focal area included five research projects investigating techniques for measuring the permeability of concrete. The techniques investigated in the research included ultrasonic pulse velocity and rapid chloride permeability. One project investigated the effect of GGBFS on concrete permeability.

Shrinkage

Eight projects were included in the shrinkage focal area. The main area of research in shrinkage was drying shrinkage and its effect on concrete. Research was also conducted regarding lightweight aggregate and its effects on the creep and shrinkage properties of concrete.

Workability

Sixteen projects were provided to the research team regarding establishing workability. Much of the research focused on using well-graded aggregates. Other research included set time determination with the incorporation of SCMs and high-volume fly ash concrete mix designs.

Remaining Research

The remaining research was placed into the categories of durability, overlays, joints, high-performance concrete, aggregate, and pavement design. Nearly every participating agency conducted research regarding the durability of PCC pavements or bridge structures, with a heavy focus on D-cracking. Other durability research was conducted on continuously reinforced concrete pavements, fiber reinforced concrete pavements, and salt degradation.

Research in the overlay category focused on reflective joints, thin and ultra thin whitetopping, and both bonded and unbonded overlay performance. Joint research included preventative maintenance, rehabilitation and repair of deteriorated joints, alignment of dowel bars, slab length, sawing and sealing, and dowel bar performance. The high-performance concrete research focused on cracking potential and structural response. Research in aggregates included using aggregates as a base material and the polishing/friction characteristics of aggregates. Pavement design research was focused on implementing and evaluating the 2002 Mechanistic-Empirical Pavement Design Guide.

State Practices

The state practices results showed wide variation in each state’s mix design process, mix design minimums and maximums, and properties tested on both fresh and hardened concrete. Other variations included fresh and hardened concrete test procedures and typical concrete mix designs. The complete results for the state practices survey are shown in Appendix B.4.

The survey results showed that 47% of the states had contractor-provided mix proportions. An additional 29% of the states allowed contractor's mix proportions in certain circumstances. The remaining 24% had state-provided mix designs.

Fresh concrete properties specified included workability/slump, segregation, set time, water/cement ratio (w/cm), and plastic shrinkage cracking. Every state, with the exception of South Dakota, specifies w/cm. Nearly every state also specifies fresh concrete workability/slump and air content. North Carolina is the only state specifying set time, New York is the only state with a specification in place for segregation, and Indiana has minimum cement content specifications in place for reducing plastic shrinkage cracking.

Hardened concrete properties measured included strength at opening, strength at 28 days, and permeability. Six of the 17 states do not require destructive testing for strength at opening, and 5 of the 17 states do not require testing for strength at 28 days. Minnesota and Indiana are the only states requiring permeability measurements in the case of bridge structures. Kansas, New York, North Carolina, Ohio, and Texas have testing requirements for concrete durability; namely freeze/thaw, ASR, and sulfate attack.

Typical w/cm minimum values ranged from no minimum w/cm to 0.45 in Georgia. Typical maximum w/cm ranged from 0.40 to 0.56. Typical slump values depended upon pavement application and the paving process, and typical air values varied from state to state depending upon whether the state was in a freeze/thaw region.

For typical concrete mix designs, data was obtained regarding water, cement, SCMs, chemical admixtures, and aggregate batch quantities. Typical cement and water contents ranged from 440 to 800 pounds per cubic yard (pcy) and 198 to 289 pcy, respectively. Typical maximum aggregate size ranged from 0.5 in. to 2.0 in. The common SCMs included both class C and class F fly ash, GGBFS, and silica fume. Fifteen of the 17 states are using either class C or class F fly ash in their concrete pavements. Other SCMs used included diatomaceous earth, metakaolin, and Badger pozzolan. Both air entraining admixtures and conventional to mid-range water reducers are in typical concrete mix designs.

Seven of the 17 states currently have a combined aggregate gradation design in place, and only 2 of the 17 states do not have an aggregate source approval system in place for concrete pavement mix design.

Problem Projects

Analysis of the problem projects submitted to the research team showed a total of 18 projects from 6 states. Respondents were asked to evaluate the severity of the problem on a scale of 1–5, with 5 being the most severe, and to classify the mix-related problems objectively into seven areas of workability, strength, consistency, shrinkage, air content, permeability, and other.

Respondents were also asked to evaluate probable causes of distress and to note whether the problems were persistent throughout the project, whether any post-construction investigative testing was conducted, and whether or not the problem resulted in a change in specifications. Table 2 shows the results of the surveys.

The problem project survey results showed an average severity of 3.4 for all projects submitted. For the mix-related problems, nearly every response included more than one contributing factor to premature pavement distress. Workability, strength, and other causes were the leading categories responsible for mix-related problems, at 33% of the attributed causes. Air content and consistency were the next leading mix-related problems, at 28% and 22%, respectively. Shrinkage and permeability were objectively determined to be the least likely mix-related problems, at 17% and 6%, respectively.

Table 2. Problem Project Survey Results

		Mix Related Problems							Probable Causes						
State	Severity	Workability	Consistancy	Shrinkage	Strength	Air Content	Permeability	Other	Material Related	Construction Related	Within Specifications	Environmental Related	Persistant Problem	Post Construction Investigative Testing	Specification Change
Iowa	4	X				X			X	X	X	X	X	X	X
	4	X				X			X	X	X	X		X	X
	4	X				X			X	X	X	X	X	X	X
	4							X	X	X	X		X	X	X
Minnesota	2		X			X		X	X	X			X		X
	3	X	X	X	X	X	X	X	X				X		
	1			X				X	X			X			X
Missouri	5	X	X						X	X			X	X	
Nebraska	3			X					X	X	X	X	X	X	X
	2			X					X	X		X		X	X
	2			X					X	X	X	X	X	X	X
	4							X	X	X	X		X	X	X
North Carolina	4			X					X	X	X	X	X	X	X
Wisconsin	3	X			X				X		X		X	X	X
	5				X				X		X	X	X	X	
	5							X	X		X	X	X	X	X
	3		X						X	X			X	X	
	4								X		X			X	

Next, the respondents were asked to evaluate the probable causes of premature pavement distress. Every problem project noted a material-related cause. Of the probable causes, construction-related causes made up 67% of the surveys, and only 33% of the problem projects were problematic due to specification. Environmental conditions were considered to have contributed to the problem in 56% of the projects.

Survey results showed that for 78% of the projects reported, the problem persisted throughout the project. Post-construction testing was completed on 83% of the projects to determine the causes of premature pavement distress. Seventy-two percent of the projects prompted a change in specifications to address the premature pavement distresses that occurred.

The survey results showed that identifying materials that may have incompatibility issues or the potential to cause premature pavement distress needed to be a key research focus. Results also showed construction-related causes of distress. This finding suggested that the research needed to focus on optimizing the construction process to eliminate or reduce the amount of construction-related pavement distress problems. The environmental-related causes of distress can be reduced with proper construction techniques, specifically proper finishing and curing methods.

Preliminary Suite of Tests

A preliminary suite of tests was developed as a basis for evaluation in this research. From this suite of tests, a final recommended testing procedure has been proposed to ensure long-term pavement performance. The goal was to include tests that provide useful information and results that are easy to interpret, as well as tests that can reasonably be performed routinely in terms of time, expertise, training, and cost. Another goal was to include tests that are a form of process control for the contractor, tests that provide real-time results for immediate acceptance, and tests that examine critical properties.

The tests examine concrete pavement properties in five focal areas: (1) workability, (2) strength development, (3) air system, (4) permeability, and (5) shrinkage. For each of these areas, tests were identified as existent and adequate, existent but needing further development, or nonexistent and needing to be developed. The tests were considered for relevance at three stages in the concrete paving process: mix design, preconstruction verification, and construction quality control. Table 3 outlines a template for tests that take into account the three stages and five concrete pavement properties. Appendix D lists the tests selected for each cell.

The list of tests in the suite was narrowed to approximately 40 (see Appendix D). Each test was described in detail, including what the test tells about the material or concrete, test procedures, training needed before running the test, and ways the test relates to the suite of tests overall.

Table 3. Tests of Concrete Properties in Five Focal Areas at Three Stages

	Mix Design	Preconstruction Mix Verification	Construction Quality Control
Workability			
Strength development			
Air system			
Permeability			
Shrinkage			

A pilot project in Iowa was used to evaluate the suite of tests from late August to early October 2003. This served as a trial run for evaluating the tests and helped the research team refine the suite of tests to a feasible number and scope. In Phase II, the tests selected for the suite were evaluated and further refined at construction sites in states participating in the project. These projects are further explained in the following section.

PHASE II AND III. FIELD DEMONSTRATIONS AND REFINED SUITE OF TESTS

Phase II and III Overview

As part of Phase II and III, the research team conducted shadow construction projects in each participating state to evaluate the preliminary suite of tests and demonstrate the testing technologies and procedures using local materials. These states, the specific projects within the states, and the dates of the research team's visits are listed in Table 4.

Table 4. Field Visits to Participating States

Participating State	Location	Site Visit Dates
South Dakota	I-29	September 18–28, 2006 (Phase III research)
Nebraska	N/A	Nebraska was not visited due to withdrawal from study
Wisconsin	US 151	October 18–29, 2004
Minnesota	Trunk Highway 14	August 29–September 8, 2006
North Dakota	I-94	June 20–28, 2005
Missouri	Route 27, Avenue of the Saints	August 2–12, 2004
Kansas	I-35, I-635/I-70	August 30–September 10, 2004
Michigan	I-94 and I-96	September 20–30, 2004
New York	US 15 and I-86	August 8–16, 2006 (Phase III research)
Texas	I-20	April 15–May 6, 2005
Louisiana	US 167	March 20–30, 2006
Georgia	I-75	May 15–May 24, 2006
North Carolina	US 64 and I-85	November 8–18, 2004
Indiana	Lynch Road Extension	October 26–November 3, 2005
Ohio	I-275	October 17–26, 2005
Iowa	US 34	June 6–16, 2005
Oklahoma	I-35	April 3–13, 2006

A state-of-the-art Mobile Concrete Research Lab was designed and equipped to facilitate the demonstrations. The suite of tests performed at each shadow project and the mobile lab are described below.

This chapter will also highlight unusual occurrences during the shadow projects and identify other tests identified during the state visits.

Summaries describing the activities and observations of the research team at each shadow project are provided in Appendix C. However, note that one of the participating states was not visited and is therefore not included in Appendix C, and two of the participating states included in the appendix were visited during Phase III research activities. Nebraska was involved in the MCO project only for the first three years and therefore was not visited, and South Dakota and New York were visited during Phase III research.

Suite of Tests

Table 5 shows each test in the suite of tests as defined by the five focal concrete properties. The table also includes the laboratory performing the test (either the Mobile Concrete Research Lab or Central Laboratory) and the corresponding ASTM and AASHTO test numbers, if applicable. Further information regarding the suite of tests can be found in the Testing Guide tech transfer.

Table 5. MCO Suite of Tests

Focal Property	Test Name	Laboratory Performing Test	ASTM	AASHTO
Workability	X-Ray Fluorescence	Central Laboratory		
	Combined Grading	Mobile Laboratory		
	Penetration Resistance (False set)	Mobile Laboratory	C 359	T 185
	Cementitious Materials Temperature Profile Coffee Cup Test	Mobile Laboratory		
	Water/Cementitious Materials Ratio (Microwave)	Mobile Laboratory		
	Unit Weight	Mobile Laboratory	C 138	T 121M / T 121
	Heat Signature (Quadrel iQdrum)	Mobile Laboratory		
	Concrete Temperature, Subgrade Temperature, Project Environmental Conditions (weather data)	Mobile Laboratory		
Strength Development	Set Time	Mobile Laboratory	C 403	
	Concrete Maturity	Mobile Laboratory	C 1074	T 325
	Flexural Strength and Compressive Strength	Mobile Laboratory	C 78 & C 39 / C 39M	T 97 & T 22
Air Content	Air Void Analyzer	Mobile Laboratory		
	Air Content (pressure)	Mobile Laboratory	C 231	T 152
	Air Content (Hardened Concrete)	Central Laboratory	C 457	
Permeability	Chloride Ion Penetration	Central Laboratory	C 1202	T 277
Thermal Movement	Coefficient of Thermal Expansion	Central Laboratory	C 531	TP 60

X-Ray Fluorescence

X-ray fluorescence (XRF) was conducted on the cementitious materials from each state to quantify the chemical composition of each binder. Knowing the chemical composition of the binders is important for identifying potential field problems, i.e. false set, flash set, or other workability/compatibility issues, that may arise due to an imbalance in sulfates.

Combined Grading

Aggregate gradation plays an important role in fresh concrete workability. The research team conducted a sieve analysis on the mixture proportions to determine the combined gradation. The combined gradation was then analyzed and placed on the workability factor versus coarseness factor chart to assess the fresh concrete characteristics that could be expected.

Coffee Cup Test

For each state, the coffee cup test was conducted to determine the quick heat generation characteristics of the cementitious materials. The coffee cup test procedure is as follows:

1. Obtain representative samples of cementitious materials and record the material temperature.
2. Cool or warm the cementitious materials and water to 70˚F ± 3˚F.
3. Mix 500g of cement with 200g of water, or mix 500g of cement and SCM blended at the mix design ratios.
4. Vigorously shake the mixture for about 20 seconds in a 1 liter Nalgene bottle. Start the timer when the water is introduced. Pour the slurry mixture into a 3 in. by 6 in. cylinder when mixing is complete.
5. Set the container in an insulated enclosure block of Styrofoam with a cylindrical void that fits tightly around the container. Open the lid, insert a thermometer, and read the temperature. Close the lid ten seconds after insertion and record as the initial temperature.
6. Open the lid and read the temperature at 1 minute intervals (timer reads 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 minutes). Close the lid and record the temperature readings at each interval.
7. Plot the results, with temperature on the y-axis and time on the x-axis.

Initial criteria for the coffee cup test were provided by Grace Admixtures staff. If temperature change exceeds 3˚F in any 5 minute period, then there may be early stiffening issues in the field. However, the research team noted that most tests that have exceeded this criterion are still workable in the field.

The cementitious materials are usually sampled from a truck, and the research team feels that the test results may indicate a difference between loads. However, under normal circumstances the material will be unloaded from the truck before the test results are known. The research team therefore views this test as an aid to troubleshooting field problems, as the test may flag a detrimental change in cement or cementitious materials chemistry. Figure 2 shows the coffee cup test equipment.

Figure 2. Coffee Cup Test Equipment

Set Time

The penetration set time test was conducted according to ASTM C 403 with a minor variation. The mortar for the test was sieved from the fresh concrete using a handheld vibrator with a custom made #4 sieve, shown in Figure 3. The fresh mortar was then placed into a coffee can and tested in accordance with ASTM C 403.

Figure 3. Handheld Vibrator and #4 Sieve Used for Set Time Test

Microwave Water/Cementitious Materials Ratio

The microwave water content test is conducted on fresh concrete obtained in the field at the point of paving operations. The test indicates the w/cm ratio in the fresh concrete. Many studies have shown the important effect of w/cm for the long-term durability of concrete.

The test procedure for the microwave water content is as follows:

1. Obtain a representative sample of fresh concrete from the grade and transport the sample to the laboratory.
2. Record the mass of a wooden block, cloth, and bowl.
3. Weigh out about 1,500 g of fresh concrete.
4. Cover the concrete with the cloth and microwave for five minutes.
5. Stir and record the mass.
6. Repeat the microwave process in increments of two minutes, recording the mass between microwave periods.
7. Stop when the difference in mass between consecutive microwave intervals is less than 1 g.

The resulting loss in water, combined with mix design proportions (i.e., w/cm and absorption of the aggregates), is utilized to estimate the w/cm for the concrete mixture.

Concrete Temperature, Subgrade Temperature, Project Environmental Conditions

For each visit to the grade, the research team recorded the concrete temperature, subgrade temperature, and environmental conditions such as wind speed and direction, ambient air temperature, and relative humidity. A mobile weather station was also used to measure the environmental conditions and any precipitation for each state project.

The data recorded from the mobile weather station was used with HYPERPAV II, a computer prediction model that helps determine critical stresses in the pavement structure. A critical stress occurs when the tensile stresses in the pavement structure are greater than the tensile strength gain envelope, resulting in transverse cracks. Using HYPERPAV II, the contractor or state DOT can estimate the correct time for sawing the transverse joints.

Air Content in Hardened Concrete

The air content in the hardened concrete was estimated using a modified ASTM C 457 test. The hardened air void structure was estimated using a rapid air analyzer, shown in Figure 4. The concrete cores taken from each state were prepared using the following procedure:

1. Saw the core into three equal sections (top, middle, and bottom).
2. Saw a 1/2 to 3/4 inch thin section out of the center of the core (top to bottom).
3. Polish the sample with 6 μm grit.
4. Blacken the polished core surface with a roll on black ink or with a black marker.
5. After the ink is dry, smear and fill the air voids and surface with a mixture of zinc oxide and petroleum jelly, making the air voids white in color.

6. Scrape the surface with a razor blade, removing the excess petroleum jelly-zinc oxide mixture.
7. Conduct the rapid air analysis.

The rapid air analyzer uses the contrast between the blackened paste and aggregate and the white air voids to determine the air void diameter when conducting a liner traverse. The computer analysis conducts the linear traverse and analysis in about three minutes. The resulting output is the air content percentage, the specific surface of the air voids, and a spacing factor.

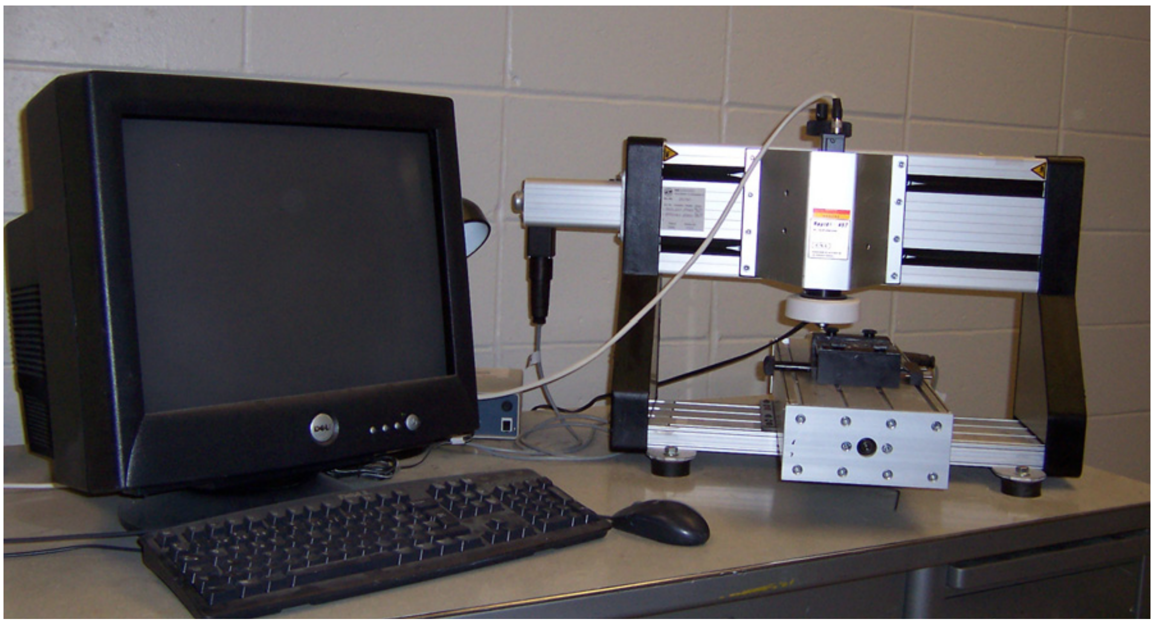

Figure 4. Rapid Air Analyzer

MCO Mobile Concrete Research Lab

The complex logistics of the shadow project research led the research team to realize that a mobile testing laboratory would be necessary. In order for testing to be timely and effective, the researchers would need an onsite lab to both conduct the research and demonstrate new procedures. The industry partners involved in the project also recognized the need for a mobile concrete research lab to facilitate this and other PCC research on a national level. Such a lab would bridge the gap between lab and field, bringing high-tech laboratory equipment to the construction site.

The ACPA, state/regional concrete paving associations, and Iowa State University contributed funding to purchase and equip a trailer to be used as a mobile concrete lab. The specifications of the mobile lab were developed based on the suite of tests for the MCO project, as well as likely future needs. The pilot project in Iowa helped the research team understand the space required for the tests so that appropriate room could be incorporated into the mobile lab design (see Figure 5).

All stakeholder input and revisions culminated in the final custom design. The 44-foot Featherlite trailer is suitable for towing by a medium-duty truck with a flat bed. The trailer's gooseneck style makes it more maneuverable than a semi and less costly to own and operate, with the additional advantage of having the pull vehicle available to transport material around the construction site. See Figure 6 for an external view of the mobile lab.

Figure 5. Inside the Mobile Lab

Figure 6. The Mobile Lab Parked Curbside

With the following equipment, the mobile lab was fully outfitted to perform the suite of tests identified in Phase I.

Workability

- Sieves/sieve shakers to determine coarse and fine aggregate gradations
- Mortar penetrometer for set time of mortar (ASTM C 403)
- Vicat consistency apparatus to test early stiffening
- Insulated container for heat evolution quick test (early stiffening of cement and fly ash)
- Flow table for early stiffening flow table test (Dan Johnston method; modified ASTM C 1437) (see Figure 7)
- Slump cone for inverted slump test
- Two iQdrum calorimeters to determine heat signature of mortar and concrete
- Infrared noncontact temperature measuring device (thermo gun) to measure concrete temperature and base temperature

Strength

- Concrete compression tester with 250,000 lb capacity and molds to measure compressive and flexural strength development
- Jig for splitting tensile test
- Microwave oven to determine w/c ratios
- Concrete maturity loggers (Command Center and intelliRock Systems)

Air System

- AVA with isolation base and sample collection equipment to measure air void system of fresh concrete (see Figure 8)
- Two pressure meters to measure air content of fresh concrete using pressure method (ASTM C 231)
- 50 kg scale and 0.1 g balance to measure air content of fresh concrete using unit weight test
- Foam index test for air entrainment

Shrinkage

- Davis Vantage Pro full-time weather station and Kestrel handheld weather station for weather conditions (see Figure 9)
- Two wireless laptop computers with global positioning system (GPS) and HIPERPAV software

Other

- Hobart paste/mortar mixer
- 60 in. x 24 in. x 21 in. temperature-controlled curing tank
- Cordless hammer drill
- Cell phones and wireless internet access

- Digital camera
- Large screen projector
- 2 ft. x 4 ft. portable work table

Figure 7. Flow Table Test Apparatus

Figure 8. Using the AVA

Figure 9. Mobile Lab Weather Station

Air Void Analyzer

Overview

An important piece of equipment for the mobile lab, the AVA with isolation base (see Figure 10) can be used to evaluate the air void system of fresh concrete accurately on the jobsite, including total volume of air, size of air voids, and distribution of air voids. With this information, quality control adjustments to concrete batching can be made in real time to improve the air void spacing and thus increase freeze-thaw durability. This technology offers many advantages over current practices for evaluating air in hardened concrete.

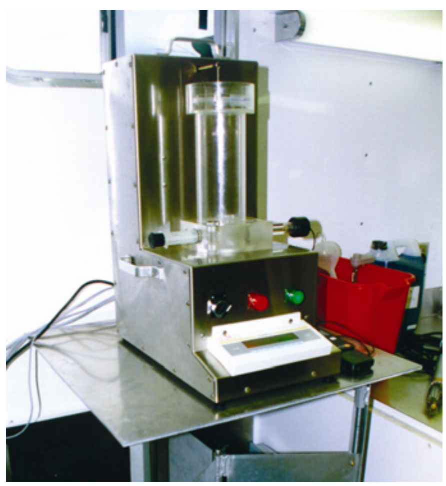

Figure 10. Air Void Analyzer

Concrete Air Void System Parameters

The air void system in concrete is critical to providing adequate freeze-thaw resistance in regions where freeze-thaw damage is a concern. Concrete air void system parameters include total volume of air, size of air voids, and distribution of air voids. However, total air content is often the only air void system parameter considered during quality control evaluation of fresh concrete.

Total Volume of Air

The total volume of air in concrete is the only factor regularly tested in fresh concrete. However, total air content does not provide the most complete or accurate measure of freeze-thaw durability.

Size of Air Voids

The size of air voids in concrete is measured by specific surface. Specific surface is the ratio of the air voids' surface area to their volume; smaller voids have a higher specific surface. Specific surface is an important factor in determining potential freeze-thaw durability.

Distribution of Air Voids

The distribution of air voids in concrete is measured by spacing factor. The spacing factor is the average maximum distance from any point in the cement paste to the periphery of an air void. Of all the air void system parameters, spacing factor may have the greatest impact on freeze-thaw durability. In general, a spacing factor of less than 0.20 mm is preferable.

Air Void System and Freeze-Thaw Durability

Freeze-thaw cycles significantly contribute to premature concrete pavement deterioration. As water in concrete expands during freezing, the pressure water produces increases in relation to the distance it must travel to reach the nearest air void. The more closely the air voids are spaced, the less likely that the pressure of freezing water will damage the concrete.

Ensuring that concrete has an air void system with closely spaced entrained air voids can improve concrete freeze-thaw durability, including improved scaling resistance. With adequate air void distribution, the ice formed in capillary pores in concrete will expand into adjacent voids without causing spalling and concrete deterioration.

Air entraining agents are added to concrete mixtures to stabilize the air bubbles in the concrete mixture in an attempt to minimize freeze-thaw damage. However, the air void structure can be adversely affected during the construction cycle, including admixture incompatibility and over-vibration.

With the timely additional information provided by AVA testing, improvements in the spacing factor can be made by increasing the dosage of air entraining agent or using a different air entraining agent.

AVA Technology Description

The AVA is a portable device that comes in a carrying case. A liquid with known viscosity is placed in the bottom of the AVA riser cylinder, and the rest of the cylinder is filled with water (see Figure 11). The AVA-2240 release liquid is blue and comes in 5-liter containers. Each test requires 200 ml of liquid.

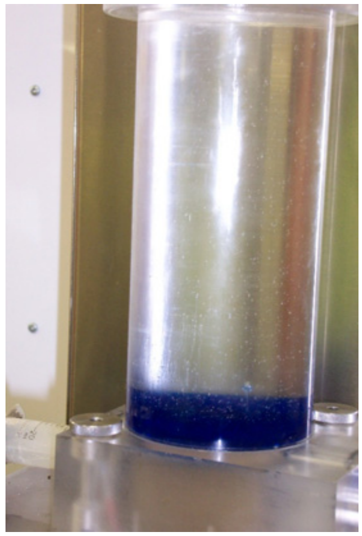

Figure 11. Bubbles Rising from the Blue AVA Liquid

A percussion drill is used to vibrate a wire cage into fresh concrete, and mortar (excluding aggregate larger than 6 mm) fills the cage. A syringe is used to extract a 20 cm^3 mortar sample from the cage. The mortar sample is then injected into the viscous liquid at the bottom of the AVA riser cylinder, and the sample is gently stirred for 30 seconds.

Air bubbles released from the mortar rise through the viscous liquid and then through the water in the rise cylinder. The rate at which the bubbles rise is a function of their size: larger bubbles rise faster than smaller ones, according to Stoke's Law. The bubbles collect at the top of the cylinder under a buoyancy recorder bowl attached to a balance. The buoyancy of the bowl changes over time. During AVA testing, the weight change over time is recorded for 25 minutes or until no weight change is recorded for 3 consecutive minutes. In this way, the rate of air loss is measured.

The AVA is used in conjunction with a laptop computer. With the data recorded during the AVA test, the computer's software uses an algorithm to report the specific surface, spacing factor, and total air content.

In 2004, the PCC Center (now the CP Tech Center) custom-designed its Mobile Concrete Research Lab to allow the AVA to be used in the field without being affected by external vibrations. A portal was built in the floor of the mobile lab to accommodate the AVA. During testing, a three-legged stand is lowered through the floor portal to rest on the ground. A weather shield surrounds the base of the stand (see Figure 12). The AVA sits on a deck on top of the stand within the lab (see Figure 13). The AVA is protected by the trailer but does not touch the trailer. This set-up provides an accurate method of using the AVA in the field for more timely, convenient, and cost-effective quality control.

Figure 12. Outside View of the Weather Shield for the AVA

Figure 13. AVA on its Three-Legged Stand in the Mobile Lab

Limits of Conventional Tests of Air in Concrete

Fresh Concrete Tests: Incomplete Information

Two tests are commonly used to measure the air content of freshly mixed concrete: the pressure method using the pressure meter (ASTM C231) and the volumetric method using the roll-o-meter (ASTM C173). These tests measure total volume of air only, and not size or distribution of air voids.

Hardened Concrete Test: Too Late for Adjustments

Until recently, the only method to evaluate the complete concrete air void system involved taking a sample core of the concrete after it had hardened (ASTM C457). By this method, the spacing factor and specific surface are measured in the laboratory using a microscope. This typically takes a minimum of three days, too long to make adjustments to the concrete mixture.

AVA Test: Timely and Complete Air Void System Analysis

The AVA is a piece of equipment that can be used to evaluate the complete air void system of fresh concrete accurately. (For more details, see Magura 1996; AASHTO 2003; FHWA 2004.) A concrete sample was typically obtained from the jobsite and transported to a nearby building for testing. With results available in under an hour (typically about 30 minutes), quality control adjustments in concrete batching can be made to improve the air void spacing in future batches and thus increase freeze-thaw durability.

AVA Experience

Since 1999, the FHWA has used the AVA on concrete paving projects in many states. About half the projects met air content specifications using conventional quality control tests (measuring only total air content) but had air void spacing factors outside acceptable limits for adequate freeze-thaw durability. The AVA helped correct the air void systems in real time.

In response to premature joint distress determined to be caused by poor air void spacing, the Kansas Department of Transportation began using the AVA in 2001. The cost savings for 2001–2002 projects were estimated to be over $1 million. In 2002, the Kansas DOT developed specifications based on the AVA, establishing a minimum total air content based on a maximum spacing factor of 0.25 mm. The AVA is now used in Kansas for prequalification of concrete mixtures in the laboratory and verification of the mixtures at the jobsite.

Advantages of the AVA

The AVA offers the following advantages over conventional tests of air in concrete:

- With AVA results during construction, real-time admixture adjustments can be made that can improve the air void structure and thus the freeze-thaw durability of the concrete.

- AVA test results provide more complete concrete air void system analysis than conventional fresh concrete testing, which only measure total air content.
- AVA test results correlate closely (within 10%) with results obtained on hardened concrete using ASTM C 457.
- The AVA provides results in a timelier manner than concrete core tests so that real-time adjustments can be made.
- The AVA isolation base allows AVA testing on the jobsite, which offers time and cost benefits over transporting the mortar sample to a nearby building for AVA testing.

Other Tests Identified During the State Visits

This section describes two other tests identified during the state visits. The tests included the free-free sonic strength test in North Carolina, which estimates concrete strength, and time domain reflectometry (TDR), which indirectly determines the w/cm ratio.

Free-Free Sonic Strength Test, North Carolina

During the North Carolina shadow project, the North Carolina DOT was conducting a research project that studied nondestructive testing for concrete strength measurement, entitled "Feasibility of Using Compressive Strength Test Results for Acceptance Testing of Concrete Pavements." The research evaluated the dynamic modulus test in a free-free resonant column. The advantage of this test is that it is fairly easy to perform on cores prior to testing them for compressive strength. Dr. Miguel Picornell visited the Mobile Concrete Research Lab while it was onsite to explain and demonstrate the test procedure. He and Dr. Jiann-Long Chen are faculty at North Carolina A&T State University and are the principal investigators for this research.

The research evaluated the correlation between the compressive, flexural, and split tensile test results and the results of the free-free resonant column test. Dr. Picornell brought test equipment to the mobile lab and demonstrated the test procedure for the research team (Figure 14). The results were very promising. However, because the MCO field research was focused on plastic concrete properties and only limited hardened strength tests were performed, the research team did not find it feasible to incorporate this non-destructive strength test into the shadow projects' suite of tests.

Nondestructive tests are the goal of concrete testing whenever possible. As this test develops, it should be investigated as an addition to the conventional strength tests and, possibly in the future, a replacement for destructive tests.

Figure 14. Free-Free Sonic Strength Test

Time Domain Reflectometry

Time domain reflectometry (TDR) is a technique used to determine the dielectric constant and the electric conductivity of a medium. The technique measures the time it takes for a step pulse of electromagnetic radiation to travel along waveguides that are surrounded by a medium. Upon reaching the end of the waveguides, the pulse is reflected and the travel time and velocity can be measured. The dielectric constant of the material that surrounds the waveguides, which causes deviations in the velocity of the pulse, can thus be measured. When properly calibrated, the device can use the measured dielectric constant to determine volumetric water content indirectly. The electric conductivity of the medium also causes attenuation of the TDR signal, and measuring the initial and long-term voltages of the system correlates to the medium. With calibration, the device can indirectly determine cement content.

Using TDR to measure water-cement ratio and concrete strength development has been explored by researchers from Purdue University, led by Dr. Vincent P. Drnevich (Yu 2004a; Yu 2004b). At a site in Indiana, the researchers demonstrated the techniques they had been investigating using TDR.

Unusual Occurrences during the State Visits

This section details the unusual occurrences noted during or after the research team's visits to the states, notably North Dakota, North Carolina, and Wisconsin. Specifically, the pavement observed in North Dakota exhibited random cracking after the research team left, the pavement in North Carolina exhibited issues involving low strength, and the pavement in Wisconsin experienced premature traffic.

North Dakota Cracking

The pavement placed during one day of paving experienced random cracking approximately two weeks after the research team left the North Dakota project. The cracks occurred transversely and longitudinally (see Figures 15 and 16). HIPERPAV analyses performed during the demonstration project testing indicated that the pavement had the potential for random cracking, but no cracking occurred during testing, nor were any random cracks apparent on the paving placed prior to the research team's arrival.

Subsequent conversations with North Dakota DOT staff indicate that delayed sawing was a factor. Other contributing factors may have included the relatively slow strength gain of the concrete mixture and the combination of subbase friction and stiffness. The research team has also observed a handful of projects where HIPERPAV predicted random cracking while none occurred. These observations should not serve as an excuse to ignore HIPERPAV predictions, but they should warn that even slight changes in the weather or mix characteristics can result in random cracking. Proposed improvements to HIPERPAV should make it easier to identify the sensitivity of HIPERPAV variables that contribute to cracking potential.

Premature Driving on the Slab in Wisconsin and North Carolina

Incidents involving vandals driving on a fresh concrete pavement and leaving indentations in the concrete are rare. However, this situation arose on two consecutive shadow projects in 2004, one in Wisconsin and one in North Carolina (Figure 17).

Figure 15. Random Longitudinal Crack in North Dakota Pavement

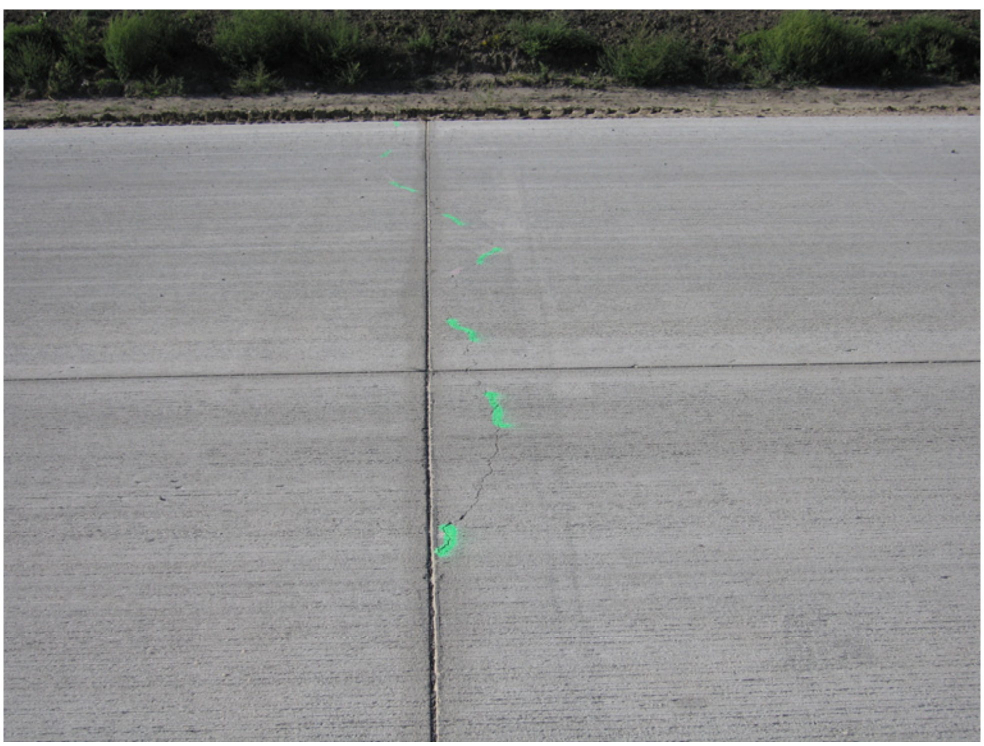

Figure 16. Random Transverse Crack in North Dakota Pavement

The first incident occurred at the Wisconsin shadow project, during the night after the second day the research team was onsite. Presumably, a pickup truck got onto the slab during the evening and drove several hundred feet down one lane before driving off the pavement on the other side. The Wisconsin DOT and the contractor evaluated various courses of action to repair the damage. The research team was able to assist these efforts by drilling cores in the affected area. These cores were provided to the Wisconsin DOT for analysis.

The other incident occurred on the North Carolina shadow project. The westbound roadway was being constructed during the research team's visit, but in the eastbound lanes, opposite the current construction, tire tracks from a car were evident. The car had driven west on the eastbound roadway, stopped, turned around, and had driven back east in the other lane. Again, the North Carolina DOT and the contractor evaluated various methods for repairing the damage. The research team was able to assist by taking core samples for evaluation from the affected areas.

Figure 17a

Figure 17b

Figure 17c

Figure 17. Driving on the Slab Too Early in North Carolina and Wisconsin

Low Strength in North Carolina

After noting low compressive strengths during the North Carolina state visit, the research team repeated the compressive strength tests in a laboratory setting. The results were inconclusive in determining the contributing cause of the low compressive strengths. One theory proposed was that the aggregate used was covered with clay or contained to large amount of deleterious fines.

Phase II and III Key Findings

This section, divided by test type, presents the data from all states visited. The results obtained from the Mobile Concrete Research Lab are presented first, followed by laboratory analysis results.

Combined Grading

Combined grading plays an important role in fresh concrete workability and hardened concrete durability. A well-graded concrete mix generally has a relatively low cementitious material content, which leads to a lower probability of shrinkage cracking. The combined gradation results for each state are shown in Figure 18. Note the five states within the well-graded 1 1/2 to 3/4 inch area, including Iowa, North Dakota, Michigan, Missouri, Indiana, and Minnesota. Although Oklahoma, Louisiana, Texas, and Ohio are not within the well-graded area that is shaded, they fall within the control lines, indicating that they are desirable but may be gap graded. Kansas, Wisconsin, and Georgia fall above the control line, indicating that mixtures from those states are sandy, and early cracking may be an issue associated with those mixtures.

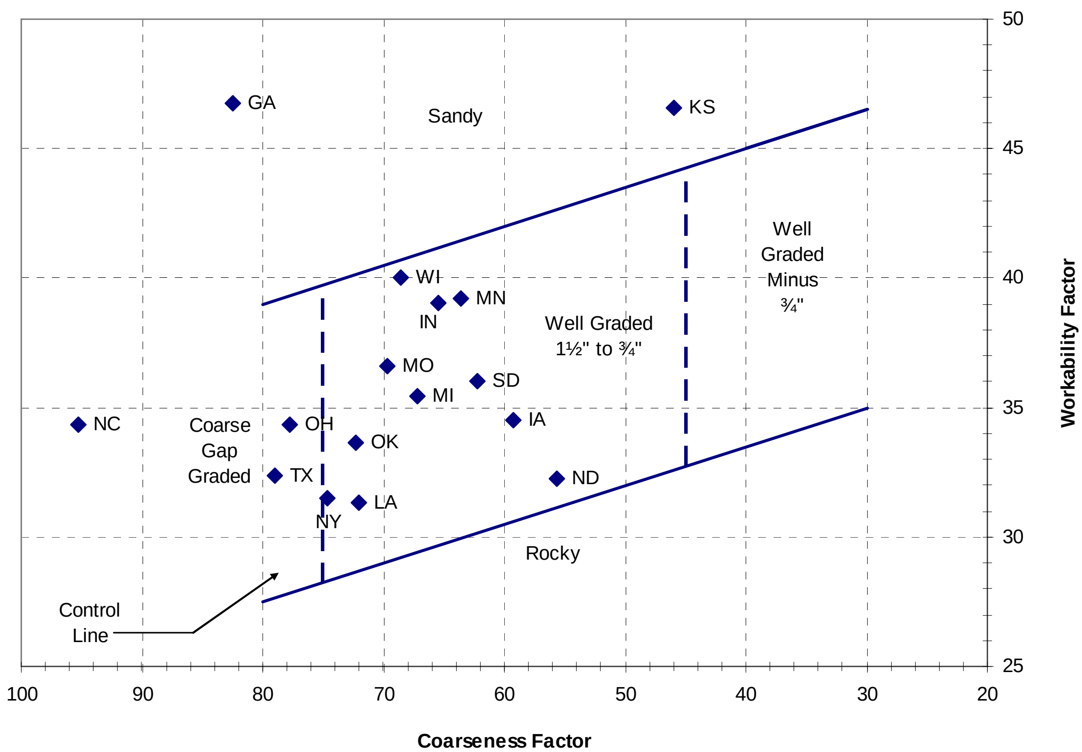

Figure 18. Workability Factor vs. Coarseness Factor for all States, Combined Gradation

False Set

The false set test indicates early stiffening. Early stiffening of the concrete leads to a variety of problems during field construction, including decreased workability and reduced handling time. The results for the false set tests are shown in Table 6. Note that most portland cements and SCMs exhibited false set characteristics. The research team noted that, even though these test results indicated false set, the concrete mixtures were easily placed in the field.

Table 6. False Set Data for Each State

State	P.C. False Set (yes or no)	P.C. and SCM False Set (yes or no)
GA	no	no
IA	yes	no
IA	yes	no
KS	yes	no
KS	yes	no
KS	no	no
LA	no	no
MI	yes	no
MI	yes	no
MN	yes	yes
ND	no	no
NY	yes	yes
OK	yes	yes
SD	yes	no
TX	yes	no
TX	yes	no
TX	yes	no
TX	yes	no
TX	yes	no
TX	yes	no
WI	yes	no

Slump and Flow

The slump test is an indicator of the workability of fresh concrete. The general guideline for slipform paving is that the contractor can pave at any slump, as long as the edges hold their shape. Each field sampling trip to the paving operation included a slump and mortar flow test. The results are summarized in Figure 19. Note the fair correlation between slump and mortar flow.

The correlation between slump and mortar flow is fair, due to the inherent difference between the two tests. The slump test is a static test and therefore measures the yield stress of fresh concrete. The flow test is conducted on mortar only and mostly measures viscosity. Due to the differences in what the two tests measure (i.e. viscosity or yield stress), the results show a rather low correlation.

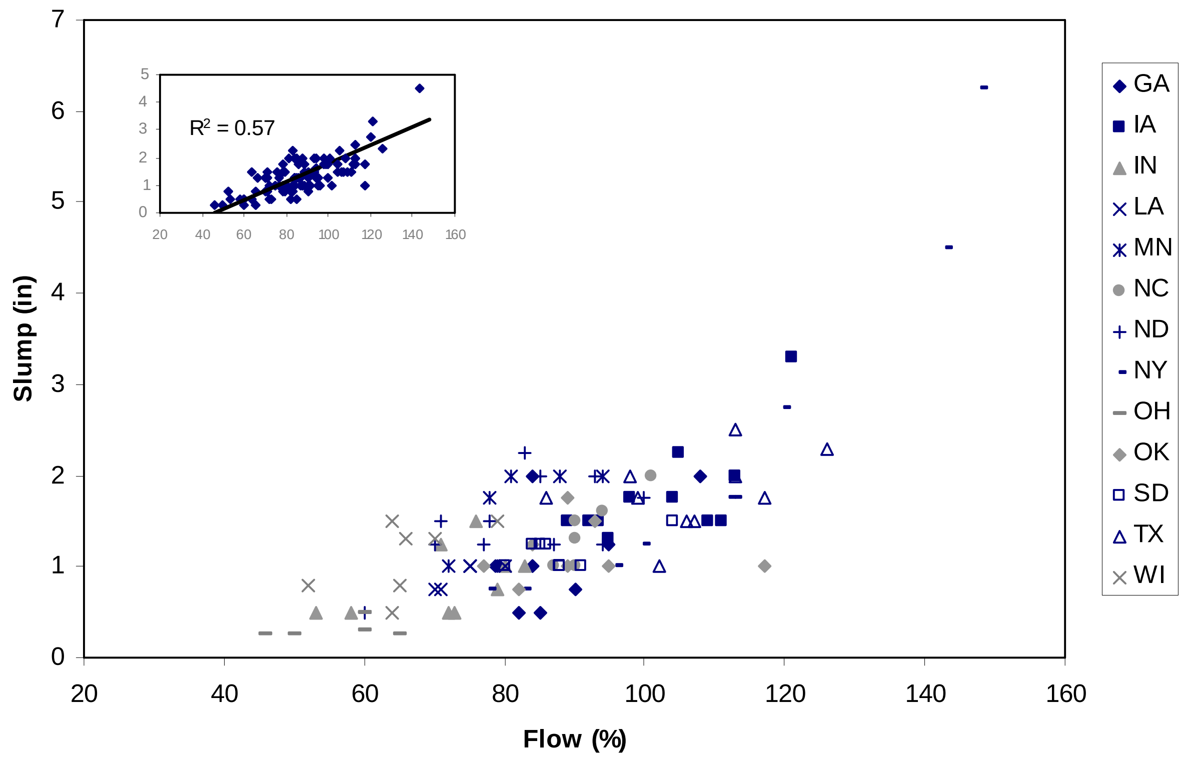

Figure 19. Slump versus Flow for All States

Coffee Cup Test

The coffee cup test indicates whether the cementitious materials have changed significantly from a previous batch, which can have a detrimental impact on the paving operation. The coffee cup test results for the Louisiana state visit are shown in Figure 20. Note the results from PC #1A and PC #1B are repeated using the same portland cement sample to determine whether the coffee cup test is repeatable. The results show essentially the same heat generation curve, indicating that the test results are repeatable. Also note the different shapes of the curves for PC #2 and PC #3. The differing shapes of the curves may indicate variability in cement chemistry or a change in cement sources.

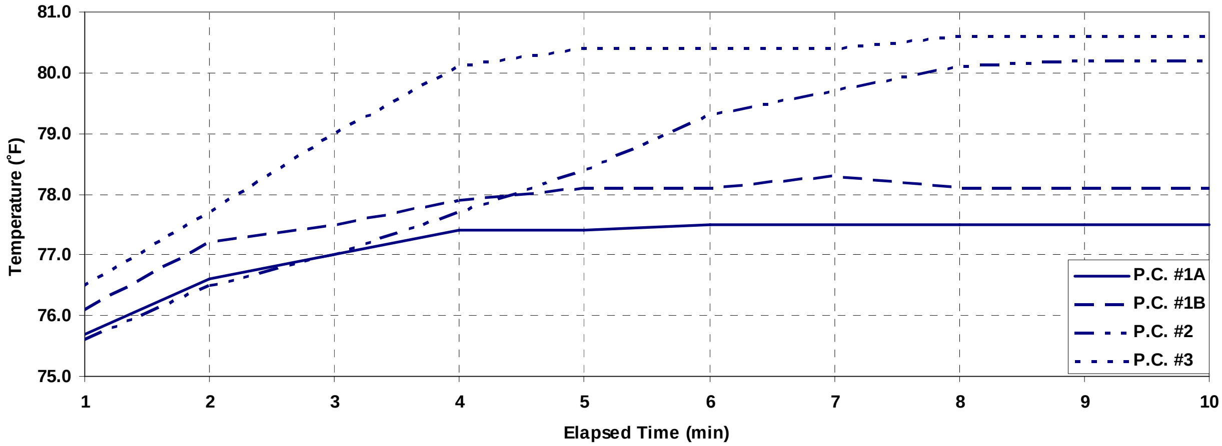

Figure 20. Coffee Cup Test Results for the Louisiana State Visit

Set Time

The set time of concrete depends on several variables, including air temperature, subgrade temperature, concrete temperature, admixture dosage rates, cement content, and SCM content and chemistry. From the contractor's perspective, the times to initial and final set are important for joint cutting. If the joints are not sawed at the proper time, uncontrolled transverse cracking may occur.

Figure 21 shows the initial and final set times for each state visit determined in accordance with ASM C 403. An initial set of 500 psi (penetrometer) ranged from about 4 to 9.5 hours, and a final set of 4,000 psi (penetrometer) ranged from about 5.5 to 12 hours. Figures 22 and 23 show the correlation between portland cement content and the initial set and final set, respectively. Set time decreases as cement content increases. Note that the correlations exclude the Wisconsin data point as an outlier. Also note that the data fit is poor, with an R^2 value of 0.51 for the initial set versus cement content, while the final set versus cement content produced a good fit, with an R^2 value of 0.70.

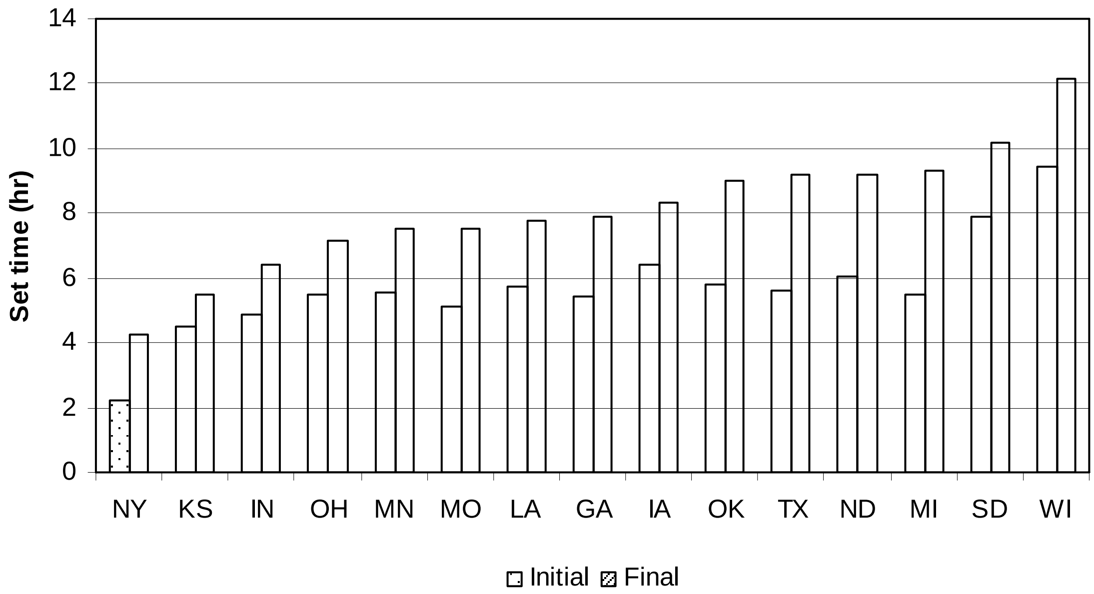

Figure 21. Initial Set and Final Set for Each State Visit

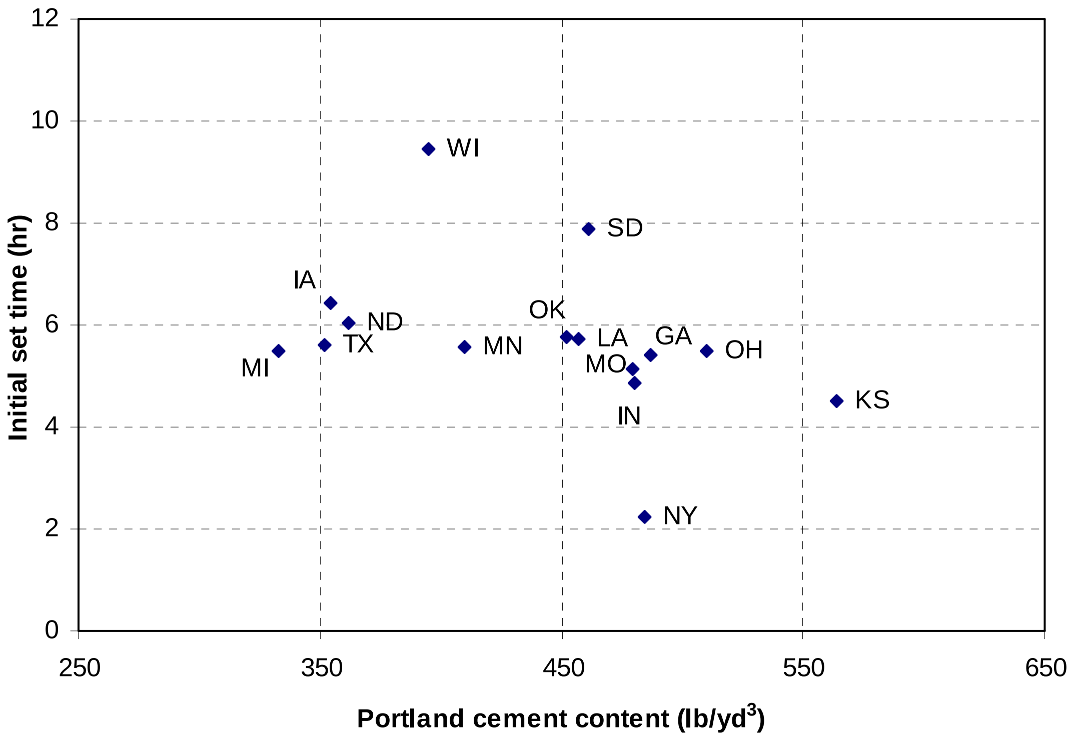

Figure 22. Initial Set versus Portland Cement Content

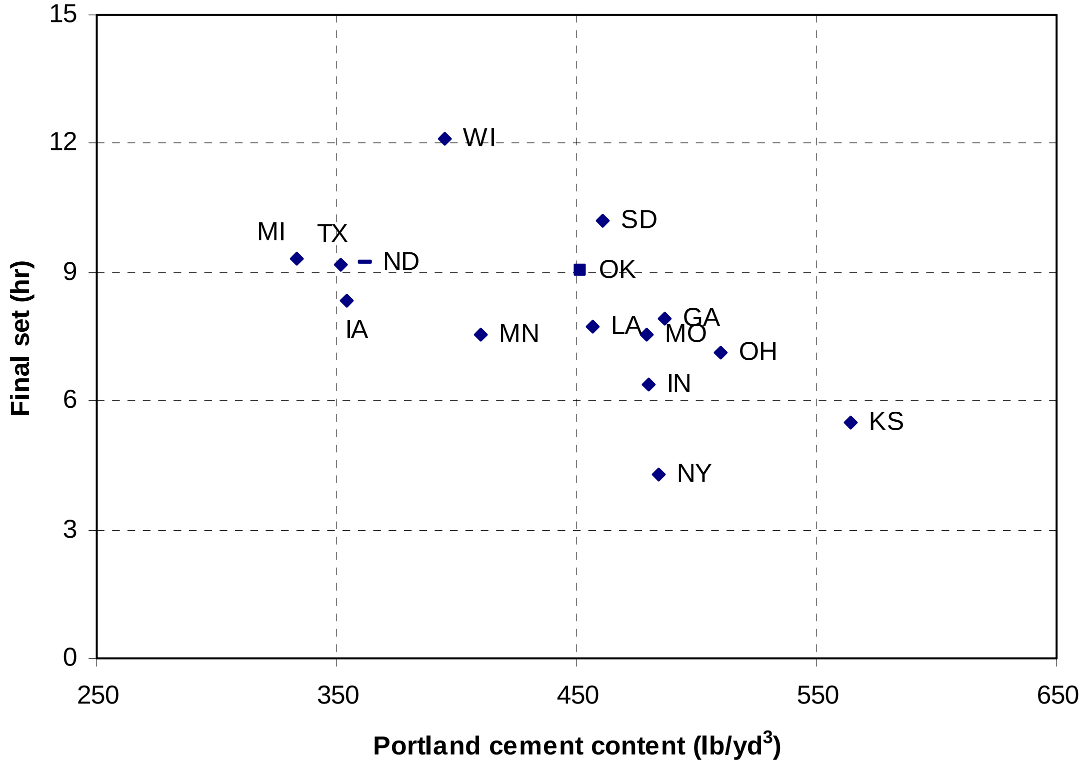

Figure 23. Final Set versus Portland Cement Content

Microwave Water/Cementitious Materials Ratio

The w/cm ratio of concrete is important because it plays a large role in the workability of fresh concrete and in the long-term durability of hardened concrete. Table 7 shows the results for microwave water content. Note the narrow minimum and maximum ranges for Minnesota, North Dakota, and Michigan. The research team believes that these narrow ranges occurred because those states used the w/cm ratio as a pay item for PCC pavement construction. Figure 24 shows the results graphical form. Note that the diamonds represent the average of all tests and the lines represent the range of values obtained during field testing. The research team believes that the microwave water/cementitious materials test may be an indicator of the batch-to-batch consistency.

Table 7. Microwave w/cm for All States

State	Minimum	Maximum	Average	# of Samples
MN	0.34	0.38	0.36	11
ND	0.34	0.38	0.37	9
IN	0.34	0.40	0.37	9
SD	0.37	0.44	0.39	10
OK	0.35	0.43	0.39	7
OH	0.37	0.42	0.40	4
WI	0.39	0.44	0.41	7
IA	0.39	0.47	0.43	11
KS	0.41	0.46	0.44	4
GA	0.41	0.51	0.45	11
NC	0.42	0.51	0.46	5
NY	0.43	0.53	0.48	9
LA	0.41	0.51	0.49	6
MI	0.48	0.51	0.49	4
TX	0.47	0.58	0.50	9
MO	0.41	0.41	0.41	1

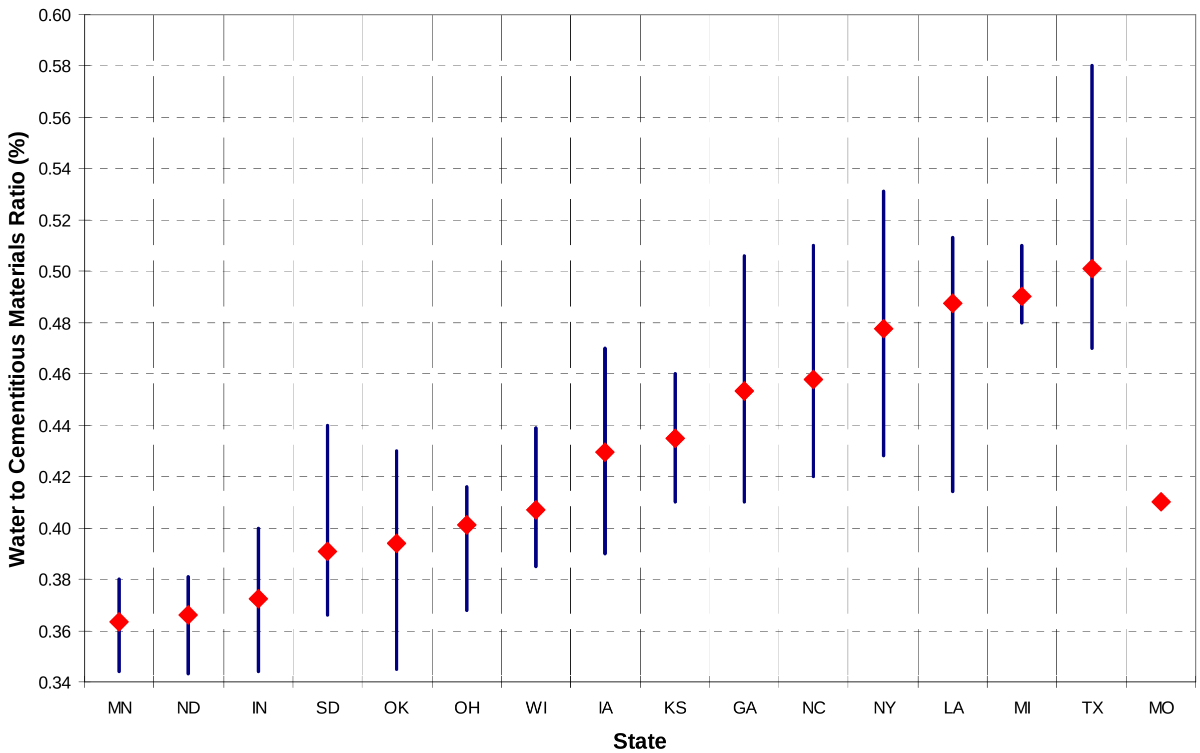

Figure 24. Microwave w/cm for All States

Unit Weight and Air Content

The air content of fresh concrete can be measured using the pressure method and the gravimetric method. This section describes the results obtained using both procedures and their correlations.

The air content results obtained using the pressure method are shown in Figure 25. The results show that as the air content is increased, the unit weight of the concrete decreases. The decrease in unit weight occurs because a larger volume of the fresh concrete is air voids. Note that North Carolina appears to fall out of the general trend. Figure 26 shows only a poor correlation between fresh concrete air content and unit weight according to the pressure method, most likely due the imprecise nature of the unit weight test.

The air content results obtained using the gravimetric method are shown in Figure 27. Note the improved correlation between air content and unit weight. The better correlation occurs because the air content is measured based on the unit weight values and the theoretical mix design proportions. Again, note that North Carolina appears to fall out of the general trend shown by the other states. Figure 28 shows the fair correlation, with an R^2 about 0.44, between gravimetric and volumetric air content.

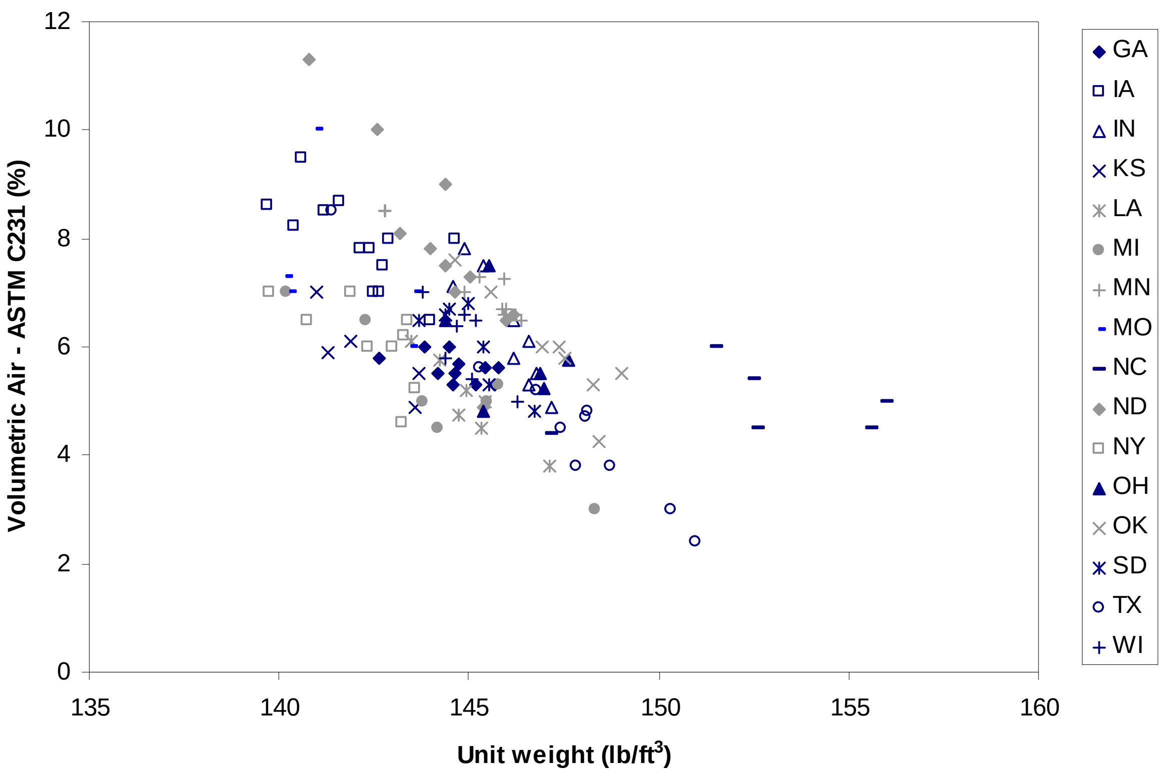

Figure 25. Air Content (Pressure Method) vs. Unit Weight of Fresh Concrete

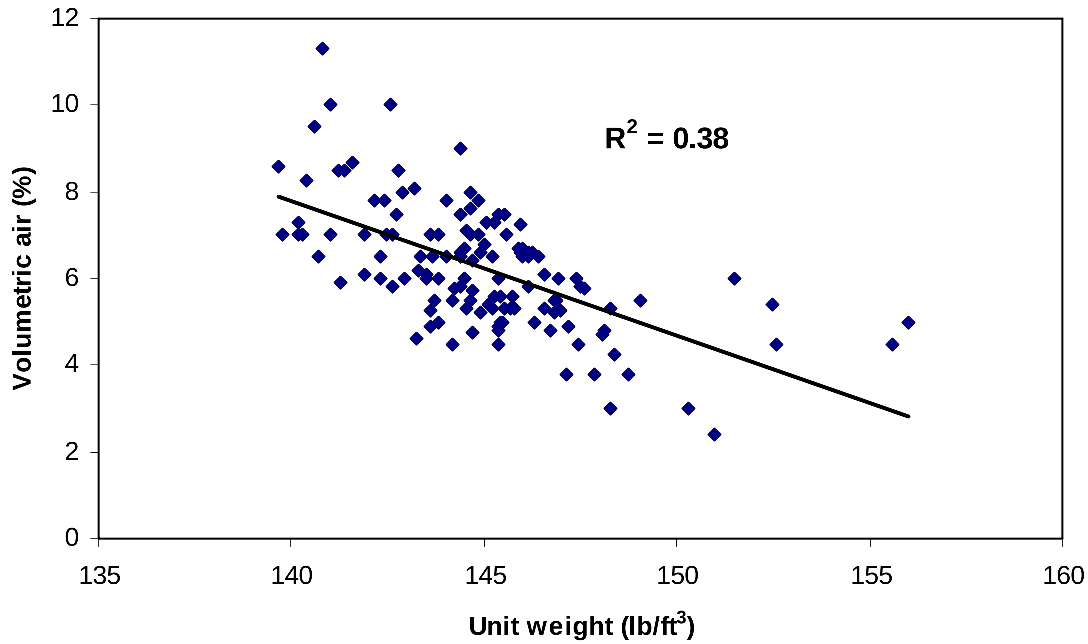

Figure 26. Volumetric Air Content–Unit Weight Correlation

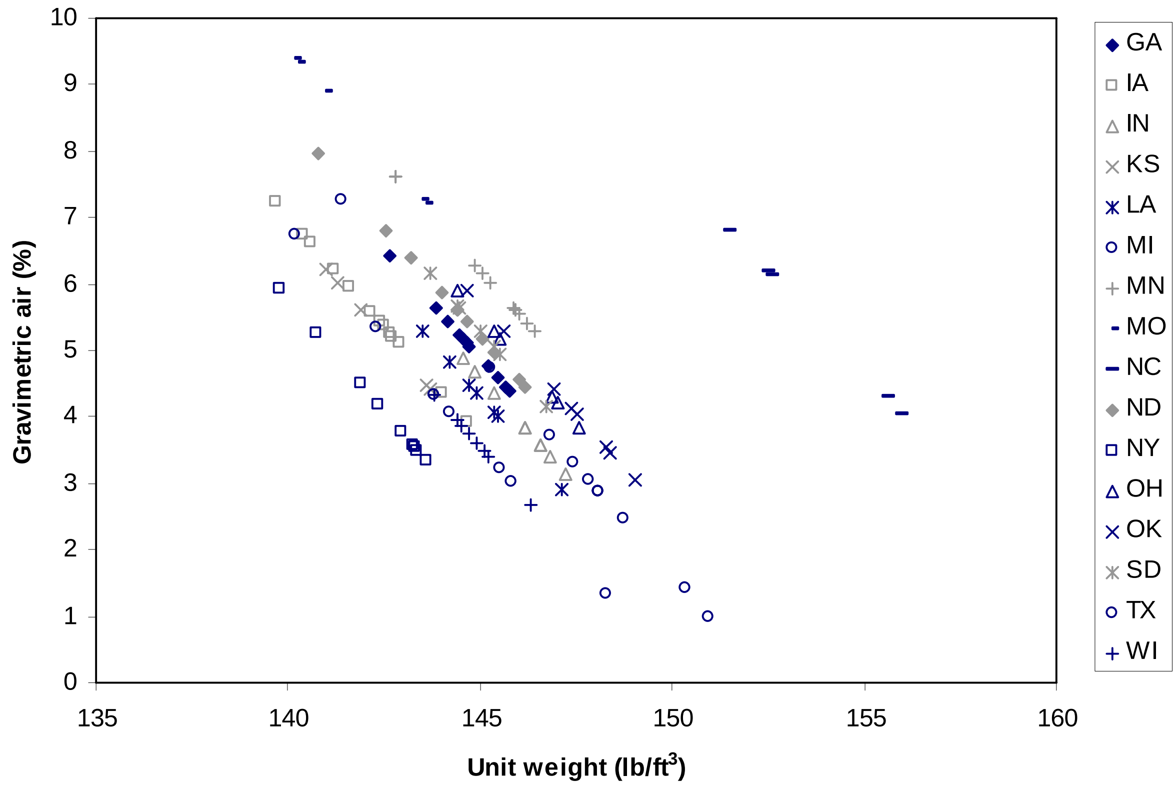

Figure 27. Gravimetric Air Content vs. Unit Weight of Fresh Concrete

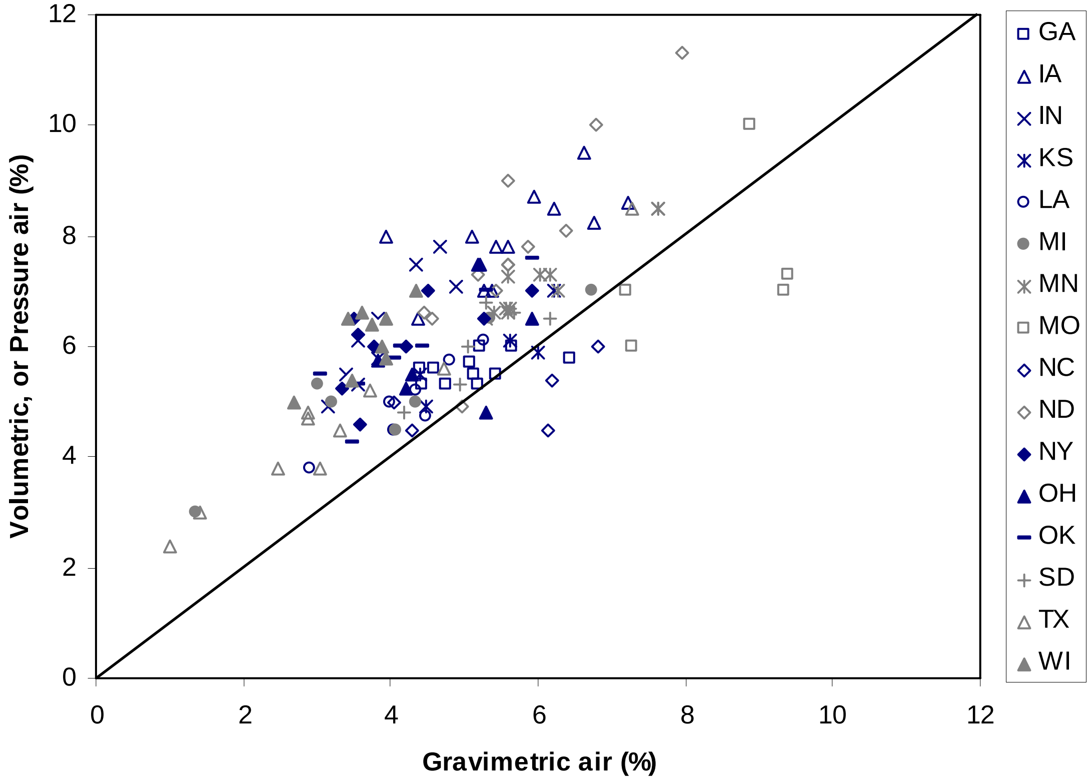

Figure 28. Correlation between Gravimetric Air Content and Volumetric Air Content

Air Void Analyzer

As stated above, a good air void system in concrete is desirable for freeze-thaw durability. The AVA allowed the research team to characterize the air void system in the fresh concrete for each state visited. The AVA results from each state were compared to the results from the other states, and the results were compared to other air content measurements. The AVA results were also compared to determine whether a difference in air void structure was observed at between-vibrator locations versus on-vibrator locations. AVA results obtained behind the slipform paver were also compared to results obtained in front of the paver to determine the effects of slipform paving on the spacing factor and specific surface.

Figure 29 shows the correlation between air content, air bubble size, and spacing factor for all AVA testing completed. The correlation is poor for the larger diameter air bubbles, but it is good for the bubble diameters smaller than 300 microns.

Note that the air contents determined by the AVA do not equal the air contents determined by the pressure or gravimetric methods. These differences exist because the AVA does not measure the larger bubble sizes and ends the test at 25 minutes, even though there may be smaller bubbles remaining in the blue fluid-mortar mixture.

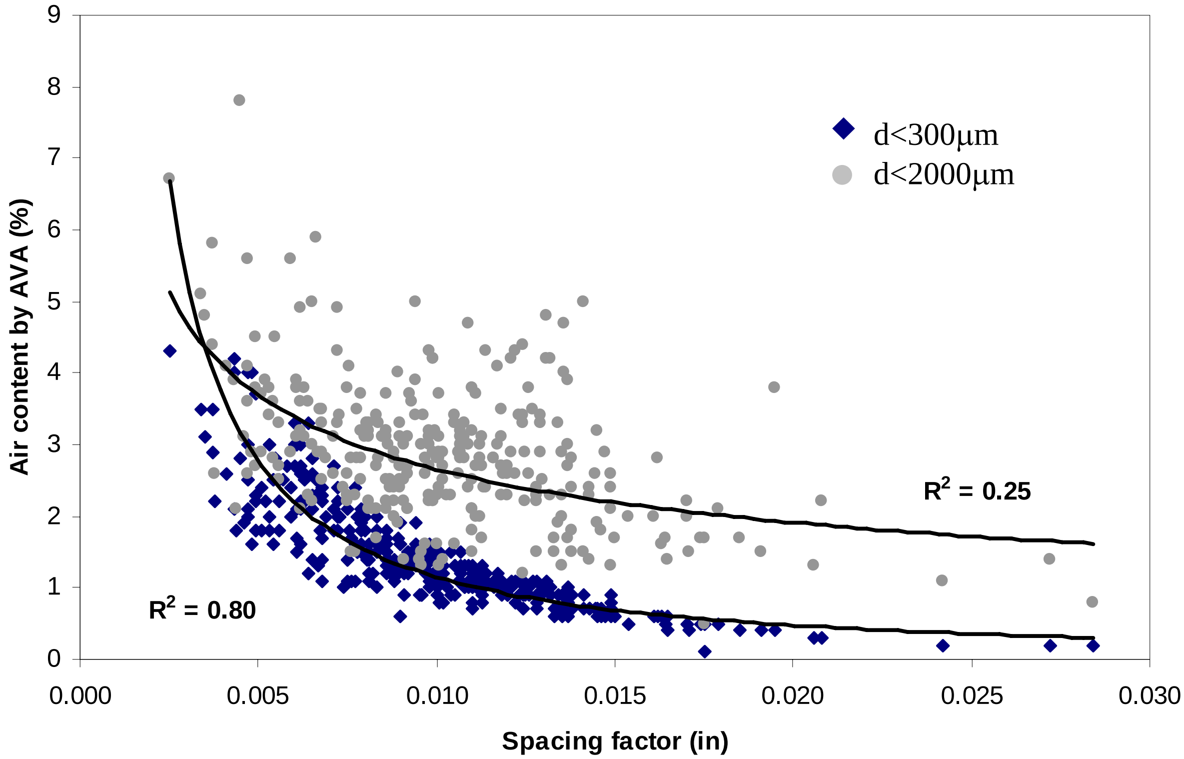

Figure 29. Relationship between AVA Air Content, Bubble Size, and Spacing Factor

Figures 30 and 31 show the relationship between specific surface and spacing factor according to the AVA data for all states. Note the good correlation between specific surface and spacing factor in Figure 32. This good correlation between specific surface and spacing factor is expected based on the published correlation equation used by the AVA. An increase in specific surface indicates that the bubble diameter is decreasing, providing more bubbles. The increase in bubbles per unit volume then decreases the distance between any two air bubbles, reducing the spacing factor.

Figure 32 shows the relationship between the on-vibrator and between-vibrator spacing factors. Note that about half of the results fall above and below the line of equality, which suggests that vibration has little effect on spacing factor when compared to samples taken from between the vibrators. The same trend is valid for the entrained air voids below 300 micron. The authors note that the relationships presented here for locations ahead, behind on vibrator trail and behind between vibrator trail, are for these mixtures only.

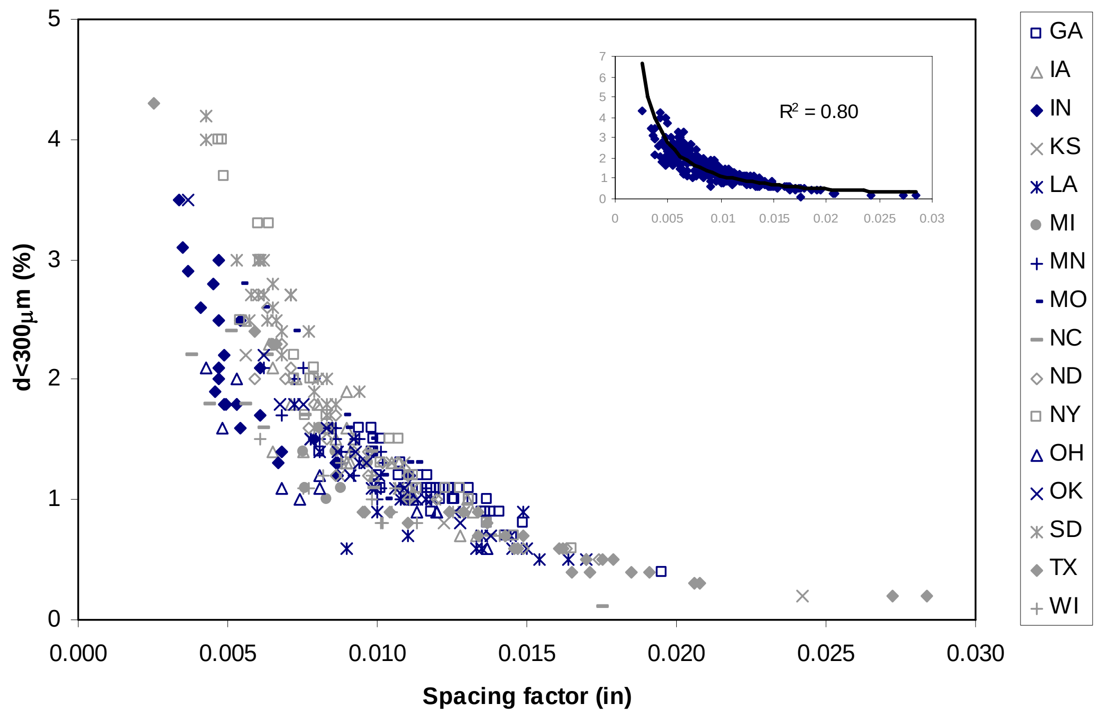

Figure 30. Correlation between 300 μm Diameter Bubble Size and Spacing Factor

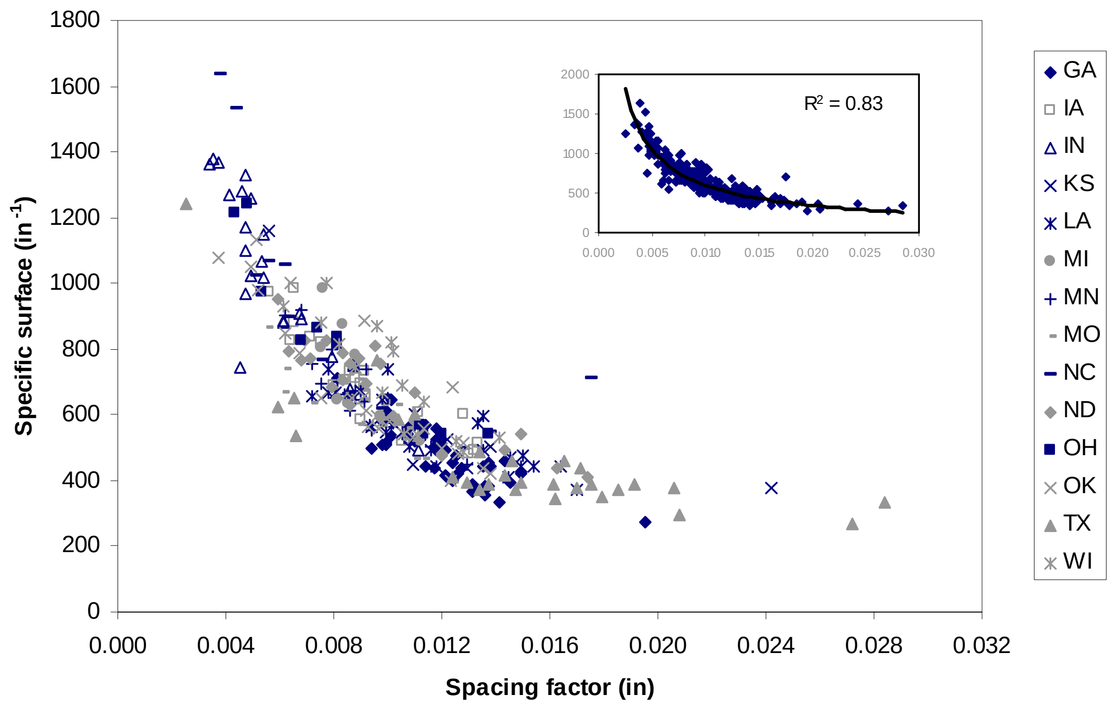

Figure 31. Relationship between Specific Surface and Spacing Factor for All AVA Data

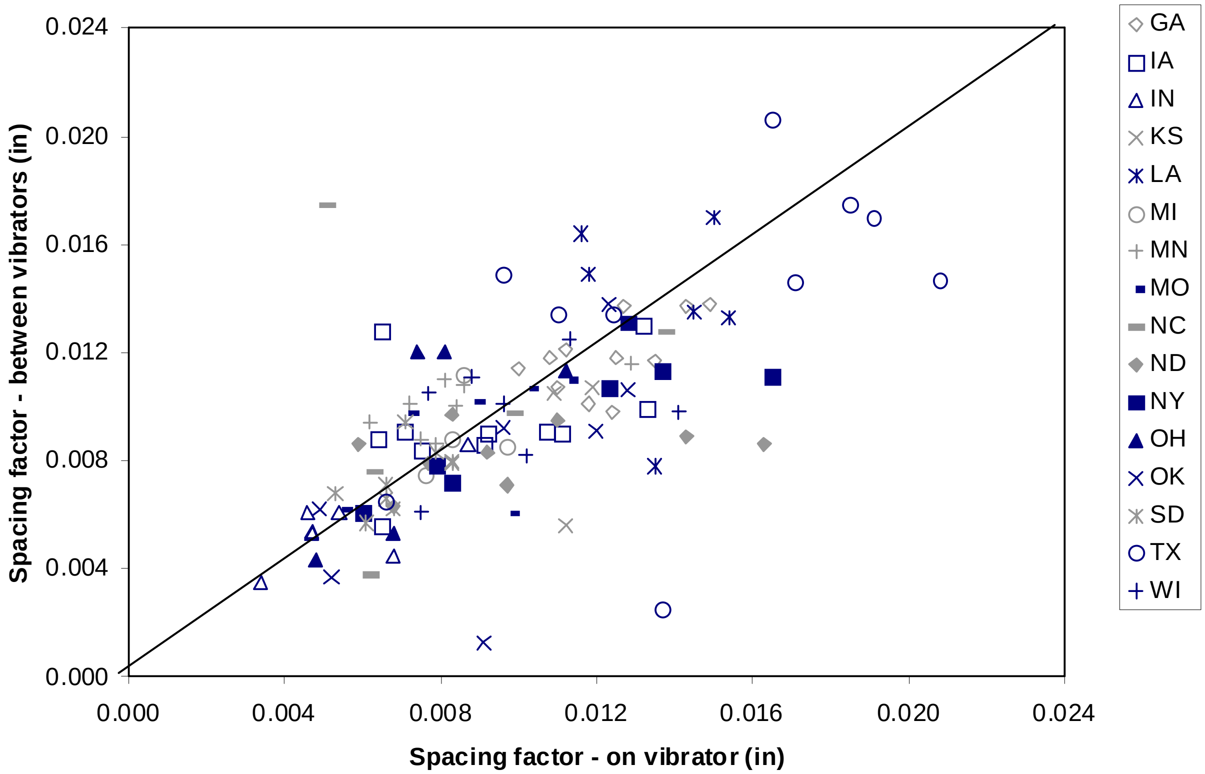

Figure 32. Spacing Factor between Vibrators vs. Spacing Factor on Vibrators

Figure 33 shows the relationship between the on-vibrator and between-vibrator samples of 300-micron-diameter bubbles. Note that more of the d_{300} bubbles lie on the on-vibrator side. This shows that, although vibration does not severely affect spacing factor, the percentage of air less than 300 microns is affected.

Figure 34 shows the correlation between spacing factor and air content as measured by the pressure method. Note that the correlation is not good, but that the data aligns closely with the findings of the Canadian Cement Association (see Figure 35), for which the spacing factor decreases as the concrete air content increases.

Figures 36 and 37 show the spacing factor and specific surface, respectively, before the paver and behind the paver for Oklahoma, Georgia, and Louisiana. Note that there is no significant difference for specific surface or spacing factor. This shows that the slipform paver did not significantly affect the specific surface or spacing factor for these three states' air void systems.

Figures 38 and 39 show the percentage of air content less than d_{2000} microns and the percentage of air content less than d_{300} microns, respectively, before and behind the paver. Note that the results are significantly different for the percentage of air content less than d_{2000}. These results suggest that the larger air voids are being vibrated out of the pavement when passing through the slipform paver. The results for the percentage of air content less than d_{300} are not significant for

Georgia and Oklahoma, but the results are significant for Louisiana. The results show a small drop in the percentage of air content less than 300 microns, expected due to the vibration of concrete as it passes through the paver.

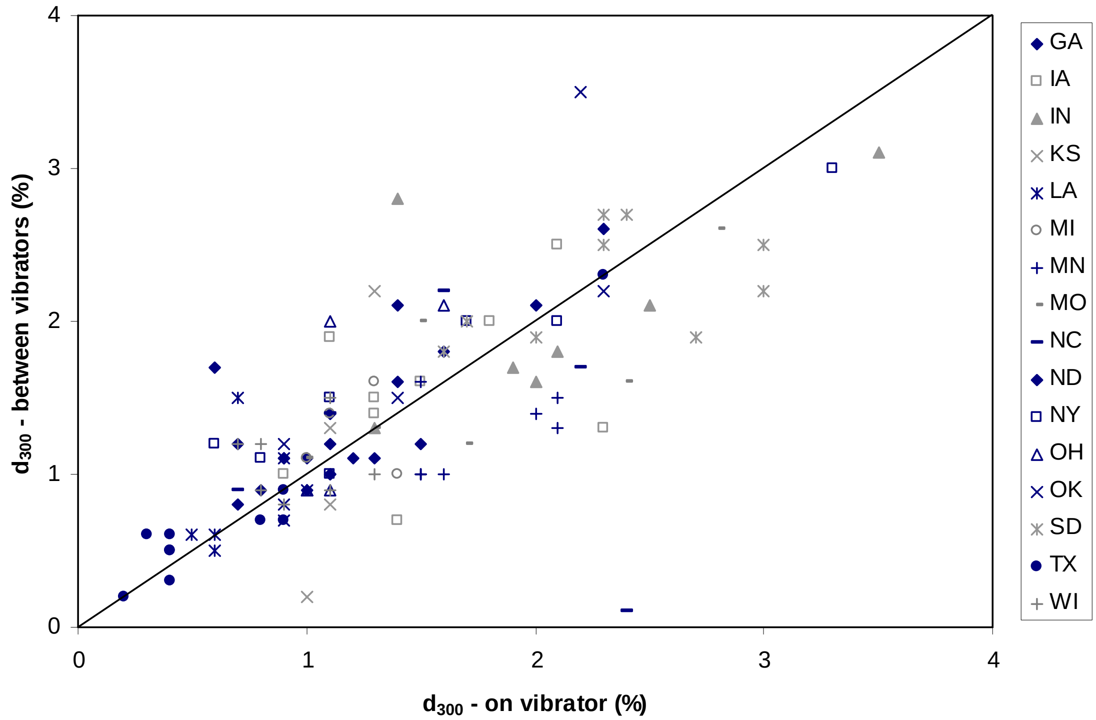

Figure 33. d_{300} between Vibrators vs. d_{300} on Vibrators

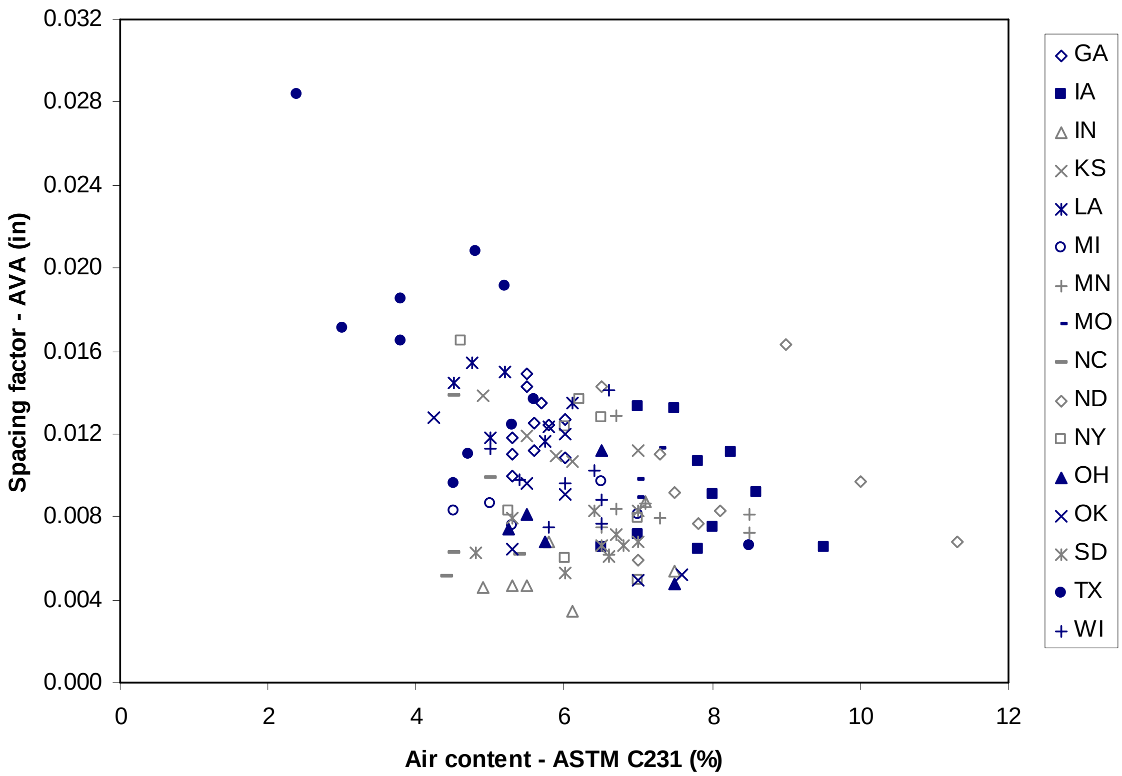

Figure 34. Spacing Factor vs. Pressure Method Air Content

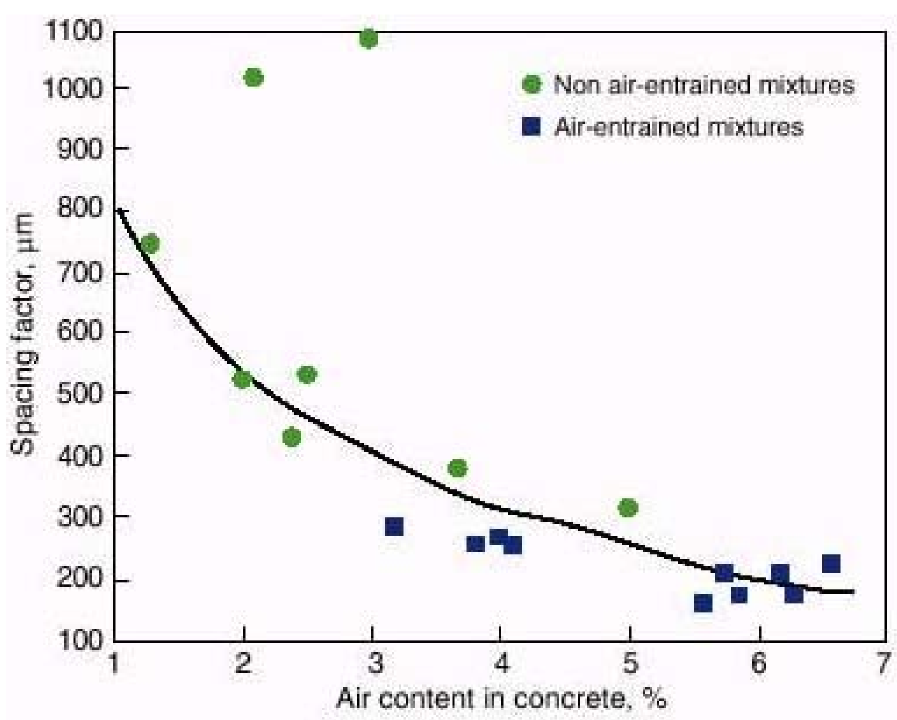

Figure 35. Spacing Factor vs. Air Content (Canadian Cement Association)

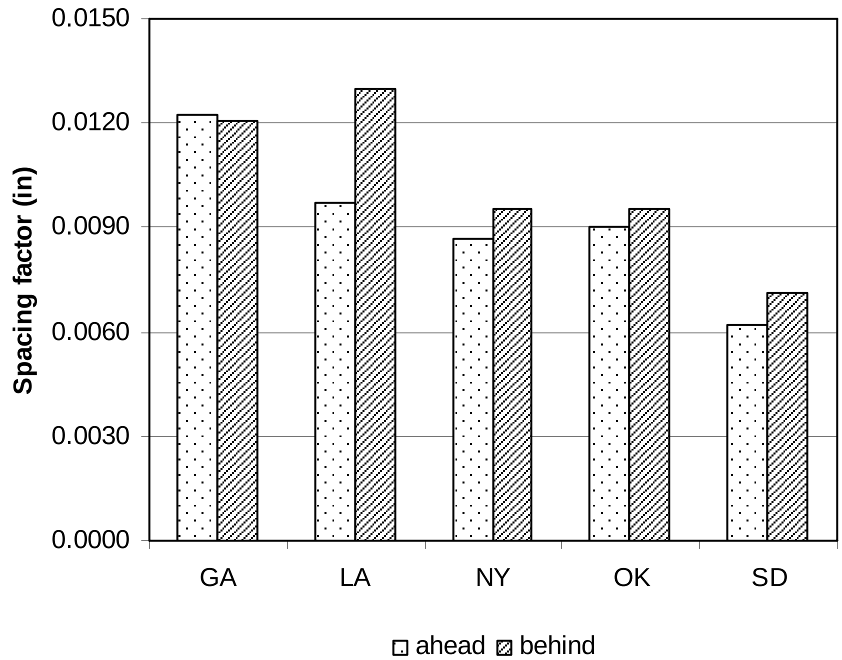

Figure 36. Spacing Factor in Front and behind the Paver for GA, LA, and OK

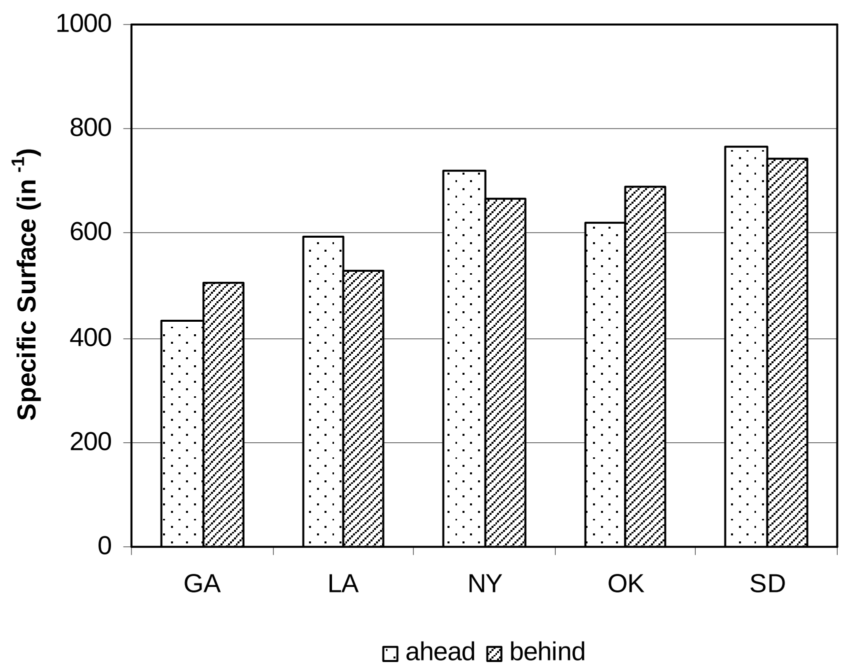

Figure 37. Specific Surface in Front and behind Paver for GA, LA, and OK

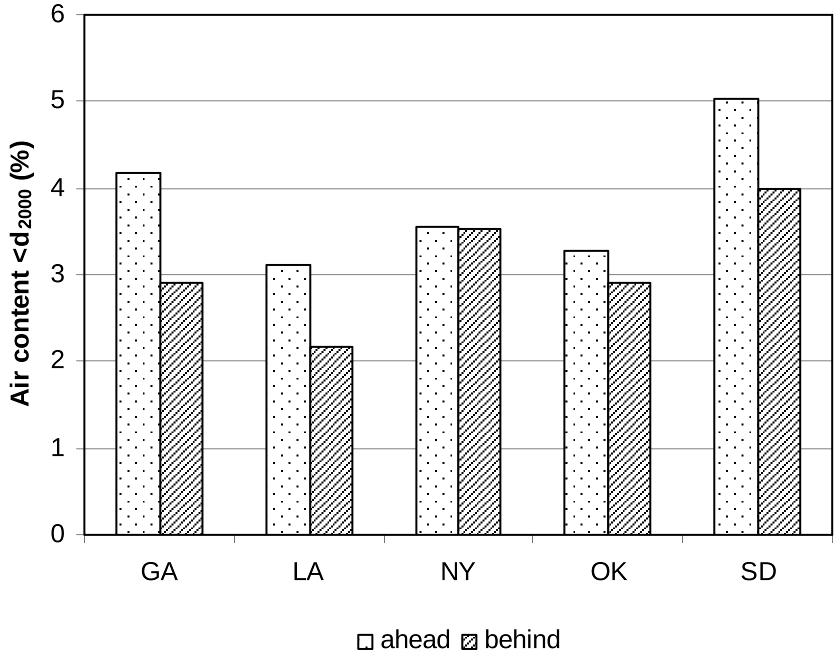

Figure 38. Percent Air Content <d_{2000} in Front and behind Paver

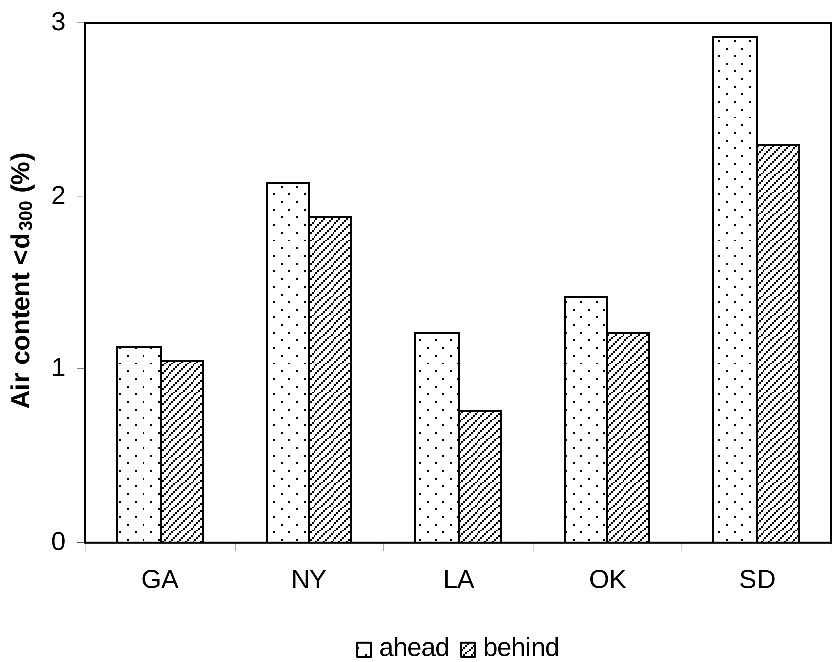

Figure 39. Percent Air Content <d_{300} in Front and behind Paver

Statistical Analysis

A statistical analysis of the AVA data was conducted using JMP. The significance of sampling location was determined at alpha = 0.05. Table 8 shows the t-test results comparing sampling locations. In the table, "No" indicates that there is no statistically significant difference between the results of the two sampling locations. Note the first t-test was used to determine if the sampling location significantly affected the results for samples obtained behind the paver either on or between vibrators. The second t-test was used to determine if the sampling location is significant for samples obtained ahead of the paver and behind the paver either on or between vibrators.

Table 8. T-test Results Comparing Sampling Locations

Sampling Location*	Air Content	Specific Surface	Spacing Factor	% D < 300 μm
BOV – BBV	No	No	No	No
AP – BOV – BBV	Yes	No	No	No

***AP, BOV, and BBV represent testing locations of ahead of paver, behind on vibrator, and behind between vibrators, respectively**

The results in Table 8 show when all sixteen states are tested together, the sampling location is not significant when interpreting the AVA results. These results show that the paving operations noted in these states did not significantly affect the entrained air void system during the paving operation when comparing spacing factor. These results are important due to the ease of sampling ahead of the paver compared to behind the paver while finishing operations are taking place.

Once the entire data set was analyzed, each state was analyzed by itself to identify if there were significant differences in the AVA results when comparing sampling locations. Table 9 shows the results for each state sampling location comparisons. Note a "No" and a "Yes" indicates no significant difference and a significant difference in the sampling locations, respectively.

The results in Table 9 show no significant differences in each state's results when comparing between the behind the paver between vibrator and behind the paver on vibrator sampling locations when comparing specific surface and spacing factor. Note the results from MN did show that sampling location significantly affects the results for % D < 300 μm. These results may explain the increased deterioration that is sometimes observed in the hardened concrete at the vibrator trail locations.

The results from Table 9 also show that the ahead of the paver sampling location did significantly affect the AVA testing results for specific surface (GA) and % D < 300 μm (SD). This result was not observed in the overall analysis most likely due to the variability of the AVA test procedure.

Table 9. T-test Results Comparing Sampling Locations for Each State

State	Sampling Locations*	Air Content	Specific Surface	Spacing Factor	% D < 300 µm
SD	BOV - BBV	No	No	No	No
	AP - BOV	Yes	No	No	Yes
	AP - BBV	Yes	No	No	Yes
GA	BOV - BBV	No	No	No	No
	AP - BOV	Yes	Yes	No	No
	AP - BBV	Yes	Yes	No	No
NY	BOV - BBV	No	No	No	No
	AP - BOV	No	No	No	No
	AP - BBV	No	No	No	No
MO	BOV - BBV	No	No	No	No
KS	BOV - BBV	No	No	No	No
MI	BOV - BBV	No	No	No	No
WI	BOV - BBV	Yes	No	No	No
NC	BOV - BBV	No	No	No	No
TX	BOV - BBV	No	No	No	No
IA	BOV - BBV	No	No	No	No
ND	BOV - BBV	No	No	No	No
MN	BOV - BBV	No	No	No	Yes
OH	BOV - BBV	No	No	No	No
IN	BOV - BBV	No	No	No	No
LA	BOV - BBV	No	No	No	No
OK	BOV - BBV	No	No	No	No

***AP, BOV, and BBV represent testing locations of ahead of paver, behind on vibrator, and behind between vibrators, respectively**

Rapid Air

The air void structure of hardened concrete provides adequate freeze-thaw durability when the proper air void structure is entrained and durable aggregates are used in construction. The rapid air test results are similar to those for the AVA, in that the specific surface and spacing factor of the air void system are measured. However, while the output for each test is the same, the results are generally unequal. This is likely caused by the way the results are measured. The AVA measures all bubbles for 25 minutes, while the rapid air test measures air bubbles on a linear traverse that may or may not count all bubbles. These different measurement methods will lead to varying results.

Figure 40 shows the relationship between specific surface and spacing factor for all state visits, according to the rapid air results. Note the weak trend showing a decreasing specific surface as the spacing factor increases. Also note that AVA provides better correlation between these two air properties (Figure 31). Figure 41 shows the relationship between the AVA specific surface and rapid air specific surface. Note that the rapid air test tends to predict larger specific surface values than the AVA test. Figure 42 shows the relationship between AVA spacing factor and rapid air spacing factor. Note that the AVA predicts a larger spacing factor than the rapid air test, which may explain why a sample may fail the AVA test but pass a rapid air or linear traverse test.

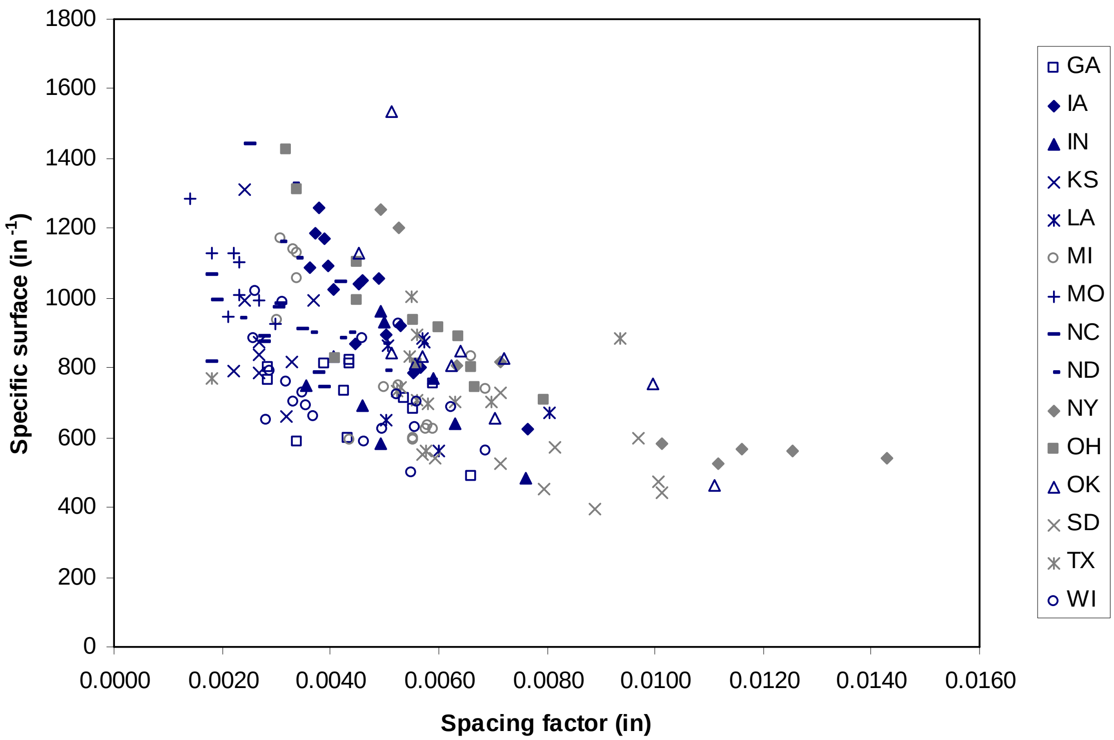

Figure 40. Specific Surface vs. Spacing Factor for the Rapid Air Results

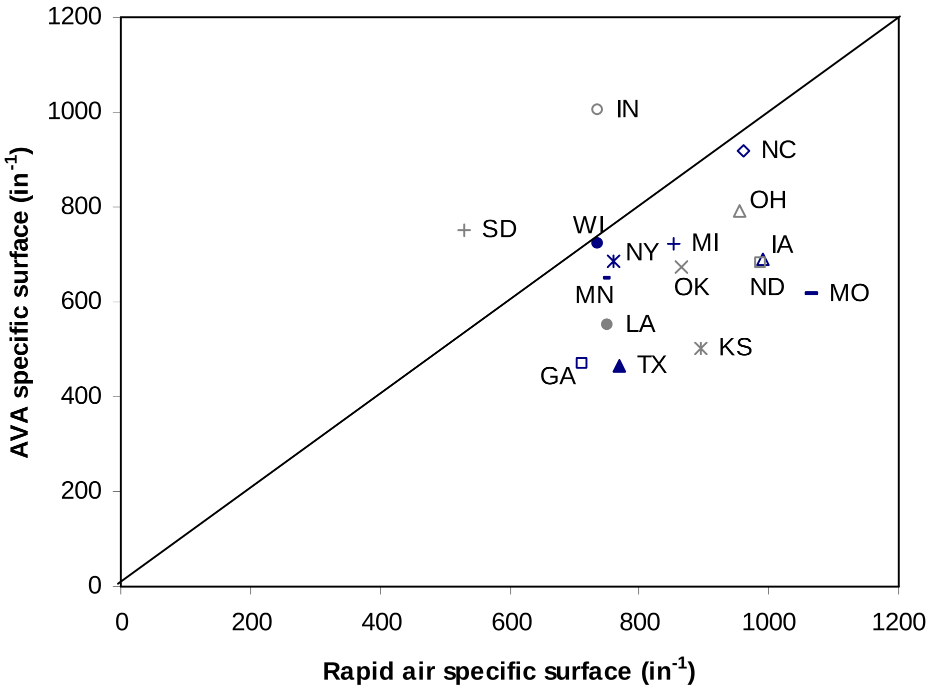

Figure 41. AVA Specific Surface vs. Rapid Air Specific Surface

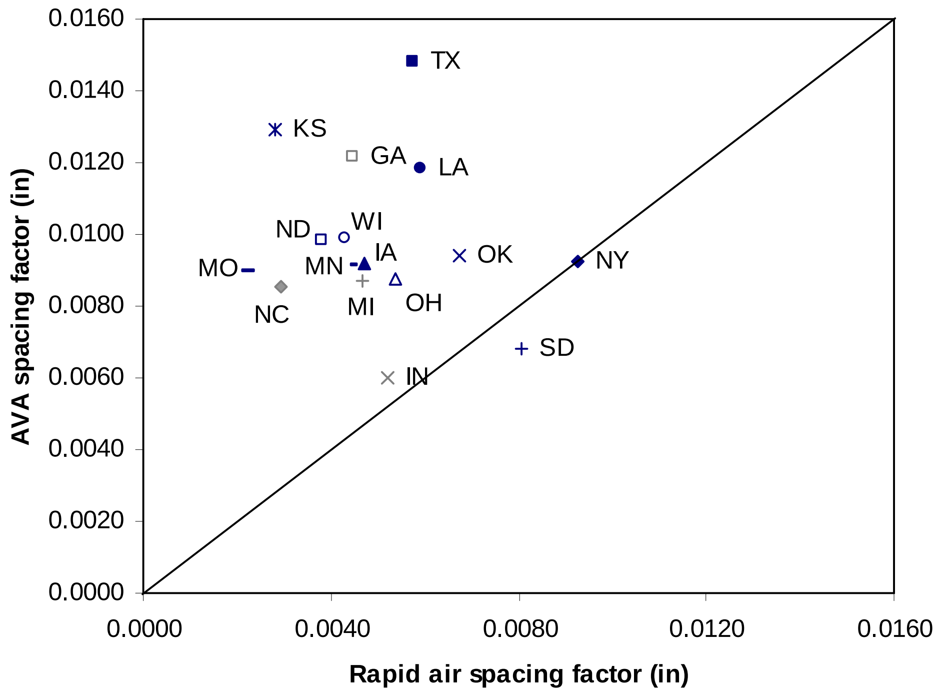

Figure 42. AVA Spacing Factor vs. Rapid Air Spacing Factor

For specific surface and spacing factor, Figures 43 and 44, respectively, show the relationship between the average AVA data and rapid air test data for each state. Note the tendency of the rapid air test to predict large specific surface values and the tendency of the AVA to predict increased spacing factors, thereby, the AVA results indicate a less durable concrete.

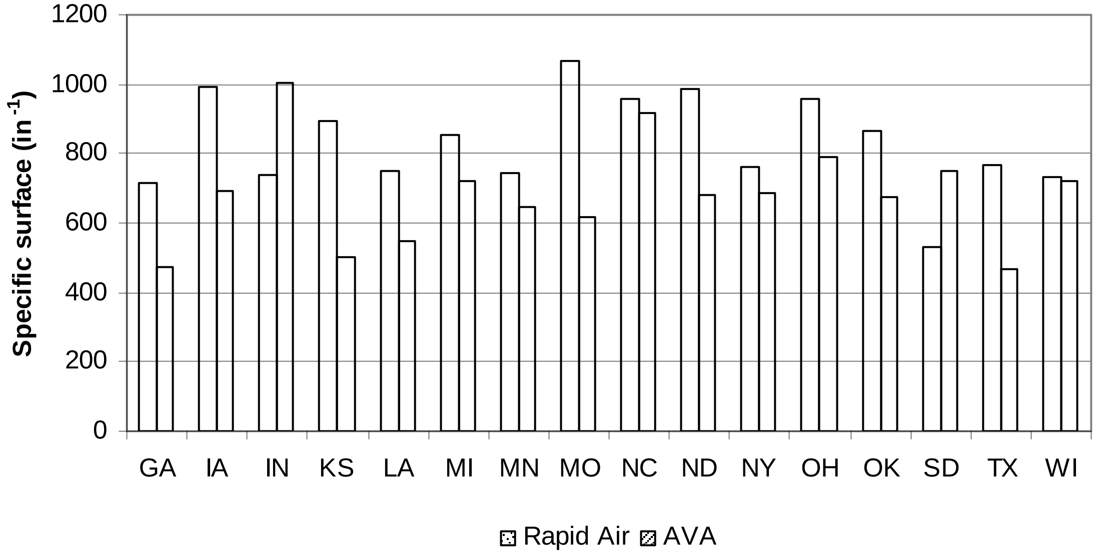

Figure 43. AVA and Rapid Air Specific Surface Comparison for Each State

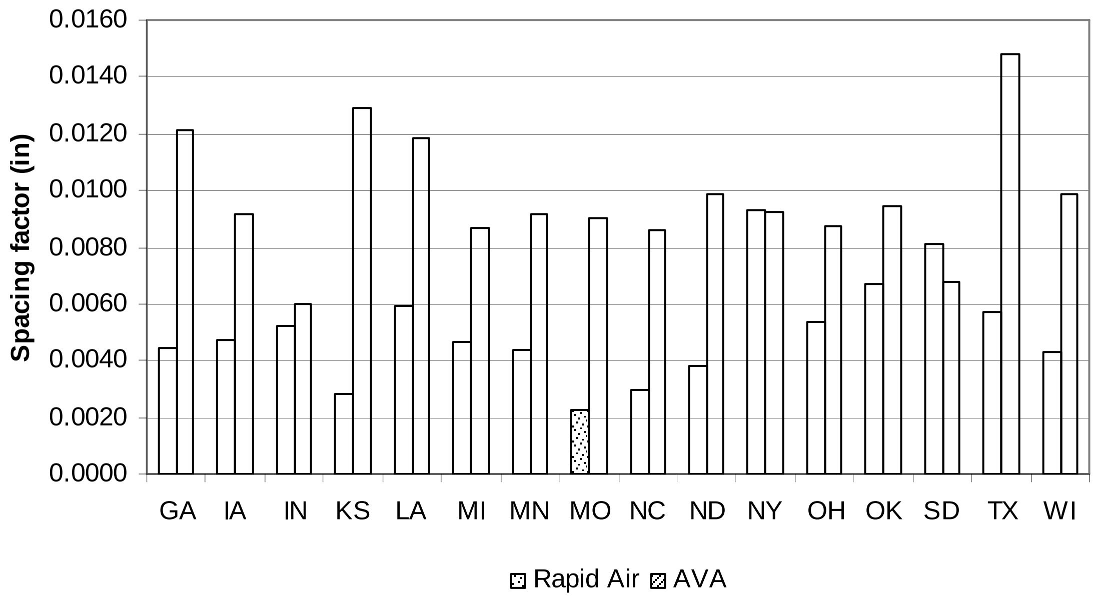

Figure 44. AVA and Rapid Air Spacing Factor Comparison for Each State

The rapid air test was generally conducted over three sections of the core: top, middle, and bottom. The results (shown in Figures 46 and 47) show a slightly decreasing spacing factor and specific surface from the top of the core to the bottom. This trend is expected because the top of the pavement is more directly subjected to the effects of vibration during paving. The authors note that although the spacing factor is increased near the surface, the concrete is still expected to be durable.

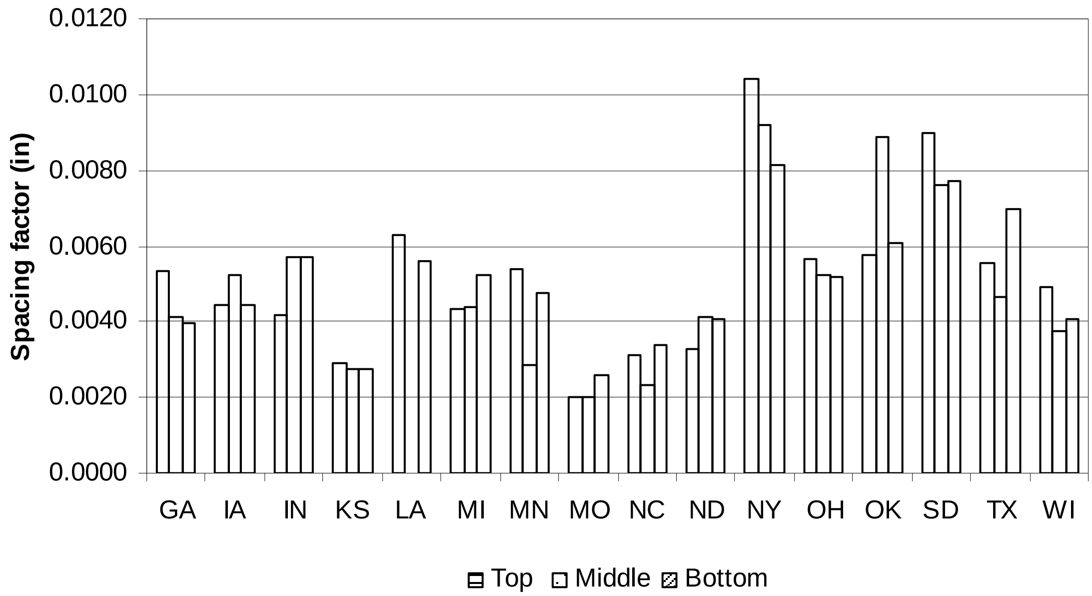

Figure 45. Rapid Air Specific Surface vs. Pavement Depth for Each State

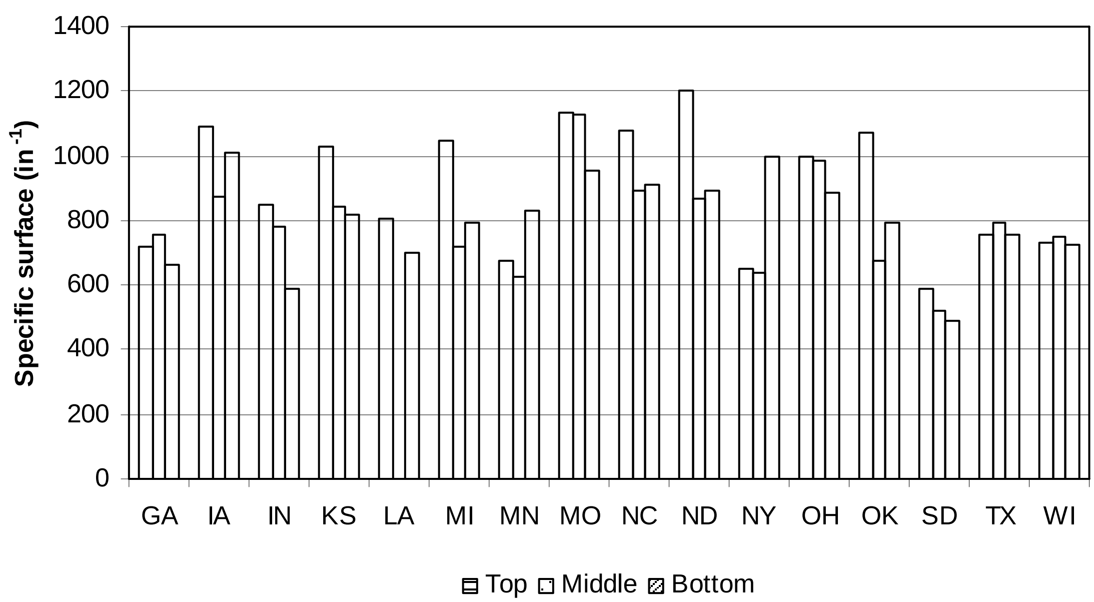

Figure 46. Rapid Air Spacing Factor vs. Pavement Depth for Each State

Compressive Strength

Concrete compressive strength is generally used as an acceptance criterion for opening the roadway to traffic. Early-age compressive strength is important to contractors because it allows them to decide when to use the finished pavement as a haul road for construction traffic or when to allow lane shifts. Figure 29 shows the three- and seven-day compressive strengths for each state in order of three-day compressive strength. As noted in Appendix B.4, the strength requirement for opening the pavement to traffic was generally 3,000 psi. Nearly all concrete mixes for each state reached that milestone in seven days, with about 64% reaching 3,000 psi after three days.

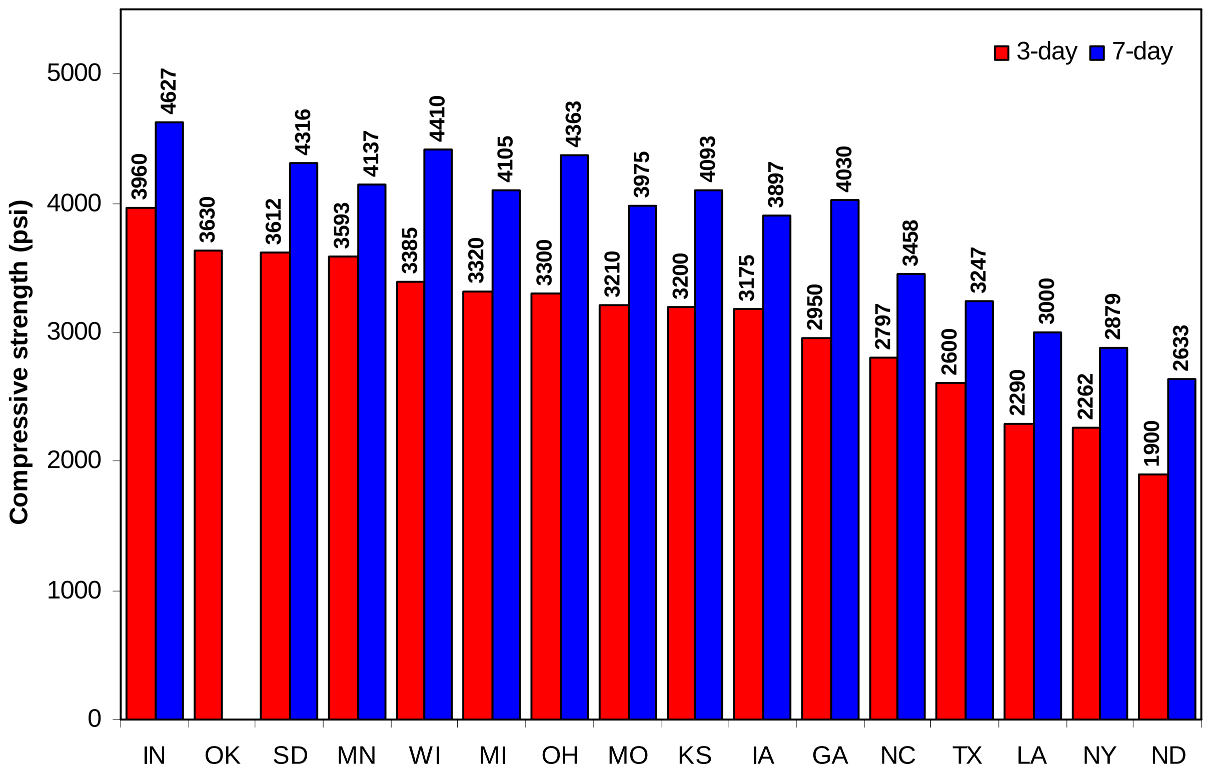

Figure 47. Average Three- and Seven-Day Compressive Strengths for Each State

Coefficient of Thermal Expansion

The coefficient of thermal expansion (CTE) of concrete is an important property because it plays a role in pavement length change. The CTE of concrete is influenced by factors that include coarse and fine aggregate type and concrete mix design. Table 10 shows the results of CTE testing for ten states. During each state visit, the CTE test was completed twice on a core cut from the pavement. Note that the limestone values are generally lower than the other values, as expected. Note that the sixteen states are not all represented, due to the lack of available cores (obtained during the site visit) from the missing states.

Table 10. CTE Results for Each State

State	CTE ($x10^{-6}/^{o}C$)	Coarse	Fine
OK	8.7	Limestone	Natural
TX	9.6	Limestone	Natural
IN	10.6	Limestone	Natural
NC	11.2	Granite	Natural
MN	11.2	Gneiss	Natural
SD	11.5	Quartz	Natural
ND	11.8	Gravel	Natural
NY	11.9	Gravel	Natural
IA	12.0	Limestone	Natural
OH	12.0	Gravel	Natural
GA	12.1	Granite	Natural
LA	13.3	Gravel	Natural

Rapid Chloride Permeability

The permeability of concrete can have an important effect on many concrete problems, including freeze-thaw, sulfate attack, and alkali silica reaction attack. An impermeable concrete limits the reactions for each attack mechanism due to the inability of the concrete to transport ions and water. Table 11 shows the rapid chloride permeability results taken during each state visit. Note that the varying rapid chloride permeability classes may be due to the varying cure lengths for each state prior to testing. The results may also be affected by the addition of SCMs.

Figure 48 shows the rapid chloride permeability results in graphical form. Note that the red, yellow, light green, and green shading refer to high, moderate, low, and very low rapid chloride permeability classes, respectively. The results indicate that low rapid chloride permeability concrete may be more able to resist the ingress of chloride ions due to salt application.

Table 11. Rapid Chloride Permeability Results

State	Charge Passed (Coulombs)	Permeability Class
MN	182	Very Low
IN	377	Very Low
TX	415	Very Low
IA	466	Very Low
SD	547	Very Low
OH	634	Very Low
NY	815	Very Low
OK	1020	Low
LA	1451	Low
GA	1941	Low
MO	2723	Moderate
WI	3188	Moderate
MI	3412	Moderate
NC	3530	Moderate
KS	5363	High

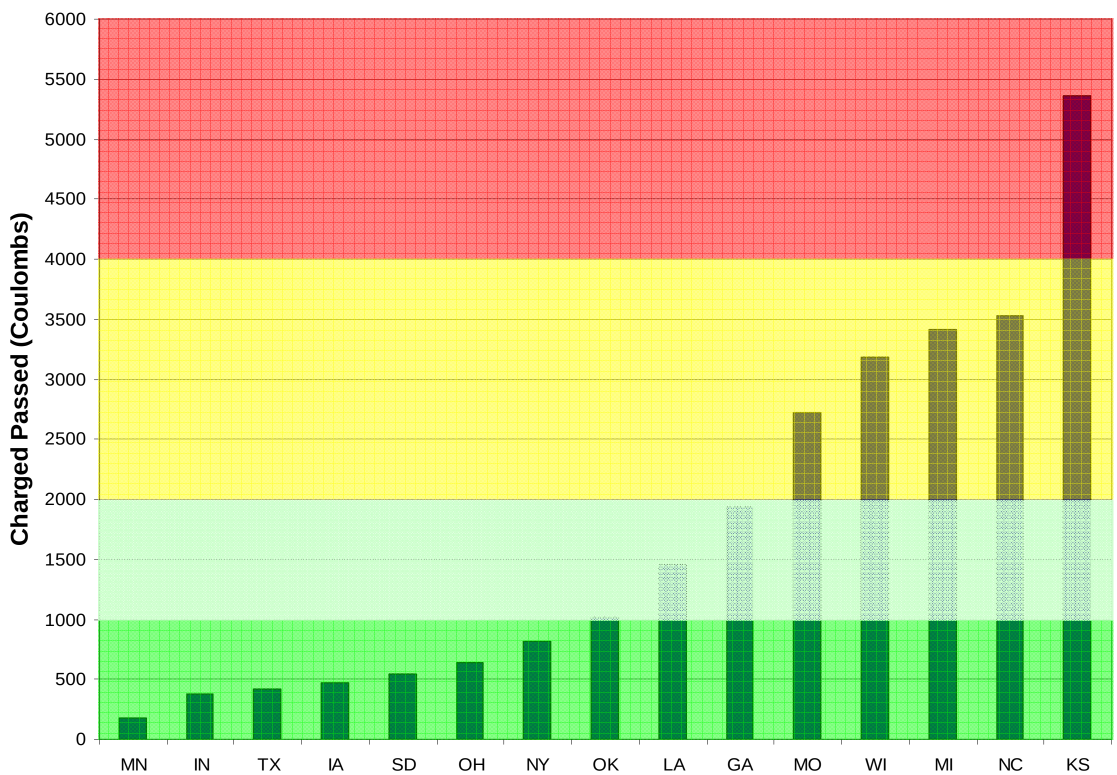

Figure 48. Rapid Chloride Permeability Results

Freeze-Thaw

The freeze-thaw test was used to correlate the spacing factor of fresh concrete to freeze-thaw durability. For the purposes of this study, the research team extracted a four-inch core from the pavement and placed it into the freeze-thaw tank. Note that the results, shown in Figure 49, represent only one sample from each of six states. The results indicate that the Ohio pavement may not perform as well as the others tested, but the freeze-thaw durability factor still exceeds failure criteria.

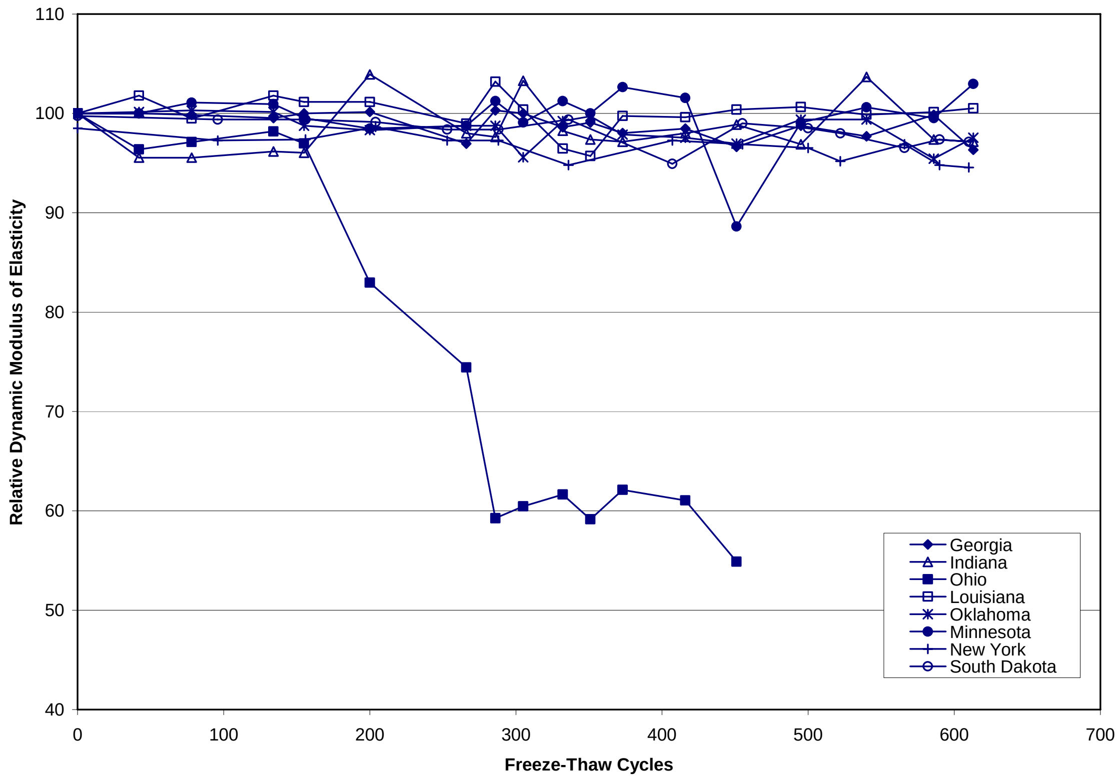

Figure 49. Freeze-Thaw Results for GA, OH, OK, IN, LA, MN, NY, and SD

X-Ray Fluorescence

XRF is a powerful tool for identifying individual elemental compositions and their respective quantities present in a sample. Table 12 shows the average XRF results for portland cement samples in seven states. The remaining states were not tested due lack of available funds. Note the low standard deviations on the materials, which indicate uniform cement chemistry. Table 13 shows the standard deviation and average XRF results of the fly ash samples in seven states. Note the larger standard deviations of these components compared to the portland cement standard deviations. The larger standard deviations can be attributed to the fact that fly ash is not a manufactured product like portland cement. Table 14 shows the average XRF results for the Michigan GGBF slag. Note the XRF results showed nothing unusual for all materials tested.

Table 12. Portland Cement XRF Results

Chemical	Missouri		Kansas		Michigan		Wisconsin		North Carolina		Texas		Iowa	
(%)	Average	Stdev	Average	Stdev	Average	Stdev	Average	Stdev	Average	Stdev	Average	Stdev	Average	Stdev
CaO	64.73	0.35	63.99	0.12	63.03	0.12	62.09	0.19	63.94	0.19	64.39	0.07	58.27	0.01
SiO_2	20.54	0.21	20.93	0.23	19.58	0.07	20.02	0.12	20.26	0.10	20.40	0.37	23.78	0.16
Al_2O_3	5.17	0.08	5.00	0.08	5.36	0.00	4.73	0.07	4.66	0.11	4.39	0.12	5.51	0.05
Fe_2O_3	2.37	0.04	3.30	0.09	2.26	0.01	3.08	0.03	3.22	0.01	3.74	0.01	2.70	0.04
MgO	2.89	0.25	1.67	0.06	4.13	0.03	3.72	0.02	2.89	0.07	1.42	0.03	4.66	0.06
K_2O	0.13	0.02	0.47	0.06	1.06	0.03	1.63	0.03	0.88	0.03	0.64	0.16	0.64	0.01
Na_2O	0.09	0.01	0.23	0.02	0.21	0.00	0.18	0.00	0.18	0.01	0.19	0.02	0.15	0.00
SO_3	2.97	0.14	3.02	0.08	3.54	0.01	4.21	0.14	2.74	0.03	3.42	0.12	2.79	0.05
P_2O_5	0.13	0.00	0.14	0.01	0.07	0.00	0.06	0.00	0.10	0.00	0.16	0.00	0.10	0.00
TiO_2	0.36	0.01	0.33	0.01	0.25	0.00	0.22	0.01	0.23	0.01	0.20	0.01	0.32	0.00
SrO	0.06	0.00	0.14	0.02	0.05	0.00	0.05	0.00	0.15	0.00	0.17	0.00	0.04	0.00
Mn_2O_3	0.16	0.00	0.10	0.01	0.11	0.00	0.05	0.00	0.26	0.00	0.53	0.01	0.52	0.00
LOI	1.32	0.12	1.59	0.12	1.56	0.00	1.40	0.01	0.93	0.06	2.80	0.16	0.86	0.07
Total	99.6	0.42	99.3	0.17	99.6	0.26	100.0	0.24	99.5	0.12	99.7	0.08	99.5	0.28

Table 13. Fly Ash XRF Results

Chemical	Missouri		Wisconsin		North Carolina		Texas		Iowa		ASTM Limits	
(%)	Average	Stdev	Average	Stdev	Average	Stdev	Average	Stdev	Average	Stdev	Class F	Class C
SiO_2	35.81	0.56	33.58	0.09	57.43	0.44	50.89	1.80	31.48	0.73		
Al_2O_3	19.16	0.26	18.34	0.11	29.40	0.41	20.02	0.60	18.35	0.13	Sum 70% Min.	Sum 50% Min.
Fe_2O_3	6.09	0.04	6.39	0.12	5.89	0.39	7.20	0.56	5.60	0.06		
CaO	24.29	0.33	27.81	0.20	0.85	0.04	13.31	1.11	28.01	0.70		
Na_2O	1.81	0.07	1.90	0.03	0.26	0.00	0.56	0.00	2.92	0.08		
MgO	5.85	0.07	4.39	0.03	0.83	0.01	2.66	0.09	6.58	0.36		
P_2O_5	1.26	0.04	1.46	0.03	0.12	0.01	0.15	0.05	0.94	0.05		
SO_3	2.14	0.08	2.89	0.05	0.01	0.01	0.89	0.16	3.01	0.20	5.0% Max	5.0% Max
K_2O	0.42	0.01	0.29	0.00	2.40	0.03	0.95	0.08	0.33	0.02		
TiO_2	1.47	0.04	1.58	0.01	1.52	0.02	1.23	0.02	1.39	0.04		
SrO	0.44	0.01	0.56	0.01	0.06	0.00	0.30	0.03	0.56	0.01		
Mn_2O_3	0.02	0.00	0.06	0.00	0.03	0.00	0.15	0.03	0.03	0.00		
BaO	0.82	0.02	0.86	0.01	0.10	0.01	0.19	0.01	0.81	0.01		
LOI, %	0.46	0.03	0.21	0.01	2.30	0.36	0.32	0.02	0.48	0.01	6.0% Max	6.0% Max
Total	99.6	0.34	100.1	0.06	98.9	0.56	98.5	0.51	100.0	0.46		

Table 14. GGBF Slag XRF Results for Michigan

Chemical (%)	Average	Stdev
SiO_2	36.58	0.03
Al_2O_3	9.64	0.01
Fe_2O_3	0.64	0.00
CaO	36.75	0.00
MgO	10.54	0.05
S	1.01	0.00
Na_2O	0.32	0.00
K_2O	0.35	0.00
TiO_2	0.49	0.00
P_2O_5	0.02	0.00
Mn_2O_3	0.48	0.00
SrO	0.04	0.00

Differential Scanning Calorimetry

Differential scanning calorimetry (DSC) testing was performed to determine the gypsum content of the cements used in the first five state visits. DSC uses heat to drive off moisture and change the sample, outputting characteristic peaks that allow the user to identify the amounts of materials at each peak. Table 15 shows the DSC results for gypsum content (in percent) for the first year of testing.

Table 15. DSC Results for Year One

State	Average Gypsum Content (%)	Stdev
MO	2.35	0.71
KS	2.72	0.86
MI	1.15	0.43
WS	1.99	0.16
NC	0.99	0.30

CONCLUSIONS AND RECOMMENDATIONS

Over the past four years, the MCO project has evaluated many new and existing test procedures in both laboratory and a field environments. One clear conclusion from this extensive effort is that no magic black box exists that will tell the owner or agency everything there is to know about the quality of a pavement. In fact, many of the procedures included in the final suite of tests do not currently have the precision that would allow acceptance criteria to be defined for them.

Since its inception, the MCO project has been evaluating test procedures and new technologies with the overall intent of preventing premature pavement failures. The mobile lab trailer afforded the research team the opportunity to evaluate these test procedures in a field environment on a myriad of different material combinations. One obstacle to the research was that none of the demonstration projects offered the opportunity to observe materials or construction processes that might be considered as having the potential for premature distress. Fortunately, those projects are few and far between, which is a good thing from the perspective of the overall quality of concrete pavements.

Long-term durability is related to a combination of concrete properties. To make matters more confusing, the combination of concrete properties that yield durable concrete in one climatic region is different from what is required in another region. For example, air entrainment is critical in a wet-freeze environment, while it is not necessary in a non-freeze region. Based on current practice and historical experience, state highway agencies can specify a combination of concrete properties that they predict will result in a durable pavement. Commonly, acceptance criteria are based on combinations of strength, thickness, air content, and combined gradation. However, there are other properties that can be evaluated in a laboratory during the mixture design stage: permeability, time of set, air void structure, and heat signature. Rather than establishing acceptance criteria for all of these properties, verification and process control testing can be performed on individual projects to identify when the materials and/or construction processes change in a manner that may negatively impact the long-term durability of the pavement. Monitoring change through the use of additional test procedures and Statistical Process Control (SPC) techniques is the basis for implementing the suite of tests.

Two likely scenarios exist for the implementation of these research results. First, state highway agencies may include the suite of tests in a specification that requires the contractor to perform quality control testing as described in the suite of tests. Second, increased use of innovative contracting techniques, such as warranties, design–build–maintain–operate, and public–private partnerships, will drive contractors' attention from meeting initial acceptance criteria towards focusing on eliminating premature pavement failures that result in unanticipated maintenance costs.

Regardless of the motivation (specification or limiting liability) for using the suite of tests as a quality control (QC) tool, implementing SPC is integral to moving forward with the suite of tests for the prevention of premature failures. In general, the current state of QC procedures is better described as duplicative acceptance testing rather than true process control. Coupling SPC with the suite of tests will provide feedback that will enable the identification of changes in the materials or construction processes that may contribute to premature failures.

If the objective is to prevent premature pavement failures, and assuming that a project is started with materials and construction processes that will yield a durable pavement, then it would be useful to know when something in the materials and/or processes changes. The primary purpose of using Statistical Process Control (SPC), specifically control charts, is to identify change. Their function is not to indicate whether a test result passes or fails acceptance criteria, but rather to indicate if a test result was unusual. Three conditions must be consistently met to achieve high levels of quality:

1. The process is stable (only common cause variability is present).
2. The process is capable (common cause variability must be small enough to permit consistent results within the specified tolerances).
3. The process is on target (the process is consistently performing near the specified target).

Finally, the *Implementation Manual for Quality Assurance* published by the American Association of State Highway and Transportation Officials states, “The need for contractors to use statistical control charts cannot be overemphasized. A control chart provides a visual indication of whether a process is in control.”

Quality control (QC) in whatever form is a process that is used to facilitate producing a product that meets specifications. Thus, QC efforts may involve tests and/or observations of factors that are not necessarily specification requirements, but need to be monitored to assure specification compliance.

Many of the acceptance criteria used for concrete pavements cannot be measured for days or even weeks after the pavement is in place. Measuring alternative material characteristics and properties during the construction process is the only way that currently exists to identify material deficiencies and/or construction processes that may contribute to the premature failure of a pavement.

The tests in the revised suite of tests have the potential to advance concrete pavement technology in two specific ways. First, some of the tests are geared for concrete paving contractors to use as field quality control measures. These tests allow contractors to determine whether the product they are placing has the desired performance-related properties and, if not, to make real-time modifications to the mix or construction practices. The tests allow contractors to meet requirements for incentives more efficiently. Second, some of the tests will be useful for representatives from the pavement owner agencies to use to measure pavement properties during field inspection.

Conclusions

This project has yielded many important findings. Conclusions based on these findings are presented in Table 16.

Table 16. Phase II and III Test Types and Conclusions

Test Type	Conclusions
Slump and Flow	A moderate correlation was observed between slump and mortar flow.
Combined Grading	Well-graded mixes were observed to hold edge shape to a better degree than non-well-graded mixes and were generally easier to finish.
False Set	The laboratory test results indicate false set for the state visits, but there seemed to be no problem placing the subsequent concrete during the field paving operations.
Coffee Cup Test	The coffee cup test is repeatable and may be an excellent tool for determining the consistency of delivered cementitious materials.
Set Time	Initial set values ranged from 4 to 9.5 hours, and final set values ranged from 5.5 to 12 hours.
Microwave Water/Cementitious Materials Ratio	Microwave w/cm results ranged from an average of 0.36 to an average of 0.50. The range of obtained testing values varied for each state, but the range was observed to be smaller in states that used w/cm as a pay item.
Unit Weight and Air Content	Both the gravimetric and volumetric air contents correlated with unit weight, as expected. Unit weight measurements provide a valuable tool for determining batch-to-batch and day-to-day uniformity.
Compressive Strength	Compressive strength results indicated adequate compressive strengths at three days, and in-place maturity sensors indicated in-place strengths that were more than adequate after seven days.
Air Void Analyzer	AVA results were somewhat variable, but the test is still considered a good indication of air void structure for fresh concrete.
	AVA results indicate a better relationship between air content and spacing factor when comparing bubble size fractions less than 300 µm to bubble size fractions less than 2000 µm.
	AVA-measured specific surface and spacing factor are well correlated, as expected.
	AVA results indicate that there is no discernable difference in spacing factor for samples tested on or between the vibrators.
	AVA results for d<300 µm on and between the vibrators show more air voids within the desired d<300 µm, indicating a more refined air void structure on the vibrator than between the vibrators.
	A weak correlation exists between air content as measured by the pressure method and AVA-measured spacing factor.
	For two of the three projects tested, AVA spacing factors obtained before the paver were not significantly different than those obtained behind the paver.
	AVA results for the percentage of air bubbles less than 2000 µm showed a more refined air void structure in results obtained before the paver than results obtained after the paver.
	A weak correlation exists between the results for rapid air spacing factor and specific surface.

Test Type	Conclusions
	AVA spacing factor results tend to be more conservative than the rapid air results.
	AVA test results are not significantly affected by sampling location when comparing ahead of the paver to behind the paver on a vibrator to behind the paver between vibrators.
Coefficient of Thermal Expansion	In general, the CTE results showed lower values for limestone aggregates, as expected.
Rapid Chloride Permeability	Rapid chloride permeability results ranged from very low to high. The results are difficult to interpret due to the varying ages of the tested specimens and different mixture proportions.
Freeze-Thaw	Concrete from most states fared well in terms of freeze-thaw testing, with durability factors above 95. However, Ohio fared poorly with a lower durability factor.
X-Ray Florescence	The XRF results indicate nothing unusual for each material tested.
Differential Scanning Calorimetry	DSC testing revealed a wide range of gypsum contents for the state projects. However, sampling error may have led to this amount of variability.

Recommendations

Based on the key findings in Phase II and III, the research team makes the following recommendations:

- Continue AVA testing as an indication of day-to-day uniformity and as a method for catching any apparent air void structure problems in the early stages of construction.
- Conduct additional research to correlate AVA results with hardened air results to indicate freeze-thaw durability.
- Conduct additional research on the coffee cup test to determine the limitations on measurable and observable changes in cement chemistry.
- Continue to monitor each section observed during the state visits, with reoccurring visits every 5 to 10 years for the next 40 years to document pavement durability.
- Assist with pavement monitoring by making a website available to each state for posting photographs and related information regarding the states' respective pavement sections.

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APPENDIX B. PHASE I DATA

B.1. State Visit Requested Information Form

MATERIAL AND CONSTRUCTION OPTIMIZATION FOR PREVENTION OF PREMATURE PAVEMENT DISTRESS IN PCC PAVEMENTS

STATE VISIT REQUESTED INFORMATION

State Procedures

- ❑ **Concrete Mix Design**
  - o Who provides the mix design?
    - ❑ State
    - ❑ Contractor/Supplier
  - o What procedure is used to develop the mix design?
    - ❑ ACI 211.1
    - ❑ A state specific procedure
    - ❑ Past experience
    - ❑ Another procedure
  - o What concrete properties are specified (hardened or fresh) in contract documents? For example, is concrete strength, slump, etc. specified?

    Mark the properties that are commonly specified:

Specified?		
	Workability / Slump	Fresh Concrete Properties
	Bleeding	
	Segregation	
	Set	
	w/cm (water-to-cementitious materials ratio)	
	Plastic Shrinkage Cracking	
	Strength at Opening	Hardened Concrete Properties
	Strength at 28 days	
	Coefficient of Thermal Expansion (CTE)	
	Drying Shrinkage	
	Permeability	
	Resistance to freezing and thawing	Concrete Durability
	Resistance to sulfate attack	
	Resistance to ASR	
	Abrasion Resistance	
	Corrosion Resistance	
	Other (specify)?	

  - o In addition to the specified properties, what properties are targeted (desired), but are not specified? Fresh ones are targeted for the best possible placement / construction? Hardened ones for increased concrete durability?

Of the properties that are not specified, rank their importance, with 1 the most important:

Rank		
	Workability	Fresh Concrete Properties
	Bleeding	
	Segregation	
	Set	
	Plastic Shrinkage Cracking	
	Strength / Stiffness	Hardened Concrete Properties
	Coefficient of Thermal Expansion (CTE)	
	Drying Shrinkage	
	Permeability	
	Resistance to freezing and thawing	Concrete Durability
	Resistance to sulfate attack	
	Resistance to ASR	
	Abrasion Resistance	
	Corrosion	
	Other (specify)?	

- What are the typical values of the following mix design parameters for paving concrete? Please denote the method of construction, *i.e.* slip-formed (SF), formed paving (FP), or other.

  - w/c

    Min.__________, Max. __________, Typical__________

  - Slump (in)

    Min.__________, Max. __________, Typical__________

    Method of Construction: __________________________

    Min.__________, Max. __________, Typical__________

    Method of Construction: __________________________

  - Air content (%)

    ___ ± ___% to ___ ± ___% Application: ______________________

    ___ ± ___% to ___ ± ___% Application: ______________________

    ___ ± ___% to ___ ± ___% Application: ______________________

    ___ ± ___% to ___ ± ___% Application: ______________________

  - Water content (lb/cu.yd)

_____ to _____ lb/cu.yd Application:________________

_____ to _____ lb/cu.yd Application: ________________

_____ to _____ lb/cu.yd Application: ________________

- Cement content (lb/cu.yd)

  _____ to _____ lb/cu.yd Application:________________

  _____ to _____ lb/cu.yd Application:________________

  _____ to _____ lb/cu.yd Application:________________

- Maximum size of coarse aggregate (in)

☐ 3/8	☐ 1	☐ 3
☐ ½	☐ 1½	☐ 6
☐ ¾	☐ 2	☐ 6+

- Coarse aggregate (lb/cu.yd)

  _____ to _____ lb/cu.yd Application:________________

  _____ to _____ lb/cu.yd Application: ________________

- Fine aggregate (lb/cu.yd)

  _____ to _____ lb/cu.yd Application:________________

  _____ to _____ lb/cu.yd Application:________________

- Which of these SCMs are commonly used in your concrete mix design? (Check all that apply)

  - ❑ Class F Fly Ash Application: ________________
  - ❑ Class C Fly Ash Application: ________________
  - ❑ GGBFS Slag Application: ________________
  - ❑ Silica Fume Application: ________________
  - ❑ Metakaolin Application: ________________
  - ❑ Volcanic Ash/Pumicite Application: ________________
  - ❑ Calcinated Shale Application: ________________
  - ❑ Opaline Shale Application: ________________
  - ❑ Calcinated Clay Application: ________________
  - ❑ Diatomaceous Earth Application: ________________
  - ❑ Other (describe) Application: ________________

- Which of these chemical admixtures are commonly used in your concrete mix design? (Check all that apply)

- ❑ Air entraining admixtures Application: ________________
- ❑ Conventional water reducer Application: ________________
- ❑ Mid-range water reducer Application: ________________
- ❑ High-range water reducer Application: ________________
- ❑ Accelerator Application: ________________
- ❑ Retarder Application: ________________
- ❑ Corrosion inhibitor Application: ________________
- ❑ Shrinkage reducer Application: ________________
- ❑ ASR inhibitors (*i.e.* Lithium) Application: ________________
- ❑ Hydration control admixtures Application: ________________
- ❑ Other (describe) Application: ________________

o What combinations of cement type + SCM (supplementary cementitious materials) + chemical admixtures are ***most commonly used*** in your paving mixes?

Please provide the types and dosages.

- Cement: Type I/II, Type III, Type IP, Type IS, or other cement.
- SCMs: Fly Ash Class F or C, Silica Fume, Slag, Metakaolin.
- Chemical admixture: water reducer (WR), mid-range water reducer (MRWR), high-range water reducer (HRWR), accelerator, retarder, air entraining admixture (AEA) or other.

Cement Type (lb/cu yd)	SCM (lb/cu yd)	Chemical Admixture (fl oz / cwt)

Comments:

- Have you experienced compatibility problems between mix components like SCMs and chemical admixtures?

  “Symptoms” 1 to 4 such as,

- ☐ Less than expected water reduction (1)
- ☐ Rapid loss of slump (2)
- ☐ Fast set (3)
- ☐ Abnormally retarded setting (4)
- ☐ Other ______________________(5)
- ☐ Other ______________________(6)

- What were the *complete* mix designs (lb)/ dosages (floz/cwt)? How was the problem corrected?

  Symptom #__ Symptom #__ Symptom #_

Water	______________________________________
Portland Cement	______________________________________
Fly Ash Class C	______________________________________
Fly Ash Class F	______________________________________
Slag	______________________________________
Silica Fume	______________________________________
WR	______________________________________
MRWR	______________________________________
HRWR	______________________________________
AEA	______________________________________
Acclerator	______________________________________
Retarder	______________________________________
Other ___________	______________________________________

Correction for Symptom #__:

Correction for Symptom #__:

Correction for Symptom #__:

o Do you require a combined aggregate gradation design/analysis procedure? If yes, what one or ones?

- Do you have an aggregate sources approval system? If yes, explain.

- Do you require testing of the cementitious materials, beyond normal certification testing? If yes, what tests?

- What fresh concrete tests are required? Please cite name/number of specification/test procedure.
  - Slump Test Method: _________________
  - Air Content Test Method: _________________
  - Unit Weight Test Method: _________________
  - Time of Setting Test Method: _________________
  - Plastic shrinkage cracking susceptibility Test Method: _________________
  - Heat of hydration Test Method: _________________

- What hardened concrete tests are required? Please cite name/number of specification/test procedure.
  - Resistance to freezing and thawing?

    Test Method: _________________
  - Strength, What is the typical design strength?

    Test Method: _________________
  - Permeability?

    Test Method: _________________
  - Shrinkage – restrained or free?

    Test Method: _________________
  - Creep?

    Test Method: _________________
- Have you ever used fibers in a paving mix? Yes ☐ No ☐
  - If so, which fiber type?
    - ❑ Steel
    - ❑ Polypropylene

- ❑ Polyester
- ❑ Polyolefin
- ❑ Nylon
- ❑ Carbon
- ❑ Other (describe)

- How was the mix design adjusted for the fibers?

  Was there a change in the water content?

  Were chemical admixtures used?

  Some other method?

Comments:

o Please rank the primary concerns about concrete durability in your state?
(1 – not a concern, 2 – rarely a concern, 3 – sometimes, 4 – often, 5 - always)

	Rank
❑ Freeze-thaw resistance / Scaling resistance	___
❑ DEF susceptibility	___
❑ ASR susceptibility	___
❑ Chemical attack	___
❑ Abrasion resistance	___
❑ Fatigue cracking	___
❑ Other (describe)	___

If possible, please attach some of the typical mix designs used by your state for paving concrete.

	Mix #1	Mix #2	Mix #3
Water	___	___	___

Portland Cement ______________________________________

Fly Ash Class C______________________________________

Fly Ash Class F ______________________________________

Slag ______________________________________

Silica Fume ______________________________________

WR ______________________________________

MRWR ______________________________________

HRWR ______________________________________

AEA ______________________________________

Acclerator ______________________________________

Retarder ______________________________________

Other ___________ ______________________________________

Comments:

- **Project testing**
  - Do you require field trial-batch testing?
    - If yes, what tests are required?
  - Do you require tests on field materials prior to paving?
    - If yes, what tests are required?

QC/QA

- What concrete tests are required? And what test is performed?
  - Air? ☐ Yes ☐ No
    Test Method:
  - Slump? ☐ Yes ☐ No
    Test Method:
  - Strength? ☐ Yes ☐ No
    Test Method:
  - Maturity? ☐ Yes ☐ No
    Test Method:
  - Beams? ☐ Yes ☐ No
    Center point or third point?
    Test Method:
  - Compression? ☐ Yes ☐ No
    Test Method:
  - Split tensile? ☐ Yes ☐ No
    Test Method:
  - Other? (Describe) ☐ Yes ☐ No
    Test Method:

Research

- What research, especially local/in-house research, have you or others in your state conducted that relates to the five concrete properties focused on in this study?
  - Workability
  - Strength development
  - Air content
  - Permeability
  - Shrinkage

  This should include materials tests, concrete tests, and any other research that would be relevant to this project.

- Please provide reports, write-ups, or data for these research efforts if available.

B.2. Compilation of State Research

The following research was provided to the project team in the initial phase of the project. This annotated bibliography may not represent the greater existing research.

Strength Development

Cross, W., E. Duke, J. Kellar, and D. Johnston. 2000. *Investigation of Low Compressive Strengths of Concrete Paving, Precast and Structural Concrete*. Report No. SD98-03-F. Pierre, SD: Office of Research, South Dakota Department of Transportation.

> This research examines the causes for a high incidence of catastrophically low compressive strengths, primarily on structural concrete. The source for the low strengths was poor aggregate paste bond associated with air void clusters and poorly formed cement paste in the interfacial region adjacent to the aggregate. An interaction between the synthetic air entraining admixtures, used as substitutes for vinsol resin, and low-alkali cements was directly tied to the problem, with high summertime temperatures also contributing to the problem. The synthetics appear to be more hydrophobic and form thinner walled air bubbles and develop rapid draining bubble flocculations more readily than vinsol resin, all of which can lead to significant reductions in strength. The South Dakota Department of Transportation specified the sole use of vinsol resin air entraining agents along with water reducers and these measures have minimized the incidence of low strengths. Laboratory testing of concrete mixes with various air entraining admixtures demonstrated that an interaction was taking place with one cement, and petrographic and chemical analysis of the cements used in the testing implicated alkali sulfates as a potential source of the interaction. Testing of the synthetic air entraining admixtures showed they have substantially different properties compared to vinsol resin. Mixtures of the synthetics and vinsol resin with 50% or more vinsol resin behaved similarly to vinsol alone.

Early-Age Evaluation of a High-Performance Concrete Pavement. Ohio Research Institute for Transportation and the Environment.

> High-performance concrete (HPC) pavement has recently attracted great interest because of potentially longer service lives and reduced life-cycle costs. General design criteria have been established for these pavements by various federal and state transportation agencies. Ground granulated blast furnace slag (GGBFS) is one material used in the construction of HPC pavements.
>
> The purpose of this technical note is to discuss the effects of GGBFS on the curing and early performance of HPC pavement on one project in Ohio. Field measurements included slab temperature and slab curvature. Maturity functions were used to determine the effect of GGBFS on strength gain in the concrete.
>
> During this study, environmental strain was monitored with gauges mounted in a few slabs at the time of construction, and dynamic deflection was measured later on the hardened slabs with a Dynatest falling weight deflectometer.

The research projects listed in Table B.2.1 were completed under the direction of the Iowa Department of Transportation. The table lists the research pertaining to strength development. The project number, title, end date, and principle investigator are also listed.

Table B.1. Summary of Iowa DOT research related to strength development

Proj.	No.	Title	End	PIs
HR	1031	Fly Ash (Demo 59)	6/1/87	K. Isenberger
HR	2012	Fly Ash Pavement Sections		T. Cackler
HR	2057	Early Strengths of PCC on US 20 Near Ft. Dodge		--
HR	2072	Field Evaluation of Ash Grove Type IP Cement (I-29 in Pottawattamie Co.)	6/1/99	J. Grove
HR/TR	40	Steam Curing of Concrete at Atmospheric Pressure	1/1/59	S. Roberts
HR/TR	200	Fly Ash in Portland Cement Concrete Pavement - Monona Co.	1/1/80	O. Ives
HR/TR	201	Fly Ash in Portland Cement Concrete Pavement - Woodbury Co.		C.E. Leonard
HR/TR	380	Maturity & Pulse Velocity Measuremts for PCC Traffic Opening Decisions	3/31/98	J. Cable
HR/TR	451	Investigation Into Improved Pavement Curing Materials and Techniques - Phase I & II	9/30/02	K. Wang/J. Cable
HR/TR	479	Investigation Into Improved Pavement Curing Materials and Techniques: Part II (Phase III)	4/30/03	J. Cable
MLR	7502	Evaluation of Argentine Nondestructive Test for Determining Concrete Compressive Strength	2/1/75	R. Less
MLR	8106	Fly Ash Concrete Compressive Strength & Freeze-Thaw Durability	6/1/81	K. Isenberger
MLR	8406	Strength-Temperature Study of Fly Ash Concrete	8/1/84	B. Brown
MLR	8407	Evaluation of Fly Ash in Water Reduced Paving Mixtures	6/1/85	B. Brown
MLR	8707	Early Strength of Class B, C & F Portland Cement Concrete	11/1/87	J. Grove
MLR	8906	Field Evaluation of Accelerated Cure Modified C-Mix Concrete	5/1/89	J. Grove
MLR	9203	Affect of Fly Ash on Concrete Compressive Strength		C. Narotam
MLR	9307	Evaluation of Concrete Patching Mixes & Opening Time Using Maturity Concept		--
MLR	9406	Evaluation of Various Cements in Combination With Ground Slag or Class F FlyAsh	10/1/94	S. Gent
MLR	9503	An Investigation of Concrete Maturity	6/1/95	C. Ouyang
MLR	9601	Maturity of Concrete: Field Implementation	4/1/96	C. Ouyang
MLR	9703	Field Evaluation of QMC Strength Variability	7/98	S. Tymkowicz

Missouri Department of Transportation. 2003. *MoDOT Application of Maturity Technology*. Research Investigation 93-007. Jefferson City, MO: Research Development and Technology, Missouri Department of Transportation.

In December 2002, inspectors looked to the concrete maturity method to facilitate reconstruction operations of a structure's northern bent, which was severely impacted in a tractor-trailer accident. The maturity method is recognized as a more reliable and timely method than testing conventional 6"x12" compressive strength cylinders. Application of the maturity method allowed earlier form removal and completion of the bridge repairs than if concrete cylinders had been used for strength determination. As a result, the bridge was opened to traffic earlier than if conventional methods had been used.

Application of maturity technology can provide an ideal, nondestructive means of facilitation construction operations including sawing pavement joints, coring pavement, opening pavement to traffic, removing formwork, cold- and hot-weather concreting, and others. While the maturity method is valuable, it has some limitations. But it has demonstrated itself as a desirable and reliable means of indicating in situ compressive strength and facilitating construction operations.

New Flexural Strength Requirements for Portland Cement Concrete Pavements (PCCP).

Current designs for PCC pavements have increased in thickness compared to those in the past. Thirty years ago, it was common for PCCP to be 8 to 10 inches thick based on then-current traffic data and growth projections. At this time, it is now known that these projections were underestimated, especially concerning heavy commercial traffic. A considerable number of these pavements are still performing satisfactorily beyond their anticipated design life. Taking today's increased traffic into account, there is a call to increase pavement thickness to as much as 15 inches. Such an increase in pavement thickness has caused a concern both in economic feasibility and constructability.

To alleviate this substantial increase in pavements thickness, the strength of the pavements must increase. Due to increasing the design flexural strength of the concrete, it has become important that new testing standards and procedures are put in place to minimize thickness.

Rettner, D. L. 1992. State of Minnesota Office Memorandum to Roger Skogen from the Office of Materials and Research. Minnesota Department of Transportation, July 21, 1992.

The subject of this memo is concrete mix design test sections on S.P. 5507-47. There was a high rate of low core strength in these concrete pavements. The Concrete Engineering Unit tried two different modified mix designs with different fly ash substitution rates. The test sections were one-mile-long sections of each mix design, separated with one-mile control section of the standard mix design. Four additional control beams per test section were required so that the concrete strength gain could be better determined.

Staton, J. F. 1995. Investigation of Low 28-Day Strength of Portland Cement Concrete (Memorandum). Michigan Department of Transportation, December 13, 1995.

The subject research project was established to investigate reports as to the causes of low 28-day compressive strengths of PCC for construction projects from the 1994–1995 construction season. The problems related to low compressive strength appear to be a result of variability in quality control during the cement manufacturing process. The outcome of several discussions with industry was that high levels of quality control during manufacturing, along with continuous improvements in the consistency of raw materials, has minimized the probability that the product is responsible for the strength deficiencies of the concrete. The Michigan Department of Transportation staff is not thoroughly convinced of that fact, however.

Staton, J. F. and J. D. Anderson. 1996. *Laboratory Evaluation of High-Durability Pavement Concrete Mix Design*. Research Project 94TI-1736. Lansing, MI: Michigan Department of Transportation.

During early 1995, the Materials Research Group embarked on a mission to develop a portland cement concrete (PCC) mix design for use in high-durability pavements (HDP). Pavement concretes of this type may be used for applications where high anticipated future traffic volumes warrant special pavement design considerations. The expected payoff by taking this foresight approach would be reduced long-term maintenance costs, reflecting lower life-cycle costs represented by actual costs attributed to repairs, and additional indirect savings in terms of user delay costs. This laboratory investigation shows that using the largest practical top-size coarse aggregate in a PCC mixture is an important component for producing a highly durable, cost-efficient concrete pavement. The HDP mix design included in this study showed that using a 50.0 mm (2 in.) top-size coarse aggregate enhances the strength characteristics of the concrete. This study also shows that high-quality, larger top-size coarse aggregate in the concrete mixture should produce greater aggregate interlock across a pavement crack interface.

Sehn, A. L. 2002. *Evaluation of Portland Cement Concretes Containing Ground Granulated Blast Furnace Slag*. Research Project No. 14559 (0). Report FHWA/OH-2002/022. Columbus, OH: Ohio Department of Transportation; Federal Highway Administration.

A two-part laboratory experimental program was conducted to evaluate the strength and durability of various concrete mix designs. In part I of the study, the influence of using grade 120 ground granulated blast furnace slag (GGBFS) on the strength and durability properties of concrete was evaluated. GGBFS was used to replace portland cement at replacement rates ranging from 0% to 75%. Other test variables included the use of cements with different alkali contents, fly ash, silica fume, and type K cement. Strength testing included compression strength, flexural strength, and splitting tensile strength. Durability testing included freeze-thaw resistance, shrinkage testing, rapid chloride ion penetration testing, and abrasion resistance testing. Based on the test results, the addition of GGBFS at rates as high as 55% of the total cementitious material resulted in strengths that, after 14 days, equaled or exceeded those of the baseline concrete mix. The incorporation of GGBFS in the concrete mix significantly improved the resistance to chloride ion penetration. In part II of the study, the influence of coarse aggregate size on the strength and durability of the ODOT Class C mix designs was evaluated. Coarse aggregate sizes included #57, #467, and #357. The ODOT high-performance concrete mix designs were also included in the study. Test results are presented in tabular and graphical formats.

Woolstrum, G. 2005. *Utilizing the Maturity Method*. Research in progress (completion date August 1, 2005). R-01-04. Lincoln, NE: Nebraska Department of Roads. http://ndorapp01.dor.state.ne.us/research/rpms.nsf/.

The maturity method for determining concrete strength is being conducted on several projects in Nebraska. This method relates temperature of concrete and time to a predetermined strength curve to estimate strength of the pavement slab. This method eliminates the need to have samples brought to the lab in order to determine when to open the project to traffic. By inserting thermocouples into the freshly poured pavement, curing time can be monitored throughout the day.

Air System

Missouri Department of Transportation. 2003. *Advanced Research of an Image Analysis System for Hardened Concrete*. Research Investigation 98-006. Jefferson City, MO: Research Development and Technology, Missouri Department of Transportation.

The characteristics of the air-void system in concrete, such as void size and spacing, serve as valuable tools in assessing the resistance of concrete to freezing and thawing and can help determine concrete durability and long-term performance. With testing methods, a human operator must participate to distinguish among the various concrete constituents (air, paste, aggregate). Researchers have proposed completely automated systems using image analysis to replace the human operator. Though human operators have several disadvantages, it is felt that the human operator is still needed for the best results. Developing an automated system that would produce results as accurate as human-based ones would have great impact on concrete testing and research.

A national pooled fund study is underway to develop and validate an image analysis system for determining the parameters of the air-void system in hardened concrete. The MoDOT and NNSA-KCP have developed a prototype image analysis system with a baseline capability of analyzing hardened concrete and determining its air void characteristics. The goal of the pooled fund study is to develop an image analysis system that processes results as accurately as a human-based system.

AASHTO Technical Implementation Group. *Fresh Concrete Air Void Analyzer: A Technical Background Paper*. CD-ROM.

The air-void system in concrete is commonly singled out as the most significant factor in freeze-thaw resistant concrete. Researchers believe that the pressure developed by water as it expands during freezing depends upon the distance the water must travel to the nearest air void. The voids must be close enough to relieve the pressure. Thus, smaller, closely spaced voids provide better protection than larger, more distant voids.

Commonly used field test methods are only capable of measuring the volume of air voids, not the size or spacing of the voids. In an effort to address this problem, researchers in Europe developed the air void analyzer (AVA) in the late 1980s to characterize the air void structure of fresh concrete. The clear advantage of the AVA is its ability to obtain air void structure information from fresh concrete in less than 30 minutes. With this information, adjustments can be made in the production process to rectify any problems with the air void system during concrete placement.

To improve the durability of concrete used in transportation structures, the AASHTO Technical Implementation Group strongly encourages state DOTs to specify air void system characteristics and adopt the use of the AVA for quality control.

AASHTO Technology Implementation Group. *Introducing the Air Void Analyzer (AVA)*. CD-ROM and Brochure.

The size and distribution of air voids in concrete determine the durability of the concrete. Concrete with an adequate air void system has better freeze-thaw durability, sulfate resistance, and scaling resistance. The air void analyzer (AVA) measures the air void characteristics of fresh concrete, useful for verifying and controlling the air-void system before and during production. While roll-o-meter and pressure meter tests measure the total air content, the AVA measures the size of the voids and their distribution. By vibrating a wire cage into fresh concrete using a percussion drill, AVA specimens are collected. Entrained air content, spacing factor and specific surface are then reported. Testing can be done almost anywhere, and results are immediate.

A Kansas case history is discussed where pavement less than 10 years old was cracked and deteriorating at joints, even though the aggregate was sound and met specifications. Poor spacing factors were to blame. For a distress prevention strategy, the AVA was also used to monitor concrete paving projects. When contractors were given immediate results, they were able to make immediate improvements in the concrete air systems of ongoing projects and enabled future cost savings.

Iowa Department of Transportation. *Iowa Barrier Rail Mix Design Development*. Ames, IA: Iowa Department of Transportation.

In 1998, the Iowa DOT made an investigation into slipformed median barrier rails to improve the Iowa Class D-57 mix design. The major problem is the difficulty of air entrainment, which in turn results in poor durability. It was decided to use well-graded aggregates (Shilstone principles applied) together with a reduced cement paste content. The new mix design, named barrier rail (BR), achieved better results than D-57, including better workability, higher air content with a lower amount of AEA, higher strength, lower permeability, and less cracking. Later, further changes such as the use of slag (up to 20%) and fly ash (up to 15%) were applied to BR. The Shilstone method of well-graded aggregate mix design was also applied to QMC for pavements in 2000 and is in practice now.

The research projects listed in Table B.2.2 were completed under the direction of the Iowa Department of Transportation. The table lists the research pertaining to the air void system. The project number, title, end date, and principle investigator are also listed.

Table B.2. Summary of Iowa DOT research related to air void system

Proj.	No.	Title	End	PIs
HR/TR	183	Fatigue Behavior of High Air Content Concrete	7/1/77	D. Y. Lee, F. Klaiber
HR/TR	197	Fatigue Behavior of High Air Content Concrete, Phase II	1/1/79	D. Y. Lee, F. Klaiber
HR/TR	396	Image Analysis for Evaluating Air Void Parameters of Concrete	2/28/98	S. Schlorholtz
MLR	7101	An Investigation of the Chemical Method of Determining the Air Content of Hardened Concrete	3/1/71	M. Sheeler
MLR	8505	Air Entrainment and PCC Durability		--
MLR	9207	Correlation of Air Content of Concrete		C. Narotam
MLR	9903	Plastic Air Versus Hardened Air by High Pressure Air Meter		T. Hanson/J. Hart

Permeability

The research projects listed in Table B.2.3 were completed under the direction of the Iowa Department of Transportation. The table lists the research pertaining to concrete permeability. The project number, title, end date, and principle investigator are also listed.

Table B.3. Summary of Iowa DOT research related to concrete permeability

Proj.	No.	Title	End	PIs
MLR	8611	Rapid Determination of Permeability of PCC by AASHTO T277-83	9/1/87	J. Nash

Karaca, H., I.O. Yaman, and H. Aktan. 2000. *Evaluation of Concrete Permeability by Ultrasonic Testing Techniques, Phase III, Final Report.* Repot No. RC-1403. Detroit, MI: Civil Engineering Department, Wayne State University.

> The development and verification of a nondestructive test for early-age assessment of concrete bridge deck durability is described. The test is based on ultrasonic pulse velocity (UPV) of longitudinal waves measured on field concrete and compared to measurements made on standard specimens. The test has potential implementation in QC/QA specifications for measurements of performance parameters. The test is also being promoted for intelligent health monitoring of infrastructure concrete, for example, in timing maintenance interventions. Intelligent monitoring is quantified by a parameter called paste quality loss (PQL). Standard concrete specimens made from a field concrete mixture are used as reference measures. The measurements of the reference specimens indicated that the PQL parameter computed from the UPV measurements as early as the 28th day is a good predictor of soundness. The UPV measurements made at increasing age of concrete clearly document the rapid loss of soundness of improperly cured concrete decks. Moreover, tests were performed on two actual bridge decks to test the efficiency of the UPV measurement procedure.
>
> The methods and procedures developed during this research are specifically calibrated for concrete bridge deck durability assessment starting at an early age. Potential uses for these techniques are (1) in determining the QC/QA specification performance parameters and (2) in timing the positive maintenance interventions for intelligent health monitoring. Future research should deal with developing relations between UPV and concrete performance.

Ramakrishnan, V. 2000. *The Determination of the Permeability, Density, and Bond Strength of Non-Metallic Fiber Reinforced Concrete in Bridge Deck Overlay Applications*. Report No. SD1998-18-F. Rapid City, SD: South Dakota School of Mines and Technology.

This final report presents the procedures and results of the rapid chloride permeability, density, and bond strengths of cores taken from non-metallic fiber reinforced concrete (NMFRC) and plain low slump dense concrete (LSDC) bridge deck overlays constructed earlier on a bridge at Exit 212 over I-90 (I-90/US 83) and Exit 32 on I-90. Both the filled in-place and laboratory bond tests were performed for cores drilled in the field. The density and chloride permeability were also determined for the concrete specimens cast in the laboratory with five different compacting efforts for each different concrete used in the construction of the bridge decks.

A comparison of the results from the field and laboratory mixes had indicated a good bond between the overlay concrete and the old concrete, and the bond strength was greater than the tensile strength of the old concrete because in all cores the failure was in the old concrete. The chloride permeability mainly depended on the cement content and compacting effort used in making the cylinders. The addition of fibers did not influence the chloride permeability and density of the concrete. Recommendations are made regarding the equipment and testing procedures for designing the NMFRC mix and regarding the equipment and testing procedures for QC in the field.

Staton, J.F. Investigation of PCC Pavement Using Ground Granulated Blast Furnace Slag (Memorandum). Michigan Department of Transportation, September 18, 1995.

The subject technical investigation was established to conduct a short-term study regarding incorporation of ground granulated blast furnace slag (GGBFS) as a partial substitute for Type I portland cement in concrete pavements. It was determined that this pozzolanic material may provide beneficial properties related to long-term performance of PCC pavements, such as an overall decrease in permeability. Also, less initial heat is developed in the concrete, reducing early-age internal concrete stresses due to excessive heat. Our study indicates that 40% substitution by weight of Type I portland cement with grade 100 minimum GGBFS would be optimum for PCC pavements. The predominant lack of usage of GGBFS has been due to economic deficiencies in shipping and storage, resulting in excessive material handling expense.

Udegbunam, O., I.O. Yaman, and H. Aktan. 1998. *Evaluation of Concrete Permeability by Ultrasonic Testing Techniques. Phase I.* Report No. RC-1403. Detroit, MI: Wayne State University.

The overall goal of this research is to provide a measure for the durability of concrete bridge decks. Quantification of concrete durability is essential if durability requirements are to be included in QA/QC specifications. A significant parameter of concrete deck durability is related to its permeability. Selected literature regarding concrete pore structure characteristics, specifically porosity and pore size, is reviewed. The influence of these characteristics on the elastic properties of concrete is also reviewed. An expression that relates permeability and ultrasonic pulse velocity (UPV) is formulated. An experimental program is established and conducted to verify the relation between concrete permeability and UPV. Five groups of specimens corresponding to different water-cement ratios (w/c) were cast and were tested for permeability and UPV at the age of 28 days. The permeability tests were made in accordance with AASHTO T 277, “Rapid Test for Permeability to Chloride Ions,” and AASHTO T 259, “Chloride Ion Penetration.” The relationship between permeability and UPV is defined, and the statistical significance is shown. The results show a measurable relationship between permeability and UPV in the range of w/c tested.

Yaman, I. O., O. Udegbunam, and H. Aktan. 1999. *Evaluation of Concrete Permeability by Ultrasonic Testing Techniques, Phase II.* Detroit, MI: Wayne State University.

The goal of this research presented to develop a rapid, nondestructive permeability test that can be performed during the early ages of concrete. The proposed test procedure is based on ultrasonic pulse velocity (UPV) methods. The research is based on the hypotheses that there is a measurable relationship between UPV and permeability. The objectives of this phase are in two categories. One category is the evaluation of the effects of aggregate type, entrained air, and water reducing admixtures on UPV and permeability. The other is the review and resolution of some of the anticipated field implementation problems. The first proposed study should deal with developing the paste efficiency relation for high-performance concrete mixtures. The second study should develop guidelines for the use of UPV of determining concrete permeability in a manner similar to 7- or 28-day compressive strength. In that case, both concrete strength and durability can be documented. A final study should include the development of deterministic mechanistic models for the life-cycle cost of concrete bridge decks.

Yaman, I. O., H. Karaca, and H. Aktan. 2001. *Evaluation of Concrete Permeability by Ultrasonic Testing Techniques. Phase IV.* Report No. RC-1403. Detroit, MI: Wayne State University.

The nondestructive test procedure for quantifying bridge deck concrete’s future durability is based on the fundamental relationship between ultrasonic pulse velocity (UPV) and permeability of an elastic medium. An experimental study using standard concrete cylindrical specimens documented adequate sensitivity between UPV and permeability. The test procedure uses a parameter directly proportional to the increase in field concrete permeability, called paste quality loss (PQL). The PQL is computed from UPV measurements on standard concrete specimens made from field concrete mixture and measurements of field concrete. Deck replacement projects on three NHS bridges are used as demo sites to implement the test procedure. The respective 56-day PQLs demonstrate a significant variability in the permeability of the three bridge decks. Field permeability tests are also conducted by Figg’s apparatus for comparison purposes. PQL evaluation from post-construction measurements proved to be an effective and reliable means of testing the bridge deck’s future durability.

The PQL measure developed in this research will be a useful feedback tool for evaluating the impact of an isolated parameter on durability. Potential use of the durability measure may be for health monitoring of bridge decks for the timing of preventive maintenance procedures. In this implementation, the bridge deck UPV will be measured intermittently. Changes will be documented with the rate of change in UPV, which can be correlated to the deck deterioration rate. A clear model between the UPV changes and deck deterioration can be developed by testing of multiple decks at different levels of deterioration.

Shrinkage

Bruinsma, J. E., Z.I. Raja, M.B. Snyder, and J.M. Vandenbossche. 1995. *Factors Affecting the Deterioration of Transverse Cracks in JCRP.* MDOT Contract 90-0973. Lansing, MI: Department of Civil and Environmental Engineering, Michigan State University.

Jointed Reinforced Concrete Pavement (JRCP) develops transverse cracks as the drying and thermal shrinkage of the concrete is resisted by friction with the supporting layers. These cracks deteriorate with time and traffic due to loss of aggregate interlock load transfer capacity. However, unusually rapid deterioration of these cracks has even observed on some recently constructed projects in Michigan. This rapid crack deterioration leads to accelerated maintenance requirements and shortened service lives. This research report describes the development, conduct and results of a laboratory investigation to determine the relative effects of selected factors on the deterioration of transverse cracks in JRCP. Based on the results of these tests, it is recommended that pavement made with concrete derived from recycled concrete aggregate or slag should feature structural designs that minimize reliance on aggregate interlock in any area of the design (i.e., at joints or cracks). The use of blended aggregates (recycle concrete or slag combined with suitable natural aggregates) may be useful to provide additional design reliability, but is probably not necessary for the types of designs described above. Moreover, pavement made with concrete that includes relatively weak aggregate particles, such as slag and recycled concrete, should (a) use mix designs that provide concrete strengths that are comparable to those of concrete made with virgin aggregates, (b) use structural designs that reduce pavement stresses to levels that are appropriate for the strength that will be obtained, or (c) do both.

The research projects listed in Table B.2.4 were completed under the direction of the Iowa Department of Transportation. The table lists the research pertaining to concrete shrinkage. The project number, title, end date, and principle investigator are also listed.

Table B.4. Summary of Iowa DOT research related to concrete shrinkage

Proj.	No.	Title	End	PIs
HR/TR	136	Creep & Shrinkage Properties of Lightweight Aggregate Concrete Used in Iowa	9/1/70	D. Branson, B. Meyers
MLR	7102	A Study of the Relative Durability and Drying Shrinkage of Concrete Using Various Retarders	7/1/71	S. Carey
MLR	8509	Length Change of PC Concrete Due to Moisture Content	3/1/87	V. Marks
MLR	8612	Determination of Tension Crack Development in Plastic PCC with Retarding Admixture	9/1/87	K. Jones, O.J. Lane
MLR	8905	Drying Shrinkage in PC Concrete	3/1/90	K. Jones
MLR	9303	Effect of Cement & Sand Components on Expansion in ASTM P-214 Test		C. Narotam
MLR	9306	Concrete Prism Testing		C. Narotam

Establishing Workability

Hudson, B. 2003. Discovering the Lost Aggregate Opportunity. *Pit & Quarry*, October 2003: 32–34.

The purpose of Shilstone's aggregate specification was to make a better-quality concrete and reduce shrinkage and curling in large floor slabs. For aggregate producers, this aggregate is difficult to manufacture. This particular specification is gaining more acceptance than most, but it may have some basic flaws. Some of these flaws are that people are applying these specs. without understanding, and they are too rigid and difficult to follow. This article includes excerpts from the question and answer forum at www.aggregateresearch.com.

Iowa Department of Transportation. *Investigation on Use of Higher Volume Class C Fly Ash*. Ames, IA: Iowa Department of Transportation.

In the study, performance of higher volume Class C fly ash in ternary mixes (portland cement, GGBFS, and fly ash) was investigated. It was intended to evaluate the performance of various combinations of fly ash and portland cement in terms of workability, finishability, strength, maturity, permeability, air void distribution, and durability (F/T). Test sections were cast with different combinations of Type I/II cement, Type I(SM), and Class C fly ash (15% and 20% replacements). The results obtained from the test section on US 34 showed that 5% increase in fly ash replacement resulted in no significant difference in strength, permeability, and hardened air characteristics.

The research projects listed in Table B.2.5 were completed under the direction of the Iowa Department of Transportation. The table lists the research pertaining to establishing concrete workability. The project number, title, end date, and principle investigator are also listed.

Table B.5. Summary of Iowa DOT research related to establishing concrete workability

Proj.	No.	Title	End	PIs
HR	1066	Evaluation of Mixing Time vs Concrete Consistency & Consolidation	8/1/97	J. Cable
HR	1068	Evaluation of Paver Vibrator Frequency Monitoring & Concrete Consolidation (ACPA $86,616)	6/1/98	Jim Cable
HR/TR	505	Improving PCC Mix Consistency & Production by Mixing Improvements	9/30/05	V. Schaefer
MLR	7504	An Investigation of Concrete Setting Time	4/1/75	G. Calvert
MLR	9504	Vibration Study For Consolidation of Portland Cement Concrete	1/1/97	S. Tymkowicz, R. Steffes
MLR	9510	Instrumentation of Paver Vibrators	1/1/99	R. Steffes
MLR	9602	Determination of Concrete Workability		R. Steffes
MLR	9701	Mini Slump Cone Test Procedures and Precision	11/00	T. Hanson
MLR	9702	Vibratory Effects in Reinforced PCC Pavement	5/1/97	B. Steffes
MLR	9703	Field Evaluation of QMC Strength Variability	7/98	S. Tymkowicz
MLR	9804	Core Analysis of Slip Formed Barriers	9/99	T. Hanson/B. Steffes
MLR	9905	Field Evaluation of Water Reducers With Type I (sm) Cement		J. Grove/T. Hanson

Johnston, D. 1996. *Evaluation of the Performance of Set Retarders and High Range Water-Reducers in Typical SDDOT Concrete Mixes*. Report No. SD92-076-F. Pierre, SD: Office of Research, South Dakota Department of Transportation.

This research examines whether cement-admixture compatibility problems exist and investigates methods of reducing the potential impact of undesirable interactions, such as premature stiffening, rapid slump loss, and unpredictable setting behavior. Severe incompatibility problems with both set retarders and high-range water reducers were observed with specific samples of two of the three cements and all of the admixtures tested and appear to be directly related to the C_3A content of the cement. Although mixes using retarders did not exhibit the same degree of deterioration in concrete mix properties as high-range water reducers, both admixture types developed adverse and unpredictable behavior. Set retardation was inhibited with some cement-retarder combinations and premature stiffening; rapid slump loss and inability to entrain sufficient air occurred when these same cement samples were used in concrete mixes with high-range water reducers. Delayed addition of admixtures eliminated most of the problems encountered, with a 5–10 minute wait usually sufficient to restore normal behavior. Field trials using set retarders and high-range water reducers are recommended to develop guidelines for routine admixture use with a significant reduction in potential compatibility problems.

Sethre, D. 2003. Aggregate Optimization: Its Time Has Come. *Hard Facts*, Summer 2003.

Until recently, aggregate optimization has been one of the least understood tools for ride and smoothness enhancements in all of the concrete paving industry. Much of the discussion has been based on durability benefits of reducing mix paste contents through the use of uniformly graded aggregates to fill voids in the matrix. The theory states that the paste is the least durable component of concrete, while aggregate is the most durable. Even nominal attempts to fill gaps in concrete gradations have brought profound benefits for lower concrete permeability characteristics at lower paste contents, as shown by recent NDDOT-funded research.

The use of more uniformly graded aggregates has been found to be a major solution to problems of segregation in normal mixes, as compared to ordinary gap-graded mixes composed of large stone and sand. Use of aggregate optimization techniques improved workability to the extent that pavement smoothness was no longer an issue. Jim Lafrenz, Director of Airports as ACPA National, has a spreadsheet available for evaluating aggregate gradations for workability.

Durability

Iowa Department of Transportation . *1992-1997 Core Investigation and 2003 Conclusions*. Ames, IA: Iowa Department of Transportation.

> In 1996, new specifications (lowering SO_3 and alkali contents of PC, increasing plastic air content, limiting vibration) were implemented to prevent the premature deterioration of concrete pavements. An investigation was carried out into concrete cores obtained from the pavements constructed in 1992 and 1997. The study showed that the new specifications imposed in 1996 resulted in better concrete pavement performance. In addition, use of GGBFS or fly ash improves the pavement resistance against deterioration.

Arnold, C. J. 1981. *The Relationship of Aggregate Durability to Concrete Pavement Performance, and the Associated Effects of Base Drainability*. Research Report No. R-1158. Lansing, MI: Testing and Research Division, Michigan Department of Transportation.

> It is evident that Michigan has problem aggregates in many localities, since D-cracking is appearing on many projects of 10 years or more of age, even at 3 1/2 to 4 years on the US 10 Clare experimental pavements of this study. The early results of the experimental installation at Clare show the deleterious effects of poor base drainage on concrete pavement performance. Improved drainability for all future base course construction should be pursued. Effort should also be put into identifying and evaluating sources and specifying corrective size changes or material substitution where warranted. Additionally, serious consideration should be given to raising the minimum acceptable durability rating by applying the latest principles to adjust the gradation of the coarse aggregate and make other appropriate mix design changes to obtain all practically attainable improvements in longevity of performance. It is also recommended that durability requirements be increased for the more critical applications. Some significant benefits should result from such procedures. However, additional data are needed to separate the better performing aggregates from those that cause early deterioration. Also, any test that can be developed to identify D-cracking aggregates in less time than the long-term freeze thaw test would be a boon to this endeavor.

Barnhart, V. T. 2001. *Inspection of Pavement Problems on I-275 and on I-75 from the Ohio Line Northerly to the Huron River*. Research Report R-1390. Lansing, MI: Construction and Technology Division, Michigan Department of Transportation.

> The purpose of this study was to verify the conclusions reached in previous reports regarding poor drainage and filter problems on both I-275 and I-75 and with the open-graded drainage course (OGDC) on I-75. The purpose was also to verify the conclusion reached in the placement of the continuously reinforced concrete (CRC) reinforcement and longitudinal cracking on I-275.
>
> I-275 project findings: Pavement surveys, conducted in 1977, indicated some longitudinal cracking and punch-out failures on three of the projects. The conclusions reached in the previous reports regarding the causes for the longitudinal cracking are still valid. Since the studies were done in the late 1970’s and early 1980’s, questions have been raised regarding the relative location (depth, bar spacing, alignment) of CRC reinforcement bars and whether the longitudinal cracking in the CRC pavement follows the bars. The longitudinal cracking in the CRC pavement does follow the longitudinal reinforcement bars.
>
> I-75 Project Findings: In 1980, a study was conducted to determine the cause of performance problems in the roadway constructed between 1955 and 1957 and widened between 1973 and 1974. The conclusions reached in Part 1 of the 1980 study could not be confirmed, as the concrete pavement

was completely removed and recycled during reconstruction between 1984 and 1990. The conclusion reached in Part 2 of the 1980 study regarding the problems with the subbase is still valid. However, the conclusions regarding the dense-graded aggregate base are not valid, as the base was removed during reconstruction.

Barnhart, V. T. 1998. *Inspection and Performance Evaluation of Prefabricated Drainage System (PDS) in Cooperation with Monsanto Company*. Research Report R-1341. Lansing, MI: Construction and Technology Division, Michigan Department of Transportation.

This study involved the investigation of geocomposite prefabricated drainage systems (PDS) installed on construction projects that included crack and seat, break and set, rubblizing, recycling PCC, concrete overlays and reconstruction, and underdrains to evaluate the performance of the PDS. The study concluded that the PDS is performing well. While there was some evidence of J-ing of the bottom and occasional bending over of the top of the PDS, these factors did not appears to obstruct the flow of water through the system. There was no evidence of calcium carbonate precipitate found in the core or on the filter fabric of the PDS on the project sites where the concrete pavement had been rubblized or where untreated crushed concrete or asphalt-treated crushed concrete was used as the open-graded drainage course. Further research should continue to determine the long-term performance of all underdrains where the open-graded drainage course (OGDC) is used in conjunction with a dense-graded aggregate or geotextile separator.

Branch, D. E. 1995. *Concrete Pavement Restoration, Final Report*. Research Report R-1327. Lansing, MI: Materials and Technology Division, Michigan Department of Transportation.

For the past 25 years, the MDOT Research Laboratory has conducted several studies to develop effective maintenance procedures for concrete pavement. The procedures were developed for daylight closures to minimize the inconvenience and hazard to motorists caused by maintenance operations. By 1982, the department used dowelled repairs as a standard procedure. The dowels are loose fitting in holes drilled in adjacent slabs. The restoration work described in this report uses repair techniques previously developed in addition to new ones. The pavement selected for restoration was a 20-year-old, 9 in. reinforced concrete slab with 71 ft.. joint spacings and joints sealed with preformed neoprene seals. Deteriorated joints were repaired using full-depth repairs having dowelled joints with the dowels grouted-in-place using an epoxy grout. Some mid-slab failures were repaired by tying the new concrete to the existing slab using grouted-in-place No. 10 deformed bars. The deteriorated intersections of the longitudinal and transverse joints were restored using 4–ft by 4-ft. full depth repairs tied in place with grout-in No. 5 deformed bars. Spalls along the joint grooves were repaired partial-depth with fast-set premixed mortar; the neoprene seals were replaced with silicone sealant; the longitudinal joints were resealed using a low-modulus hot-poured sealant; and surface pop-outs were fixed using fast-set premixed mortar. The performance of the various restoration techniques were evaluated over a five-year period.

Chapin. L. T. and J. B. Dryden. 2001. An Evaluation of the Cost Effectiveness of D-Cracking Preventive Measures. Report No. FHWA/OH-2002/05. Bowling Green, OH: Bowling Green State University.

D-cracking has long been a serious problem in the deterioration of concrete pavements in severe weather climates. After much research, the mechanics and variables involved in the destructive forces of concrete D-cracking are becoming known. This study focuses on these variables that include analysis of the cost effectiveness in using certain preventive measures to reduce premature deterioration of concrete pavement due to D-cracking. These variables include aggregate source, cement source, joints, types of pavement, vapor barrier, cure, and subbase.

A test road located on State Road (SR) 2 near Vermilion, Ohio was built in 1974 and 1975 with specific sections to investigate the role of subbase drainage systems, pavement joint design, subbase materials, joint sealant, different aggregate sources and size, different cements, types of cure, and joint spacing. In 1998, this field study was done on the Vermilion project to evaluate many of the factors that were initiated on the pavement.

Clowers, K.A. 1999. *Seventy-five Years of Aggregate Research in Kansas*. Report FHWA-KS-99/1. Topeka, KS: Kansas Department of Transportation.

The Kansas Department of Transportation (KDOT) has a long history of aggregate research directed towards finding the most reliable and durable aggregate for highway construction. Beginning with a study on freeze-thaw durability in 1928, this paper summarizes the historical development of aggregate research conducted over the last 75 years. Research studies have focused predominantly on freeze-thaw damage (D-cracking) and alkali-silica reaction (ASR). This research has contributed significantly towards the development of current specifications. Today, KDOT pavements are relatively free of ASR and D-cracking.

Girard, R.J., E.W. Myers, G.D. Manchester, and W.L. Trimm. 1982. D-Cracking: Pavement Design and Construction Variables. *Transportation Research Record* 853: 1–9.

Reported map cracking and D-cracking problems observed on portland cement concrete (PCC) pavements in Missouri from the late 1930s to 1981 are briefly discussed. Investigations involving studies in the laboratory and constructed pavements have contributed significantly to a better understanding of the deterioration process and its cause. Type, characteristics, and maximum size of coarse aggregate; source of cement; design of concrete mix; and type of base have been or are being studied in the field or laboratory to determine their influence to frost susceptibility of concrete. Missouri has increased the service life of its PCC pavements. This has been accomplished by (a) not using river and glacial gravels in construction of PCC pavements and (b) subjecting limestones that have a known history of D-cracking problems to increased quality restrictions, which has resulted in some ledges and entire quarries and formations being eliminated. However, D-cracking remains and, in terms of required maintenance and service life, is still a problem.

Van Dam, T.J. 2005. *Guidelines for Early-Opening-to-Traffic Portland Cement Concrete for Pavement Rehabilitation*. NCHRP 18-04B. Washington, D.C.: Transportation Research Board.

The study objective is to develop guidelines for materials, mixtures, and construction techniques to obtain long-term durability of early-opening-to-traffic portland cement concrete (EOT PCC) for pavement rehabilitation. The study focuses on two types of EOT PCC mixtures: Those that are suited for opening to traffic within 6 to 8 hours after placement and those that can be opened to traffic within 20 to 24 hours of placement. Furthermore, the study is limited to full-depth rehabilitation that includes full-depth repair and slab replacement.

Embacher, R. A. and M. B. Snyder. 2003. Refinement and Validation of the Hydraulic Fracture Test. *Transportation Research Record* 1837. 80–88.

This study was undertaken to improve the Minnesota Department of Transportation’s (MnDOT) ability to rapidly evaluate the potential freeze-thaw durability of coarse aggregate sources intended for use in portland cement concrete (PCC) pavement applications. This was to be accomplished by refining the hydraulic fracture tests (HFT) and validating that apparatus and procedures using Minnesota aggregates. The following conclusions can be drawn from this study: The HFT and data analysis procedure appear to be well correlated with concrete specimen dilation measurements obtained from freeze-thaw testing. This suggests that the modified hydraulic fracture test offers a reliable, relatively rapid alternative to predicting the D-cracking potential of coarse aggregate on

properly air-entrained concrete. There is a strong correlation between hydraulic fractures tests outputs and concrete test specimen dilation data obtained from rapid freezing and thawing tests. This links coarse aggregate top size to freeze-thaw durability for potentially non-durable aggregate sources.

More freeze-thaw and hydraulic fracture tests should be performed using the small test chamber on additional aggregate sources. Additional hydraulic fracture testing should be performed using the modified large hydraulic fracture test chamber. Additional tests and research should be performed to verify and determine the nature of the outlier hydraulic fracture test results. Also, additional test and research should be performed to verify and determine the nature of the differences in hydraulic fracture test results obtained using the small and large chambers. Future development research should investigate the way that carbonate aggregate pore properties relate to HFT and freeze-thaw test results.

Evaluation of Base Materials under PCC Pavement. Ohio Research Institute for Transportation and the Environment.

In 1990, a distressed portion of SR 2 in Erie and Lorain Counties near Vermilion, Ohio was replaced with test sections designed to investigate the effects of base type on D-cracking, slab length on transverse slab cracking, and natural versus manufactured sand on skid resistance. Twelve sections constructed for the study of base type on D-cracking were located in the westbound lanes of SR 2 between Station 1835+10 in Erie County and Station 90+23 in Lorain County. While no evidence of D-cracking is apparent to date in these sections, numerous transverse slab cracks observed in sections with Ohio 307NJ and cement-treated free draining base suggest these materials should not be used as a base directly under PCC pavement. This technical note provides a review of the performance of these test sections.

Halverson, A. D. 1982. Recycling Portland Cement Concrete Pavement. *Transportation Research Record* 853: 14–17.

Quality aggregates for highway construction are in short supply in many parts of Minnesota. Although the current total supply is adequate, the distribution of sources results in localized shortages. It is sometimes necessary to import high-quality aggregate from distant locations. Haul distances can increase aggregate prices substantially, add to the overall project cost, and require the expenditure of sizable amounts of energy. One available source of aggregate is existing portland cement concrete (PCC) pavement currently in need of reconstruction. Reusing this aggregate would result in cost savings in aggregate-short areas, conserve natural resources, and conserve energy in the form of fuel savings when aggregates must be acquired from distant sources. A research study is described that was undertaken to determine the feasibility of recycling PCC pavement, evaluate the new recycled pavement, determine the cost-effectiveness of recycling versus conventional paving, and determine the amount of energy consumed and natural resources conserved. Economic and engineering factors led to the selection of a 16-mile segment of US-59 form Worthington to Fulda in southwestern Minnesota for the study. The project results are evaluated based on pavement performance and energy and cost comparisons.

The research projects listed in Table B.2.6 were completed under the direction of the Iowa Department of Transportation. The table lists the research pertaining to concrete durability. The project number, title, end date, and principle investigator are also listed.

Table B.6. Summary of Iowa DOT research related to concrete durability

Proj.	No.	Title	End	PIs
HR	1021	High Range Water Reducers in PCC Made With D-Crack Susceptible Coarse Aggregate		S. Moussalli

Proj.	No.	Title	End	PIs
HR	1063	Pooled Fund Study for Premature Rigid Pavement Deterioration	1/1/97	D. Gress
HR	1065	Durability of Highway Concrete Pavements (PCA 50%)	12/1/99	J. Clifton
HR	1081	Development of In-Situ Detection Methods for Material Related Distress (MRD) in Concrete Pavements, Phase II Extension	12/31/04	S. Schlorholtz/K. Wang
HR	2022	Iowa Pore Index Test		W. Dubberke
HR	2037	ERES "Performance/Rehabilitation of Rigid Pavements"		M.I. Dater
HR	2074	A Different Perspective for Investigation of PCC Pave Deterioration		V. Marks
HR/TR	9	Performance of Various Thicknesses of Portland Cement Concrete Pavement		C. A. Elliott
HR/TR	10	Durability of Portland Cement Concrete	6/1/69	B. Brown
HR/TR	120	Concrete Popouts	2/1/67	R. Handy
HR/TR	141	Deterioration of PCC Pavements	5/1/73	J. Lane
HR/TR	146	Preliminary Studies of Remedial Measures for Prevention of Bridge Deck Deterioration	3/1/70	H. Ellery, F. Klaiber
HR/TR	250	A Nondestructive Method for Determining the Thickness of Sound Concrete on Older Pavements	11/1/82	V. Marks
HR/TR	258	Frost Action in Rocks and Concrete	4/1/86	T. Demirel
HR/TR	270	Development of Training Aids and Demonstration of PCC Pavement Rehabilitation (Demo 69)	9/1/88	R. Given, M.J. Knutson
HR/TR	271	Effects of Deicing Salt Compounds on Deterioration of PC Concrete	11/1/85	J. M. Pitt
HR/TR	272	Development of a Conductometric Test for Frost Resistance of Concrete	1/1/88	T. Demirel, B. Enustun
HR/TR	299	Control of PCC Deterioration Due to Trace Compounds in Deicers (Ph 1, 2, & 3)	10/31/91	J. Pitt
HR/TR	327	Evaluation of the Chemical Durability of Iowa Fly Ash Concretes	3/31/93	K. Bergeson
HR/TR	355	The Role of Magnesium in Concrete Deterioration (+Executive Summary)	10/31/94	R. Cody, P. Spry, A. Cody
HR/TR	358	Evaluation of Microcracking and Chemical Deterioration in Concrete Pavements	10/31/95	S. Schlorholtz, J. Amensen
HR/TR	384	Expansive Mineral Growth and Concrete Deterioration	8/31/97	R. Cody
HR/TR	406	Determine Initial Cause for Current Premature PCC Pave Deterioration	11/30/00	S. Schlorholtz
HR/TR	469	Reduction of Concrete Deterioration by Ettringite Using Crystal Growth Inhibition Techniques-Part II-Field Eval of Inhibitor Effectiveness	5/30/04	P. Spry/R. Cody
HR/TR	473	Rehabilitation of Concrete Pavements Utilizing Rubblization and Crack and Seat Methods	12/31/04	Brian Coree
HR/TR	480	Investigation of the Long Term Effects of Concentrated Salt Solutions on Portland Cement Concrete	7/14/04	
MLR	7103	Durability Study of Type II Cements	6/1/71	S. Carey
MLR	7201	A Study of the Reliability of the ASTM C-666 Freeze-Thaw Test	9/1/72	V. Marks
MLR	7301	Method to Increase Durability of Reactive ("D" Cracking) Coarse Aggregate in PCC	8/1/73	R. Less
MLR	7705	Chloride Penetration into LSDC (IA System) Resurfacing Mixes	4/1/77	G. Calvert
MLR	8404	Durability of Concrete With Additives	7/1/85	J. Lane, S. Moussalli
MLR	8408	Reduction of D-Cracking Deterioration by Increasing Density of Concrete		S. Moussalli
MLR	8502	Fly Ash Effects on Alkali-Aggregate Reactivity		R. Allenstein
MLR	8508	Durability of Fly Ash Concrete Containing Class II Durability Aggregates	7/1/86	S. Moussalli, J. Myers
MLR	8801	Pavement Evaluation of Iowa 44 in Audubon & Guthrie Counties (D-Cracking)		K. Jones & J. Nash
MLR	9001	Evaluation of Test Method to Measure Response of Aggregate Cement-Fly Ash Combinations to D		--
MLR	9101	Evaluation fo Deterioration on US 20 in Webster County	12/1/91	--
MLR	9409	Durability of Concrete Pavents Using Cements With Different Alkali Contents	5/1/97	C. Ouyang

Proj.	No.	Title	End	PIs
MLR	9505	Freeze/Thaw Durability Testing of Oversanded Bridge Floor Concrete	5/1/95	C. Ouyang
MLR	9512	Ground Granula Blast Furnace Slag Concrete Resistance to Salt Scale		C. Ouyang/T. Hanson
MLR	9513	Freeze/Thaw Resistance of Cement With Excess Free Lime		T. Hanson
MLR	9708	The Effect of Cement and Water Reducers on Concrete Durability	7/00	T. Hanson
MLR	9802	Effect of Waterproofing Admixture Ipanex on Concrete Durability	3/99	T. Hanson
MLR00-03	200003	Evaluation of Long Term Durability of PCC Using Intermediate Sized Gravels to Optimize Mix Gradations		J. Hart
MLR00-04	200004	Study of Chloride Intrusion into PCC Pavements		B. Gossman/K. Jones

Jensen, W. 2004. *Pavement Quality Indicators*. Research in progress – P563. Lincoln, NE: University of Nebraska and Nebraska Department of Roads. http://ndorapp01.dor.state.ne.us/research/rpms.nsf/.

Several innovative pavement technologies have been introduced in the Nebraska road system by NDOR during the past decade. These include retrofitting of dowel bars into pavement joints, continuous "daylighting" of granular subbase material, lime- and fly ash-modified subbgrades, longitudinal tining, PCC overlays for asphalt concrete, crumb rubber overlays, and many others. The proposed research will evaluate a specified number of pavement sections where innovative technologies have been used and compare these sections to nearby conventional pavement sections. Analyses will include annual maintenance cost(s), cracking indices, faulting indices, international roughness indices, decibel measurements, faulting, shoulder rating, spalling at joints and other selected criteria. This research can be used to evaluate annual maintenance costs for specific innovative pavement sections versus annual maintenance costs for more conventional pavement systems. Research will also allow comparison of various pavements quality indicators from conventional pavements versus those same indicators for the more innovative pavement systems.

McReynolds, R. 2004. *Midwest States Accelerated Testing Program*. SPR-3(047). Topeka, KS: Kansas Department of Transportation. http://www.pooledfund.org/projectdetails.asp?id =202&status=23.

As part of a national effort to improve pavement performance in the United States, Departments of Transportation in Iowa, Kansas, Missouri, and Nebraska are designing a number of new pavement mixes and structures. To learn more about the performance of these new designs and products before they are put on the road, large scale testing is necessary in an experimental setup that represents actual road conditions and real world situations. For this, an accelerated testing facility was built in Kansas. Testing is being conducted under actual road conditions that include exposure to both highway traffic (repetitive loading) and adverse environmental effects (temperature and moisture variations). The goal is to provide DOTs with data about pavement performance in a test environment, thus allowing for analysis and possible adjustments before undergoing the expense of paving on construction projects. The benefits from eliminating mistakes in the laboratory instead of on the road and the large reduction in time for evaluation and verification could represent hundreds of thousands of dollars in saving to the state DOTs on just a few projects. The long-term potential benefits are high with respect to the research/testing investment. This directly translates into time saving and reduction in maintenance and production costs and fewer accidents or hazardous situations on the road in work zones during road repairs.

Klieger, P., G. Monfore, D. Stark, and W. Teske. 1974. D-Cracking of Concrete Pavements in Ohio. Report No. OHIO-DOT-11-74. Skokie, IL: Portland Cement Association.

A three-phase program was undertaken to determine the extent and severity of D-cracking in Ohio and to determine the role of drainage and materials properties in its development. A rating system was

established to evaluate the performance of materials, coarse aggregate in particular, in existing pavements. Data from these surveys have been processed for storage in a computerized retrieval system. Laboratory freeze-thaw testing has identified the importance of source of coarse aggregate in the development of distress and has provided strong evidence that reducing the maximum particle size of the aggregates may reduce or eliminate the development of D-cracking. A test procedure has been recommended for identifying coarse aggregate sources and gradations vulnerable to freeze-thaw failure in pavements. Source of cement was found, in laboratory tests, to be of minor importance, while level of air entrainment within the existing specified range was found to be of essentially no importance in this problem. The presence of bulk water or only capillary held water in granular subbases was found to have little differential effect on the degree of saturation of certain coarse aggregate materials in simulated pavements exposures. A test road has been designed to verify the importance of certain materials factors in the development of D-cracking, and a gage has been developed to measure moisture changes in subbases and pavement slabs.

Majidzadeh, K. 1973. *Field Study of Performance of Continuously Reinforced Concrete Pavements*. Report. No. OHIO-DOT-09-74. Columbus, OH: Ohio Department of Transportation.

In this report, the results of field observations on CRC pavements constructed in the state of Ohio are presented. The field performance parameters such as deflection, moduli variability, support conditions, crack spacing and pattern, and drainage conditions are evaluated and related to pavement structural conditions. The results of pavement core strength data are used to develop interrelations between material properties and life expectancy of the CRC pavement structure. The concept of concrete maturity and the strength-maturity relations are used as a basis for a proposed design scheme. The results of field curing conditions and the effects of curing methods on the crack spacing and pattern have also been investigated.

This field study has shown that the crack spacing and pattern is independent of curing conditions and is mostly affected by the climatic condition prevailing during construction. It is also shown that, in CRC pavements constructed using soil-cement or lime-fly ash mixture, the transverse cracks in the pavement structure have, in all instances, penetrated into the base course. The drainage conditions in these pavements have been shown to be of critical significance. Similarly, this study has demonstrated the extent of variability observed in the construction of these pavements. The field observation of the performance of an overlayed structure on a CRC pavement has indicated that reflection cracking would occur in areas where the continuity of steel reinforcement has been destroyed.

Majidzadeh, K. and R. Elmitiny. 1982. *Long-Term Observations of Performance of Experimental Pavements in Ohio*. Report No. FHWA/OH-81. Worthington, OH: Resource International.

This report presents long-term evaluation data and analyses for eight experimental pavement projects constructed in Ohio. The study projects include both rigid and flexible pavements and are scattered throughout the state. Pavement age is currently approaching 10 years for some projects. The pavements were extensively monitored and tested at the time of construction, and during 1979 and 1980, as part of this research study. Collected data included pavement condition rating of visible distress, Dynaflect defection, test properties of core and subgrade samples, and estimated remaining structural life and overlay requirements.

Majidzadeh, K. 1977. *Observations of Field Performance of Continuously Reinforced Concrete Pavements in Ohio*. Report No. OHIO-DOT-12-77. Columbus, OH: Ohio Department of Transportation.

This report documents the fact that the Chang-Majidzadeh design criteria can be used to predict crack spacing in CRC pavement structures. The Chang-Majidzadeh model is also found to be in agreement with the NCHRP proposed design criteria. The following major points of agreement were identified. (1) The optimum average crack spacing in CRC pavements is five feet. Crack spacings smaller than five and greater that eight feet are not desirable. (2) Crack spacing is more uniform in thicker CRC pavements (nine inches) than in thin pavements (six inches). (3) Depth of steel reinforcement has a significant influence on crack spacing. As the ratio of steel depth to pavement thickness increases, an increase in crack spacing results. That is, the placement of steel at depths above mid-depth results in closer crack spacing. (4) The results of the analysis indicate that the location of steel reinforcement affects the crack opening. The placement of steel reinforcement below mid-depth results in excessive crack opening. This finding is in agreement with the results of field observations. (5) Optimum crack spacing, crack opening and steel stress are greatly dependent on the environmental conditions during the curing period. Air temperature and climatic conditions such as cloud cover (radiation flux) affect the temperature distribution in the pavement concrete during the plastic and hardened states. Temperature variations during early curing periods and the temperature differential during the service life affect the pavement performance.

Majidzadeh, K. 1989. *The Ohio Pavement Rehabilitation Demonstration*. Report No. FHWA/OH-89/017. Westerville, OH: Resource International.

This report presents a cooperative study initiated in 1983 by the Federal Highway Administration (FHWA) and the Ohio Department of Transportation (ODOT). Its purpose was to establish cost and performance data for various rehabilitation strategies in Ohio. The Ohio Pavement Rehabilitation Demonstration Program consisted of ten projects: four unbonded concrete overlays, one modified concrete pavement restoration, three crack and seat projects with various asphalt overlay thicknesses, one thin asphalt concrete overlay on an under sealed concrete pavement with new composite shoulders, and a six-inch asphalt concrete overlay over a D-cracked pavement with minimal joint repair. The construction operations have been documented and the performance of each project was periodically monitored. Monitoring included condition rating, crack surveys, deflection testing, roughness measurement, and ride quality.

Majidzadeh, K. and L.O. Talbert. 1971. *Performance Study of Continuously Reinforced Concrete Pavements*. Report No. OHIO-DOT-03-72. Columbus, OH: Ohio Department of Highways; U.S. Department of Transportation.

This research documents the performance of CRCP on Ohio roads.

Munoz, S. R. and E. Y. J. Chou. 195. *Identification of Durability Problems Under Concrete Pavement Joints*. Report No. ST/SS/95-004. Toledo, OH: The University of Toledo.

This study investigated curability problems encountered under concrete pavement joints. For this study, concrete cores were taken at three different locations in Ohio. The core samples varied in the type of aggregate and cement used in the mix. Core samples taken at the joint showed large amounts of deterioration, while samples taken at distances away revealed no signs of distress. A survey was conducted with all the departments of transportation in the U.S., in which 19 states reported experiencing a similar type of concrete joint distress. The responses from the survey indicated that the cause of the distress might be from a high concentration of compressive stress or chemical activity. Laboratory tests including petrographic analysis, air content, and chloride-ion content were conducted on the core samples taken at the three sites. Also, a scanning electron microscope was used in order to determine whether any deleterious substances could be identified. The results showed that the aggregate at all sites were intact, hard, and sound. The results from the tests indicted that leaching of the cement is occurring from prolonged saturation at the joint. It is recommended that the drainage at the joint be improved and deicers with no gypsum or sulfur be used in order to prolong the life of the joint.

Muethel, R.W. 1989. *Calcium Carbonate Precipitate from Crushed Concrete.* Research Report No. R-1297. Lansing, MI: Materials and Technology Division, Michigan Department of Transportation.

Inspections of geotextile-wrapped drainage system installations have revealed that geotextile filters can become coated with a calcium carbonate precipitate, which has been found to occur when leachable calcium compounds are present in the drainage course aggregates. Laboratory tests for calcium carbonate precipitation have identified crushed portland cement concrete as an aggregate that produces heavy calcium carbonate deposits when crushed to fine aggregate size. Tests for calcium carbonate precipitation have indicated that aggregates such as gravel, crushed stone, and blast furnace slag do not produce heavy calcium carbonate deposits when crushed to fine aggregate size. This investigation was designed to determine the comparative amount of calcium carbonate precipitate produced by crushed concrete 5G open-graded drainage coarse, an aggregate that predominantly contains coarse-sized particles. In addition to the crushed concrete, samples of gravel, crushed stone, and blast furnace slag were tested as control aggregates representing three major types of material available for drainage courses. Results indicated that crushed concrete fines passing the No. 4 sieve can produce heavy calcium carbonate precipitates, and coarser material has the potential for producing continued calcium carbonate deposition. No calcium carbonate precipitation resulted from soak tests conducted on the gravel and crushed stone control aggregates. A negligible amount of calcium carbonate precipitation was formed by the blast furnace slag control aggregate.

It is recommended that crushed concrete fines passing the No. 4 sieve should not be used in conjunction with drainage systems containing geotextile filter fabrics. Additionally, crushed concrete for 5G open-graded drainage course should be limited to installations where drainage gradients are adequate to prevent stagnant water conditions. Finally, calcium hydroxide depletion should be investigated as a contributor to the deterioration of pavements at joints and cracks where continued chemical activity is likely to occur. Leaching of the calcium hydroxide component of concrete may be a significant contributor to the deterioration of pavements at joints. This process has received little attention and should be investigated.

Muethel, R.W. 1987. *Development of Test for Calcium Carbonate Precipitation in Aggregate.* Research Report No. R-1286. Lansing, MI: Materials and Technology Division, Michigan Department of Transportation.

Inspections of prefabricated drainage system (PDS) installations have revealed calcium carbonate deposits plugging geotextile filters. The deposits have occurred in systems using steel furnace slag as open graded drainage course (OGDC). The findings resulted in a departmental moratorium on the use of steel furnace slag in PDS installations. This project was established to develop a laboratory test to identify aggregates that would produce carbonate deposits in drainage installations. Selected aggregates including steel furnace slag, blast furnace slag, crushed Portland cement concrete (PCC), crushed limestone, and crushed dolomite were tested using the laboratory procedure. The steel furnace slag and crushed concrete aggregates produced heavy carbonate deposits. No deposits formed from the blast furnace slags, limestone, or dolomite.

Muethel, R.W. 1989. *Freeze-Thaw Evaluation of Selected Rock Types From a Composite Sample of Michigan Gravel.* Research Report No. R-1301. Lansing, MI: Materials and Technology Division, Michigan Department of Transportation.

The glacial gravels of Michigan contain a mixture of durable and non-durable rock types. Twenty-four rock types sorted from glacial gravel obtained from 49 selected sources were subjected to the standard MDOT laboratory acceptance tests for aggregates, including those for freeze-thaw durability, abrasion loss, and sulfate soundness loss. Additional information was obtained form specific gravity, absorption, and Iowa Pore Index determinations. Results of the laboratory tests supported the MDOT classification. The deleterious rock types showed low freeze-thaw durability in concrete; the durable rock types showed high durability. The durable rock types exhibited no ill effects form vacuum saturation pre-treatment for freeze-thaw testing. Most of the deleterious rock types displayed undesirable pore characteristics similar to the D-cracking carbonates investigated in Iowa. The deleterious rock types also recorded lower specific gravities and higher absorptions that the durable rock types indicating that heavy media separation can remove most of the deleterious rock types from Michigan glacial gravels. The carbonate rock constituents including possible D-cracking particles were not evaluated, but will be investigated in a separate study.

Novak, E.C. Jr. 1983. *Infiltration of Subbase Sand Into Open Graded Drainage Course (OGDC) Bases.* Research Report R-1211. Lansing, MI: Testing and Research Division, Michigan Department of Transportation.

This abbreviated study was conducted to determine whether open-graded drainage course material (OGDC) bases could be expected to perform satisfactorily when placed directly on sand subbase and to evaluate the effectiveness of filter fabric for improving performance when placed between OGDC base and subbase layers. Both rigid and flexible pavements were to be considered in the study. However, much of the information obtained is not specific enough to offer definite conclusions at this time. Also, the effect that subbase frost action might have on settlement of the pavement surface could not be established.

The results show that unless a filter fabric separates base and subbase layers, sand will infiltrate into voids of OGDC bases. The degree to which sand infiltration takes place will govern the performance of OGDC bases and ultimately influence pavement surface performance. Based on results of this study and presumed environmental effects, the following conclusions regarding the performance of OGDC bases appear to be warranted. On rigid pavements, a layer of filter fabric between OGDC and subbase layers should ensure good performance of OGDC bases under any subbase condition. OGDC bases should perform satisfactorily when placed directly on a sand subbase when the subgrade permeability is equal to or greater than the subbase. OGDC bases may or may not perform satisfactorily when placed on a sand subbase layer subject to a loss of density.

Oehler, L.T. 1978. Salt Degradation Study Memorandum, Re: Research Report R-1100. Michigan Department of Transportation, November 29, 1978.

This report contains statistics obtained from data sent to the MDOT in November 1978. The average salt gradation of 30 samples of variance was used to analyze the data. A table lists the analyses of the 30 samples that were taken from a salt shipment.

Opland, W.H. and V.T. Barnhart. 1995. *Evaluation of the URETEK Method for Pavement Understanding.* Research Report No. R-1340. Lansing, MI: Materials and Technology Division, Michigan Department of Transportation.

This project was initiated in 1993 to evaluate the use of URETEK 486 high-density polyurethane as a method of raising and undersealing concrete pavement slabs. The URETEK method is a patented process that was originally developed in Europe, involving special high-density polyurethane for an undersealing compound, which distinguishes URETEK form typical grouting mixtures used in mud-jacking operations. The URETEK method improved the base support where the pavement was severely cracked. However, where the cracks were either hairline or open 1/8 in. or less, there was little improvement in the base support. Where the pavement was severely faulted, the URETEK did raise the pavement and provided a temporary increase in base stability. The URTEK method had some insulating effect of the base that caused differential frost heaving when the adjacent lane was not similarly undersealed. As expected, the depth of the penetration of the URETEK into open graded drainage course (OGDC) was dependent on the gradation (porosity) of the OGDC. While base support was initially improved, the base support decreased somewhat during the one-year trial period. Therefore, more evaluation is needed to determine if URETEK is an effective method of undersealing and raising pavements supported on open-graded drainage courses.

It is recommended that URETEK not be used as a substitute for mud-jacking for pavements with open-graded bases. However, additional limited testing is warranted to gain further experience and knowledge about the materials limitations and capabilities. At this time, URETEK should only be considered as an alternate to mud-jacking on pavements with dense-graded aggregate bases.

Paxton, J.T. 1982. Ohio Aggregate and Concrete Testing to Determine D-Cracking Susceptibility. *Transportation Research Record* 853: 20–24.

Several laboratory test methods were analyzed to determine their capability of indicating the D-cracking susceptibility of coarse aggregates. Two methods were modified versions of ASTM C666 A and B, two were unconfined freeze-thaw tests of the aggregate, and the remaining two were standard sodium and magnesium soundness tests. The major modification of the ASTM C666 test methods was to determine the elongation of the test specimens versus routine weight-loss determinations and/or sonic modulus determinations. Results are evaluated by plotting the percentage of expansion versus the number of cycles completed and calculating the area under the curve generated. Although 10 specimens are used in the testing, the 2 high and 2 low test results are removed before final analysis. The correlation of this test method with service records of various aggregates was found to be good; however, when the same coarse aggregates were tested in sodium sulfate, magnesium sulfate, or unconfined freeze and thaw, the results did not correlate well with the service records.

Paxton, J.T. and W.R. Feltz. 1979. *Development of Laboratory and Field Methods for Detecting D-Cracking Susceptibility of Ohio Coarse Aggregates in Concrete Pavements*. Report No. FHWA/OH/79/006. Columbus, OH: Ohio Department of Transportation.

The phenomenon known as D-cracking cannot be detected in concrete pavements, prior to its appearance at the surface, by any nondestructive method other than coring. Several potential methods of detection available to the researchers have been investigated on test slabs and actual pavements without success. Several laboratory test methods were analyzed. It was hoped these would indicate the D-cracking susceptibility of coarse aggregates, when used in concrete for pavement slabs. Two methods were modified versions of ASTM C-666 A and B, two were unconfined freeze-thaw tests of the aggregate and the remaining two were standard sodium and magnesium soundness tests. Although ten specimens were used in testing, the two high and tow low test results are removed before final analysis. The correlation of this test method with service records of various aggregates was fond to be excellent; however, when the same coarse aggregates were tested in sodium sulfate, magnesium sulfate or unconfined freeze and thaw, the results did not correlate well with the service records.

Peterson, K.R., T. Van Dam, and L.L. Sutter. 2002. *Assessment of the Cause of Deterioration on US-23 South of Flint, Michigan*. Draft Technical Report. Houghton, MI: Michigan Tech Transportation Institute, Michigan Tech Civil & Environmental Engineering Department.

Sections of US-23 south of Flint are suffering extensive map cracking and joint deterioration in spite of the fact that they were constructed only nine and a half years ago in 1992. An adjacent section constructed the following year using comparable design features and materials remained in good condition with little sign of visual distress. Eighteen cores were taken, nine from the mix design used in 1992 and nine from 1993.

Based on the results of this study the following conclusions can be drawn. Most of the concrete initially had an air-void system that was adequate to protect the paste against freeze-thaw damage. Since construction, the air-voids have been filling with secondary mineral sulfate deposits, which may be compromising the air-void efficiency. Also, the chert particles in the fine aggregate are undergoing a deleterious alkali-silica reaction in all of the “poor” pavement sections. The total alkalis measured were in excess of that recommended for mild alkali-silica reactivity protection. The poorest performing section had a sulfate content that was 30% in excess of what would be expected based on the mixture design alone. Two hypotheses have emerged that can partially explain the deterioration. The first centers on the alkali-silica reactivity of the chert particles in the fine aggregate, which is aggravated by the high total alkalinity and mitigated by the presence of Class F fly ash. The second focuses on the dissolution of the calcium sulfide and the formation of sulfate-bearing mineral, which results in a type of internal sulfate attack. Generally, the permeability of concrete made with slag concrete needs to be conclusively and authoritatively documented. Also, a well-designed factorial experiment needs to be conducted to evaluate both the ASR and calcium sulfide dissolution issues, and the interaction between the two.

Nebraska Department of Roads. Nebraska Hwy 33–US 77 Interchange west to county line: Grind and Concrete Repair & Surface Shoulder 12219. Project No. RD-33-6(1014). Lincoln, NE: Nebraska Department of Roads.

This research discusses the work on 8 in. plain concrete pavement constructed in 1955. It consists of diamond grinding and texturing mainline concrete pavement surface for profile improvement. Project information is detailed, as well as equipment, diamond grindings, methods of measurement, and basis of payment.

Saraf, C.L. and K. Majidzadeh. 1995. *Utilization of Recycled PCC Aggregates for Use in Rigid and Flexible Pavements*. FHWA/OH-95/025. Westerville, OH: Resource International.

This research was conducted to demonstrate the feasibility of using recycled crushed concrete form old pavements as aggregates in new PCC and asphalt pavements and to develop guidelines and criteria for making cost-effective decisions concerning the recycling of PCC pavements. This study included several activities: preconstruction evaluation of recycled PCC aggregates, construction monitoring and evaluation of mixes, post construction evaluation of mixes, and data analysis.

Cores of the old pavement (PCC) were obtained before their removal and tested in the laboratory. The aggregate from the crushed cores were then used to prepare trial mixes and measure the strength characteristics of the recycled mix. Also, shortly after the construction of all test sections, 32 cores from rigid pavement test sections and 24 cores from flexible test sections were obtained. These samples were also tested in the laboratory to determine various characteristics of concrete and asphalt mixes. Sixteen slabs out of a total of 216 slabs of recycled concrete mix developed transverse cracks at the mid-slab after about 2 months of their opening to traffic. Based on the results of this study it was concluded that the use of recycled PCC aggregates in concrete mix is a feasible alternative. However, the use of sand portion of recycled aggregates in concrete mix is not practical because this material has very high absorption compared to natural sand.

Sargand, S. and G. Hazen. 1999. *Coordination of Load Response Instrumentation of SHRP Pavements – Ohio University*. FHWA/OH-99/009. Athens, OH: Ohio University.

The Ohio Department of Transportation constructed an experimental pavement for the Strategic Highway Research Program (SHRP) on U.S. 23 north of Columbus, which included 40 asphalt and concrete test sections in the SPS-1, 2, 8, and 9 experiments. These sections contained various combinations of structural parameters known to affect performance. To enhance the value of this pavement, sensors were installed in 18 test sections to continuously monitor temperature, moisture, and frost within the pavement structure, and 33 test sections were instrumented to monitor strain, deflection, and pressure generated by environmental cycling and dynamic loading. Also, two weigh-in-motion systems and a weather station were installed to continuously gather the necessary traffic and climatic information required to properly interpret the performance data. Nondestructive testing conducted with the FWD and Dynaflect, and five series of controlled vehicle test were performed between 1995 and 1998 to assess the response of these test sections to dynamic loading. This report documents how the instrumentation was installed and monitored, provides details of the controlled vehicle tests, and summarizes results of the nondestructive testing.

Sargand, S. 1994. *Development of an Instrumentation Plan for the Ohio SPS Test Pavement (DEL-23-17.48)*. Report No. FHWA/OH-94/019. Athens, OH: Ohio University.

A Specific Pavement Studies (SPS) program, formulated under the Strategic Highway Research Program (SHRP), consists of nine experiments, four of which will be included in this DEL-23 project. The Ohio Test Road consists of SPS-1, SPS-2, SPS-8, and SPS-9 experiments, all constructed for this project where the climate, soil, and topography are uniform throughout. In this comprehensive instrumentation plan, 33 sections are to be instrumented. LTPP guidelines require four instrumented sections in each of the SPS-1 and SPS-2 experiments for the study of seasonal factors and dynamic response. DEL-23 includes an additional 9 instrumented sections for the SPS-1 experiment, 12 sections for the SPS-2 experiment, and 2 sections each in the SPS-8 and SPS-9 experiments to study structural response parameters. A total of 18 sections will be instrumented for the study of seasonal factors, ten more sections than required by SHRP.

This report provides a detailed description of types of sensors, installation methodology, calibration procedures and wiring schematics for instrumentation of pavements for the Ohio SHRP SPS Test Road to measure environmental factors and structural response. Environmental or climatic parameters include temperature, base and subbase moisture, and frost depth. Structural response parameters entail strain, deflection, pressure, and joint opening.

Sargand, S. 2000. *Effectiveness of Base Type on the Performance of PCC Pavement on ERI/LOR 2*. Interim Report for Continued Monitoring of Instrumented Pavement in Ohio. Report No. FHWA/OH-2000/005. Athens, OH: Ohio University.

This interim report discusses the current status of the ERI/LOR 2 research project that is investigating the effects of various base materials and design features on the performance of portland concrete cement pavement. In 1990, rehabilitation for the initial project begun in 1974 was undertaken through the construction of additional test pavements in Erie County and Lorain County. Six base types and two aggregate sources were used in the new test sections. One of the aggregate base sources was considered resistant to D-cracking. The other was considered susceptible to D-cracking. The six bases tested included ODOT 304, 310, 3071A, 307NJ, and asphalt and cement-treated free draining bases.

Nondestructive testing was performed in June and August 1999. FWD tests were conduced to determine load transfer on the test sections. Cracks in slabs were also evaluated through inspection and taking concrete cores. These core samples indicated that most of the cracks were initiated at the pavement surface and propagated downward. No D-cracking has been observed in the test sections. An extensive series of laboratory tests has also been completed to determine resilient modulus and the strength of each base type. To date, the sections with bases 307NJ and CTFDB are performing poorly and have developed a substantial number of cracks. The ATFD base is performing the best of the test bases. Additional monitoring is needed to assess the overall performance of each base type and to address potential D-cracking.

Simonsen, J.E. and E.C. Novak, Jr. 1981. *Concrete Pavement Performance Problems and Foundation Investigation of I-75 from the Ohio Line Northerly to the Huron River*. Research Report No. R-1171. Lansing, MI: Testing and Research Division, Michigan Department of Transportation.

These data indicate that the installation for subbase underdrains may be beneficial in removing gravity drainable water from subbase and side slope areas in those cases where the subbase materials contain gravity drainable water. Such drains could also serve to reduce the tie required for subbase consolidation. However these benefits may not significantly improve the pavements performance for two reasons: (1) the add-on lane is already heavily transverse cracks; (2) faulting is caused by pumping of the base which should be largely unaffected by the presence of a subbase underdrain.

The results of this investigation adds to growing evidence that rigid pavement foundations are not free draining. The foundation on I-75 was found to be deficient in two critical respects: the base permeability and frost susceptibility is similar to that of silts, and the subbbase has a high water-holding capacity. In the case of rigid pavements, such foundation deficiencies can be minimized by using a greater thickness of concrete than would be used for a non-deficient foundation and buy using reinforcing steel and load transfer devices. It is recommended that a ‘plowed in’ retrofit subbase underdrain be installed to improve foundation drainage conditions. The repair of distressed areas should be made after placement of retrofit underdrains and within two weeks after the pavement had been sawed into removable slabs.

Smiley, D.L. 1995. *First Year Performance of the European Concrete Pavement on Northbound I-75 – Detroit, Michigan*. Research Report R-1338. Lansing, MI: Materials and Technology Division, Michigan Department of Transportation.

This report describes the performance of the I-75 European concrete pavement reconstruction project approximately one year after construction. The experimental features of the pavement design were assimilated from designs used in Germany and Austria. The objective of this project is to determine whether innovative features of typical rigid pavement designs used in European countries can be applied cost effectively to conventional designs and construction methods used for rigid pavement in the United States. Two concerns that currently prohibit their use in American designs are (1) their relatively high initial costs and (2) their unknown effect of life-cycle costs over the pavement’s service life.

The European pavement appears to be performing as expected, except for the disappointing results pertaining to the exposed aggregate surface as a means to reduce traffic noise levels. Specific points of interest about the project are summarized as follows: no surface distress features have developed on the European pavement. The EPDM joint seals art performing satisfactorily. The exposed aggregate surface appears to have lost macro-texture in the two inner lanes of northbound I-75. Surface friction numbers increased and the exposed aggregate surface provides only a slight reduction in exterior Leq noise levels.

Stark, D. 1986. *The Significance of Pavement Design and Materials in D-cracking*. Interim Report. FHWA/OH-86/008. Skokie, IL: Construction Technology Laboratories.

A two-phase program was undertaken to verify, under field conditions, that reducing maximum aggregate particle size can minimize or eliminate D-cracking. This study was carried out also to determine the role of other materials and environmental factors in D-cracking which are not amenable to laboratory study. One phase consisted of repeat pavement surveys of existing pavements to determine whether reducing maximum particle sizes has alleviated D-cracking. The other, primary, phase consisted of monitoring the performance of a test road near Vermilion, Ohio, using visual

inspections and moisture measurements and examinations of concrete cores. Visual inspections confirm that reducing the maximum particle size does minimize or eliminate D-cracking. Other observations indicate that pavement concrete on clay subgrade, stabilized granular bases with and without artificial drains, and vapor barriers, performed similarly with respect to the initial development of D-cracking. Type of joint seal, including no seal, had no significant effect of D-cracking. Moisture measurements of cores indicated an increase in degree of saturation of concrete after one year, with a general leveling off after that period. Saturation levels were, overall, somewhat higher near the bottom than near the top of the slab. Examination of cores revealed that D-cracking is developing upward from near the bottom of the slab. Other observations revealed that where maximum aggregate particle size was reduced to avoid D-cracking, a greater incidence of intermediate transverse cracking developed with attendant faulting. It is recommended that the test road continue to be monitored through visual inspection and examination of cores.

Stark, D. 1991. *The Significance of Pavement Design and Materials in D-Cracking*. Final Report. FHWA/OH/91/009. Skokie, IL: Construction Technology Laboratories.

A two-phase investigation was carried out to determine the efficacy of reducing the maximum size of coarse aggregate to minimize freeze-thaw damage and the development of D-cracking in highway pavements. This included evaluation factors not amenable to laboratory conditions. One phase consisted of repeat pavement surveys of already existing pavements to determine whether reducing maximum particle sizes of coarse aggregate alleviated D-cracking. Results are summarized in an interim report for this project, dated December 1986. The other, primary phase was the construction and monitoring of a test pavement on SR2 near Vermilion, Ohio, which incorporated design as well as materials variables with respect to D-cracking (and other performance characteristics). Results after 16 years of service (1975 through 1999) indicate that reducing the maximum size of coarse aggregate can alleviate D-cracking, and that, once initiated as seen at the wearing surface, traffic loading becomes an important factor in propagating the extent and severity of deterioration. “Daylighting” the granular subbase (no artificial drains) greatly improved the rideability of the pavement, while other factors, such as source of cement, joint sealants, subbase vapor barriers, and longitudinal drains were of minor, if any, significance. Other effects on performance also were noted. For example, reducing the maximum size of coarse aggregate tended to increase the frequency of transverse cracks, many, if not most, of which were faulted. Unsealed joints appeared to perform as well as joints containing sealants. Tied concrete shoulders appeared to greatly alleviate faulting and pumping.

Ohio Research Institute for Transportation and the Environment. 1997. *The Ohio Strategic Research Program; Specific Pavement Studies*. Athens and Columbus, OH: Ohio Research Institute for Transportation and the Environment; Ohio Department of Transportation.

As part of its support for the Strategic Highway Research Program (SHRP), the Ohio Department of Transportation and Federal Highway Administration constructed a comprehensive test road. This project affords SHRP with a unique opportunity to compare the performance of pavement sections in these experiments at one site where topography, soil, and climate are uniform. To enhance the value of this test road, seasonal and dynamic response instrumentation were installed in 34 of the 40 test sections by civil engineering faculty, staff, and students from six universities in Ohio. Falling Weight Deflectometer and controlled vehicle loadings will be used to gather response data on these sections under a variety of environmental conditions and periodically throughout their service lives. These data will provide the pavement community with valuable insight into the effects of climate and cumulative traffic loadings on performance.

Traylor, M.L. 1982. Efforts to Eliminate D-Cracking in Illinois. *Transportation Research Record* 853: 9–14.

Severe D-cracking on interstate pavements prompted the Illinois Department of Transportation to initiate a program to identify and eliminate the use of D-cracking aggregate. More than 200 crushed-stone and gravel sources were evaluated by using both the Iowa pore index and ASTM C-666 freeze-thaw tests. Shortcomings in the Iowa pore index test have resulted in its use being limited to a screening test. The results of the freeze-thaw program have formed the basis for a specification that the state believes will guarantee the durability of future pavements.

Traynowicz, M. *Early Concrete Pavement Deterioration*. Research in progress (completion date August 1, 2008). R-02-07. Lincoln, NE: Nebraska Department of Roads. http://ndorapp01.dor.state.ne.us/research/rpms.nsf/.

The Nebraska Department of Roads has experienced some early deterioration in concrete pavements. The types of deterioration need to be determined, as well as ways to slow or stop it. The objective of this research is to produce longer lasting concrete pavements by determining the causes of early deterioration and learning how to prevent it. As a result of this research, the researchers expect to gain familiarity with potential problems they will face with certain mixes and to understand ways they can retard or prevent those problems from occurring. By learning more about what causes the concrete deteriorations, the team can minimize or slow those reactions and produce a longer lasting surface.

Tuan, C. *Durability of PCC*. Research in progress (completion date June 30, 2004). ASR P547 with Supplement 1. Lincoln, NE: University of Nebraska and Nebraska Department of Roads. http://ndorapp01.dor.state.ne.us/research/rpms.nsf/.

NDOR material engineers, aggregate suppliers, cement suppliers, suppliers of pozzolanic materials, and concrete producers believe that there is a need to quantify the reactivity levels of the aggregates from the various sources frequently used in Nebraska and that there is a need to find simple means to mitigate the unwanted expansion and deterioration of concrete.

This proposal is for phase one of a possible two-phase project. The objective of the Phase One project is to develop a detailed testing program involving ASTM C 1260 and C 1293 tests to evaluate the reactivity levels and the ASR potential of the various Nebraska aggregates in combination with various amounts of cements, fly ashes (Class C and F), granular blast furnace slag and calcined clay. Phase one will develop a comprehensive test matrix and program plan. The development of the matrix and plan will be the result of input from interested parties in the concrete industry. The results of the phase one test matrix and program plan will take the guesswork out of which tests to conduct in phase two of this project. Phase two involves the execution of the test matrix involving an extensive testing program and data analysis. Based on the findings, specifications for the use of various aggregates, cements, and pozzolans will be drafted and circulated for adoption by NDOR.

Tuan, C. *Lithium Field Implementation Trials*. Research in progress (completion date June 30, 2005). RDT-QX5(1). Lincoln, NE: University of Nebraska and Nebraska Department of Roads. http://ndorapp01.dor.state.ne.us/research/rpms.nsf/.

This research opportunity is provided by FHWA to implement lithium-based technology in field projects through FHWA division offices. This project is proposed to be a joint effort of NDOR, the U.S. Army Corps of Engineers, Omaha District (USACE), and the University of Nebraska-Lincoln (UNL). The objective of this research is to develop materials and application procedures to stabilize or reduce the ASR distress mechanism in existing and aged concrete using lithium saturation and pressure injection treatment. Expected results from the proposed research include reduced ASR-related deterioration, improved concrete durability, improved life-cycle performance, and reduced maintenance costs. The lithium treatment should produce a revitalized, ASR-stable concrete pavement without the cost and downtime of traditional concrete repair or replacement operations.

Van Dam, T., N. Buch, K.R. Peterson, and L.L. Sutter. 2002. *A Study of Materials-Related Distress (MRD) in Michigan's PCC Pavements, Phase 2.* Research Report RC-1425. Houghton, MI: Michigan Technological University.

Materials-related distress (MRD) is of concern to the Michigan Department of Transportation, potentially affecting all concrete transportation structures including pavements, bridges, retaining walls, barriers and abutments. MRD is a direct result of a component breakdown within the concrete matrix due to the interaction between the concrete and its surrounding environment. The specific MRD mechanism and extent varies with location due to differences in local environmental factors, concrete constituent materials, construction practices, deicer applications, and traffic. MRD can occur even in properly constructed PCC pavements having adequate structural capacity, resulting in costly, premature concrete deterioration and eventual failure. This study investigated the occurrence of MRD in Michigan's concrete pavements, using a variety of investigative techniques, including visual assessment, nondestructive deflection testing, strength and permeability testing, microstructural characterization, and chemical methods to determine the causes of observed distress. Based on this investigation, specific recommendations were made regarding treatment of distressed pavements and approaches to avoid the occurrence of these distresses in future concrete pavement construction.

The hypothesis regarding the dissolution of calcium sulfide should be tested. It is recommended that a controlled laboratory study be initiated to investigate the following: the dissolution process and how it is effected by cement properties and total alkalinity; the relationship between ASR in the chert constituent of the fine aggregate and the presence of slag coarse aggregate; the ability of fly ash and GBFS to mitigate the effects of calcium sulfide dissolution and ASR in the fine aggregate.

The densified paste region characterized by unhydrated cement grains adjacent to the slag particles should be studied to determine its effect, if any, on the observed deterioration. A parametric study of all slag concrete pavements should be conducted using mix design and construction data as well as field inspections. This limited study has found that Class F fly ash might offer a way to improve the durability of concrete made with slag coarse aggregates, whereas Class C fly ash has had an apparently negative impact. A more detailed large-scale study should be implemented to confirm this finding and determine if other variable are also instrumental.

Williams, G.J. and E. Chou. 1994. *Performance Evaluations of Rigid Pavement Rehabilitation Techniques*. Report No. ST/SS/94-002. Toledo, OH: The University of Toledo.

This study investigated the effectiveness of six concrete pavement rehabilitation techniques: full depth repair, joint restoration, pavement overlay, concrete pavement restoration, crack and seat, and subsealing. Conclusions on the effectiveness of the techniques were based on functional and structural data collected on 10 projects around the state of Ohio. Observations of trends in the data over time and over traffic loads along with statistical analysis comprised the methods used to analyze the data for the conclusions. The results indicate joint spacing of less than 27 feet improves the effectiveness of joint/full depth repair on joint performance. Portland cement concrete overlays outperform asphalt concrete overlays both functionally and structurally. Sawing and sealing joints in asphalt concrete overlays perform better than not sawing and sealing joints in asphalt concrete overlays. Concrete pavement restoration is not very effective as a rehabilitation technique. Subsealing improves the soil conditions underneath a pavement. Finally, crack and seated portland cement concrete pavement outperforms non-crack and seated portland cement concrete pavement when used underneath an

asphalt concrete overlay. The results obtained here should be complimented with additional data to add further confidence to these results.

Overlays

Baladi, G. and T. Svasdisant. 2002. *Causes of Under Performance of Rubblized Concrete Pavements.* Research Report RC-1416. East Lansing, MI: Pavement Research Center of Excellence, Michigan State University.

When asphalt concrete is placed on top of an existing concrete pavement, within a relatively short time (3 to 5 years depending of the thickness of the AC overlay and the pre-overlay repairs of the original concrete pavement) the resulting composite pavement typically exhibits reflective cracking from the underlying concrete pavement. Since 1986, the Michigan Department of Transportation (MDOT) and other state highway agencies are rubblizing concrete pavements to prevent reflective cracking through the bituminous surfaces. Over time, special provisions for rubblizing concrete pavements have evolved. However, some rubblized pavement projects are very successful and are expected to last their intended design life. Others are underperforming and have shown a reduced service life. The underperforming pavement sections have shown various types of distress, including cracking, rutting and raveling. The overall objective of this study is to determine the causes of under performance of rubblized concrete pavements. Rubblization of deteriorated concrete pavements is a viable rehabilitation option that requires more detailed quality control measures than conventional asphalt pavements. It is strongly recommended that quality control measures be revisited, tightened, and strictly enforced.

Barnhart, V.T. 1989. *Field Evaluation of Experimental Fabrics to Prevent Reflective Cracking in Bituminous Resurfacing*. Research Report No. R-1300. Lansing, MI: Materials and Technology Division, Michigan Department of Transportation.

This study involved the installation of six different types of commercially available fabric strips as reinforcement over conventionally repaired joints and cracks on a 0.9-mile section of concrete pavement being prepared for asphalt resurfacing. The purpose of the study was to compare the performance of fabric-treated and untreated repaired joints and cracks in the overlay. The field results from these projects indicate that the use of the experimental fabrics as overly reinforcement to reduce reflective cracking did, to some extent, extend the length of time for reflective cracking to show through the bituminous overlay. While there is some evidence that the experimental fabrics perform as crack resistant material, none of them have met the manufacturers' claims that they will either greatly reduce or completely prevent reflective cracking.

South Dakota Department of Transportation. 1998. Section 550: Bridge Deck Preparation and Resurfacing. *1998 Standard Specifications for Roads and Bridges*. Pierre, SD: South Dakota Department of Transportation. http://www.sddot.com/operations/docs/specbook/550DUAL.pdf

The types of coarse aggregate in the existing and low-slump bridge decks are discussed. The fine aggregates used in the portland cement concrete in the "Low Slump Dense Concrete Bridge Deck Overlay" and "Class A45 Concrete Fill" and the testing of the fine aggregate are discussed. The known aggregate sources are included as well as several other details regarding the PCC used for SDDOT projects.

Eacker, M.J. 2000. *Whitetopping Project on M-46 Between Carsonville and Port Sanilac.* Research Report No. R-1387. Lansing, MI: Construction and Technology Division, Michigan Department of Transportation.

This report summarizes the construction of both projects of thin and ultra-thin concrete overlays (i.e., whitetopping) on M-46 between Carsonville and Port Sanilac. This is the first whitetopping project constructed in Michigan by the Michigan DOT. The purpose of this trial project is to study whitetopping as an alternative to standard bituminous fixes for rehabilitating deteriorated bituminous pavements. A project to the west of the whitetopping project was constructed using several of MDOTs standard bituminous methods. Construction went as planned, with no significant changes to report for either fix type. The only deviation from the plan was the thickness of the whitetopping sections. The 150 mm proposed sections were paved at 203 mm (average of 15 cores), and the proposed 75 mm inlay was paved at 106 mm (average of 3 cores). The increase was due to necessary grade and crown correction.

The research projects listed in Table B.2.7 were completed under the direction of the Iowa Department of Transportation. The table lists the research pertaining to concrete overlays. The project number, title, end date, and principle investigator are also listed.

Table B.7. Summary of Iowa DOT research related to concrete overlays

Proj.	No.	Title	End	PIs
HR	513	PC Concrete Overlay - Pottawattamie County	12/1/84	J. Lane, D. Smith
HR	520	Thin Bonded PCC Overlay	10/1/89	J. Lane
HR	527	Crack and Seat PCC Paving Prior to ACC Resurfacing (saw and seal ACC Joints)	12/1/91	J. Smythe
HR	528	Nongrouted Bonded PCC Overlay - City of Oskaloosa	1/1/92	V. Marks
HR	531	"Fast Track" PCC Overlay	12/1/89	J. Lane
HR	537	Evaluation of Bonded PCC Using Infrared Thermography (Inc HR-1045)	12/1/89	R. Dankbar
HR	559	Ultra Thin PCC Overlays	7/31/00	J. Grove, J. Cable
HR	561	Bonded Overlay Grout Evaluation	1/1/95	J. Cable
HR	1009	Bonded Thin Lift, Nonreinforced PCC Resurfacing and Patching (MLR-77-2)		J. Bergren
HR	1024	Thin Bonded Portland Cement Concrete Resurfacing (film)	11/1/80	V. Marks
HR	1045	Evaluation of Bond Retainage in PCC Overlays	2/1/88	R. Dankbar
HR	2015	Portland Cement Concrete over Broken Pavement		--
HR/TR	34	Thin Concrete Resurfacing	12/1/60	B. Myers
HR/TR	165	Experimental Steel Fiber Reinforced Concrete Overlay -1		V. Marks, R. Betterton
HR/TR	165	Experimental Steel Fiber Reinforced Concrete Overlay -2	3/1/89	V. Marks, R. Betterton
HR/TR	191	Bonded Thin-Lift Non-Reinforced Portland Cement Concrete Resurfacing	6/1/80	M. Johnston
HR/TR	244	Detection of Concrete Delamination by Infrared Thermography	11/1/82	B. Brown
HR/TR	277	Cracking and Seating PCC Pavement Prior to Resurfacing to Retard Reflective Cracking	7/1/96	W. Smith, R. Munn
HR/TR	279	Cracking and Seating PCC Pavement Prior to Resurfacing to Retard Reflective Cracking - Fremont County	7/1/96	D. Miller
HR/TR	288	Field Evaluation of Bonded Concrete Resurfacing	10/31/86	Shiraz Tayabji
HR/TR	291	Performance of Nongrouted Thin Bonded PCC Overlay	10/1/90	J. Lane, W. Folkerts
HR/TR	329	Hydrodemolition Preparation for Dense Concrete Bridge Overlays (TERMINATED)	12/1/94	V. Marks
HR/TR	341	Bond Enhancement Techniques for PCC Whitetopping	9/30/96	G. Harris/B. Skinner
HR/TR	432	Ultrathin PCC Overlay Extended Evaluation	12/31/04	J. Cable
HR/TR	466	Evaluation of Unbonded Ultrathin Whitetopping of Brick Streets	6/30/06	J. Cable
HR/TR	478	Evaluation of Composite Pavement Unbonded Overlays (Installation and Maintenance of Weigh In Motion Detection System on Iowa Hwy 13 in Delaware Co.)	6/30/06	P. Meraz/J. Cable
HR/TR	511	Design and Construction Procedures for Concrete Overlay and Widening of Existing Pavements	9/30/05	J. Cable - H. Ceylan - F. Fanous
MLR	7702	Bonded, Thin-Lift, Non-Reinforced PCC Resurfacing	5/1/77	Bergren, Britson, Schroeder

Proj.	No.	Title	End	PIs
MLR	8001	Bonded PCC Resurfacing	11/1/80	J. Bergren
MLR	8301	Bonding Agents for PCC and Mortar	8/1/83	B. Brown
MLR	8602	Early Bond Str. Determined by 007 Bond Test & Direct Shear		O. J. Lane

King, W.M. 1992. *Design and Construction of a Bonded Fiber Concrete Overlay of CRCP (Louisiana, Interstate Route 10, August 1990)*. Report No. FHWA/LA-92/266. Baton Rouge, LA: Louisiana Transportation Research Center.

The purpose of this study was to evaluate a bonded steel fiber reinforced concrete overlay on an existing eight-inch CRC pavement on Interstate 10 south of Baton Rouge, LA. The project objectives were to provide an overlay with a high probability for long term success by using a concrete mix with high cement content, internal reinforcement, and good bonding characteristics. The existing 16-year-old CRC pavement had carried twice its design load and contained only a few edge punch-out failures per mile. A 4-inch concrete overly was designed for a 20-year service life. An additional level of reinforcement bonding was provided that utilized curb type reinforcement bars epoxied into the existing slab. The primary purpose in the additional reinforcement was to provide positive bonding at the slab edges where thin overlays have a tendency to debond due to curling and/or warping. A nine-inch tied concrete shoulder was added to increase the pavement's structural capacity.

The overall Serviceability Index of the pavement increased from 3.4 to 4.4, with measured Profile Index levels typically below the five-inch/mile specification. Tests revealed excellent bond strengths, and reduced edge deflections by 60% under a 22,000 pound moving single-axle loading. Cores taken over transverse cracks in the overlay indicated reflection cracking from the transverse cracks in the original pavements. The final results reveal an estimated 35% of these cracks have reflected through, and debonding has not occurred at the pavement edges. Anticipation of reflective cracking was one consideration in using the steel fibers, which provide three-dimensional reinforcement.

Minnesota Department of Transportation. June 25, 2003. *Materials Performance System; Concrete Pavement Evaluation System (COPES) Data*. St. Paul, MN: Minnesota Department of Transportation.

This source illustrates data from route 71 in Minnesota, beginning from MP 126.26 to end at MP 129.32 in Kandiyohi County, Minnesota. The current surface is unbonded overlay-JPCP with a previous surface of JPCP. The joint system, dowels, mix design, drainage, and many other items are detailed.

Missouri Department of Transportation. 2000. *Bonded Concrete Overlay (Fast Track) – Route I-70, Cooper County*. Final Summary of Performance. Report No. RDT 00-002B. Jefferson City, MO: Missouri Department of Transportation.

This bonded concrete overlay project was constructed on I-70, Cooper County, during the summer of 1991 using "Fast Track" high early strength paving mixture. The high early strength concrete bonded overly was constructed with Type III cement to obtain a minimum compressive strength of 3,500 psi in no more than 18 hours. The original pavement was prepared by coldmilling, shotblasting, and airblasting before overlaying. A neat grout, made of Type I cement and water, was sprayed directly on the pavement.

Several problems arose during the paving of the overlay. An average of two transverse cracks was observed within two days of paving. The remaining concrete overlay was saw cut at 20-foot intervals to help control random cracking. The pavement continued to have random cracking. The mixer unit had problems with buildup of hardened concrete in the drum. The overlay had mud pockets and

segregated concrete with a raw unmixed sand layer or a weak sandy layer after paving. Since construction, the transverse cracking, longitudinal cracking, debonding, and map cracking in the concrete bonded overlay has continued to show a large increase of deterioration, especially at the locations of original pavement repairs.

The poor performance of the high early strength mix used on this project observed during construction, and in performance to date, indicated that the mix may be the source of some of the pavement distresses noted. When using a high early strength mix, strict quality control should be recommended to prevent concrete mixture, placing, and curing problems. Further research should be pursued to closely evaluate the concrete bonded overlay mix used on this project.

Simonsen, J.E. and A.W. Price. 1985. *Performance Evaluation of Concrete Pavement Overlays.* Construction Report. Research Report No. R-1262. Lansing, MI: Materials and Technology Division, Michigan Department of Transportation.

With a large portion of the concrete highway system in need of major rehabilitation work, a renewed interest in concrete overlays has surfaced as a possible alternative to recycling the existing pavement. In 1984, the MDOT constructed two concrete overlays for the purpose of evaluating their performance compared to recycled pavement and to compare the long-term cost effectiveness of the two rehabilitation systems. Also, the use of a thin sand-asphalt layer as a bond-breaker between the existing concrete surface and the new overlay was evaluated with respect to controlling reflective cracking in the concrete overlay.

Simonsen, J.E. and A.W. Price. 1989. *Performance Evaluation of Concrete Pavement Overlays.* Final Report. Research Report No. R-1303. Lansing, MI: Materials and Technology Division, Michigan Department of Transportation.

Concrete overlays were a common method used by the MDOT to rehabilitate deteriorated roads. Twenty-one overlays, from four to six inches, were placed between 1932 to 1954. All of these were of the unbonded type with a bituminous coat used as the separation medium. One overlay is still in service after 35 years. Now, with the interstate and other routes needing rehabilitation or reconstruction, the concrete overlay has again emerged as an alternative to total reconstruction. The newer overlays are thicker, 6–13 inches, and normally unbonded. Two seven-inch reinforced, unbonded, and dowelled concrete overlays were constructed in 1984.

Observations, measurements, examinations of cores, and load tests indicate that the overall performance of the 1984 overlays to date have been satisfactory. It is estimated that using an overly instead of recycling will result in at least a $35,000 savings per mile of two-lane pavement. Field and laboratory data indicate that overlays will have a favorable life-cycle cost compared to recycled pavements. Based on the performance of the two overlays, it is concluded that concrete overlays are a viable alternative to recycling when the existing facility can accommodate the extra overlay thickness.

It is recommended that careful consideration be given during the design process to the condition of the existing pavement and to the volume of commercial traffic the overlay will carry. It is also recommended that severely deteriorated and patched areas in the existing pavement be repaired to minimize failure in the overlay at these locations. It is recommended that consideration be given to improve the effectiveness of the debonding layer.

Staton, J.F. and A.R Bennett. 1990. *Performance Evaluation of Concrete Pavement Overlays to Reduce Reflective Cracking*. Research Project 90 F-168. Lansing, MI: Michigan Department of Transportation.

Two methods being studied at the inception of this research project were (1) recycling the existing

slab and (2) overlaying the existing concrete with bituminous concrete. The initial cost of recycling a pavement is relatively high and has since been discontinued as an alternative for reconstruction in Michigan due to its suspected poor performance. Overlaying with bituminous concrete has not been satisfactory due to reflective cracking in the overlay. Two types of PCC overlays were constructed on this project. One overly was a bonded type placed directly over the existing PCC pavement after rubblizing. The second PCC overlay was constructed as an unbonded type by placing a bituminous-sand mix layer on the existing PCC pavement surface before overlaying with the PCC. The rubblized and unbonded overlay area were subdivided into three sections incorporating different subbase drainage techniques to study effects of drainage on pavement performance.

Woolstrum, G. *Concrete Overlay-White Topping.* Research in progress (completion date August 1, 2006). R-02-02. Lincoln, NE: Nebraska Department of Roads. http://ndorapp01.dor.state.ne.us/research/rpms.nsf/.

NDOR currently uses asphalt overlays. However these overlays cannot prevent the reoccurrence of rutting and reflective cracking. In general, using a concrete overlay can prevent or rehabilitate these types of deterioration. The goal of the research project is to evaluate the whitetopping treatment to determine whether this is something NDOR should do more of, whether whitetopping is cost effective, and hen whitetopping should be used rather than asphalt overlay. From this research, we expect to determine the usefulness of white-topping. Historically, asphalt state highways require asphalt resurfacing an average of 8–12 years. Concrete overlays could be expected to last to 20–25 years or more without major rehabilitation.

Joints

Arnold, C.J., M.A. Chiunti, and K.S. Bancroft. 1982. *A Five-Year Evaluation of Preventative Maintenance Concepts on Jointed Concrete Pavement*. Research Report No. R-1185. Lansing, MI: Testing and Research Division, Michigan Department of Transportation.

Experimental jointed concrete pavement preventive maintenance procedures were used on 270 lane miles of I-75 and I-696 during the summer of 1975. These procedures included an objective rating on the condition of the joints, selection of the worst joints for replacement and the use of pressure relief joints at structures and at least every 850 ft., in pavement sections where repairs were not made. The conclusions were that pressure relief joints are effective in delaying joint blow-ups in the 99-ft. slab reinforced pavements with base plates and poured joint sealants. Also, preventative maintenance concepts have accomplished the intended goal of delaying emergency-type repairs for five years for more.

Arnold, C.J., M.A. Chiunti, and K.S. Bancroft. 1981. *Jointed Concrete Pavements Design, Performance and Repair*. Research Report No. R-1169. Lansing, MI: Testing and Research Division, Michigan Department of Transportation.

Background information is presented concerning the performance and problems related to postwar pavements with the 99 ft. reinforced slabs, load transfer, and base plates under the joints. Newer pavements have been designed with successively shorter slab lengths and still use load transfer and reinforcement. An experimental installation having extreme variations in drainability is discussed, and the effects of base drainage on the performance of the concrete pavement as well as the inter-relationships with aggregate quality are demonstrated. Highly variable performance with changes in course aggregate source is shown as well. The faulting of pavement joints due to rearrangement of fine base materials is shown. The effects of pressure build up in older pavements is discussed, along with strategies for pressure relief, experimental pressure relief projects, preventative maintenance, and the development of the techniques for locating pressure relief joints and installing joint filer.

Arnold, C.J. 1974. *Pressure Induced Failures in Jointed Concrete Pavements and a Machine for Installation of Pressure Relief Joints*. Research Report No. R-949. Lansing, MI: Testing and Research Division, Michigan Department of Transportation.

This report considers jointed reinforced concrete pavements. Joint failures in concrete pavements have caused traffic hazards and maintenance problems for many years. When an expansive force exceeds the strength of a deteriorated joint, a blow-up or localized crushing occurs. Problems of this nature usually begin when the pavement is 10–15 years old. Pressure relief joints have been installed at several locations. The same type of joint fillers has been used in conjunction with repairs. Although the foam seems to provide an effective joint seal when the joint closes upon it, opening of the joint allows penetration of water into the base. It became evident that the filler should be placed with some initial compression so that the opening of the joint can be accommodated, the seal maintained, and the sealer kept in place.

Buch, N., M.A. Frabizzio, and J.E. Hiller. 2000. *Factors Affecting Shear Capacity of Transverse Cracks in Jointed Concrete Pavements (JCP).* Report RC-1385. East Lansing, MI: Pavement Research Center of Excellence, Michigan State University.

Environmental and/or traffic-related stresses can lead to the development of transverse cracking in jointed concrete pavements (JCPs). Deterioration of transverse cracks over time can result in loss of serviceability and loss of structural capacity in such pavements. An understanding of the factors affecting transverse cracking in JCPs and the ability to assess when and how to repair pavements with this distress are therefore two issues of importance to transportation agencies. Addressing these issues, the primary objectives of this research were to study the effects of various factors on transverse cracking in JCPs and to demonstrate methods of evaluating these cracked pavements. Field data collected from in-service JCPs located throughout southern Michigan was used to accomplish these objectives. Joint spacing, concrete coarse aggregate type, and shoulder type were found to have significant effects on transverse crack development and/or performance. Three analysis procedures based on the use of FWD data (back calculations of pavement support and stiffness parameters, determination of crack performance parameters, and assessment of void potential near cracks) were demonstrated to evaluate cracked JCPs. Results form theses FWD analyses were used to develop threshold limits necessary for performing evaluations with these procedures. In conjunction with the field testing, a laboratory study of large-scale concrete slabs was performed. This involved the collection and analysis of load transfer data from a variety of concrete slabs with different coarse aggregate types and blends. This laboratory study verified findings from the field study.

Buch, N., L. Khazanovich, and A. Gotlif. 2001. *Evaluation of Alignment Tolerances for Dowel Bars and Their Effects on Joint Performance*. Final Report. East Lansing, MI: Pavement Research Center of Excellence, Michigan State University. CD-ROM.

The Michigan Department of Transportation (MDOT) uses dowel bars to assure that adequate load transfer takes place across transverse joints in rigid pavements. Dowel bars are placed at pavement mid-depth, and care is taken to minimize the detrimental effects of misalignment. The dowel bar's performance is a key factor that directly affects the service life of the joint. The objective of this study is to develop justifiable tolerance levels that ensure that doweled joints do not cause high levels of stress and damage due to misaligned dowels. The study reported herein included the development of several finite element models using a commercial finite element package, ABAQUS. A comprehensive PCC-dowel interaction model was developed and calibrated/validated using the results of a pullout test. The analysis of misaligned dowels showed that uniform vertical misalignment did not cause significant resistance to joint horizontal movements. At the same time, non-uniform misalignment may cause joint lock-up and premature pavement failure. Although the magnitude and uniformity of dowel misalignment are significant factors affecting joint performance, its interaction with other factors should be considered.

Chatti, K., D. Lee, and G.Y. Baladi. 2001. *Development of Roughness Thresholds for the Preventive Maintenance of Pavements based on Dynamic Loading Considerations and Damage Analysis.* Research Report RC-1396. East Lansing, MI: Pavement Research Center of Excellence, Michigan State University.

The objective of this study was to investigate the interaction between surface roughness, dynamic truck loading and pavement damage to determine roughness threshold. This threshold would be used in the pavement management system as an early warning for preventive maintenance action. This was done by testing the hypothesis that there is a certain level of roughness (roughness-threshold values) at which a sharp increase in dynamic load occurs, thus causing an acceleration in pavement damage accumulation. The research was successful in validating the above hypothesis by (1) Identifying empirical relationships between roughness and distress using current indices from in-service pavements and (2) developing similar relationships between surface roughness and theoretical pavement damage using the mechanistic approach.

The above relationships allowed for determining critical ranges of RQI, at which distress and theoretical pavement damage accelerate. Reasonable agreement was obtained between theoretically derived and empirically derived ranges. However, these RQI were too wide to be adopted at the project level. It was therefore concluded that the RQI was not suitable for predicting dynamic truckloads at the project level, i.e., for a specific pavement profile.

Consequently, a new roughness index, called the Dynamic Load Indices (DLI), was developed for the purpose of identifying “unfriendly” pavement profiles form a dynamic truck loading aspect. The new index was used to develop tables showing the predicted life extension that would be achieved by smoothing a pavement section with a given remaining service life (RSL) for different DLI levels. These tables can be used to decide when smoothing action needs to be taken in order to get a desired life extension for a particular project. Comparison with RSL values derived using actual distress growth over time from in-service pavements allowed for determining the optimal range of DLI-values that would lead to the desired life extension upon smoothing the pavement surface. The results showed that such preventive maintenance smoothing action is best suited for rigid pavements.

Chiunti, M.A. 1976. *Experimental Short Slab Pavements; Construction Report*. Research Report No. R-1016. Lansing, MI: Testing and Research Division, Michigan Department of Transportation.

This report describes the pavement construction on an experimental portion of freeway on relocated US 10 northwest of Claire, MI. The project was constructed to evaluate the performance of short-slab unreinforced pavement placed on conventional base, on a porous bituminous drainage blanket, and on a bituminous stabilized base. There have been some difficulties in constructing continuously reinforced pavements with slipform equipment, and there are indications of rebar corrosion in this type of pavement built with slag aggregate. Although exiting pavements of this type have performed well, the above-mentioned problems have led to reconsideration of rigid pavement design for areas of relatively light commercial traffic. Concrete pavements that require less steel and/or those that can be built at lower costs are to be evaluated. The purpose of this study is to obtain relative performance information on several alternate pavement designs.

Cook, J. P., I. Minkarah, and J. F. McDonough. 1981. *Determination of Importance of Various Parameters on Performance of Rigid Pavement Joints*. Report No. FHWA/OH-81/006. Columbus, OH: Ohio Department of Transportation.

The objective of the present study was to evaluate the effects of various parameters on an experimental concrete pavement in Ross County, OH. Variables included in the pavement were (1) joint spacing, (2) sub-base stabilization, (3) coating of dowel bars, and (4) configuration of the saw cut and (5) the use of skewed joints. Both long-term and short-term horizontal movements caused by temperature and vertical movement of slab ends under known axle loads were measured. A record of cracking and spalling of the pavement is also included. A statistical analysis of both long- and short-term movement was conducted, and recommendations for joint design are included.

Cook, J., F. Weisgerber, and I. Minkarah. 1990. *Development of a Rational Approach to the Evaluation of Pavement Joint and Crack Sealing Materials*. Report No. FHWA/OH-91-007. Cincinnati, OH: University of Cincinnati.

This study included interviews, field evaluations, measurements of gap motions, laboratory testing, and stress analysis relating to highway pavement crack and joint seals. Both asphalt and concrete pavements were included. This report provides extensive comparative data on the behavior of a wide variety of sealant material and seal configurations. Successful sealing practices, such as the "saw and seal" technique for asphalt overlays, and widespread problems, such as maintaining an effective bond to concrete, have been documented fully. The primary results, conclusions, and recommendations are summarized in three sets of guidelines provided in appendices. These are guidelines for (1) predicting the potential of materials for use as sealants, (2) selecting seal materials and configurations, and (3) evaluating sealants in place.

Cool, J.P. and I. Minkarah. 1973. *Development of an Improved Contraction Joint of Portland Cement Concrete Pavements*. Report No. OHIO-HWY-19-73. Cincinnati, OH: University of Cincinnati.

This report deals with the contraction joints in portland cement concrete pavement. The variables studied that affect joint behavior are (1) joint spacing, (2) subbase stabilization, (3) coating of dowel bars, (4) configuration of the sawcut, and (5) use of skewed joints. Hand gage readings, taken monthly, give the yearly curve of joint movement. Electronic instrumentation gives a continuous record of the daily slab movements and measures pavement deflection under known axle loads. A condition report of the pavement after one year's use is included, and tentative recommendations are made for an improved contraction joint.

Eacker, M.J. and A.R. Bennett. 2000. *Evaluation of Various Concrete Pavement Joint Sealants.* Research Report No. R-1376. Lansing, MI: Construction and Technology Division, Michigan Department of Transportation.

A test section of pourable sealants was placed on reconstructed I-94 between Watervliet and Hartford in the fall of 1994. Five sealants, Dow 888 and 890SL, Sikaflex 15LM and 1CSL, and Crafco Roadsaver SL, were each used to seal 60 contraction joints. Preformed neoprene, Michigan's standard sealant, was used on the remainder of the job. The sealants were visually evaluated and rated twice a year for three and a half years. Sikaflex 1CSL performed the best of the pourable sealants. It had the best sealing rating after 44 months and the failures it did have were small. It was followed by Dow890SL, which also had small failures but more than Sikaflex 1CSL and Sikaflex 15LM. Crafco Roadsaver SL and Dow 888 both performed poorly. Crafco Roadsaver SL had a mixture of small to moderate failures, about half of which were cohesive. Dow 888 had many large failures, including a handful of joints where the sealant is completely missing. The preformed Neoprene performed better than any of the pourable sealants. It is in the same condition as when it was first placed. Weathering is not a problem with any of the sealants. Debris intrusion is a function of the sealing. With more sealant failures, more debris can enter the joint reservoir. Preformed neoprene should remain the standard sealant when sealing contraction joints in new concrete pavements. Silicones and polyurethanes should not be used as a joint sealant for new pavements.

Felter, R.L. 1982. Concrete Pavement Cracking, Interim Report (Memorandum). Research Report No. R-1198. Michigan Department of Transportation, June 29, 1982.

This project was established in 1978 to evaluate the effectiveness of cracking concrete pavement, prior to placing a bituminous overlay, to reduce reelection cracking in the overlay. An inspection party visited the three US 2 projects in March 1982. Most cracking started near an outside edge of a pavement lane and proceeded across the pavement in one direction and across the adjacent shoulder in the other. The existing aggregate shoulders and a 3 ft. bituminous ribbon were left in place along one side during construction. It was felt that the crack in the shoulder material extending out from the joints was instrumental in initiating the reflection cracks. A bituminous acceleration ramp was left in place in one location, with the existing cracks initiating reflection cracks in the overlay. It was also felt that the reinforcing steel in these projects may be encouraging the slabs to remain intact and diminishing the effectiveness of the pavement cracking.

Hansen, W., A. Definis, E.A. Jensen, P.H. Mohr, C.R. Byrum, G. Grove, T.J. Van Dam, and M. Wachholz. 1998. *Investigation of Transverse Cracking on Michigan PCC Pavements over Open-Graded Drainage Courses*. Research Report RC-1401. Ann Arbor, MI: University of Michigan.

Some OGDC projects have developed premature transverse cracking with associated spalling and faulting. The objective of this project was to investigate these projects to determine the cause(s) of the cracking and the relationships, if any, the cracking may have with the OGDC base layer. Field measurements were used to quantify the amounts of transverse cracking and spalling for each project. The results were plotted vs. pavement age. In general, both distress types follow unexpected trends over time with very little, if any, spalling development during the first 10 years. These results corroborate MDOT findings using PMS performance data that indicates there is no premature deterioration of OGDC pavements compared to pavements constructed on dense-graded bases. However some pavements have developed severe spalling and faulting after 13 years. The most plausible reasons for the associated distress were trapped water in the subbases/subgrade and clogged outlet drains. No evidence was found that indicates the OGDC by itself was a major contributor to the observed severe distress.

The results from this study suggest that improvements in both construction and in the concrete mix are needed. Given that MDOT is moving towards JPCP as its standard pavement type, premature mid-slab cracking and spalling must be avoided. High PCC placement temperatures (>80°F), especially during morning hours on hot summer days, should be avoided, as premature transverse cracking can be expected. Nighttime paving would help reduce this problem.

Hansen, W. and E.A. Jensen. 2001. *Transverse Crack Propagation of JPCP as Related to PCC Toughness.* Research Report RC-1404. Ann Arbor, MI: University of Michigan.

The purposes of this project were (1) to improve the aggregate interlock property in jointed plain concrete pavement (JPCP) containing a midslab transverse crack and (2) to improve concrete resistance to cracking from mechanical loading effects. The aggregate interlock property of a transverse crack was studied using a large-scale test frame supporting a 3.0 m long by 1.8 m wide by 250 mm thick JPCP slab resisting on a typical MDOT highway foundation. A total of 7 JPCP slabs, 96 large beams, and 243 cylinders were tested in this study. The different slab concretes were supplied from ready-mix plants using MDOT mix proportions. Seven concrete mixes containing different coarse aggregate types and sizes were tested at different ages to evaluate their resistance to cracking.

The major findings were as follows. Aggregate interlock properties of a cracked PCC slab can be greatly improved if the concrete contains strong coarse aggregate, which provides a rough-textured crack surface that provides a “ball and socket” effect due to the protruding and intact aggregates.

Strong coarse aggregates also provide a greater resistance to crack propagation. Improvements of about 35% were gained for concretes with similar strength, but containing different coarse aggregate types. Concrete slabs, irrespective of aggregate type, were found to be crack-sensitive, which is in accordance with established factory theory. Once partially cracked, the remaining tensile resistance was far below that expected from strength theory using remaining cross-sectional area. It is therefore important to repair cracked slabs, as the fatigue life is expected to be reduced.

Hansen, W. and T.J. Van Dam. 1997. *Premature Deterioration in Michigan Jointed Concrete Pavements on Open Graded Drainage Courses*. Ann Arbor, MI: University of Michigan.

Approximately 10% of the projects constructed with the new OGDC materials have been developing various distresses at relatively high rates over time. The distresses observed have typically consisted of premature transverse cracking and slightly accelerated faulting and spalling. This premature distress development has spurred this study to investigate the factors that may be causing them.

Hauge, H.A 2003. Discussion on Curing and Sealing. *Hard Facts*, Summer 2003.

Curing and sealing are two distinct processes. Curing is a temperature and moisture control process that ensures proper development of the engineering properties of a concrete placement. Sealing is a process in which compounds are applied to the surface of hardened concrete to reduce the penetration of contaminants into to the concrete. Sealers are typically not applied until the concrete placement has had a chance to cure for 28 days. The results of proper curing are more durable and more wear-resistant concrete. Methods of curing are wet curing and membrane curing. Concrete sealers are designed to supplement, not replace, the weathering characteristics of a durable, properly cured concrete surface. Different concrete sealers are film-forming and penetrating sealers.

Holbrook, L.F. and W.H. Kuo. 1974. *General Evaluation of Current Concrete Pavement Performance in Michigan; Jointed Concrete Pavement Deterioration Considered as a Probability Process.* Research Report No. R-905. Lansing, MI: Testing and Research Division, Michigan Department of Transportation.

A large variety of techniques were used to measure and predict jointed concrete pavement structural performance for 128 projects with up to 15 years of performance history. It was decided to explore pavement performance with selected performance variables found to have a high frequency of occurrence in the pavement condition surveys. Transverse cracking was chosen as the subject of five pilot performance models that were designed to predict crack incidence probability for any point in time up to 15 years of service. The Markov chain approach gave the best correlations with field data and thus was generalized into a form suitable not only for transverse cracking, but joint performance as well.

Because blowups are a serious hazard and maintenance problem, this state of joint deterioration was singled out for special analysis. In particular, 5- and 10-year survey data, together with crude information on coarse aggregate composition, were used to predict future blowup occurrence. The authors recommend that the 5-year condition survey be eliminated in favor of a 7-, 8-, or even 10-year survey. Also, careful attention should be given to acceptance testing programs designed for coarse aggregate pits known to contain gravel-lime-stone mixes in roughly a 50/50 proportion. Early survey information should be used to estimate future joint performance. If this is facilitated with models developed in this report, good estimates can be made of 15-year performance. This same performance estimation program is used to focus attention on problem projects so that additional condition surveys can be made.

Ioannides, A. and I. Minkarah. 2002. *Ohio Route 50 Joint Sealant Experiment*. Report No. FHWA/OH-2002/019. Cincinnati, OH: University if Cincinnati.

This research entailed the construction and evaluation to date of a four-lane highway near Athens, Ohio. The purpose of this project has been to evaluate concrete pavement performance in connection with various sealant types and joint configurations in the wet-freeze climatic zone. Fifteen different material-joint configuration combinations have been used. The new pavement consists of a 250-mm (10-in.) jointed reinforced concrete slab with 21-ft. joint spacing, placed over a 100-mm (4-in.) free-drainage base layer, constructed over a 150-mm (6-in) crushed aggregate subbase, resting over the predominantly silty clay local subgrade. The highway has a 20-year design period. The eastbound lanes have been open to traffic since spring 1998, whereas the westbound lanes have been serving traffic since spring 1999. Three joint sealant, profilometer, and pavement performance surveys are described in this report. These evaluations were conducted in October 2000, June 2001, and October 2001 in accordance with an evaluation plan developed by the University of Cincinnati research team based on statistical principles. Sealant effectiveness values are calculated and treatments are ranked according to a rating scheme that describes each sealant type very good, good, fair, poor, or very poor.

Results from these evaluations are analyzed and compared to those from earlier inspections to delineate the major trends exhibited by the test pavement. During the March 2000 evaluation, a significant flooding event was witnessed. The Hocking River, which runs along the highway, could not handle the amount of water from the storm. Several fields adjacent to the roadway were flooded and the drainage ditches overflowed. Following the flooding, several transverse cracks were noticed in the pavement. Both the development of structural distresses and the drainage features of the pavement system are also examined in this report. It is reported that significant mid-slab cracking has been observed in the test pavement, but that this distress appears unrelated to the performance of the sealant treatments. It is anticipated that pavement and sealant performance monitoring will continue for several years. Several recommendations for future investigations are formulated.

Ioannides, A.M., I.A. Minkarah, J.A. Sander, and A.R. Long. 2002. *Mechanistic-Empirical Performance of U.S. 50 Joint Sealant Test Pavement (Fall 1999 to Fall 2000)*. Cincinnati, OH: University of Cincinnati.

This research project entailed the construction and evaluation to date of a four-lane highway near Athens, Ohio. The main purpose of this project has been to evaluate concrete pavement performance in connection with various sealant types and joint configurations in the wet-freeze climatic zone.

Ioannides, A.M., I.A. Minkarah, Hawkins, B.K., and J.A. Sander. 1999. *Ohio Route 50 Joint Sealant Experiment Construction Report (Phases 1 and 2) and Performance to Date (1997-99)*. Cincinnati, OH: University of Cincinnati.

This research project entailed the construction and evaluation to date of a four-lane highway near Athens, Ohio. The main purpose of this project has been to evaluate concrete pavement performance in connection with various sealant types and joint configurations in the wet-freeze climatic zone.

The research projects listed in Table B.2.8 were completed under the direction of the Iowa Department of Transportation. The table lists the research pertaining to concrete joints including joint seals and joint deterioration. The project number, title, end date, and principle investigator are also listed.

Table B.8. Summary of Iowa DOT research related to concrete joints

Proj.	No.	Title	End	PIs
HR	541	Scott Co. Load Transfer Retrofitting (See HR-2033)		--
HR	1080	Synthesis of Dowel Bar Research	8/15/02	M. Porter
HR	2078	Soff-Cut Centerline Joint and Potential Cracking Problem	6/1/95	R. Steffes

Proj.	No.	Title	End	PIs
HR	2092	Hot Poured Joint Sealant Bubbles		R. Steffes
HR/TR	318	Evaluation of Preformed Neoprene Joint Seals	4/1/94	R. Steffes
HR/TR	343	Non-corrosive Tie Reinforcing and Dowel Bars for Highway Pavement Slabs	11/30/93	M. Porter
HR/TR	408	Glass Fiber Composite Dowel Bars for Highway Pavement	5/31/01	M. Porter
HR/TR	420	Field Evaluation of Alternative Load Transf Device Location in Low Traffic Volume Pavements	12/31/03	J. Cable/C. Greenfield
HR/TR	510	Laboratory Study of Structural Behavior of Alternative Dowel Bars	10/31/05	M. Porter - J. Cable - F. Fanous - B. Coree
HR/TR	520	Evaluation of Dowel Bar Retrofits for Local Road Pavements	7/31/08	J. Cable/M. Porter
IR	730	Joint Sealing - Without Backer Rope, Sta. 1060-1070		R. DeBok
MLR	9705	Soffcut Sawed PCCJoint Ends		B. Steffes
MLR00-05	200005	Longitudinal Joint Forming In PCC Pavements		R. Steffes
MLR00-05	200005	(MLR-00-05A) Patent for Joint Former for Plastic Concrete		R. Steffes
MLR03-01	200301	Transverse Joint Forming in PCC Pavements	6/1/08	R. Steffes

Khazanovich, L., N. Buch, and A. Gotlif. 2001. *Evaluation of Alignment Tolerances for Dowel Bars and Their Effects on Joint Performance.* Research Report RC-1395. East Lansing, MI: Pavement Research Center of Excellence, Michigan State University.

Dowel bars are placed at pavement mid-depth, and care is taken to minimize the detrimental effects of misalignment. Misalignment may result from misplacement (initially placing the dowels in an incorrect position), displacement (movement during the paving operation), or both. The objective of this study is to develop justifiable tolerance levels that ensure that doweled joints do not cause high-level stresses due to misaligned dowels. This may lead to a possible construction cost savings without jeopardizing pavement performance. The first stage of this project involves the development of finite element models capable of analyzing PCC stress due to dowel misalignment. The study included the development of several finite element models using a commercial finite element package, ABAQUS. A comprehensive PCC-dowel interaction model was developed and calibrated/validated using the results of a pullout test.

Majidzadeh, K. and L. Figueroa. 1988. *Evaluation of the Effectiveness of Joint Repair Techniques and Pavement Rehabilitation Using the Dynaflect*. Westerville, OH: Resource International.

The purpose of this research was to determine how the Dynaflect deflection measurement device can help in joint repair and pavement rehabilitation.

Majidzadeh, K. and V. Behaein. 1988. *A Study to Develop a Base of Data for Joint Repair Techniques*. Report No. FHWA/OH-89/007. Columbus, OH: Ohio Department of Transportation.

This study was initiated to identify and collect the data elements required to identify various joint repair techniques and then develop a computerized data base to store the data. As a result the user will be able to (1) identify exact locations of each repair technique, (2) list all repair techniques that were done on any given year/county/route and log mile, and (3) perform joint condition rating and enter into the system.

Measurement of Dowel Bar Response in Rigid Pavement. Ohio Research Institute for Transportation and the Environment.

The effectiveness of load transfer between adjacent slabs is an important component of long-term rigid pavement performance. When load transfer is minimal or non-existent, concrete slabs must carry the full weight of tuck axles across their entire length. This condition results in high dynamic tensile stresses being induced in the slab and high dynamic compressive stresses being generated in the base and subgrade. Dowel bars are placed in rigid pavement contraction joints as a mechanism for distributing traffic loads over multiple slabs through vertical shear and/or bending moments, and thereby, reducing stresses in the slab and base. Unfortunately, premature distress is often observed around rigid pavement joints. The purpose of this project was to instrument and install a total of 12 dowel bars in an in-service pavement and monitor their response under environmental cycling and dynamic loading. This examination may provide insight into the reasons for premature distress.

Minkarah, I., A. Bodocsi, R. Miller, and R. Arudi. 1992. *Final Evaluation of the Field Performance of Ross 23 Experimental Concrete Pavements*. Report No. FHWA/OH-93/018. Cincinnati, OH: The University of Cincinnati.

This project is a continuation of the research done from 1972 to 1981 on a jointed portland cement concrete pavement test section located in the southbound lane of Ohio Route 23 in Chillicothe, Ohio. Several variables were incorporated into the pavement: joint spacing, type of base, type of dowels and type of sawcut. Short- and long-term horizontal movements caused by temperature were evaluated over a two-year period. Vertical movements under known axle loads were also determined. Dynaflect and FWD were measured at the same time as the vertical movements. A statistical analysis was conducted of the horizontal and vertical movement data. A record of the damage to the pavement during the 20-year span was also made. Analysis of the statistical data and pavement damage led to conclusions about joint design and spacing limitations. The in situ permeability of the base was measured, the concrete was examined petrographically, and the extent of chloride penetration was determined.

Minkarah, I. and J.P. Cook. 1975. *A Study of the Effect of the Environment on an Experimental Portland Cement Concrete Pavement*. Report No. OHIO-DOT-19-75. Cincinnati, OH: The University of Cincinnati.

The objective of this study was to evaluate the effects of the pavement environment, such as temperature change and heavy truck traffic, on an experimental PCC pavement in Ross County, Ohio. Variables included in the experimental pavement were joint spacing, subbase stabilization, dowel bar coating, configuration of the saw cut, and the use of skewed joints. Horizontal slab movements caused by temperature and vertical movement of the slab ends under known axle loads were measured. A complete record is included of mid-slab cracking and crack growth. Also included is a summary of the surface spalling of the pavement and the spalling of the bottom of the pavement at the joints.

Minkarah, I. and J.P. Cook. 1975. *A Study of Field Performance of an Experimental Portland Cement Concrete Pavement*. Report No. OHIO-DOT-19-74. Cincinnati, OH: The University of Cincinnati.

An experimental section of PCC pavement on US 23 in Ross County, Ohio, was studied. Variables included in the experimental pavement were joint spacing, subbase stabilization, dowel bar coating, configuration of the saw cut, and the use of skewed joints. The yearly curve of joint movement is plotted from hand gage readings. Electronic instrumentation is used to give a continuous record of daily horizontal slab movements. Deflection of the slab ends under known axle loads is measured. A complete record to date is also given of the progress of mid slab cracking. Spalling at the bottom of the pavement is measured and plotted for each of the 101 contraction joints in the project.

Richards, A.M. 1976. *Causes, Measurement and Prevention of Pavement Forces Leading to Blowups*. Report No. OHIO-DOT-10-76. Akron, OH: The University of Akron.

A survey o f blowup activity in Ohio’s concrete pavements was conducted. One hundred seventy-two

blowups of various severities were reported during 1975 and 1976. A survey of blowup literature in the United States was conducted and resulted in an extensive bibliography of material dealing with jointed concrete pavements. A method of measuring residual strains within a concrete pavement was developed. Strain gage rosettes are attached to the walls of a core hole by means of an installation tool that was invented for this project. The hole is over-cored and the relief strains are measured. Availability theory has been adapted to allow computation of state of stress in the original slab at the level of the gages. Laboratory and field tests were conducted. Computer models of the over core and an entire pavement slab were developed using the STRUDL package. Various temperature loadings and boundary conditions were also studied.

Sargand. S. 2002. *Continued Monitoring of Pavement in Ohio*. Report No. FHWA/OH-2002/035. Athens, OH: Ohio University.

Performance and environmental data continued to be monitored throughout this study on the Ohio SHRP Test Road. Response testing included three new series of controlled vehicle tests and two sets of nondestructive tests. Cracking in two SPS-2 sections with lean concrete base confirmed observations elsewhere that PCC pavement may not perform well when placed on a rigid base. Of the five types of base material used on LOG 33 and evaluated for their effect on AC pavement performance, deflection measurements on the asphalt treated base fluctuated most with changes in temperature. None of the other bases were sensitive to temperature. Cement-treated base had the lowest deflection. On unbound material, bases containing large-size stone have the lowest deflection. The preponderance of data collected in the laboratory and at the ERI/LOR2 site suggests that PCC pavement performs poorly on 307 NJ and CTFD bases. All sections with 25-foot slabs, except those with ATFD base and the section with 13-foot slabs on 307 NJ base, had significant transverse cracking. The 13-foot long slabs on a 307 NJ base also had some longitudinal cracking. Considering the relatively short time these pavement sections had been in service, this level of performance was considered unacceptable. The ATFD base appeared to be performing best. On JAC/GAL 35, subgrade stiffness had a significant effect on dowel bar response. Looseness around dowel bars affected their ability to transfer load. Larger diameter and stiffer dowel bars provided better load transfer across PCC joints. The most effective dowel bar in these tests was the 1.5 in. diameter steel bar. The performance of 1 in. steel dowel bars were similar to 1.5 in. fiberglass bars. One-inch diameter fiberglass dowel bars were not recommended for PCC pavement. While undercutting PCC joint repairs initially reduced the forces in dowel bars, the effectiveness of the undercut diminished over time. Dowel bar forces were about the same in the Y and YU types of joint repairs after some time.

Sargand, S.M. and G.A. Hazen. 1993. *Evaluation of Pavement Joint Performance*. Report No. FHWA/OH-93/021. Athens, OH: Ohio University.

In this study, field performance of steel and fiberglass dowels used for load transfer in rigid pavement repair sections was evaluated. Electric strain gages were cemented to dowel rods to determine shear forces, moments, torques and axial loads. Repair sections were instrumented to measure concrete and surface stresses. Loads were applied using FWD and single and tandem axle trucks. Truck speeds were varied between 5 and 65 mph. Analysis of field data examined force variations due to truck speed and size, the material of the dowels, and Y or YU joints. The dominating forces in the dowel rods were moments and vertical shear forces. Field performance data was compared to analytical solutions using modified versions for ILLI-SLAB. One inch diameter fiberglass dowels are not recommended for rigid pavement, and there was not a sufficient benefit to warrant YU joints. ILLI-SLAB was not capable of predicting the true response of the joints. Recommendations were made for dowels and joint repair in rigid pavement sections.

Sargand, S. and E. Cinadr. 1997. *Field Instrumentation of Dowels*. Report No. ST/SS/97-002. Athens, OH: Ohio University.

Four types of dowels, 1.5 inch diameter epoxy-coated steel bars, 1.5 inch diameter fiberglass, and 1.5 inch deep steel and fiberglass I-beams, were instrumented with strain gages and installed. Forces that developed in these dowel bars due to curling and nondestructive testing using FWD were examined. Based on the results, it can be concluded that generally moments due to curling were significantly higher than moments developed during the nondestructive testing (FWD). Also, forces in the fiberglass dowels were less than those in the steel dowels. It is obvious that dowel bars function as a load transfer mechanism at joints, but they also served to reduce the magnitude of curling joints.

Sargand, S. and G.A. Hazen. 1996. *Instrumentation of a Rigid Pavement System*. Report No. FHWA/OH-97/001. Athens, OH: Ohio University.

This research focused on developing a comprehensive field instrumentation program to measure the in situ responses of a concrete pavement system subjected to FWD loading and various environmental conditions. Responses measured were slab stresses, vertical slab deflection, temperature gradient through the slab thickness, base and subgrade soil moisture content, and load transfer pressures at the slab-base interface. Moisture content was found to increase up to 50% once an expansion crack developed. The temperature gradient through the slab was not linear. Deflections were greatest at the joints for environmental and FWD testing. Significant stresses and deflections developed in all lengths of slabs tested. The lowest stresses were recorded in the 21-foot slabs. Strain measuring sensors were able to detect stress relief due to cracking. Load transfer pressures at the slab-base interface and the moisture level of the base and subgrade did not appear to be significant. Three-dimensional finite element modeling was shown to be effective for calculating deflections and stresses that develop due to changes in environmental factors and nondestructive testing.

Sargand, S. 2001. *Performance of Dowel Bars and Rigid Pavement*. Report No. FHWA/HWY-01/2001. Athens, OH: Ohio University.

In 1997, an experimental high-performance jointed concrete pavement was constructed on US 50 east of Athens, Ohio. In this pavement, 25% of the portland cement was replaced with ground granulated blast furnace slag. Epoxy-coated steel dowel bars were used throughout most of the project to provide load transfer across the joints to adjacent slabs. Fiberglass dowels and stainless steel tubes filled with concrete were installed in a few joints to compare their effectiveness with the epoxy-coated bars. A limited number of epoxy-coated steel and fiberglass bars were instrumented with strain gauges to measure bending moments and vertical shear induced in the bars as the concrete cured, during environmental cycling of moisture and temperature in the concrete slab, and as the FWD applied dynamic loads near the pavement joints. Thermocouples were installed to monitor temperature at different depths in the concrete layer during the strain measurements. The strain data indicated that (1) significant stresses were generated in the dowel bars and in the concrete surrounding the dowel bars soon after the concrete was placed, (2) temperature gradients in the concrete slabs caused high stresses in the bars, and (3) stress levels generated in the fiberglass dowel bars were less than those generated in the epoxy-coated steel bars.

Sargand, S. and D. Beegle. 1995. *Three Dimensional Modeling of Rigid Pavement*. Report No. ST/SS/95-002. Athens, OH: Ohio University.

A finite element program has been developed to model the response of rigid pavement to both static loads and temperature changes. The program is fully three-dimensional and incorporates both the common twenty-node brick element and a thin interface element and a three-node beam element. The interface element is used in the pavement-soil interface and in the joints between slabs. The dowel bars in the joints are modeled by the beam element, which included flexural and shear deformations. Stresses, strains, and displacements are computed for body forces, traffic loads, and temperature

changes individually so that the program can be used to obtain either total stresses for design or strain changes to compare with experimental data.

The effects of varying the material properties in the pavement, base, subgrade, interfaces, and dowels are investigated to identify those parameters which most influence the solution. Results of various interface thicknesses and dowel diameters also are presented. A further study is conducted to determine the effect of average pavement temperature on the curling stresses and displacements. Finally, results from the program are compared with experimental curling displacements and stresses.

Sehn, A. 2000. *Load Response Instrumentation of SHRP Pavements*. Report No. FHWA/OH-2000/016. Akron, OH: The University of Akron.

During the 1995 construction season, the Ohio Department of Transportation (ODOT) constructed a series of pavement test sections on US 23 in Delaware County, Ohio. The project includes pavements in four of the Specific Pavement Studies (SPS) of the Strategic Highway Research (SHRP). The SPS sections present in the project include (1) SPS-1 Structural Factors for Flexible Pavements, (2) SPS-2 Structural Factors for Rigid Pavements, (3) SPS-8 Environmental Effects in the Absence of Heavy Loads, and (4) Asphalt Program Field Verification Studies. The instrumentation for the pavement test sections was installed through a coordinated effort involving the ODOT, the contractor for the project, and research teams for six universities throughout Ohio.

The work performed during this project consisted primarily of calibration and installation of 60 earth pressure cells for the ODOT SHRP pavement instrumentation project. Each earth pressure cell was calibrated twice in the laboratory to determine its calibration factor and to verify proper operation and repeatability of the instrument. Results of the calibrator phase of the project indicated that each of the pressure cells functioned properly at the time of calibration and repeatable pressure cell response to applied pressure was confirmed. The report contains details on the calibration procedures and the field installation procedures. The calibration factor from each calibration test and the complete responses recorded for each calibration test are included.

Simonsen, J.E. and A.W. Price. 1989. *PCC Pavement Joint Restoration and Rehabilitation.* Final Report. Research Report No. R-1298. Lansing, MI: Materials and Technology Division, Michigan Department of Transportation.

The objective of this project was to develop a joint repair detail that would function properly for a 10-year period. It was required that the repair be opened to traffic within eight hours and its construction would be adaptable to mass production techniques. Laboratory studies were conducted that led to the development of mechanized drilling of horizontal holes in the end faces of the existing slab. To obtain adequate eight-hour concrete strength, a nine-sack concrete mix accelerated with calcium chloride was used. The developed techniques and materials were field tested. The experimental repairs using step-cut tied joints proved successful. Ten loose fitting dowels were used in repair joints, which had performed satisfactorily in the past. The experimental repairs using step-cut tied end joints performed well, but those installed under contract did not. The failures occurred in the epoxy-grouted portion of the tie bars. The performance of loose fitting doweled joints depends on good base support, properly sized dowel holes, exact matching of the new concrete surface to the elevation of the existing pavements, and good durability and abrasion characteristics of the aggregate used in the concrete pavement to be repaired.

It is concluded that, when properly constructed, loose fitting doweled joints will provide several years of service without excessive faulting. They should only be used on pavements 15 years old or older. On newer pavements and pavement with low abrasion value aggregates, the use of epoxy grout for fastening the dowel is recommended.

Simonsen, J.E., and A.W. Price. 1985. *Restoration and Preventive Maintenance of Concrete Pavements.* Research Report R-1267. Lansing, MI: Materials and Technology Division, Michigan Department of Transportation.

In 1976, the MDOT began a study aimed at developing a preventive maintenance program for reinforced concrete pavements having neoprene-sealed transverse joints. The developed procedures were to be such that traffic could be maintained throughout the repair and compatible with daylight lane closures. The procedures applied involved using five fast-set patching materials for joint groove spall repairs, removing damaged or malfunctioning contraction joint seals and resealing with new neoprene seals, removing tight and frayed neoprene expansion joint seals, resawing the joint groove, and resealing the joint with either a liquid sealant or a neoprene seal. Early cracking and bond failure in repairs during the first few months of service appear to be related to errors in proportioning and placing the material rather than to traffic load.

It is concluded that restoring concrete pavements using the techniques employed is feasible, provided the pavement contains high-quality aggregates and major base problems are not present. Recommendations for future restoration projects suggest that the possibility of overnight lane closures be considered as a means of reducing cost and to allow use of patching materials less sensitive to construction problems than the current fast set materials. It is also recommended that the MDOT adopt the restoration techniques and a standard preventive maintenance program for new concrete pavements, as well as recycled and overlaid ones.

Simonsen, J.E., F.J. Bashore, and A.W. Price. 1981. *PCC Pavement Joint Restoration and Rehabilitation; Construction Report*. Research Report No. R-1179. Lansing, MI: Testing and Research Division, Michigan Department of Transportation.

The objective of this project is to develop a tied joint for use between existing and new concrete pavement slabs that can be constructed rapidly without extensive hand labor. When used in conjunction with a dowelled joint in the repair center, the tied joint will provide necessary load transfer and eliminate faulting. On the basis of this study, it is concluded that the use of tied joints constructed by grouting tie bars into drilled holes in the existing concrete is a practical way of preventing faulting of repair slabs. The time required to drill the holes is less than half the time it takes two personnel to save the steel for tying into an existing slab. It is estimated that the tied joints should give satisfactory performance for at least 10 years and add slightly to the cost of the lane repair.

Simonsen, J.E., F.J. Bashore and A.W. Price. 1983. *PCC Pavement Joints Restoration and Rehabilitation.* Research Report R-1235. Lansing, MI: Testing and Research Division, Michigan Department of Transportation.

In 1968, the MDOT initiated an experimental project to develop repairs for concrete pavements that could be opened to traffic the same day they were placed and maintain their structural integrity for a number of years. The result was the use of precast concrete slabs as a standard repair method during 1972 and most of 1973. From 1974 until 1982, cast-in-place repairs using undoweled joints were used on all repair projects. Doweled joints were not used because they were labor intensive and time consuming to place. The use of undoweled repairs was intended as an interim method to maintain the pavements until overlaying or reconstruction. However, overlaying was postponed, so many of the undoweled repairs have served well beyond their intended life and some of the slabs had tilted.

Better repair methods were needed to lengthen the service life of concrete pavements. In 1979, the MDOT began testing a non-tilting joint between new and old concrete. The process of constructing the repair joint would need to be mechanized. It was determined that horizontal dowel holes could be

machine-drilled into the hardened concrete slab quickly. Several other tied joints, using deformed bars mortared into the drilled holes with epoxy, were tested. The most promising of these were the results of field tests indicated that tied joints could be constructed without much difficulty. Repairs constructed by installing dowels in drilled holes and those having tied end joints with a doweled expansion joint in the center were done. Tied joints performed satisfactorily, but failures developed that were determined to be caused by misproportioning of the epoxy binder. The MDOT is now using doweled joints exclusively. Ten dowels, 1 5/16 inches diameter, are inserted in 1 3/8-inch machine-drilled holes. Expansion joints are constructed by placing a compressible filler material over the dowels and against the existing concrete end face.

Staton, J.F. 1995. *Construction and Performance Monitoring of Hinged Joint Pavement, I-94.* Research Project No. 95 TI-1790. Lansing, MI: Materials and Technology Division Project Assignment Form.

The objective of this investigation was to monitor the long-term performance of the hinge-joint pavement test section on eastbound I-94, south of Benton Harbor, Michigan, constructed in 1995. Several cycles of field monitoring were performed, including crack survey and joint movement measurements. This project indicates that the overall performance of the pavement test section is not associated with the particular joint detail exhibited by the hinge-joint. Any localized failures found within the test section were also found in areas outside of the test section. These distresses were determined to be related to excessive plastic and drying shrinkage cracks in the concrete as a result of the highly absorptive blast furnace slag aggregate.

Weinfurter, J.A., D.L. Smiley, and R.D. Till. 1994. *Construction of European Concrete Pavement on Northbound I-75 - Detroit, Michigan*. Research Report No. R-1333. Lansing, MI: Materials and Technology Division, Michigan Department of Transportation.

This report describes the design and construction of the experimental pavement reconstruction project on I-75 (Chrysler Freeway) in downtown Detroit, Michigan, between I-375 and I-94 (Edsel Ford Freeway). The experimental features were assimilated from European pavement designs and incorporated into the plans and specifications of Federal Project IM 75-1(420), Michigan Project IM 82251/30613A. The European pavement was constructed to compare the European with American pavement designs and demonstrate the applicability of certain European concepts to the U.S. highway system.

The initial saw depth for the longitudinal and transverse joints in the two-layer pavement should be revised. German research has shown that forming plane-of-weakness joints in the lean concrete base by notching is just as effective as sawing. The notching action pushed aggregate particles to either side to form the plane-of-weakness. The variable spacing of dowel bars in a basket assembly should be oriented such that the spacing between bars actually represents a standard uniform spacing, but with missing bars. This will reduce the fabrication costs for the baskets.

High-Performance Concrete

Sargand, S. 2003. *Evaluation of HPC Pavements in Nelsonville, Ohio*. TRB research in progress. Athens, OH: Ohio University. http://rip.trb.org/browse/dproject.asp?n=7735.

The objective of this study is to apply the concrete mix used by Dr. Clelik Ozyildirim in “Evaluation of HPC Pavement in Newport News, Virginia” to the reconstruction of US Route 33 in Nelsonville, Ohio. Three test sections, each consisting of 1,000 feet, will be constructed as part of the US 33 reconstruction. In each test section, 500 feet will be cured with membranes; the other 500 feet will be cured with burlap. The following parameters will be monitored during the concrete curing, service, and nondestructive testing: (1) temperature profile during curing with thermocouples, (2) temperature

as a function of time for the maturity test, (3) shape of the slab with dipstick and stationary profilers, (4) shape of the slab using ODOT profilers, (4) joint movement of the slabs, and (5) deflection during nondestructive testing.

The research projects listed in Table B.2.9 were completed under the direction of the Iowa Department of Transportation. The table lists the research pertaining to high-performance concrete. The project number, title, end date, and principle investigator are also listed.

Table B.9. Summary of Iowa DOT research related to high-performance concrete

Proj.	No.	Title	End	PIs
MLR	9805	High-Performance Concrete for Bridge Decks		C. Ouyang

Sargand, S. 2002. *Application of High-Performance Concrete in the Pavement System Structural Response of High-Performance Concrete*. Report No. FHWA/OH-2001/15. Columbus, OH: Ohio Department of Transportation.

A concrete pavement was constructed on US 50 east of Athens, Ohio, to determine the influence of ground granulated blast furnace slag on the curing of a high-performance concrete pavement and on the performance of that pavement as it was subjected to environmental cycling and nondestructive testing with a FWD. Three test sections of high-performance concrete and one control section constructed with ODOT Class C concrete were instrumented and monitored closely to determine any differences in response and performance. The high-performance sections contained 25% ground granulated blast furnace slag. Several joints were not sealed to evaluate their performance when compared to joints sealed in accordance with ODOT specifications.

Based on laboratory tests and field data, the following conclusions were derived from this pavement. Temperature gradients generated between the surface and bottom of concrete slabs during the curing process can have a significant impact on the formation of early cracks. Large values of strain recorded in the field during the curing period indicated that the two sections of high-performance pavement constructed on October 1997 would likely experience early cracking, as was observed. Field data indicted that a third high-performance section and a control section containing standard ODOT class C concrete, both constructed in October 1998, had a lower probability of exhibiting early cracking, and no cracks were observed. The uncracked section of high-performance concrete had less initial warping than did the control section constructed at the same time with standard ODOT Class C concrete. Early cracking in the other two cracked high-performance sections precluded any comparison with the uncracked sections. FWD data indicated that the uncracked high-performance section experienced slightly less deflection at the joints than did the section containing standard concrete, suggesting less curvature and less loss of support under these slabs than under slabs constructed with standard concrete. FWD joint deflections were higher in the cracked high-performance sections after one year of service than before the sections were opened to traffic probably due to the presence of the cracks. Limited data suggested that moisture in the subgrade at sealed and unsealed joints was similar and, in some cases, more under the sealed joints than under the unsealed joints. FWD deflections at sealed joints were generally higher than at the unsealed joints.

Miller, R. and Mirmiran, A. 2003. *Transverse Cracking of High-Performance Concrete Bridge Decks After One Season or Six to Eight Months*. TRB research in progress. Cincinnati, OH: University of Cincinnati. http://rip.trb.org/browse/dproject.asp?n=7688

The objectives of this study are to establish better HPC concrete mixes that not only achieve the required strength, permeability, and durability properties, but also exhibit lower shrinkage, easier mixing and finishing, and more tolerance to field variances of consolidation, curing application, and traffic vibrations due to phased construction. This will be accomplished as follows: (1) investigate the cause of cracking in existing HPC bridge decks; (2) recommend needed changes in field controls, specifications, and concrete mixes; and (3) investigate the effectiveness of the proposed changes and solutions and validate them by laboratory and field testing.

Wojakowski, J. 1998. *High-Performance Concrete Pavement*. Report FHWA-KS-98/2. Topeka, KS: Kansas Department of Transportation.

Portland cement concrete pavements of especially high quality became an area of interest in the early 1990s and precipitated a tour by representatives of industry and government to observe European construction practices. Following the tour, the FHWA developed a research program to encourage and aid states in constructing high-performance concrete pavement (HPCP). Important criteria for research projects were service life and costs, innovative design and materials, and construction productivity and quality. This Kansas HPCP research project was conceived to address most of the criteria enumerated above. Specific test sections generally one-half to one kilometer in length were built with the following special features and materials: (1) single saw cuts w/o sealing the joint, (2) fiberglass dowels, (3) and X frame load transfer device, (4) early saw cuts, (5) polyolefin fibers, (6) longitudinal tining, (7) high solids curing compound, (8) two-lift construction, (9) recycled asphalt pavement millings as intermediate size aggregate in PCCP in bottom lift, (10) lower water-cement ratio concrete, (11) hard, igneous coarse aggregate in PCCP in top lift with a pozzolan, and (12) random transverse tining. Most materials and test sections performed as expected, with the exception that interpanel cracking occurred between the 18.3-meter (60-foot) joints of the polyolefin fiber section. The cost increase for the two-lift construction was significant, though the first lift was placed using only a spreader. Test sections will be evaluated and monitored for the next five years.

Aggregate

Gupta, J.D. and W.A. Kneller. 1993. *Precipitate Potential of Highway Subbase Aggregates*. Report No. FHWA/OH-94/004. Toledo, OH: The University of Toledo.

Tufaceous material has been observed clogging pavement drains along highways in northeastern Ohio. Previous studies suggest that the free lime (CaO) present in subbase material is the source of the deposition of the tufa. Nine slag samples that consisted of air-cooled blast furnace (ACBF), open hearth (OH), basic oxygen furnace (BOF), electric arc furnace (EAF), and two recycled portland cement concrete (RPCC) were evaluated for their tufa precipitate properties. Various X-ray, SEM, physicochemical tests, leachate studies, and surface area measurements were performed to characterize the precipitate potential of these samples. The results of these tests indicted that all of the slags, except the ACBF slag, are prone to produce tufa. X-ray diffraction and SEM analyses indicate that one RPCC sample does not contain free lime. The leachate study shows that both samples produce tufa. Therefore, presence of free lime or portlandite in the cement paste of the concrete can result in tufa precipitation.

ODOT requires six months aging of slags before they are used. The test results shows that the aging of slags for six months or more does not decrease the free lime content enough to prevent the formation of tufa deposits.

Gupta, J. 2002. *Magnitude Assessment of Free and Hydrated Limes Present in RPCC Aggregates*. Report No. FHWA/OH-2002/014. Toledo, OH: The University of Toledo.

The tendency of tufa to block pavement drains in northeastern Ohio can be associated with the total calcium content of the aggregate materials. In the present project, recycled portland cement concrete (RPCC) aggregates are examined when leached with acidic water formed by carbon dioxide dissolved in water. The RPCC aggregates were supplied by the Ohio department of Transportation (ODOT) from various sections of the interstate highways in Ohio. The locations of samples and a summary of the components in terms of course aggregate, fine aggregate, and cement are quoted in the D-cracking report. All the RPCC aggregates were around 30 years old. X-ray power diffraction (XRD) data and thermal analysis data established the portlandite, dolomite, and calcium carbonite content of the RPCC aggregates. An ethylene glycol test indicated that the free calcium oxide content has been reduced in most samples to around 0.5% due to carbonation over 30 years. A ratio of Mg/Ca ions of greater than 0.60 indicates that the aggregates have higher concentrations of Ca_2 ions and may result in the precipitation of calcium carbonate or tufa. In laboratory studies, the ambient temperature of pouring concrete (below 50°F) has shown a higher incidence of tufa precipitation. This may be due to incomplete hydration. The study recommends establishing an Mg/Ca ratio before using RPCC aggregates as base/subbase course. It is also recommended that contractors limit the use of RPCC aggregates to coarse size only.

The research projects listed in Table B.2.10 were completed under the direction of the Iowa Department of Transportation. The table lists the research pertaining to concrete aggregates including aggregate gradations. The project number, title, end date, and principle investigator are also listed.

Table B.10. Summary of Iowa DOT research related to concrete aggregates

Proj.	No.	Title	End	PIs
HR	563	Improved Gradation of PCC Mixtures	10/1/96	T. Hanson
HR	1061	Evaluation of Concrete Mix Characteristics Using a Total Gradation Design		
HR/TR	86	Relationship of Carbonate Aggregate to Serviceability of PCC	6/1/65	J. Lemish
HR/TR	118	Carbonate Aggregates for Portland Cement Concretes	11/1/67	J. Lemish
HR/TR	266	The Relationship of Ferroan Dolomite Aggregate to Rapid Concrete Deterioration	11/1/86	W. Dubberke
HR/TR	336	Thermogravimetric Analysis of Carbonate Aggregate to Predict Concrete Durability	3/1/93	W. Dubberke
HR/TR	337	Investigation of Rapid Thermal Analysis Procedures for Prediction of the Service Life of PCCP Carbonate Coarse Aggregate	6/30/93	S. Schlorholtz, K. Bergeson
IR	710	Recycled PCC in Base Shoulder and Fillet Construction		
MLR	6901	Lightweight Aggregate Use in Structural Concrete	4/1/69	G. Calvert
MLR	7703	PCC Utilizing Recycled Pavement	1/1/77	J. Bergren, R. Britson
MLR	7706	Recycling of Portland Cement Concrete Roads in Iowa		
MLR	8806	Fine Sand for Use in PC Concrete	3/1/89	K. Jones
MLR	9408	Coarse Aggregate Gradations for PCC	4/1/95	C. Ouyang
MLR	9604	Laboratory Study of the Leachate From Crushed PCC Base Materials		B. Steffes

Struble, B. 2003. *Larger-Sized Coarse Aggregate in Portland Cement Concrete Pavement and Structures*. TRB research in progress. Cincinnati, OH: University of Cincinnati. http://rip.trb.org/browse/dproject.asp?n=7703.

Given that the efficiency of an optimum concrete mix is controlled by the amount of cement employed and that the paste is usually responsible for most of the durability and cracking problems encountered, the goal of this research will be to determine whether the cement efficiency of standard ODOT mixes can be improved through the use of larger aggregate. The project will seek to develop and validate mechanistic-based correlations to assess and quantify the influence of aggregate size on strength, chloride resistance, abrasion resistance, freeze-thaw resistance, creep, and shrinkage. The effect of aggregate size on curling, warping, cracking, and load transfer will also be considered.

Liang, R. 2000. *Polishing and Friction Characteristics of Aggregates Produced in Ohio*. Report No. FHWA/OH-2000/001. Akron, OH: The University of Akron.

This report describes research investigating the specific causes of rapid polishing behavior of aggregates produced in Ohio and developing practical testing procedures for evaluating the ability of aggregates to provide adequate skid resistance over the intended service life. The properties investigated include the polish number of each aggregate, the petrographic and mineralogical properties, the acid insoluble residue (AIR), chemical analysis, and soundness properties. Aggregates collected from 20 quarries and extracted from cores taken from two pavement sections were subjected to accelerated polishing using the British Wheel, and the friction values were recorded using the British pendulum. A detailed petrographic analysis was performed by observing the thin sections under an image analyzer. Also, the loss of polish number in pure minerals was studied for correlating samples with the petrographic analysis. The results of the soundness tests and the laboratory chemical analysis were obtained from the ODOT laboratories. The results of this research showed that polish number is significantly affected by the insoluble residue content and the percent carbonate content. A high polish number is observed in aggregates having 60% to 70% dolomite and 20% to 30% calcite. Physical occurrences, like the crystallinity and the cementing properties of minerals also play a dominant role on the polish number. The research demonstrated that polishing tests accompanied by petrographic analysis on the aggregates could be a successful way in testing aggregate samples for their polishing properties. Data from mineralogical and AIR tests are vital in deciding the minerals that dominate the polishing properties of aggregates. A practical and screening procedure has been devised for the selection of polish test, and a more detailed petrographical analysis has been developed via an image analyzer. Selection criteria were given for adoption by the ODOT.

Pavement Design

Abdelrahman, M. 2004. *Assess Current Pavement Designs.* In progress, P545 (completion date June 30, 2003). Lincoln, NE: Nebraska Department of Roads and University of Nebraska. http://ndorapp01.dor.state.ne.us/research/rpms.nsf/.

The objective of this project is to assess the current and existing pavement design strategies in Nebraska and develop a comprehensive program to enhance the quality of new, rehabilitated, and maintained pavements. Expected benefits include establishing guidelines for selecting the best and most cost-effective strategies, designs, and techniques for new, rehabilitated, and maintained pavement facilities in Nebraska.

The assessment project (P545) has provided information on the condition of pavement sections and the effectiveness of maintenance and rehabilitation strategies in Nebraska. There are two main objectives in extending the assessment project. (1) The researchers will assess the effectiveness of specific maintenance and rehabilitation applications, as determined by NDOR personnel. This analysis will be conducted using additional data that was not considered during the original tasks of the project. The assessment will be based on performance indicators currently in use by NDOR. (2) The researchers will develop software that updates the results of the current project based on the yearly visual assessment of NDOR pavement sections and/or sources of updated information.

The extension of the assessment project will provide updates on the condition of pavement sections and the effectiveness of maintenance and rehabilitation activities in Nebraska. This information will help in evaluating and comparing the effectiveness of alternatives, optimizing the selection process of techniques, and developing new strategies considering performance and current conditions.

Abdulshafi, O., H. Mukhtar, and B. Kedzierski. 1994. *Reliability of AASHTO Design Equation for Predicting Performance of Flexible and Rigid Pavements in Ohio*. Report No. FHWA/OH/95/006. Columbus, OH: CTL Engineering.

The Ohio Department of Transportation has adopted empirical AASHTO design equations for new pavement design. This research will determine the standard deviations in traffic and performance prediction parameters in the AASHTO guide and the overall standard deviations applicable to Ohio conditions. Pavement test sites were selected to represent the statewide distribution of pavement designs in Ohio, characterized by such factors as material type, functional classification, and different climatic and soil regions. Continuous traffic data collection was accomplished by the use of weigh-in-motion devices. Pavement serviceability index (PSI) was measured by the Ohio non-contact profilometer. Core samples were obtained and several laboratory tests were conducted to determine the as-constructed material properties and variability of the design input parameters. Comparison of predicted and observed performances based on approximately four years of data indicated that the AASHTO equations do not predict the performance of flexible pavements in Ohio. The predicted and the observed performance for rigid pavement sites were essentially the same; there was no change in the observed and the predicted PSI. However, these observations were based on short-term performance data. The overall variance estimates for flexible and rigid pavements were, however, not obtained due to lack in the change of performance data for most sections.

Dudley, S.W. 1983. *Evaluation of Concrete Pavement Restoration Techniques*. Columbus, OH: Ohio Department of Transportation.

The objective of this demonstration project is to evaluate concrete pavement restoration (CPR) of a rigid pavement that remains in good condition apart from limited areas of deterioration and loss of riding comfort due to problems at joints and cracks. The steps involved in this technique are the following: underseal to fill voids, patch full and partial depth, diamond-grind faults and bumps, saw and seal joints, repair and seal isolated random cracks, and install new-type load-transfer devices in transverse joints and random cracks. A seventh step, not demonstrated, is to provide concrete sills or shoulders to better support the roadway and minimize water infiltration. Field evaluations will be made annually to determine the cost-effectiveness of the CPR system.

Duncan, T. 2003. Prescriptive vs. Performance-Based Specifications for Concrete. *Hard Facts*, Summer 2003.

Specifications for ready mix concrete have not evolved at the same pace as innovations in the concrete industry. For the most part, specifications have prescriptive provisions for the types and quantities of the mixture ingredients, limits on cementitious materials, water cement ratios, aggregate grading, etc. Prescriptive specifications inhibit innovation and professionalism in the concrete industry. They also limit the competitiveness, profitability, economy, and assignment of responsibility for concrete construction. Therefore, ready mix producers have three goals. One, requirements for concrete mixtures should be based on constructability, performance, and in-place properties. The concrete producer should be empowered to optimize mix designs for the intended performance without many of the normally seen prescriptive restrictions. Two, the producer should be qualified to make economical decisions as effective as the engineer needs while maintaining accountably for the product. Three, the submittal process should be simplified and the concrete producer should be able to make real-time adjustments to mixtures while retaining the intellectual property of the mixture composition.

The research projects listed in Table B.2.11 were completed under the direction of the Iowa Department of Transportation. The table lists the research pertaining to concrete pavement design. The project number, title, end date, and principle investigator are also listed.

Table B.11. Summary of Iowa DOT research related to concrete pavement design

Proj.	No.	Title	End	PIs
HR/TR	300	Iowa Development of Roller Compacted Concrete	12/1/87	J. Lane, M. Callahan
HR/TR	301	Iowa Development of Roller Compacted Concrete - Mills Co. (ABORTED 88/02)	5/1/92	J. Lane, M.Callahan, J. Hare
HR/TR	315	Iowa Development of Rubblized Concrete - Mills Co.	12/31/94	J. Ebmeier, M. Callahan

Masada, T. 2001. *Laboratory Characterization of Materials & Data Management for Ohio: SHRP Projects (U.S. 23)*. Project No. FHWA/OH-2001/07. Athens, OH: Ohio University.

In this research, the mechanistic properties of the pavement materials involved in the Ohio-SHRP project were measured according to the national SHRP protocols. The test program encompassed a wide variety of materials and their properties, ranging from basic index properties of the subgrade soils to resilient modulus of soils and asphalt concrete to static modulus of portland cement concrete and creep modulus of asphalt concrete. Any trends observed in the test results were pointed out to enhance our understanding of how each pavement materials behaves. In some cases, previously published empirical relationships correlating basic and advanced material properties were reevaluated in light of the latest test results.

Masada, T., S. Sargand, B. Abdalla, and L. Figueroa. 2003. *Material Properties for Implementation of Mechanistic-Empirical (M-E) Pavement Design Procedures*. Report No. FHWA/OH-2003/021. Athens, OH: Ohio University.

A comprehensive study was conducted to compile mechanistic property data for pavement materials specified and utilized in Ohio. The study consisted of three major components. In the first component, background information on the new mechanistic-empirical (M-E) pavement design/analysis procedures was researched and presented. In the second component, each of the 28 pavement-related research projects conducted for the ODOT within the last two decades was summarized, with emphases placed on pavement material properties measured and pavement distress data recorded. In the third component, the reliability of the Asphalt Institute's Witczak equation was evaluated for asphalt concrete mixtures used in Ohio in light of the latest laboratory dynamic modulus test data collected by the authors. The end result of the project was a collection of recommended hierarchical material property values and prediction methods for both rigid and flexible pavements to aid highway engineers and researchers in Ohio who wish to implement the M-E procedures.

Rea, R. 2005. *New Pavement Design.* In progress research, R-01-05 (completion date August 1, 2005). Lincoln, NE: Nebraska Department of Roads. http://ndorapp01.dor.state.ne.us/ research/rpms.nsf/.

The Nebraska Department of Roads has developed some new features for concrete paving projects. The first is a widened pavement section called the 30-foot top. This provides a pavement section with reduced edge stresses, greater load transfer, resistance to shoulder depressions from wandering trucks, and improved safety with installed rumble strips. Nebraska is also using dowel bars for load transfer on concrete pavements to eliminate faulting. Finally, pavements are being longitudinally tined. This provides a quieter, more enjoyable ride while providing a friction texture.

Other

The research projects listed in Table B.2.12 were completed under the direction of the Iowa Department of Transportation. The table lists all the remaining Iowa DOT concrete related research. The project number, title, end date, and principle investigator are also listed.

Table B.12. Summary of all other Iowa DOT concrete-related research

Proj.	No.	Title	End	PIs
HR	506	Recycled Portland Cement Concrete Pavement in Iowa (NEEP 22)	5/1/82	V. Marks
HR	538	Bettendorf Spruce Hills Drive Fast Track Paving	12/1/90	R. Holland, R. Merritt
HR	539	Automated Pavement Data Collection Equipment (Demo 960)	10/1/86	J. Cable, K. Jeyapalan
HR	541	Scott Co. Load Transfer Retrofitting (See HR-2033)		--
HR	544	Accelerated Rigid Paving Techniques (FHWA 201)	12/1/92	J. Bergren, V. Marks
HR	546	Field Evaluation of Variations of Fast Track Concrete (MLR-88-15)		J. Grove
HR	1004	Corrosion of Steel in CRC Pavement		S. E. Roberts
HR	1006	Use of Low Slump, Dense Concrete for Brdge Deck Protection and Restoration	1/1/77	J. Bergren
HR	1010	Recycled Portland Cement Concrete Pavements	3/1/78	V. Marks
HR	1015	Evaluation of Darex Corrosion Inhibitor		P. McGuffin
HR	1038	PC Paving Open House	10/1/83	J. Lane
HR	1069	Field Evaluation of Alternative PCC Pavement Reinforcement Materials		--
HR	1074	Development of a Short Course in Concrete Mixture Design & Proportioning	11/30/01	K. Hover
HR	1079	Two Stage Mixing of Portland Cement Concrete		R. Steffes
HR	2064	Retarder Overdose on IA 83 Pottawattamie County Bridge		--
HR	2065	Structural Contribution of Geogrids - Bridge Approach		C. Anderson
HR	2069	Transverse Crack Maintenance on US 71 South of Atlantic		----
HR	2076	Tine Impressions From PCC With RTV Rubber Molds	5/1/96	R. Steffes
HR	2077	I-80 Jasper PCC Test Sections	7/1/95	J. Lane
HR/TR	92	Use of Sucrose and Dextrose in Portland Cement Concrete Paving	1/1/64	S. Roberts
HR/TR	192	An Evaluation of Dense Bridge Floor Concretes	9/1/82	J. Pratt
HR/TR	206	Cement Produced From Fly Ash and Lime	5/1/80	W. Rippie
HR/TR	209	Pavement Surface on Macadam Base - Adair County	12/1/83	D. Lynam
HR/TR	225	Characterization of Fly Ash for Use in Concrete	10/1/83	T. Demirel, J. Pitt
HR/TR	286	Development of a Rational Characterization Method for Iowa Fly Ash	11/30/88	T. Demirel
HR/TR	403	Development of A Comprehensive Quality Incentive Program for PCC Paving	6/14/98	J. Cable
HR/TR	409	Evaluation of Photoacoustic Spectroscopy for Quality Control of Cement	12/31/97	G. Norton
HR/TR	484	Materials and Mix Optimization Procedures for PCC Pavements	12/31/04	S. Schlorholtz/K. Wang
HR/TR	490	Stringless Portland Cement Concrete Paving	2/28/04	J. Cable
HR/TR	512	Measuring Pavement Profile at the Slipform Paver	12/31/04	J. Cable
IR	717	PCC Over ACC (9 mi.)	8/1/77	
IR	731	Blank Band Tining Over Transverse Joints		T. Brady
MLR	8105	Evaluation of the Concrete Admixture Gla-zit	3/1/83	B. Brown
MLR	8304	Effect of Grooved Concrete on Curing Efficiency	7/1/83	J. Roland
MLR	8401	Curing Compound Efficiency on Grooved Concrete	5/1/84	M. Sheeler
MLR	8503	Fly Ash in PCC Base Mixes	8/1/86	S. Moussalli
MLR	8601	Fly Ash in PCC Base	8/1/86	S. Moussalli
MLR	8606	Roller Compacted Concrete	9/1/88	G. Calvert
MLR	8703	Field Evaluation of Class A Subbase Using Fly Ash	10/1/88	T. Parham
MLR	8704	Special Cements for Fast Track Concrete (Phase I)	6/1/88	K. Jones
MLR	8706	Evaulation of Type I Cement Fast Track Concrete	10/1/88	K. Jones
MLR	8812	Admixtures for Use as Retarders/Water Reducers in C-WR Mixes		--

Proj.	No.	Title	End	PIs
MLR	8813	Fast Track Mixes for IA 100, Linn County		J. Grove
MLR	8815	Field Evaluations of Variations of Fast Track Concrete (Transferred to HR-546)	12/1/88	J. Grove, K. Jones
MLR	8902	Pavement Evaluation Using the Road Rater(TM) Deflection Dish	12/1/89	C. Potter
MLR	8904	Evaluation of Precast & Prestressed Mix Design Using Fly Ash for		C. Narotam, K. Jones
MLR	8911	Precision & Accuracy Determination for PCC Core Testing - SHRP	2/1/90	K. Bharil
MLR	8914	Hydraulic Cement Grout Testing	8/1/90	K. Bharil
MLR	9405	Laboratory Testing of SHRP SPS-2 PCC Mixes	4/1/95	J. Grove
MLR	9704	Concrete Whiteness for Barrier Rails	9/1/97	J. Lane
MLR	9901	Evaluation of Performance Based Specifications for Blended Cements (ASTM C1157)		T. Hanson/C. Ouyang
MLR02-01	200201	Evaluating Properties of Blended Cements for Concrete Pavements	12/31/02	K. Wang
MLR02-03	200203	PCC Curing Compound Performance - Phase I & II		R. Steffes

B.3. Compilation of State Procedures

Georgia

Memo from Geoff Chapman (the Concrete Company) to Jay Page, Office of Materials & Research, Georgia Department of Transportation, January 2004.

> The Concrete Company proposed to use Class 3 pavement mix designs for reconstruction of ramps on I-75. It included data from 7- and 28-day test results.

Memo from G.M. Geary to L.E. Dent, Materials & Research, Georgia Department of Transportation, March 2002.

> This memo pertains to concrete mix designs (portland cement concrete pavement). Mix proportions were approved for use on this project, provided the concrete delivered to the roadway meets all applicable acceptance tests. Mix 1 is not approved for the stated project.

Special Provision, Section 440: Roller Compacted Concrete Shoulder Pavement. Georgia Department of Transportation, January 2004.

> The information attached is a replacement for Section 440. It includes these headings: general description, materials, construction requirements, measurement, and payment.

Standard Operating Procedure (SOP) 1: Monitoring the Quality of Coarse and Fine Aggregates. Office of Materials and Research, Georgia Department of Transportation, Revised October 2003.

> These procedures include sections on general information; fine and coarse aggregate source lists; source evaluations; source approval procedures (qualified products); establishing and maintaining an acceptable quality assurance program; policy for departmental testing, acceptance, and use of certified aggregates; removal and reinstatement to qualified products list; assistance to producers; monthly samples for complete analysis; and department of transportation materials producer files.

Standard Operating Procedure (SOP) 5: Quality Control of Portland Cement and Blended Hydraulic Cements and Quality Control of Fly Ash and Granulated Blast-Furnace Slag. Office of Materials and Research, Georgia Department of Transportation, July 2003.

> These procedures include sections on general information, documentation and use of materials, requirements for approved sources, list of approved sources, inspection, sampling and testing, and distribution points.

GDT 27. http://tomcat2.dot.state.ga.us/thesource/pdf/auxdata/gdt/gdt027.html. Accessed March 1, 2004.

> This includes information on scope, apparatus, sample size and preparation, procedures, calculations, and reporting.

GDT 28. http://tomcat2.dot.state.ga.us/thesource/pdf/auxdata/gdt/gdt028.html. Accessed March 1, 2004.

> This includes information on scope, apparatus, sample size and preparation, procedures, calculations, and reporting.

GDT 26. http://tomcat2.dot.state.ga.us/thesource/pdf/auxdata/gdt/gdt026.html. Accessed March 1, 2004.

This includes information on scope, apparatus, sample size and preparation, procedures, calculations, and reporting.

Kansas

Special Provision to the Standard Specifications 1990 Edition. Section 402, Concrete. Kansas Department of Transportation.

These specifications are for the “Concrete” section and include details on materials, mix design, mortar, commercial grade concrete, certified concrete, requirements for combined materials, mixing, delivery, and placement limitations, inspection and testing, and air-entrained concrete for pavement.

Special Provision to the Standard Specifications 1990 Edition. Section 1102, Aggregates for Concrete. Kansas Department of Transportation.

These specifications are for the “Aggregates for Concrete” section and include details on requirements, test methods, prequalification, and basis of acceptance. Included under the details section is information pertaining to coarse, fine, mixed, and miscellaneous aggregates.

Special Provision to the Standard Specifications 1990 Edition. Division 500, Portland Cement Concrete Pavement (Quality Control/Quality Assurance). Kansas Department of Transportation.

These specifications are for the “Portland Cement Concrete Pavement” section and include details on contractor quality control requirements, materials, construction requirements, and measurement and payment. Under the “Contractor Quality Control Requirements” section is information regarding quality control organization, certified technicians’ required duties, testing facilities, testing requirements, documentation, corrective action, non-conforming materials, and quality control plan.

Table of Contents, Section 5.16. Kansas Department of Transportation.

This is a copy of the table of contents, showing the section titles and revision dates of sections 5.16.00 through 5.16.59.

Construction Using Quality Control/Quality Assurance Specifications. Appendix B, Sampling and Testing Frequency Chart. Kansas Department of Transportation, February 2002.

This information includes the tests required, test method, quality control by contractor, and verification by KDOT for concrete pavement. The categories of concrete pavement are individual aggregate, combined aggregates, and concrete including Class I &/or II aggregate.

Construction Using Non Quality Control/Quality Assurance Specifications. Appendix A, Sampling and Testing Frequency Chart. Kansas Department of Transportation, February 2002.

This information includes the tests required, test method, CMS, verification samples and tests, and acceptance samples and tests for concrete pavement.

Various concrete mix designs. Kansas Department of Transportation.

These include four mix designs from different dates, two from June 7, 2002, one from January 24, 2003, and one from July 22, 2003. A materials distribution chart is included with each one.

Louisiana

Uniform Aggregate Gradation Specifications (Pavement Types B & D).

> This information describes a percent-retained chart for evaluating the combined aggregates for the proposed PCCP mix, both fine and coarse. There are two charts: Combined Aggregate Gradation 5-20 Band: Grade B and Combined Aggregate Gradation 5-20 Band: Grade D. The charts note that no two adjacent sieve sizes shall account for less than 14% of the total gradation within the #30 and 3/4” boundary.

Michigan

Portland Cement Concrete Pavement Mixture for I-75 Demonstration Project, Special Provision. Michigan Department of Transportation, May 9, 2003.

> This special provision sets forth requirements for furnishing portland cement concrete mixtures for mainline, shoulder, and miscellaneous pavement applications. The contractor does not have the option of using other concrete grades or types in lieu of the concrete mixtures described in this special provision. The prescribed materials include aggregates, cementitious materials, and concrete mixture requirements. Construction methods and measurement and payment are also discussed.

Portland Cement Concrete Grade P1 (Modified), Special Provision. Michigan Department of Transportation, August 27, 2003.

> This special provision sets forth requirements for furnishing portland cement concrete mixtures for mainline, shoulder, and miscellaneous pavement applications. The contractor does not have the option of using other concrete grades or types in lieu of the concrete mixtures described in this special provision. The prescribed materials include aggregates, cementitious materials, and concrete mixture requirements. Construction methods and measurement and payment are also discussed.

Minnesota

Plan Sheets, General Layout. Project S.P. 3412-60 (T.H. 71), Sheets 2–4 of 53. Minnesota Department of Transportation, March 13, 1998.

> This includes plans showing areas of unbonded concrete overlay and bituminous overlay sections.

Missouri

Optimized Mix with Chips. James Cape and Sons Company, July 29, 2003.

> This reference sheet shows weights per cubic yard (saturated, surface dry) of several ingredients of a contractor’s optimized PCC mix, which was tested on July 25, 2003.

Standard Missouri state mix. Missouri Department of Transportation.

> Four different reference sheets show the standard PCC mix.

Portland Cement Concrete, Field Section 501. Materials Engineering, Missouri Department of Transportation.

This section contains specifications for concrete mix design. The instructions contained are intended to supplement those contained in the Construction Manual Sec. 500.

General Construction Manual, Section Document. Section 500, Portland Cement Concrete Plant and Pavement. Missouri Department of Transportation, April 23, 1996.

This section, 501.6, contains specifications on concrete mix design with field proportions.

Nebraska

47B Concrete Pavements and 47BD Concrete for Bridges. Nebraska Department of Roads.

This discusses the amendments to Section 1002 in the 1997 *Standard Specifications and Supplemental Specifications*. A table shows the alternates for the proportioning used for 47BD concrete used in bridge decks, approach slabs, bridge rails, and barriers.

Section 1, Portland Cement Concrete. Nebraska Department of Roads.

The brands and types of cement that are accepted are shown in a table, as well as the accepted fly ash, pozzolanic, silica fume admixtures, air-entraining admixtures, water-reducing, retarding, accelerating admixtures, and finishing aids/evaporation reducers.

Section 1033, Aggregates. Nebraska Department of Roads.

A description of mineral aggregates including material characteristics, general aggregate properties, and portland cement concrete aggregate are included. Tables showing coarse aggregate for concrete gradation limits, aggregate classes and uses, sampling and testing procedures, and fine aggregate for concrete gradation limits are included.

New York

Plan sheets. New York State Department of Transportation, October 16, 2000.

Plan sheets showing Typical Plan, Cross Section, and Joint Layout, Longitudinal Joints, Joint Ties, Joint Sawing and Sealing, Transverse Joints, Joint Sawing and Sealing, Utility Isolation and Joint Layout General Notes and Guidelines, Telescoping Manhole Casting Layout, Non-Telescoping Manhole Casting Isolation, Shallow Structure Isolation, Drainage Structure Isolation and Isolation Near Manhole Castings, Multiple Utilities Isolation, and Telescoping Manhole Casting and Ring.

Freezing and Thawing, Portland Cement Concrete Cores, Test Method. Materials Bureau, New York State Department of Transportation, April 1986.

The resistance of portland cement cores when exposed to alternate freezing and thawing is determined with this method. The test methods using appropriate apparatus, procedure, and results are discussed.

Section 500, Portland Cement Concrete, Standard Specifications. New York State Department of Transportation, January 2, 2002.

This includes Section 501, “Portland Cement Concrete,” general information. Sections 501-1 through 501-5 are included. These sections offer details on description, materials (composition of materials, material requirements, concrete batching facility requirements, concrete mixer and delivery unit requirements), construction (proportioning, handling, measuring, and batching materials, concrete mixing, transporting, and discharging), method of measurement, and basis of payment.

Materials Method 9.1M: Plant Inspection of Portland Cement Concrete (Metric). Materials Bureau, New York State Department of Transportation, January 2002.

Materials Method 9.1M describes department practices involved in the plant inspection of portland cement concrete mixes. Full conformance with Materials Method 9.1 M will provide uniform inspection procedures at the plant, in an effort to minimize the chance of unacceptable concrete being incorporated into department projects. A secondary purpose is to provide proper documentation of the acceptability of the concrete as it leaves the plant.

Materials Method 9.1M consists of four sections and appendices. Sections 1 through 3 contain procedures that the plant inspector should use while inspecting and documenting the production of concrete. Section 4 describes the inspection approval procedures performed normally either by the regional materials engineer and his staff or by representatives of the Materials Bureau, as indicated.

Materials Method 9.2: Field Inspection of Portland Cement Concrete (Metric). Materials Bureau, New York State Department of Transportation, April 2002.

This Materials Method describes specific procedures for inspecting, sampling, and testing portland cement concrete to insure conformance with Department Specifications.

Material Method 9.2 consists of eight sections (A through H) discussing sampling procedures, temperature, slump test, air content test procedure, unit weight and yield test procedure, concrete cylinder fabrication, and uniformity test procedure.

Ohio

Portland Cement Concrete Pavement Using QC/QA, Supplemental Specification 888. State of Ohio Department of Transportation, January 3, 2002.

These supplemental specifications include 888.01 through 888.23. These include information on materials, concrete proportioning, properties, and equipment, aggregate handling, mixing, concrete tests, quality control, acceptance, strength, smoothness, joint sealing, pavement thickness, sampling, core evaluation, method of measurement, basis of payments, pay adjustment, and deficiencies. Appendix 1 through 3 are included and discuss proportioning, quality control, and quality assurance.

North Dakota

Portland Cement Concrete Pavement: Sections 550 and 816. North Dakota Department of Transportation.

Section 550 includes 550.01, Description, and 550.03, Required Tests for Summary. Section 816 includes 816.03, Sample Numbering, and 816.05, Aggregate Testing.

South Dakota

Hodges, D. 2002. PCC Pavement Design Mix (memorandum). Division of Planning/Engineering, South Dakota Department of Transportation, June 11, 2002.

This information describes the slipform portland cement concrete pavement mix design with modified Class F fly ash and Type I-II cement for a project in McCook County.

Hodges, D. 2003. PCC Pavement Design Mix (memorandum). Division of Planning/Engineering, South Dakota Department of Transportation, July 1, 2003.

This information describes the slipform portland cement concrete pavement mix design with modified Class F fly ash and Type I-II cement for a project in Brown and Day Counties. One mix has water reducer and one does not.

Hodges, D. 2002. PCC Pavement Design Mix (memorandum). Division of Planning/Engineering, South Dakota Department of Transportation, May 10, 2002.

This information describes the slipform Portland cement concrete pavement mix design with modified Class F fly ash and Type II cement for a project in Pennington County.

Bench-Bresher, J. 2003. Paving Mix Design (memorandum). South Dakota Department of Transportation, April 14, 2003.

Concrete Materials of Sioux Falls, South Dakota, has selected these materials to be used in the class A-45 paving mix for a project in Yankton County.

Hodges, D. Class A-45 Paving Mix. South Dakota Department of Transportation.

This includes a listing of the materials used for project NH 0235(2) in Pennington County.

Hodges, D. 2003. Paving Mix Design (memorandum). Division of Planning/Engineering, South Dakota Department of Transportation, August 14, 2003.

This includes a list of the materials, selected by the contractor, to be used in the class A-45 paving mix for project NH 0012(00)189 in Walworth County.

Wisconsin

WisDOT Internet: Doing Business. Standardized special provisions for engineering and related services consultant firms. Wisconsin Department of Transportation. http://dotnet/consultants/stsp.htm. Accessed October 7, 2003.

The standardized special provisions describe the directions and requirements of a highway work proposal that are not detailed or prescribed in the *Standard Specification* 2003 Edition. Standardized special provisions are available for WisDOT eligible engineering consultants and city, county, and municipal staff to download as zipped files from the WisDOT ft.P server.

I-90-94 Wisconsin Concrete Pavement. Wisconsin Department of Transportation.

This is a PowerPoint presentation, “RED Reports - Wisconsin Dells PCC Pavements, FWHA TWG.” It includes photos showing removal and replacement of cracked PCC pavement, but no text.

Standard Specifications for Highway and Structure Construction, 2003. Wisconsin Department of Transportation. CD-ROM.

This manual specifies material selection and construction operations for road construction projects.

B.4. Compilation of State Practices

Mix Design Summary

Mix Design Summary

			Georgia	Indiana	Iowa
Who provides mix design			Contractor/Supplier [1]	State [1]	State&Contractor/ Supplier [1]
Mix design procedure			state specific procedure/past experience [2]	other; many contractors have general mix to start with	A state specific procedure (based on shilstone gradation) / Another procedure
Specified concrete properties in contract documents	Fresh Concrete	Workability/Slump	X	non QC/QA	
		Bleeding			
		Segregation			
		Set			
		w/cm ratio	X	QC/QA and non QC/QA	X
		Plastic Shrinkage Cracking		min cement content and spec	
	Hardened Concrete	Strength at Opening	X	contractor will develop mix based on time to get on it - 550 pr flex	
		Strength at 28 days	X		X[2]
		Coefficient of Thermal Expansion			
		Drying Shrinkage			
		Permeability		only bridge decks	
	Concrete Durability	Resistance to freezing and thawing			
		Resistance to sulfate attack			
		Resistance to ASR			
		Abrasion Resistance			
		Corrosion Resistance			
	Other	Specify	Air content (fresh)	Air content pay factor for QC/QA: lot range, consistency, at the plant, point of acceptance; sec 501.28 not test behind the paver	
Rank of desired concrete properties (1 = most important)	Fresh Concrete	Workability/Slump	1		2
		Bleeding	4		
		Segregation	5		
		Set	2		3
		Plastic Shrinkage Cracking	3		
	Hardened Concrete	Strength/Stiffness	1		
		Coefficient of Thermal Expansion (CTE)	4		
		Drying Shrinkage	2		
		Permeability	3		
	Concrete Durability	Resistance to freezing and thawing	2		1
		Resistance to sulfate attack	5		
		Resistance to ASR	3		
		Abrasion Resistance	1		
		Corrosion Resistance	4	No	
	Other	Specify			
Typical values for mix design parameters			*		
	W/C ratio	Min	0.45		
		Max	0.53	QC (0.45); non QC (0.487)	0.45 / 0.48
		Typical	lower than typical	0.42-0.43	QMC Pav. / Class C
	Slump	Construction Method	SF	SF	SF
		Min	0	1.25	
		Max	3.5"[3]	3.0	
		Typical	1.0-1.5"		2.5-3.0"
		Construction Method	FF	FF	FP
		Min	0"	2	1/2"
		Max	3.5"	4	4.0"
		Typical	2.0-2.5"		3.5"
	Air Content	Application	Standard paving	Sec.501 (QC)[2]	FP
		Lower Limit	3	5.7	6.0
		+/-			1.0
		Upper Limit	6.5	8.9	
		+/-			
		Application	24 hr accelerated	Sec.502 (non QC)	
		Lower Limit	3.0	5.0	
		+/-			
		Upper Limit	6.0	8.0	
		+/-			
	Water Content	Application		Sec 501 (QC)	QMC
		Lower Limit (lb/cu. Yd)	242		213
		Upper Limit (lb/cu. Yd)	275	198	235
		Application		Sec.502 (non QC)	Class C
		Lower Limit (lb/cu. Yd)			223
		Upper Limit (lb/cu. Yd)		275	240
		Application			
		Lower Limit (lb/cu. Yd)			
		Upper Limit (lb/cu. Yd)			
	Cementitious Content	Application	Standard paving	Sec.501 (QC)	QMC
		Lower Limit (lb/cu. Yd)	541	440	540
		Upper Limit (lb/cu. Yd)	658		560
		Application	Lane replacement	Sec.502 (non QC)	Class C
		Lower Limit (lb/cu. Yd)	752	564 (specified)	571
		Upper Limit (lb/cu. Yd)			840
		Application			
		Lower Limit (lb/cu. Yd)			
		Upper Limit (lb/cu. Yd)			

			Kansas	Louisiana	Michigan
Who provides mix design			Contractor/ Supplier [1]	Contractor/ Supplier	Contractor/ State
Mix design procedure			State Specific	State Specific, Contractor's decision	
Specified concrete properties in contract documents	Fresh Concrete	Workability/Slump	X	X	X
		Bleeding			
		Segregation			
		Set			
		w/cm ratio	X	X	X
		Plastic Shrinkage Cracking			
	Hardened Concrete	Strength at Opening		X	
		Strength at 28 days	X	X	X
		Coefficient of Thermal Expansion			
		Drying Shrinkage			
		Permeability			
	Concrete Durability	Resistance to freezing and thawing	X		
		Resistance to sulfate attack	X		
		Resistance to ASR	X		
		Abrasion Resistance	X		
		Corrosion Resistance			
	Other	Specify			Air content, concrete temp
Rank of desired concrete properties (1 = most important)	Fresh Concrete	Workability/Slump	1		
		Bleeding	4		
		Segregation	5		
		Set	2	4	
		Plastic Shrinkage Cracking	3	2	
	Hardened Concrete	Strength/Stiffness	1		
		Coefficient of Thermal Expansion (CTE)	4	5	
		Drying Shrinkage	3	3	
		Permeability	2	8	
	Concrete Durability	Resistance to freezing and thawing	1	6	
		Resistance to sulfate attack	3		
		Resistance to ASR	1		
		Abrasion Resistance	3	1	
		Corrosion Resistance	3	7	
	Other	Specify			
Typical values for mix design parameters					
	W/C ratio	Min	0.40	none	none
		Max	0.45*	0.53	0.5
		Typical	0.42	0.48	0.45
	Slump	Construction Method	SF	SF	SF/FF with no WR
		Min	0.5	1	
		Max	1.75	2.5	3
		Typical	1.25		1.5
		Construction Method	FF	FF - vibrated	SF/FF with MRWR
		Min	2	2	
		Max	4	4	6
		Typical	2.5		
	Air Content	Application	SF[3]	All	SF
		Lower Limit	4	3	5.0
		+/-			
		Upper Limit	7	7	8.0
		+/-			
		Application			
		Lower Limit			
		+/-			
		Upper Limit			
		+/-			
	Water Content	Application	MA-2[4]	Pavement (Type B)	
		Lower Limit (lb/cu. Yd)			
		Upper Limit (lb/cu. Yd)		289	
		Application	All concrete, MA-1	Pavement (Type D)	
		Lower Limit (lb/cu. Yd)			
		Upper Limit (lb/cu. Yd)		269	
		Application	SF, MA-3[5]		
		Lower Limit (lb/cu. Yd)			
		Upper Limit (lb/cu. Yd)			
	Cementitious Content	Application	MA-2 & Coarse and Fine	SF pavement (Type B, 1 1/2" max)	
		Lower Limit (lb/cu. Yd)	602	545	
		Upper Limit (lb/cu. Yd)			
		Application	All concrete, MA-1	SF pavement (Type D, 2" max)	
		Lower Limit (lb/cu. Yd)	619	508	
		Upper Limit (lb/cu. Yd)			
		Application	SF, MA-3		
		Lower Limit (lb/cu. Yd)	521		
		Upper Limit (lb/cu. Yd)			

			Minnesota	Missouri	Nebraska
Who provides mix design			Contractor [1]	Non QC/QA (State) QC/QA (Contractor)	State
Mix design procedure			Industry Standard	State Standard/Other [2]	State Specific
Specified concrete properties in contract documents	Fresh Concrete	Workability/Slump	X	X	
		Bleeding			
		Segregation			
		Set			
		w/cm ratio	X	X	X
		Plastic Shrinkage Cracking			
	Hardened Concrete	Strength at Opening	X	X	
		Strength at 28 days		X	
		Coefficient of Thermal Expansion			
		Drying Shrinkage			
		Permeability	X[2]		
	Concrete Durability	Resistance to freezing and thawing			
		Resistance to sulfate attack			
		Resistance to ASR			
		Abrasion Resistance			
		Corrosion Resistance			
	Other	Specify	HPP - Strength Data	Air content	
Rank of desired concrete properties (1 = most important)	Fresh Concrete	Workability/Slump		specification	X
		Bleeding		10	
		Segregation	X[3]	3	
		Set		8	
		Plastic Shrinkage Cracking		2	
	Hardened Concrete	Strength/Stiffness		specification	
		Coefficient of Thermal Expansion (CTE)		11	
		Drying Shrinkage		9	
		Permeability	X[4]	6	
	Concrete Durability	Resistance to freezing and thawing		1	
		Resistance to sulfate attack		7	
		Resistance to ASR		4*	
		Abrasion Resistance		5	
		Corrosion Resistance		12	
	Other	Specify			
Typical values for mix design parameters					
	W/C ratio	Min		none	
		Max	0.40	0.48	0.45
		Typical		0.45	need more info
	Slump	Construction Method	SF	SF	SF[1]
		Min	1	none	0
		Max	2	2.5	3
		Typical		1.25	
		Construction Method	FF	FF	
		Min	3	none	
		Max	4	3.5	
		Typical		3	
	Air Content	Application	pavement	QC/QA - PCCP (behind paver)	SF Pavement 47B-3625[2]
		Lower Limit	5.0	5.5	5.0
		+/-			
		Upper Limit	8.0	8.5	7.5
		+/-			
		Application	HP pavement	Non QC/QA PCCP (ahead of paver)	Bridge Deck - 47BD-4350
		Lower Limit	5.5	4.0	5.0
		+/-			
		Upper Limit	8.5	7.0	7.5
		+/-			
	Water Content	Application	Pavement	SF - Typical Values	SF Pavement 47B-3625
		Lower Limit (lb/cu. Yd)		254	
		Upper Limit (lb/cu. Yd)	240	271	254
		Application		FF - Typical Values	Bridge Deck - 47BD-4350
		Lower Limit (lb/cu. Yd)		264	
		Upper Limit (lb/cu. Yd)		281	276
		Application			
		Lower Limit (lb/cu. Yd)			
		Upper Limit (lb/cu. Yd)			
	Cementitious Content	Application	pavement	SF - QC/QA[3]	SF Pavement 47B-3625
		Lower Limit (lb/cu. Yd)		564	565
		Upper Limit (lb/cu. Yd)	600	none	
		Application	HES pavement	SF - Non QC/QA	Bridge Deck - 47BD-4350
		Lower Limit (lb/cu. Yd)		564	657
		Upper Limit (lb/cu. Yd)	>600[5]	602	
		Application		FF	
		Lower Limit (lb/cu. Yd)		588	
		Upper Limit (lb/cu. Yd)		625	

			New York	North Carolina	North Dakota
Who provides mix design			State&Contractor/Supplier [1]	Contractor/Supplier [1]	State (engineer designed)
Mix design procedure			state specific procedure	ACI 211.1[2]	State specific
Specified concrete properties in contract documents	Fresh Concrete	Workability/Slump	X (Table 501 - 3)	X	X
		Bleeding			
		Segregation	X (Table 501 - 3.03 B)		
		Set		X[3]	
		w/cm ratio	X (Table 501 - 3)	X	X
		Plastic Shrinkage Cracking	X (502 - 3.14)		
	Hardened Concrete	Strength at Opening	X (502 - 3.18)	X[4]	
		Strength at 28 days		X[5]	X
		Coefficient of Thermal Expansion			
		Drying Shrinkage			
		Permeability		X[6]	
	Concrete Durability	Resistance to freezing and thawing	X	X[7]	
		Resistance to sulfate attack	X		
		Resistance to ASR	X	X[8]	
		Abrasion Resistance		X[9]	
		Corrosion Resistance		X[10]	
	Other	Specify	Air		Air content
Rank of desired concrete properties (1 = most important)	Fresh Concrete	Workability/Slump			4
		Bleeding		3	
		Segregation		1	
		Set			5
		Plastic Shrinkage Cracking		2	
	Hardened Concrete	Strength/Stiffness			1
		Coefficient of Thermal Expansion (CTE)		5	
		Drying Shrinkage		4	
		Permeability			2
	Concrete Durability	Resistance to freezing and thawing			3
		Resistance to sulfate attack		6	
		Resistance to ASR			
		Abrasion Resistance			
		Corrosion Resistance			
	Other	Specify			
Typical values for mix design parameters					
	W/C ratio	Min			
		Max		0.559 (plain) / 0.538 (fly ash)	0.48
		Typical	0.44*	0.491 / 0.500 / 0.45 (note)	0.42
	Slump	Construction Method	SF		SF
		Min			
		Max		1.5 SF / 3.0 FP	3
		Typical	40mm	1.5 / 3.0	1.5
		Construction Method	FF[3]		FF
		Min	50mm		
		Max	65mm		3
		Typical	Adjusted accordingly		2.5
	Air Content	Application	Class C (std. Mix)	concrete pavement[11]	SF
		Lower Limit	5.0	5.0	5.0
		+/-		1.50%	
		Upper Limit	8.0		8.0
		+/-			
		Application	Class F (501 - std. HES)		FF
		Lower Limit	5.0		5.0
		+/-			
		Upper Limit	8.0		8.0
		+/-			
	Water Content	Application	Class C	concrete pavement	SF
		Lower Limit (lb/cu. Yd)		258	
		Upper Limit (lb/cu. Yd)	266	275	267.4
		Application			FF
		Lower Limit (lb/cu. Yd)	Class F		
		Upper Limit (lb/cu. Yd)	272		267.4
		Application			
		Lower Limit (lb/cu. Yd)			
		Upper Limit (lb/cu. Yd)			
	Cementitious Content	Application	Class C	concrete pavement[12]	SF
		Lower Limit (lb/cu. Yd)		526	564
		Upper Limit (lb/cu. Yd)	605	564	
		Application	Class F		FF
		Lower Limit (lb/cu. Yd)			564
		Upper Limit (lb/cu. Yd)	716		
		Application			
		Lower Limit (lb/cu. Yd)			
		Upper Limit (lb/cu. Yd)			

			Ohio	Oklahoma	South Dakota
Who provides mix design			State&Contractor/Supplier [1]	Contractor/Supplier	State
Mix design procedure			ACI 211.1 (QC/QA spec) / State Std. Spec.[2]	ACI 211.1	past experience/ACI 211.1
Specified concrete properties in contract documents	Fresh Concrete	Workability/Slump	1-3" std. & QC/QA	X	X
		Bleeding			
		Segregation			
		Set			
		w/cm ratio	0.50 std. / 0.45 QC/QA	X	
		Plastic Shrinkage Cracking			
	Hardened Concrete	Strength at Opening	600psi center point flex. - std.&QC/QA	X	X
		Strength at 28 days	not required - std.4000psi+1.65σ-QC/QA	X	X
		Coefficient of Thermal Expansion			
		Drying Shrinkage			
		Permeability			
	Concrete Durability	Resistance to freezing and thawing	ASTM C666 Proc B@ 350 cycles[3]		
		Resistance to sulfate attack			
		Resistance to ASR			
		Abrasion Resistance			
		Corrosion Resistance			
	Other	Specify	Field: air content (6%); smoothness (profilograph); thickness (design - 1/2")	Air content	Air and concrete temperature
Rank of desired concrete properties (1 = most important)	Fresh Concrete	Workability/Slump	6		X
		Bleeding	14		
		Segregation	15		
		Set	13		
		Plastic Shrinkage Cracking	4	1	
	Hardened Concrete	Strength/Stiffness	2		
		Coefficient of Thermal Expansion (CTE)	8		
		Drying Shrinkage	3	2	
		Permeability	7		X
	Concrete Durability	Resistance to freezing and thawing	1	3	
		Resistance to sulfate attack	10		
		Resistance to ASR	9		X
		Abrasion Resistance	5	4	
		Corrosion Resistance	11		
	Other	Specify			
Typical values for mix design parameters					
	W/C ratio	Min			
		Max	0.45 (QC/QA) / 0.50 (Std.)	0.48	mix design dependant
		Typical	0.45 (SF)		
	Slump	Construction Method	SF[4]	SF	SF
		Min	1.0	1.0	0
		Max	3.0	3.0	2
		Typical	1.0	1.0	
		Construction Method	FF	FF	FF - A45 mix
		Min	1.0	1.0	1
		Max	6.0	3.0	3
		Typical	4.0	3.0	
	Air Content	Application	SF or FF[5]	All	SF
		Lower Limit	6.0	4.5	5.0
		+/-	2.0		
		Upper Limit		7.5	7.5
		+/-			
		Application			FF
		Lower Limit			5.0
		+/-			
		Upper Limit			7.5
		+/-			
	Water Content	Application	[6]	[1]	SF
		Lower Limit (lb/cu. Yd)			225
		Upper Limit (lb/cu. Yd)			260
		Application			FF
		Lower Limit (lb/cu. Yd)			272 Average
		Upper Limit (lb/cu. Yd)			
		Application			
		Lower Limit (lb/cu. Yd)			
		Upper Limit (lb/cu. Yd)			
	Cementitious Content	Application	Std. Mix	mainline	SF[1]
		Lower Limit (lb/cu. Yd)	550	564	624 Typical
		Upper Limit (lb/cu. Yd)	600		800
		Application	QC/QA (55.888)	shoulder	FF[2]
		Lower Limit (lb/cu. Yd)	ACI 211	470	680 - typical
		Upper Limit (lb/cu. Yd)			800
		Application			
		Lower Limit (lb/cu. Yd)			
		Upper Limit (lb/cu. Yd)			

			Texas	Wisconsin
Who provides mix design			Contractor/Supplier	Contractor
Mix design procedure			ACI 211.1	State Specific/Past Experience
Specified concrete properties in contract documents	Fresh Concrete	Workability/Slump	X	X
		Bleeding		
		Segregation		
		Set		
		w/cm ratio	X[1]	X
		Plastic Shrinkage Cracking		
	Hardened Concrete	Strength at Opening		X
		Strength at 28 days		X
		Coefficient of Thermal Expansion		
		Drying Shrinkage		
		Permeability		
	Concrete Durability	Resistance to freezing and thawing		
		Resistance to sulfate attack		
		Resistance to ASR		
		Abrasion Resistance	X	
		Corrosion Resistance		
	Other	Specify	Air/CTE/ASR (Need more info)	
Rank of desired concrete properties (1 = most important)	Fresh Concrete	Workability/Slump	1	
		Bleeding	1	
		Segregation	1	
		Set	1	
		Plastic Shrinkage Cracking	1	
	Hardened Concrete	Strength/Stiffness	1	
		Coefficient of Thermal Expansion (CTE)	1	
		Drying Shrinkage	1	
		Permeability	1	X
	Concrete Durability	Resistance to freezing and thawing	1	X
		Resistance to sulfate attack	1	
		Resistance to ASR	1	
		Abrasion Resistance	1	
		Corrosion Resistance	1	
	Other	Specify		
Typical values for mix design parameters				
	W/C ratio	Min	none	
		Max	0.45	0.42
		Typical		0.40
	Slump	Construction Method		SF
		Min		
		Max	3	2.5
		Typical	1.5	1.5
		Construction Method		FF
		Min		2
		Max		4
		Typical		4
	Air Content	Application		SF
		Lower Limit		5.5
		+/-		
		Upper Limit		8.5
		+/-		
		Application		All except SF
		Lower Limit		4.5
		+/-		
		Upper Limit		7.5
		+/-		
	Water Content	Application		Pavement
		Lower Limit (lb/cu. Yd)		225
		Upper Limit (lb/cu. Yd)		266
		Application		
		Lower Limit (lb/cu. Yd)		
		Upper Limit (lb/cu. Yd)		
		Application		
		Lower Limit (lb/cu. Yd)		
		Upper Limit (lb/cu. Yd)		
	Cementitious Content	Application	pavement	pavement
		Lower Limit (lb/cu. Yd)		565
		Upper Limit (lb/cu. Yd)	700	
		Application		
		Lower Limit (lb/cu. Yd)		
		Upper Limit (lb/cu. Yd)		
		Application		
		Lower Limit (lb/cu. Yd)		
		Upper Limit (lb/cu. Yd)		

			Georgia	Indiana	Iowa
	Maximum Size of coarse aggregate (inches)		1.0" (nominal)	1.0" (top sieve)[3]	1.5"
	Coarse Aggregate	Application	All pavements		QMC
		Lower Limit (lb/cu. Yd)	1750		1650
		Upper Limit (lb/cu. Yd)	1900		1800
		Application			Class C
		Lower Limit (lb/cu. Yd)			1150
		Upper Limit (lb/cu. Yd)			1650
	Fine Aggregate	Application	All pavements	Sec. 501 (QC)	QMC
		Lower Limit (lb/cu. Yd)	1150	35-50% of total agg.	1210
		Upper Limit (lb/cu. Yd)	1300		1350
		Application		Sec.502 (non QC)	Class C
		Lower Limit (lb/cu. Yd)		35-45% of total agg.	1350
		Upper Limit (lb/cu. Yd)			1725
	SCMs commonly used in concrete mix design	Class F Fly Ash	X[4]	X[4]	
		Application	all except accelerated	501 and 502	
		Class C Fly Ash	X	X	X
		Application	all except accelerated	501 and 502	SF, FP
		GGBFS Slag	X[5]	X	X
		Application	early strength not required	allowed but not often; fly ash cheaper	SF, FP
		Silica Fume			
		Application		many issue/spec change to ternary	
		Metakaolin			
		Application			
		Volcanic Ash/Pumicite			
		Application			
		Calcinated Shale			
		Application			
		Opaline Shale			
		Application			
		Calcinated Clay			
		Application			
		Diatomaceous Earth			
		Application			
		Other			
		Application			
	Chemical admixtures commonly used in concrete mix design	Air entraining admixtures	X	X	X
		Application	All pavements	501 and 502	SF, FP
		Coventional water reducer	X	X[6]	X
		Application	All pavements	501 and 502	SF, FP
		Mid-range water reducer	X	X	X
		Application	Lower water content	501 and 502 (not often)	SF, FP
		Accelerator	X		
		Application	Opening traffic early		
		Retarder	X	X	X
		Application	Haul time	501 and 502	Long haul, hot day
		Corrosion inhibitor			
		Application			
		Shrinkage reducer			
		Application			
		ASR inhibitors (I.e. Lithium)			
		Application			
		Hydration control admixtures			
		Application			
		Other (describe)			
		Application			
Typical combinations of cement, SCM, and chemical admixtures for paving mixes	Paving mix 1	Cement type	Type 1 & 2	PC and Blended (copmly Sec.901.01)	Type 1
		Batch weight (lb/yd)	541-752	min. 440	
		SCM	F or C fly ash, or slag[6]	pozzolan max. 20%+-5% of PC	Class C
		Batch weight (lb/yd)			20%
		Chemical admixture 1	WR (3-5 oz/CWT)		AEA
		dosage (fl oz/cwt)	Mid range WR (3-5 oz/CWT)		
		Chemical admixture 2	Accel. (3 gal./yd)		WR
		dosage (fl oz/cwt)	Retarder (<6 oz/CWT)		
	Paving mix 2	Cement type		PC and Blended (copmly Sec.901.01)[6]	Type 1&2
		Batch weight (lb/yd)		min. 564	
		SCM	26-28% fly ash[7]	fly ash max.20% / GGBFS max.30% of PC	Class C
		Batch weight (lb/yd)			20%
		Chemical admixture 1	AEA (2-5 oz/CWT)	types A-E prior to written approval	AEA
		dosage (fl oz/cwt)			
		Chemical admixture 2			WR
		dosage (fl oz/cwt)			
	Paving mix 3	Cement type		PC and Blended (copmly Sec.901.01)	
		Batch weight (lb/yd)		min. 564	
		SCM		fly ash max.10% / GGBFS max.15% of PC	
		Batch weight (lb/yd)			
		Chemical admixture 1		types A-E prior to written approval	
		dosage (fl oz/cwt)			
		Chemical admixture 2			
		dosage (fl oz/cwt)			

			Kansas	Louisiana	Michigan
	Maximum Size of coarse aggregate (inches)		1	2	
	Coarse Aggregate	Application	Pavement[6]		
		Lower Limit (lb/cu. Yd)	1000		
		Upper Limit (lb/cu. Yd)	2000		
		Application			
		Lower Limit (lb/cu. Yd)			
		Upper Limit (lb/cu. Yd)			
	Fine Aggregate	Application	Pavement[7]	Pavement[1]	
		Lower Limit (lb/cu. Yd)	~50% of total agg.		
		Upper Limit (lb/cu. Yd)			
		Application			
		Lower Limit (lb/cu. Yd)			
		Upper Limit (lb/cu. Yd)			
	SCMs commonly used in concrete mix design	Class F Fly Ash			X[1]
		Application			pavement
		Class C Fly Ash		X[2]	X
		Application		all	pavement
		GGBFS Slag		X[3]	X[2]
		Application		all	pavement
		Silica Fume	X		
		Application	bridges		
		Metakaolin			
		Application			
		Volcanic Ash/Pumicite			
		Application			
		Calcinated Shale			
		Application			
		Opaline Shale			
		Application			
		Calcinated Clay			
		Application			
		Diatomaceous Earth			
		Application			
		Other			
		Application			
	Chemical admixtures commonly used in concrete mix design	Air entraining admixtures	X	X	X
		Application	pavement	pavement	pavement
		Coventional water reducer	X[8]	X	X
		Application	pavement	pavement	pavement
		Mid-range water reducer		X	X
		Application		pavement	pavement
		Accelerator			X
		Application			patch repair
		Retarder		X	X
		Application		pavement	pavement
		Corrosion inhibitor			
		Application			
		Shrinkage reducer			
		Application			
		ASR inhibitors (I.e. Lithium)			
		Application			
		Hydration control admixtures			
		Application			
		Other (describe)			
		Application			
Typical combinations of cement, SCM, and chemical admixtures for paving mixes	Paving mix 1	Cement type	Type I/II (Low Alkali, 0.6 maximum)	Type IS	
		Batch weight (lb/yd)	550	254	
		SCM	Typically, none are used.	GGBFS Slag	
		Batch weight (lb/yd)		254	
		Chemical admixture 1	AEA	AEA	
		dosage (fl oz/cwt)	0.5 to .75	0.8 to 1.0	
		Chemical admixture 2	WR	WR	
		dosage (fl oz/cwt)	5.0	4.0 to 8.0	
	Paving mix 2	Cement type	Type II	Type I/II	
		Batch weight (lb/yd)	620	508	
		SCM			
		Batch weight (lb/yd)			
		Chemical admixture 1		AEA	
		dosage (fl oz/cwt)		0.8 to 1.0	
		Chemical admixture 2		WR	
		dosage (fl oz/cwt)		4.0 to 8.0	
	Paving mix 3	Cement type	Type II		
		Batch weight (lb/yd)	527		
		SCM	93		
		Batch weight (lb/yd)			
		Chemical admixture 1			
		dosage (fl oz/cwt)			
		Chemical admixture 2			
		dosage (fl oz/cwt)			

			Minnesota	Missouri	Nebraska
	Maximum Size of coarse aggregate (inches)		2	1	1
	Coarse Aggregate	Application	pavement	SF	SF Pavement 47B-3625
		Lower Limit (lb/cu. Yd)	no requirement	11.06 ft^3/yd^3	777
		Upper Limit (lb/cu. Yd)	no requirement	11.34ft^3/yd^3	1033
		Application		FF	Bridge Deck - 47BD-4350
		Lower Limit (lb/cu. Yd)		10.88ft^3/yd^3	683
		Upper Limit (lb/cu. Yd)		11.16ft^3/yd^3	974
	Fine Aggregate	Application	pavement	SF	SF Pavement 47B-3625
		Lower Limit (lb/cu. Yd)	no requirement	6.78 ft^3/yd^3	1927
		Upper Limit (lb/cu. Yd)	no requirement	6.95 ft^3/yd^3	2285
		Application		FF	Bridge Deck - 47BD-4350
		Lower Limit (lb/cu. Yd)		6.67 ft^3/yd^3	1695
		Upper Limit (lb/cu. Yd)		6.84 ft^3/yd^3	2154
	SCMs commonly used in concrete mix design	Class F Fly Ash	X[6]		x
		Application	pavement		pavement
		Class C Fly Ash	X	X[4]	X
		Application	pavement	pavement	pavement
		GGBFS Slag	X		
		Application	pavement		
		Silica Fume	X		X
		Application	bridge deck		bridge deck overlay
		Metakaolin			
		Application			
		Volcanic Ash/Pumicite			
		Application			
		Calcinated Shale			
		Application			
		Opaline Shale			
		Application			
		Calcinated Clay			
		Application			
		Diatomaceous Earth			
		Application			
		Other			
		Application			
	Chemical admixtures commonly used in concrete mix design	Air entraining admixtures	X	X	X
		Application	pavement	all pavements	pavement
		Coventional water reducer	X	X	X
		Application	pavement	pavement	pavement
		Mid-range water reducer	X	X	X
		Application	pavement	pavement	structures
		Accelerator	X[7]		
		Application	no response		
		Retarder	X		
		Application	bridges		
		Corrosion inhibitor			
		Application			
		Shrinkage reducer			
		Application			
		ASR inhibitors (I.e. Lithium)	X[8]		research project UNL?
		Application	pavements		
		Hydration control admixtures	X		
		Application	none for paving		
		Other (describe)			
		Application			
Typical combinations of cement, SCM, and chemical admixtures for paving mixes	Paving mix 1	Cement type	Type I	Type I	Type I/II
		Batch weight (lb/yd)	400	573	423
		SCM	Class C fly ash	none	Class F fly ash
		Batch weight (lb/yd)	170		141
		Chemical admixture 1	WR	AEA	WR
		dosage (fl oz/cwt)	unknown	0.5 to 3.0	manufacturer recommendation
		Chemical admixture 2	AEA		AEA
		dosage (fl oz/cwt)	unknown		manufacturer recommendation
	Paving mix 2	Cement type	Type I	Type I	Type IPN (15 to 25% Natural pozzolan)
		Batch weight (lb/yd)	360	486	564
		SCM	GGBFS	Class C Fly Ash	Class C or F fly ash[3]
		Batch weight (lb/yd)	190	86	Total pozzolan content < 25%
		Chemical admixture 1	WR	AEA	WR
		dosage (fl oz/cwt)	unknown	0.5 to 3.0	manufacturer recommendation
		Chemical admixture 2	AEA		AEA
		dosage (fl oz/cwt)	unknown		manufacturer recommendation
	Paving mix 3	Cement type	Type I	Type I (1/2 sack reduction)	Type IPF
		Batch weight (lb/yd)	450	465	564
		SCM	Class C fly ash	Class C Fly Ash	none[4]
		Batch weight (lb/yd)	120	81	0
		Chemical admixture 1	WR	AEA	WR
		dosage (fl oz/cwt)	unknown	0.5 to 3.0	manufacturer recommendation
		Chemical admixture 2	AEA	Type A WR[5]	AEA
		dosage (fl oz/cwt)	unknown	unknown	manufacturer recommendation

			New York	North Carolina	North Dakota
	Maximum Size of coarse aggregate (inches)		0.5" (CA 1); 1.0" (CA 2)[4]	1.5" (1.0" nominal)[13]	1.5
	Coarse Aggregate	Application	variation from 2.80=corrected sand	concrete pavement	FF
		Lower Limit (lb/cu. Yd)		1800	~60% of total aggregate
		Upper Limit (lb/cu. Yd)		2000	
		Application			SF
		Lower Limit (lb/cu. Yd)			~60% of total aggregate
		Upper Limit (lb/cu. Yd)			
	Fine Aggregate	Application	Class C	concrete pavement	SF
		Lower Limit (lb/cu. Yd)	35.8% sand	1800	~40% of total aggregate
		Upper Limit (lb/cu. Yd)		2000	
		Application	Class F		FF
		Lower Limit (lb/cu. Yd)	34.6% sand		~40% of total aggregate
		Upper Limit (lb/cu. Yd)			
	SCMs commonly used in concrete mix design	Class F Fly Ash	X[5]	X	
		Application	max. 20%	concrete pavement	
		Class C Fly Ash	X[6]	X	X[1]
		Application		concrete pavement	pavement
		GGBFS Slag	X	X	
		Application	20% for ASR use 6% microsilica	concrete pavement	
		Silica Fume	X		
		Application	bridge decks, structural work, microsilica overlay		
		Metakaolin	X[7]		
		Application	bridge decks for HP mixes		
		Volcanic Ash/Pumicite			
		Application			
		Calcinated Shale			
		Application			
		Opaline Shale			
		Application			
		Calcinated Clay	X		
		Application	bridge deck; substitute for silica fume		
		Diatomaceous Earth			
		Application			
		Other			
		Application			
	Chemical admixtures commonly used in concrete mix design	Air entraining admixtures	X	X	X
		Application	paving	concrete pavement	pavement
		Coventional water reducer	X	X	X[2]
		Application	paving	concrete pavement	pavement
		Mid-range water reducer			X[3]
		Application			pavement
		Accelerator	X		
		Application	limited to PCC repairs		
		Retarder	X	X	
		Application	always required on decks	concrete pavement	
		Corrosion inhibitor	X		
		Application	special appliactions i.e. precast		
		Shrinkage reducer			
		Application			
		ASR inhibitors (I.e. Lithium)			
		Application			
		Hydration control admixtures			
		Application			
		Other (describe)			
		Application			
Typical combinations of cement, SCM, and chemical admixtures for paving mixes	Paving mix 1	Cement type	Type II (Class C)	[14]	Type I/II
		Batch weight (lb/yd)		421 (526 typical)	394.8
		SCM	20% pozzolan	126 (fly ash - 1:1.2)	Class C fly ash
		Batch weight (lb/yd)			169.2
		Chemical admixture 1	WR		AEA
		dosage (fl oz/cwt)			manufacturer recommendation
		Chemical admixture 2	AEA		WR
		dosage (fl oz/cwt)			manufacturer recommendation
	Paving mix 2	Cement type	Type II (Class F)		
		Batch weight (lb/yd)		451 (564 typical)	
		SCM		136	
		Batch weight (lb/yd)			
		Chemical admixture 1	WR		
		dosage (fl oz/cwt)			
		Chemical admixture 2	AEA		
		dosage (fl oz/cwt)			
	Paving mix 3	Cement type	Type III (HES)		
		Batch weight (lb/yd)			
		SCM			
		Batch weight (lb/yd)			
		Chemical admixture 1	WR		
		dosage (fl oz/cwt)	(no chloride accelerators)		
		Chemical admixture 2	AEA		
		dosage (fl oz/cwt)			

			Ohio	Oklahoma	South Dakota
	Maximum Size of coarse aggregate (inches)		1.0"[7]	1.0"	1.5"
	Coarse Aggregate	Application	std. mix -slag -gravel (limestone also)	[2]	SF
		Lower Limit (lb/cu. Yd)	1360 (slag)		1680
		Upper Limit (lb/cu. Yd)			1790
		Application	QC/QA		FF
		Lower Limit (lb/cu. Yd)	ACI 211		1670
		Upper Limit (lb/cu. Yd)			1770
	Fine Aggregate	Application	std. mix -slag -gravel	[3]	SF
		Lower Limit (lb/cu. Yd)	1160		1200
		Upper Limit (lb/cu. Yd)	1350		1300
		Application	QC/QA		FF
		Lower Limit (lb/cu. Yd)	ACI 211		1125
		Upper Limit (lb/cu. Yd)			1225
	SCMs commonly used in concrete mix design	Class F Fly Ash	X		X[3]
		Application			pavement
		Class C Fly Ash	X	X	
		Application			
		GGBFS Slag	X		
		Application			
		Silica Fume			
		Application			
		Metakaolin			
		Application			
		Volcanic Ash/Pumicite			
		Application			
		Calcinated Shale			
		Application			
		Opaline Shale			
		Application			
		Calcinated Clay			
		Application			
		Diatomaceous Earth			
		Application			
		Other			
		Application			
	Chemical admixtures commonly used in concrete mix design	Air entraining admixtures	X	X	X
		Application		All	pavement
		Coventional water reducer	X	X	X
		Application		Most of the time	pavement
		Mid-range water reducer	X		
		Application			
		Accelerator	X		X
		Application	patching		patching, fast track
		Retarder	X	X	X
		Application	for concr. temp over 75; discharge after 60min (have to use it)	Summer paving	pavement
		Corrosion inhibitor			
		Application			
		Shrinkage reducer			
		Application			
		ASR inhibitors (I.e. Lithium)			X
		Application			experimental use in structures
		Hydration control admixtures			
		Application			
		Other (describe)			
		Application			
Typical combinations of cement, SCM, and chemical admixtures for paving mixes	Paving mix 1	Cement type	Type 1		I/II
		Batch weight (lb/yd)	600 / 550		561
		SCM			Class F Fly Ash - Modified
		Batch weight (lb/yd)			124
		Chemical admixture 1	as recommended		AEA - Daravair M
		dosage (fl oz/cwt)	/		unknown
		Chemical admixture 2	A or D water reducer		WR - Daracem 65 WR
		dosage (fl oz/cwt)			unknown
	Paving mix 2	Cement type	Type 1		I/II
		Batch weight (lb/yd)	550		510
		SCM	C or F fly ash		Class F Fly Ash - Modified
		Batch weight (lb/yd)	90		112
		Chemical admixture 1	as recommended		AEA - Daravair R
		dosage (fl oz/cwt)			unknown
		Chemical admixture 2			WRDA 82
		dosage (fl oz/cwt)			3.0
	Paving mix 3	Cement type	Type 1		I/II
		Batch weight (lb/yd)	385		570
		SCM	Slag (grade 100 or better)		Class F Fly Ash - Modified
		Batch weight (lb/yd)	165		125
		Chemical admixture 1	A or D water reducer		AEA - MB MBVR
		dosage (fl oz/cwt)			unknown
		Chemical admixture 2			WR - MB Master Pave
		dosage (fl oz/cwt)			unknown

			Texas	Wisconsin
	Maximum Size of coarse aggregate (inches)			1.5
	Coarse Aggregate	Application		pavement
		Lower Limit (lb/cu. Yd)		1860
		Upper Limit (lb/cu. Yd)		2170
		Application		
		Lower Limit (lb/cu. Yd)		
		Upper Limit (lb/cu. Yd)		
	Fine Aggregate	Application		pavement
		Lower Limit (lb/cu. Yd)		930
		Upper Limit (lb/cu. Yd)		1240
		Application		
		Lower Limit (lb/cu. Yd)		
		Upper Limit (lb/cu. Yd)		
	SCMs commonly used in concrete mix design	Class F Fly Ash	X[2]	
		Application	pavement	
		Class C Fly Ash	X	X
		Application	pavement	all
		GGBFS Slag	X[3]	X
		Application	pavement	all
		Silica Fume		
		Application		
		Metakaolin		
		Application		
		Volcanic Ash/Pumicite		
		Application		
		Calcinated Shale		
		Application		
		Opaline Shale		
		Application		
		Calcinated Clay		
		Application		
		Diatomaceous Earth		
		Application		
		Other		Badger Pozzolan[1]
		Application		pavement
	Chemical admixtures commonly used in concrete mix design	Air entraining admixtures	X	X
		Application	pavement	pavement
		Coventional water reducer	X	X
		Application	pavement	pavement
		Mid-range water reducer	X	
		Application	fast track pavement	
		Accelerator		
		Application		
		Retarder	X	
		Application	pavement	
		Corrosion inhibitor		
		Application		
		Shrinkage reducer		
		Application		
		ASR inhibitors (I.e. Lithium)		
		Application		
		Hydration control admixtures		
		Application		
		Other (describe)		
		Application		
Typical combinations of cement, SCM, and chemical admixtures for paving mixes	Paving mix 1	Cement type		Type I/II
		Batch weight (lb/yd)		395
		SCM		Class C fly ash
		Batch weight (lb/yd)		170
		Chemical admixture 1		WR
		dosage (fl oz/cwt)		3
		Chemical admixture 2		AEA
		dosage (fl oz/cwt)		1
	Paving mix 2	Cement type		Type I/II
		Batch weight (lb/yd)		395
		SCM		GGBFS
		Batch weight (lb/yd)		170
		Chemical admixture 1		WR
		dosage (fl oz/cwt)		3
		Chemical admixture 2		AEA
		dosage (fl oz/cwt)		1
	Paving mix 3	Cement type		
		Batch weight (lb/yd)		
		SCM		
		Batch weight (lb/yd)		
		Chemical admixture 1		
		dosage (fl oz/cwt)		
		Chemical admixture 2		
		dosage (fl oz/cwt)		

			Georgia	Indiana	Iowa
	Compatibility problems between mix components like SCMs and chemical dmixtures	(1) Less than expected water reduction	X[8]		
		(2) Rapid loss of slump	X	can happen when fly ash content goes up	
		(3) Fast set	X		
		(4) Abnormally retarded setting	X	can happen when have multiple admixtures from different companies	
		(5) Other (describe)	uncontrollable air		
		(6) Other (describe)	poor workability		
	Complete mix designs (lb/yd) / dosages (fl oz/cwt) for the above symptoms	Symptom #	!!! Have 2 examples		
		Water			
		Portland cement			
		Fly ash class C			
		Fly ash class F			
		Slag			
		Silica Fume			
		WR (oz/cmwt)			
		MRWR			
		HRWR			
		AEA (oz/cmwt)			
		Accelerator			
		Retarder			
		Other (describe)			
		Correction for symptom			
		Symptom #			
		Water			
		Portland cement			
		Fly ash class C			
		Fly ash class F			
		Slag			
		Silica Fume			
		WR			
		MRWR			
		HRWR			
		AEA			
		Accelerator			
		Retarder			
		Other (describe)			
		Correction for symptom			
		Symptom #			
		Water			
		Portland cement			
		Fly ash class C			
		Fly ash class F			
		Slag			
		Silica Fume			
		WR			
		MRWR			
		HRWR			
		AEA			
		Accelerator			
		Retarder			
		Other (describe)			
		Correction for symptom			
	Combined aggregate gradation		yes	No (not for pavement)	yes
	describe		required for fine and coarse agg.[9]		Shilstone gradation; use 0.45 Power; % retained for information only
	Aggregate sources approval system		yes	yes	yes
	explain		SOP 1. Frequent monitoring from Pit&Quarry Branch. Must be on QPL 1 or 2. Montly sampling from active source. Do well- hired 2 new geologists.	Sec.904 *AP pavement *agg. pavement graded	All carbonate sources in Iowa are based on ledge control. Sources are ranked by physical and chemical characteristics of F/T (pore size) and salt susceptibility (XRD/XRF).
	Do you require testing of cementitious		yes	yes	no
	If yes, what tests?		SOP 5.Portland cement-AASHTO M85; Fly ash-AASHTO M295; Blended cement-AASHTO M240 Slag-AASHTO M302	Sec.90 *random sample for verification from plant site *entire AASHTO M85 tests	

		Kansas	Louisiana	Michigan
Compatibility problems between mix components like SCMs and chemical dmixtures	(1) Less than expected water reduction			
	(2) Rapid loss of slump			
	(3) Fast set		X[4]	
	(4) Abnormally retarded setting	X (possibility)	X[5]	
	(5) Other (describe)			retarded set at high temperatures
	(6) Other (describe)			
Complete mix designs (lb/yd) / dosages (fl oz/cwt) for the above symptoms	Symptom #	4	4 (mix design is not available)	5
	Water		X	
	Portland cement		X	
	Fly ash class C			
	Fly ash class F			
	Slag		X	
	Silica Fume			
	WR (oz/cmwt)			
	MRWR		X	
	HRWR			
	AEA (oz/cmwt)		X	
	Accelerator			
	Retarder		X	
	Other (describe)			
	Correction for symptom		Reduced retarder	
	Symptom #			
	Water			
	Portland cement			
	Fly ash class C			
	Fly ash class F			
	Slag			
	Silica Fume			
	WR			
	MRWR			
	HRWR			
	AEA			
	Accelerator			
	Retarder			
	Other (describe)			
	Correction for symptom			
	Symptom #			
	Water			
	Portland cement			
	Fly ash class C			
	Fly ash class F			
	Slag			
	Silica Fume			
	WR			
	MRWR			
	HRWR			
	AEA			
	Accelerator			
	Retarder			
	Other (describe)			
	Correction for symptom			
Combined aggregate gradation		yes	yes	no
describe		Typically, contractors use Shilstone	Need more info	ASTM 57 with some modifications
Aggregate sources approval system		yes	yes	yes
explain		F/T beams for limestones, ASR for sands and gravels	Clay lumps, friable materials, iron ore, coal and lignite, flat and elongated, wood	Tests are done before project begins.
Do you require testing of cementitious		no	no	unknown
If yes, what tests?				

			Minnesota	Missouri	Nebraska
	Compatibility problems between mix components like SCMs and chemical dmixtures	(1) Less than expected water reduction			
		(2) Rapid loss of slump			
		(3) Fast set			
		(4) Abnormally retarded setting	X[9]		
		(5) Other (describe)	Plastic shrinkage cracks[10]	Mixing problems and inconsistent strength and air.	
		(6) Other (describe)	Rapid loss of slump[11]		
	Complete mix designs (lb/yd) / dosages (fl oz/cwt) for the above symptoms	Symptom #	4	5 (I-255 PCCP)	
		Water		240	
		Portland cement		523	
		Fly ash class C		92	
		Fly ash class F			
		Slag			
		Silica Fume			
		WR (oz/cmwt)			
		MRWR		6.0	
		HRWR			
		AEA (oz/cmwt)		1.3	
		Accelerator			
		Retarder			
		Other (describe)			
		Correction for symptom		Remains unexplained. Mixing time could be one factor.	
		Symptom #	5	5 (bridge overlay)	
		Water		233	
		Portland cement		626	
		Fly ash class C			
		Fly ash class F			
		Slag			
		Silica Fume		50	
		WR			
		MRWR		6.0	
		HRWR			
		AEA		1.3	
		Accelerator			
		Retarder			
		Other (describe)			
		Correction for symptom		Water meter at plant was not accurate. A different concrete plant was used.	
		Symptom #	6	5 (PCCP overlay, I-70)	
		Water		267	
		Portland cement		655	
		Fly ash class C		70	
		Fly ash class F			
		Slag			
		Silica Fume			
		WR		3.0	
		MRWR			
		HRWR			
		AEA		1.4	
		Accelerator			
		Retarder			
		Other (describe)			
		Correction for symptom		Build up of material on drum blade and the use of Type 3 cement.	
	Combined aggregate gradation		yes	yes	no
	describe		8/18 Chart and JMF	QC/QA project	gradation limits for CA and FA
	Aggregate sources approval system		no	yes	yes
	explain			The following tests performed on new sources. Freeze/Thaw Specific gravity, absorption, soundness, LA abrasion, soundness by water/alcohol freeze. Next, aggregates meet quality requirements for PCCP. No aggregate used unless iapproved by the State Central Lab. See file for more info.	abrasion, clay lumps & shale, freeze and thaw soundness, plasticity index, sodium sulfate soundness, calcim carbonate, organic impurities, mortar-making properties
	Do you require testing of cementitious		no	no	no
	If yes, what tests?				

			New York	North Carolina	North Dakota
	Compatibility problems between mix components like SCMs and chemical dmixtures	(1) Less than expected water reduction			
		(2) Rapid loss of slump			
		(3) Fast set			
		(4) Abnormally retarded setting		X	
		(5) Other (describe)		air entrainment problems - design issue - fluctuating LOI	
		(6) Other (describe)			
	Complete mix designs (lb/yd) / dosages (fl oz/cwt) for the above symptoms	Symptom #			
		Water			
		Portland cement			
		Fly ash class C			
		Fly ash class F			
		Slag			
		Silica Fume			
		WR (oz/cmwt)			
		MRWR			
		HRWR			
		AEA (oz/cmwt)			
		Accelerator			
		Retarder			
		Other (describe)			
		Correction for symptom			
		Symptom #			
		Water			
		Portland cement			
		Fly ash class C			
		Fly ash class F			
		Slag			
		Silica Fume			
		WR			
		MRWR			
		HRWR			
		AEA			
		Accelerator			
		Retarder			
		Other (describe)			
		Correction for symptom			
		Symptom #			
		Water			
		Portland cement			
		Fly ash class C			
		Fly ash class F			
		Slag			
		Silica Fume			
		WR			
		MRWR			
		HRWR			
		AEA			
		Accelerator			
		Retarder			
		Other (describe)			
		Correction for symptom			
	Combined aggregate gradation		yes	no	no
	describe		MM 9.1, AASHTO T21, sand 703.07, CA 703.02 (SC)	Some contractors may use (woul dallow)	
	Aggregate sources approval system		yes	yes	yes
	explain		APPROVED LIST *criteria *geology how test *have good durable agg. *703.02	*approved lis of coarse and fine agg. based on LA, soundness, mortar strength etc. *approvd list of sources *section 1000 spec (concrete 700)	Agg. sources approved by initial pit tests and monitored over time. Don't have formal list of approved sites. Tests: light weight pieces, organic impurities, mortar-making properties, sodium sulfate soundness, shale content, iron oxide particles, lignite and coal, soft particles, and L.A. abrasion.
	Do you require testing of cementitious		yes	yes	no
	If yes, what tests?		random mill testing; destination batch plant; AASHTO M85	*chem. and physical prop based on AASHTO M85, ASTM C618 and AASHTO M302	

		Ohio	Oklahoma	South Dakota
Compatibility problems between mix components like SCMs and chemical dmixtures	(1) Less than expected water reduction			
	(2) Rapid loss of slump			
	(3) Fast set			
	(4) Abnormally retarded setting	X[8]		
	(5) Other (describe)	air entrainment with high LOI fly ash		no compatibility problems
	(6) Other (describe)			
Complete mix designs (lb/yd) / dosages (fl oz/cwt) for the above symptoms	Symptom #	abnormally retarded setting		
	Water			
	Portland cement			
	Fly ash class C			
	Fly ash class F			
	Slag			
	Silica Fume			
	WR (oz/cmwt)			
	MRWR			
	HRWR			
	AEA (oz/cmwt)			
	Accelerator			
	Retarder			
	Other (describe)			
	Correction for symptom	limit the use of fly ash or slag between April to October to limit exposure to cooler water		
	Symptom #	air entrainment with high LOI fly ash		
	Water			
	Portland cement			
	Fly ash class C			
	Fly ash class F			
	Slag			
	Silica Fume			
	WR			
	MRWR			
	HRWR			
	AEA			
	Accelerator			
	Retarder			
	Other (describe)			
	Correction for symptom	limit LOI to 3%max. on fly ash by spec.		
	Symptom #			
	Water			
	Portland cement			
	Fly ash class C			
	Fly ash class F			
	Slag			
	Silica Fume			
	WR			
	MRWR			
	HRWR			
	AEA			
	Accelerator			
	Retarder			
	Other (describe)			
	Correction for symptom			
Combined aggregate gradation		no	no	not currently
describe		tried it on bridge deck, could not finish it		
Aggregate sources approval system		yes	yes	yes
explain		There is an agg. certification program. Agg. suppliers must be certified in order to be used in ODOT projects. Tested for F/T; approved by year		lightweight particles, clay lumps, organic impurities, soundness, gradation, fineness modulus; ASTM 1260 for sand before use. on aggregate sources approval system.
Do you require testing of cementitious		yes	yes	yes
If yes, what tests?		Monthly mill certs are required by the department every 180 days per cement source/type/concrete producer. Testing performed by Central Office. - normally ASTM - LOI is different		need more info

			Texas	Wisconsin
	Compatibility problems between mix components like SCMs and chemical dmixtures	(1) Less than expected water reduction		
		(2) Rapid loss of slump		
		(3) Fast set		
		(4) Abnormally retarded setting	X	X
		(5) Other (describe)	Problems obtaining strength	
		(6) Other (describe)		
	Complete mix designs (lb/yd) / dosages (fl oz/cwt) for the above symptoms	Symptom #	4	4
		Water		NR
		Portland cement		395
		Fly ash class C		170
		Fly ash class F		
		Slag		
		Silica Fume		
		WR (oz/cmwt)		3
		MRWR		
		HRWR		
		AEA (oz/cmwt)		1
		Accelerator		
		Retarder		
		Other (describe)		
		Correction for symptom		eliminated fly ash
		Symptom #	5	
		Water		
		Portland cement		
		Fly ash class C		
		Fly ash class F		
		Slag		
		Silica Fume		
		WR		
		MRWR		
		HRWR		
		AEA		
		Accelerator		
		Retarder		
		Other (describe)		
		Correction for symptom		
		Symptom #		
		Water		
		Portland cement		
		Fly ash class C		
		Fly ash class F		
		Slag		
		Silica Fume		
		WR		
		MRWR		
		HRWR		
		AEA		
		Accelerator		
		Retarder		
		Other (describe)		
		Correction for symptom		
	Combined aggregate gradation			no
	describe			
	Aggregate sources approval system		unknown	yes
	explain			limitation for deleterious substances (i.e. clay, coal lump, shale, materials finer than No.200 sieve), wear, soundness, freeze/thaw
	Do you require testing of cementitious		unknown	yes
	If yes, what tests?			Comp. cubes, activity index for SCMs

			Georgia	Indiana	Iowa
Required tests for concrete mix design	Fresh Concrete tests	Slump	X	X	
		Test method	GDT 27	AASHTO T119 (502)	
		Air content	X	X	X
		Test method	GDT 26	AASHTO T152 or C173 (502&503)	AASHTO T152 (IM 318)
		Unit weight		X	X
		Test method	GDT 28 (not req.)	AASHTO T121	AASHTO T121 (IM 340)
		Time of setting			
		Test method			
		Plastic shrinkage cracking susceptibility			
		Test method			
		Heat of hydration			
		Test method			
	Hardended concrete tests	Resistance to freezing and thawing		not for PCC but agg. approval	
		Test method		ASTM C666	
		Strength	X	X	X
		Typical design strength		570 in 7 days (501 - 1/3 pt flex.)	840psi for QMC
		Test method	AASHTO T22	AASHTO T97	AASHTO T97
		Permeability			
		Test method			
		Shrinkage			
		restrained/free			
		Test method			
		Creep			
		Test method			
	Fibers used in paving mixes	Steel			
		Polypropylene			used in research
		Polyester			
		Polyolefin			used in research
		Nylon			
		Carbon			
		Other (describe)	do use fibers in bridge deck overlay - poly		typically used in UTW
	Was there a change in the water content?				slight adjustment in water
	Where chemical admixtures used?				normal
	Other comments				
	Rank the primary concerns about concrete durability, (1)not a concern, (2)rarely a concern,	Freeze-thaw resistance / Scaling resistance	5		5 (F/T)
		DEF susceptibility	2		2
		ASR susceptibility	3		2
		Chemical attack	2		2
		Abrastion resistance	4		2
		Fatigue cracking	3		4
		Other (describe)			
		Rank			
		COMMENTS	[1] do submit but follow old mixes [2] use old mixes [3] for hand point [4] Binary blends - fly ash or GGBFS [5] Sec.430 - temp. req. for slag % [6] max. fly ash 15%, slag 50% [7] mostly fly ash; one source for Class C; can control air in C better than F; LOI varies; Lose lot of air in transit; 1.25-2 replacement of fly ash makes total 26-28% fly ash [8] dep. on specific materials - LOI [9] secs.800&801 for coarse and fine agg. Respectively; agg. is normally granite; limits flat and elongated; Georgia river rock *Class 1 - 584lbs (cement, natural sands take up water), normal - 0.53w/c; HES - 0.47w/c (up to 752lbs. cement); Sec.430 - mainline; Sec.439 - special (Class3>4000psi); Sec.504 - 24hr accelerated; 11.2 & 7-7.5cf for coarse&fine agg.; In south, up to 11.4cf of sand (better sand)	[1] QC/QA: will copy 500 sec.of spec. mix parameters and contractors - 90% --- Non QC/QA - cookbook; in 500 sec.; by voulme; min cement content; mix w/c; do a trial batch [2] 100% pay [3] 100% passing 1" sieve; Use #8 (Sec.904); D-cracking issue [4] no ternary [5] WR - A or D; Trial batches are required if you change (add or take off admixture) [6] 502 spec. -substitute more fly ash back in than cement out;substitution and 20% increase; 501 spec.- coincide; fly ash an additive	[1] State&contractoe provides std. Class C; Supplier provides QMC Pavement [2] MOR-TPL

			Kansas	Louisiana	Michigan
Required tests for concrete mix design	Fresh Concrete tests	Slump	X	X[6]	X
		Test method	AASHTO T 119	DOTD TR-207	ASTM C143
		Air content	X	X[7]	X
		Test method	AASHTO T 152	DOTD TR-202	mod. ASTM C231 or C173
		Unit weight	X	X[8]	
		Test method	AASHTO T 121	DOTD TR-201	
		Time of setting		X[9]	
		Test method			
		Plastic shrinkage cracking susceptibility			
		Test method			
		Heat of hydration			
		Test method			
	Hardended concrete tests	Resistance to freezing and thawing			
		Test method			
		Strength		X	yes
		Typical design strength		opening strength 3000psi at 7 days; 4000psi or 3600 if air entrained at 28 days	600-650 for flexure / 3000-4500 for compressive both being at 28-days
		Test method		DOTD TR-230	ASTM C39
		Permeability		X	
		Test method		ASTM C1202	
		Shrinkage			
		restrained/free			
		Test method			
		Creep			
		Test method			
	Fibers used in paving mixes	Steel		X	
		Polypropylene	X	X	
		Polyester			
		Polyolefin	X		
		Nylon			
		Carbon			
		Other (describe)			
	Was there a change in the water content?		yes		
	Where chemical admixtures used?		yes		
	Other comments		WR added	no records	
	Rank the primary concerns about concrete durability, (1)not a concern, (2)rarely a concern,	Freeze-thaw resistance / Scaling resistance	5	1	
		DEF susceptibility	1	1	
		ASR susceptibility	5	3	
		Chemical attack	1	2	
		Abrastion resistance	2	4	
		Fatigue cracking	5	4	
		Other (describe)			
		Rank			
		COMMENTS	[1] State may assist contractor in designing mix proportions. [2] 0.49 w/cm ratio is maximum for FF paving [3] 0.25mm is the maximum air void spacing factor. Any concrete with a spacing factor greater than 0.37mm shall be removed. AVA equipment is used for testing. [4] All concrete except mainline pavement. [5] Optimized PCCP concrete [6] .35 to .63 range by mass of total aggregate. Shilstone method can be used to provide justification for aggregate proportions. [7] Coarse and fine aggregates are proportioned at 50%-50% ratio by mass. Adjustments ratio can be made to improve workability. Shilstone can provide justification. [8] Super low C_3A retarded set with conv. WR??	[1] Typically, concrete mixes contain a lot of sand because it is inexpensive. Typically, concrete mixes contain a lot of sand because it is inexpensive. [2] Allow up to 20% Cl. C fly ash. [3] All up to 50% GGBFS Slag. Slag is most common SCM. [4] Typically, fast set is environmentally related. If more two or more chemical admixtures are used, they are required to be the same brand. [5] Have had some occurences of slow set with slag and retarder. Typically, slow set is environmentally related. If more two or more chemical admixtures are used, they are required to be the same brand. [6-9] Trial mixes and tests required for approval if mineral admixture or high-range water reducer are used	[1] 30 % maximum [2] 40% maximum, used commonly

Appendix D. Summary Compilation of State Practices

			Minnesota	Missouri	Nebraska
Required tests for concrete mix design	Fresh Concrete tests	Slump	X	X	X
		Test method	AASHTO T 119	AASHTO T119	NDR T119
		Air content	X	X	X
		Test method	AASHTO T 152	AASHTO T152	NDR T152
		Unit weight	X		X
		Test method	AASHTO T 121		NDR T121
		Time of setting			
		Test method			
		Plastic shrinkage cracking susceptibility			
		Test method			
		Heat of hydration			
		Test method			
	Hardended concrete tests	Resistance to freezing and thawing	yes[12]		
		Test method	ASTM C-666, Method B		
		Strength	yes	X	
		Typical design strength	500 psi flexural	Typical Strength: 4650psi Minimum strength: 3500 psi at 28 days	designated cylinder strength (3500psi)
		Test method	third point beam	AASHTO T22 at 28 days	AASHTO t22
		Permeability	yes		
		Test method	2500 coulumb max., 28-day for HPP		
		Shrinkage			
		restrained/free			
		Test method			
		Creep			
		Test method			
	Fibers used in paving mixes	Steel	X	X	
		Polypropylene	X		
		Polyester	Not sure		
		Polyolefin	X	X	X[5]
		Nylon			
		Carbon			
		Other (describe)			
	Was there a change in the water content?		yes	not significantly	
	Where chemical admixtures used?		water reducer	Type A WR	
	Other comments		The fibers drove up the water demand. Water reducers were used more recently with polyolefin fibers.	The minimum cement content was increased from 6.0 to 6.6sk/yd. Fine and coarse aggregate was changed to 45/55 by volume vs. 38/62 (Standard Ratio)	
	Rank the primary concerns about concrete durability, (1)not a concern, (2)rarely a concern,	Freeze-thaw resistance / Scaling resistance	5	5	5
		DEF susceptibility	3	2	
		ASR susceptibility	4	3	5
		Chemical attack	2	5	
		Abrastion resistance	2	5	
		Fatigue cracking	1	1	3
		Other (describe)			
		Rank			
		COMMENTS	[1] State provies mix design for projects < 5000 c.y. [2] 2500 coulumb max, 28 days for HPP [3] Encourage well-graded aggregates, 8/18 chart for HPP. Monitor vibration during paving. [4] Encourages use of additives and pozzolans to lower permeability in hardened state. [5] HES mixes are not encouraged. [6] Class F fly ash not used since late 1970's. [7] Not commonly used. [8] Fly ash and slag are used as ASR inhibitors. More effective than Lithium acc. to lab tests. [9] Maximum dosages of water reducers in combination with high SCMs replacements have caused retarded sets. [10] Maximum dosages of water reducers in combination with high SCMs replacements have caused plastic shrinkage cracks. [11] Rapid loss of slump has been caused by using the maximum dosage of WR, but not always with SCMS. [12] Freeze/thaw test is only run when potential for recycling is performed.	[1] Non QC/QA project are standard state mix designs. QC/QA mixes are by contractor's method. QC/QA mixes often have optimized gradations. The ACI absolute volume method is often used. [2] Gravel in southern part of state [3] 1/2 sack cement reduction allowed with optimized gradation. [4] 15% max Class C Fly Ash. [5] If a Type A WR is used, contractor can reduce minimum cement content by 1/4 - sack/yd^3.	[1] The maximum slump may be exceeded by use of water reducer. [2] Currently, Nebraska is starting to test air content behind the paver. [3] Class C or F fly ash may be substituted in the mix design provided the total pozzolan content does not exceed 25%. [4] No additional fly ash substitution is allowed. [5] Very limited use of fibers, only a short test section, bonded overlay

			New York	North Carolina	North Dakota
Required tests for concrete mix design	Fresh Concrete tests	Slump	X	X	X
		Test method	ASTM C143	AASHTO T119	AASHTO T 119
		Air content	X	X	X
		Test method	ASTM C231	AASHTO T152	AASHTO T 152
		Unit weight	X	X	X
		Test method	ASTM C138	ASTM C138	AASHTO T 121
		Time of setting			
		Test method			
		Plastic shrinkage cracking susceptibility			
		Test method			
		Heat of hydration			
		Test method			
	Hardended concrete tests	Resistance to freezing and thawing	X	X	yes
		Test method	NY 5023P (will send)	AASHTO T126, AASHTO T97	ASTM C-666, Method A
		Strength	X		yes
		Typical design strength			compressive
		Test method	ASTM C39 (std. compression)		AASHTO T22
		Permeability	X		
		Test method	T 277 (bridge decks - not required)		
		Shrinkage			
		restrained/free			
		Test method			
		Creep			
		Test method			
	Fibers used in paving mixes	Steel			
		Polypropylene	X[8]	X[15]	
		Polyester			
		Polyolefin	X		X[4]
		Nylon	X		
		Carbon			
		Other (describe)			
	Was there a change in the water content?				yes
	Where chemical admixtures used?		WR, AEA		AEA
	Other comments			don't know how the mix design was adjusted	No adjustment to mix design, fibers added per manufacturer's specifications.
	Rank the primary concerns about concrete durability, (1)not a concern, (2)rarely a concern,	Freeze-thaw resistance / Scaling resistance	5	1	5
		DEF susceptibility			
		ASR susceptibility	4	3	2
		Chemical attack		5	3
		Abrastion resistance	5 (friction)	2	2
		Fatigue cracking		4	2
		Other (describe)	shrinkage cracking; scaling on bridge decks	drying shrinkage cracking	
		Rank		Jim (1,5,2,5,5)	
		COMMENTS	[1] Table 501-3; HES - no standard (502 - 2.02) [2] w/c adjusted based on slump [3] fixed forms can increase slump through WR [4] spec. Table 501 - 2 5 mostly Class F; sludge fly ash costs the same [6] one source; HP or DP class [7] fits into MSF requirements [8] manual; std. Table; 703.02 2 often for CA; 703.07 sand gradation	[1] contractor submit lab data - reviewd by DOT [2] not specified but commonly used as a guideline [3] for cement used [4,5] 14 days -600psi flexure at 1/3 point; take team breaker to site and calibrate [6] inherent in cementitious content; not a concrete test [7] same as above; not test but required 5% [8] 6 known reactive agg.: special requirements, low alkali cement, use pozzolan; source approval [9] abrasion of aggregate [10] corrosion inhibitor specified at times; source approval [11] point of acceptance at grade [12] fly ash - 1:1.2 / slag - 1:1 [13] can use 67; 57m - modified SC [14] 526 min cementitous - max. fly ash 20%; normally no slag (35-50% substitution) normally Lafarge in Virginia in east part of state ready mix ternary allowed [15] allow in slope protection - maybe used once - maybe in AC	[1] Coal creek supply [2] contractor request, contract documents [3] contractor request, contract documents [4] 1 research project

Appendix D. Summary Compilation of State Practices

			Ohio	Oklahoma	South Dakota
Required tests for concrete mix design	Fresh Concrete tests	Slump	X	X	X
		Test method	C143	AASHTO T119	SD 404 (ASTM C143)
		Air content	X	X	X
		Test method	C231 / C173	AASHTO T152 or T196	SD 403 (ASTM C231)
		Unit weight	X[9]		X
		Test method	C138		SD 411 (ASTM C238)
		Time of setting			
		Test method			
		Plastic shrinkage cracking susceptibility			
		Test method			
		Heat of hydration			
		Test method			
	Hardened concrete tests	Resistance to freezing and thawing	X[10]		
		Test method	ASTM C666, PROC B: 350 cycles (SC)		
		Strength	X	X	X
		Typical design strength	*Standard procedure based on a given mix design-should achieve 4000psi: pavement design based on the 3rd point flexural strength of 750psi; acceptance (opening to traffic) is based on center point flexural strength of 600psi. *For QC/QA, cores are taken and compression tested. Required concrete strength of 4000psi+1.65(std.dev.) psi		4000-5000 psi at 28 days
		Test method	ASTM C293, ASTM C39&42	AASHTO T22 & T23	SD 420
		Permeability			
		Test method			
		Shrinkage			
		restrained/free			
		Test method			
		Creep			
		Test method			
	Fibers used in paving mixes	Steel		X	X[4]
		Polypropylene	1 research project - weigh station	X	
		Polyester	1 research project - 4"0" - twin UTW		
		Polyolefin		X	X[5]
		Nylon			
		Carbon			
		Other (describe)			
	Was there a change in the water content?				Info available in research report
	Where chemical admixtures used?				Info available in research report
	Other comments			Unknown design	Info available in research report
	Rank the primary concerns about concrete durability, (1)not a concern, (2)rarely a concern,	Freeze-thaw resistance / Scaling resistance	5	5	5
		DEF susceptibility	1	1	1
		ASR susceptibility	1	2	5
		Chemical attack	2	3	3
		Abrastion resistance	3	5	3
		Fatigue cracking	4	5	3
		Other (describe)			
		Rank			
		COMMENTS	[1] State has a standard procedure; A new QA/QC spec. requires that the contractor provides the mix design; Support spec. QA/QC 888 [2] Strength - 28; Do mix design test batch and sup mix results [3] agg. only; not PCC [4] do many requirement [5] sample ahead of paver [6] controlled by cement content or w/c ratio [7] #57 - materials in sectins 700,701,703,705 [8] 701 B - one district complains a lot; modify C618 to lower LOI from 6% to 3% [9] do in field [10] Area under the curve (% expansion vs cycles)<2.05. This is for approval of the aggregate not the specific mix .	[1] Water content is not specified [2] CA content is not specified [3] FA content is not specified [*] Cement can be replaced with supplementary cementing material on 1-1 mass basis and total replacement is limited to 50%	[1] Cementicious content includes a 112 lb/cy of Class F Fly ash typically. [2] Cementious content includes 123 lb/cy of Class F Flay ash typically. [3] Fly ash replacement is min.15% and max 20%. [4] Experimental project - 0.6% of mix. [5] Polyolefin fibers used in a few bridge deck overlays, typically 25lb/sy. See research report on file.

			Texas	Wisconsin
Required tests for concrete mix design	Fresh Concrete tests	Slump		X
		Test method		AASHTO T 119
		Air content		X
		Test method		AASHTO T 152
		Unit weight		
		Test method		
		Time of setting		
		Test method		
		Plastic shrinkage cracking susceptibility		
		Test method		
		Heat of hydration		
		Test method		
	Hardended concrete tests	Resistance to freezing and thawing		
		Test method		
		Strength		yes
		Typical design strength	flex. 570 psi or comp. 3500psi at 7 days; or flex. 680 psi or comp. 4400psi at 28 days	650psi flexural; 3000psi compressive
		Test method		AASHTO T 22 or maturity
		Permeability		
		Test method		
		Shrinkage		
		restrained/free		
		Test method		
		Creep		
		Test method		
	Fibers used in paving mixes	Steel	X[4]	
		Polypropylene		X
		Polyester	X[5]	
		Polyolefin		
		Nylon		
		Carbon		
		Other (describe)		
	Was there a change in the water content?		unknown	no
	Where chemical admixtures used?		unknown	
	Other comments		none	slump remained the same
	Rank the primary concerns about concrete durability, (1)not a concern, (2)rarely a concern,	Freeze-thaw resistance / Scaling resistance		5
		DEF susceptibility		
		ASR susceptibility		
		Chemical attack		
		Abrastion resistance		
		Fatigue cracking		3
		Other (describe)		
		Rank		
		COMMENTS	[1] 7-day strength is now correlated to 28-day strength. [2] Class F Fly Ash is most common. [3] El Paso: requires GGBFS @ 30% to 50%. [4] thin bonded and UTW pavements [5] 2 inch thin overlays	[1] Ash from incinerated paper mill sludge

Mix Verification and Quality Control Summary

Mix Verification and Quality Control Summary

State	Mix Verification				Quality Control								
	Do you require field trial-batch testing?	If yes, what tests are required?	Do you require tests on field material prior to paving?	If yes, what tests are required?	Air test required?	Air test method?	Slump test required?	Slump test method?	Strength test required?	Strength test 1	Strength test 2	Strength test 3	Other QC test required?
Georgia	yes	air, slump, comp. strength	yes	agg. (gradation), admixtures, cement and SCM (run chemistry), on QPL dowel baskets (sample twice/week), steel, submitted sample from stockpile (must be approved gradation)	yes	GDT 26	yes	GDT 27	yes		Beams (SC)	Cylinders (SC)	moisture test on agg, weekly sampling of materials
Indiana	no				yes	501;502	yes	502	yes	Maturity (SC)	Beams (SC)		unit weight - 501; relative yield - 502
Iowa	no		no		yes	AASHTO T152 (1/850yd3)	no		yes	Maturity (SC)	Beams (SC)		
Kansas	no		no		yes	AVA and AASHTO T152	yes	AASHTO T119	yes		Beams (SC)	Cores (SC)	unit weight, PCC temp, density
Louisiana	no		yes	cement, gradation, QPL compliance	yes	TR -202 (AASHTO)	yes	TR -207(AASHTO)	yes		Beams (SC)	Cylinders	
Michigan	yes	unknown	yes	unknown	yes	unknown	yes	unknown	yes		Beams (SC)	Cylinders (SC)	PCC Temp
Minnesota	no		yes	aggregate (SC)	yes	AASHTO T152	yes	AASHTO T119	yes	Maturity (SC)	Beams (SC)	Cylinders (SC)	
Missouri	no		yes	Sieve analysis, deleterious content	yes	AASHTO T152	yws	AASHTO T119	yes			Cylinders (SC)	Thickness-AASHTO T148, Smoothness spec
Nebraska	no		yes	aggregate/cementious materials (SC)	yes	NDR T121	no		yes			Cylinders	
New York	for HES	502	yes/no	approved materials ony; pre-approved	yes	ASTM C231	yes	ASTM C143	yes	all have been done in the lab			
North Carolina	no		no		yes	AASHTO T152	yes	AASHTO T119	yes	Maturity (SC)	Beams (SC)	Cylinders (SC)	
North Dakota	yes	slump, air, comp and flexural strength	yes	aggregate	yes	AASHTO T 152	yes	AASHTO T119	yes		Beams (SC)	Cylinders (SC)	yield test, unit weight
Ohio	no		no		yes	C231 or 173	yes	C143	yes	Maturity (SC)	Beams (SC)	Cylinders (SC)	smoothness and thickness
Oklahoma	no		yes	aggregate gradation	yes	AASHTO T152 or T196	yes	AASHTO T119	yes			Cylinders (SC)	
South Dakota	no		no		yes	SD 403	yes	SD 404	yes			Cylinders	PCC Temp, Unit weight, gradation, agg moisture
Texas	yes	pilot beams - 7 day correlation?	yes	pilot beams - 7 day correlation?	unknown	unknown	unknown	unknown	yes	Maturity (SC)	Beams	Cylinders	PCC Temp - max 95F ??
Wisconsin	no		yes	compressive strength	yes	AASHTO T152	yes	AASHTO T119	yes			Cylinders	PCC Temp

Note: SC = see comment.

State	Quality Control												
	General Comments	Comment 1	Com-ment 2	Comment 3	Comment 4	Com-ment 5	Comment 6	Com-ment 7	Com-ment 8	Com-ment 9	Comment 10	Comment 11	Comment 12
Georgia	*have paving schools, since not a lot of PCC (every paving project takes 1/2 day) Jay does them all; require contractors to come. Superint., paving fores, plant operator involved in project starts; sampling, building stockpiles, mix design	*Sample R/M on monthly basis so they can start paving based on this			*do pull sample of cash materials *sample steel also visual check							Third point - AASHTO T97	AASHTO T22 - depending on specification could by yardage or lot
Indiana		*a trial is required to do mix design. Do it in field before project starts									501,502	501, 502	
Iowa											for opening of 500psi MOR-CPL	third point - 1/10000yd3 information for Design Office	
Kansas												Beams determine when pavement can be opened to traffic	compressive strength and depth
Louisiana												Third point used sometimes?	
Michigan												Beams determine when pavement can be opened to traffic	Cylinders are tested at 28 days
Minnesota					Absorption, % carbonates, % spal						If requested by contractor, but new curve must be completed for mix change	3rd point	projects < 2500 cu yd
Missouri													28-day AASHTO T22
Nebraska					Approved aggregate source list								
New York							hardened air (TM 501 08T)				normal strength; meet requirement; info only for Class C		
North Carolina											ASTM C1074 (some projects)	AASHTO T126&T97	not generally specified but sometimes used optionally or in
North Dakota	No QC/QA program, only QA				Contractor performs agg. test from pit (agg. gradation, thin and elongated, soft rock, iron oxide)							3rd point, 500psi for traffic	3000 psi
Ohio				materials should already be pre-approved or certified							in development	std. spec. - center	QC/QA spec. - on cores
													AASHTO T22 & T23
South Dakota	No QC/QA program, SDDOT performs all tests												
Texas											some maturity testing		
Wisconsin													

Typical Mix Designs

Typical Mix Designs

	Georgia			Indiana			Iowa			Kansas			Louisiana			Michigan		
	Mix 1	Mix 2	Mix 3	Mix 1	Mix 2	Mix 3	Mix 1	Mix 2	Mix 3	Mix 1	Mix 2	Mix 3	Mix 1	Mix 2	Mix 3	Mix 1	Mix 2	Mix 3
Description	Class 3 Pavement	Class 1 Pavement	Class 1 Pavement	mix design submitted to project engineer (not Dist. Mats. Engr.)				QMC		MA-3	MA-3	MA-3				Need typical mixes		
Water (lb/cy)	267	170.4lt	170.4				228	216		238	234	248	242	258				
Portland Cement (lb/cy)	480	324kg	273kg				457	471		540	520	605	507	273				
Fly Ash Class C (lb/cy)	125		61kg				114	83										
Fly Ash Class F (lb/cy)																		
Slag (lb/cy)														273				
Silica Fume (lb/cy)																		
Coarse Aggregate Type	Aggreagate #57	#57 stone	#57 stone				1669	1395		Rock	Rock	Rock	unknown	unknown				
CA (lb/cy)	1868	1067kg	1067							1323	1670	1384	unknown	unknown				
Fine Aggregate Type										Sand	Sand	Sand	unknown	unknown				
FA (lb/cy)	1153	751kg	729				1393	1264		1618	1367	1499	unknown	unknown				
WR Type	Euclid Retarder 75	Boral LR	Boral LR				x	Eucon WR		unknown	unknown							
WR dosage (oz/cwt)	12(oz/yd3)							4		8.7	2.8							
MRWR (oz/cwt)													5.2	3.0				
HRWR (oz/cwt)																		
AEA Type	Euclid AEA 92	Boral Air 40	Boral Air 40				x	AEA 92										
AEA dosage (oz/cwt)	3(oz/yd3)							1		1.1	0.6	3	1.2	0.7				
Target Air (%)	4.5	5	5				6.0	6		7.0	6.5	6.5	unknown	unknown				
Accelerator																		
Retarder																		
Other																		
Comments for Mix 1	PC - Type 1 (Southern Cement); fly ash - Boral Material Tech., Juliette, GA; FA - Atlanta Sand&Burke Pit Gaillard, GA; CA - Florida Rock Palmer Station #57; unit weight 146.7 lb/ft3; strength @7=4157psi, @28=5530psi												Type IS cement used on mix					
Comments for Mix 2	PC - Type 1 (Southdown); FA - natural(Williams Sand Comp.-GA Source#198F), crushed(Martin Marietta-Jefferson Quarry); CA - Martin Marietta-Jefferson Quarry; slump(44.5&51mm); strength @24hr=2330-2690psi, @28d=730-910psi(beam), 4390-4930psi(cylinder); WR&AEA - Monroe Admix., Monroe, NC						Cement-Lafarge; fly ash-Lousia; CA-Stone city; FA-Anamosa pit; design slump 1.5"						Type IS cement used on mix					
Comments for Mix 3	PC - Type 1 (Southdown); FA - natural(Williams Sand Comp.-GA Source#198F), crushed(Martin Marietta-Jefferson Quarry); CA - Martin Marietta-Jefferson Quarry; slump(44.5&51mm); strength @24hr=2030-2370psi, @28d=765-880psi(beam), 4090-4140psi(cylinder); fly ash - Boral Flayash, Stilesboro, GA Bowen Plant; WR&AEA - Monroe Admix., Monroe, NC																	

	Minnesota			Missouri			Nebraska			New York			North Carolina			North Dakota		
	Mix 1	Mix 2	Mix 3	Mix 1	Mix 2	Mix 3	Mix 1	Mix 2	Mix 3	Mix 1	Mix 2	Mix 3	Mix 1	Mix 2	Mix 3	Mix 1	Mix 2	Mix 3
Description				State 1	State 2	Contractor Optimized	47B-Alt 1	47B-Alt 3	47B-Alt 4	Need typical mix designs			Pavement class concr.			094-128WB	094-240	094-349
Water (lb/cy)	210	210	200	233	244	240	254 max	254 max	254 max				259	259		214.91	216.56	224.91
Portland Cement (lb/cy)	400	360	450	486	573	523	423	564	564				490	576		394.8	394.8	394.8
Fly Ash Class C (lb/cy)	170		120	86		92										169.2	169.2	169.2
Fly Ash Class F (lb/cy)							141						104					
Slag (lb/cy)		190																
Silica Fume (lb/cy)																		
Coarse Aggregate Type	unknown	unknown	unknown	Limestone	Limestone	Limestone	Limestone	Limestone	Limestone							unknown	unknown	unknown
CA (lb/cy)	2250	1950	1900	1926	1953	1890	901	901	901				1952	1952		unknown	unknown	unknown
Fine Aggregate Type	unknown	unknown	unknown	Sand	Sand	Sand	Sand	Sand	Sand							unknown	unknown	unknown
FA (lb/cy)	900	1200	1250	1147	1151	1111	2102	2102	2102				1144	1144		unknown	unknown	unknown
WR Type	unknown	unknown	unknown			GRT Polychem, 400 NC	unknown	unknown	unknown				POZZOLITH-80	POZZOLITH-80		WRDA-82	WRDA-82	?
WR dosage (oz/cwt)	unknown	unknown	unknown			6.0	unknown	unknown	unknown				as recom.	as recom.		3.0	3	
MRWR (oz/cwt)																		
HRWR (oz/cwt)																		
AEA Type	unknown	unknown	unknown	unknown	unknown	GRT Polychem VR	unknown	unknown	unknown				MB AE 90	MB AE 90		unknown	unknown	unknown
AEA dosage (oz/cwt)	unknown	unknown	unknown	0.5 to 3.0	0.5 to 3.0	1.3	unknown	unknown	unknown				as recom.	as recom.		1.2	1.2	unknown
Target Air (%)	unknown	unknown	unknown	unknown	unknown	6.0	6.0	6.0	6.0				5.0	5.0		6.0	6.0	6.5
Accelerator																		
Retarder																		
Other																		
Comments for Mix 1				See file for source info. Type I cement.			Type I/II cement						Cement - Holcim(Holly Hill); Pozzolan - Proash; CA - Pomona Quarry/Greensboro; FA. - Hall Pit/Lemon Springs; AEA & WR - Master Builders; Slump - 1.50"; mortar content - 15.67 cu.ft					
Comments for Mix 2							Type IPF cement (15% to 25% class C fly ash).						Cement - Holcim(Holly Hill); Pozzolan - Proash; CA - Pomona Quarry/Greensboro;FA - Hall Pit/Lemon Springs; AEA&WR - Master Builders; Slump - 1.50"; mortar content - 15.67 cu.ft					
Comments for Mix 3				Mix contains 450 of IA and 1440 of CA.			Type I/II cement											

	Ohio			South Dakota			Texas			Wisconsin		
	Mix 1	Mix 2	Mix 3	Mix 1	Mix 2	Mix 3	Mix 1	Mix 2	Mix 3	Mix 1	Mix 2	Mix 3
Description	Need typical mix designs.			74-45-77	A-45	PCEMS 6116	Need typical mix designs.			A	A-S	A-FA
Water (lb/cy)				253	265	236				232	232	232
Portland Cement (lb/cy)				557	570	510				565	395	395
Fly Ash Class C (lb/cy)												170
Fly Ash Class F (lb/cy)				123	125	112						
Slag (lb/cy)											170	
Silica Fume (lb/cy)												
Coarse Aggregate Type				Quartize	Limestone	Limestone				unknown	unknown	unknown
CA (lb/cy)				1690	1720	1720				2028	2015	2002
Fine Aggregate Type				Sand	Sand	Sand				unknown	unknown	unknown
FA (lb/cy)				1183	1162	1298				1092	1085	1078
WR Type				WRDA 82	MB MBVR	WRDA 82				unknown	unknown	unknown
WR dosage (oz/cwt)				unknown	unknown	3.0				unknown	unknown	unknown
MRWR (oz/cwt)												
HRWR (oz/cwt)												
AEA Type				Daravair M	MB Master Pave	Daravair R				unknown	unknown	unknown
AEA dosage (oz/cwt)				unknown	unknown	unknown				unknown	unknown	unknown
Target Air (%)				unknown	6.5					unknown	unknown	unknown
Accelerator												
Retarder												
Other												
Comments for Mix 1				CA - Concrete Materials, Sioux Falls, SD. FA-Higman Sand & Gravel, Akron, IA. Fly ash from Coal Creek. More info on file.						State specified concrete mixes with 35% FA and 65% CA.		
Comments for Mix 2				CA - Pete Lien & Sons, Rapid City, SD. FA - Birdsall Sand & Gravel, Creston SD. Coal creek fly ash. More info on file.						State specified concrete mixes with 35% FA and 65% CA.		
Comments for Mix 3				CA - Pete Lien & Sons, Rapid City, SD. FA - Birdsall Sand & Gravel, Creston SD. Coal creek fly ash. More info on file.						State specified concrete mixes with 35% FA and 65% CA.		

B.5. Problem Project Data Collection Form

MATERIAL AND CONSTRUCTION OPTIMIZATION FOR PREMATURE PAVEMENT DISTRESS IN PCC PAVEMENTS

DATA COLLECTION FORM

This form can be used for new pavements or overlays. Cracking from obvious design errors, subbase failures, or other non-concrete related causes need not be included. This is intended to include past projects where distress became a concern on projects less than 15 years old. Please use one form per project.

NAME OF INDIVIDUAL(S) COMPLETING FORM: ________________________________

TITLE/POSITION: ____

PHONE: _____________________

ADDRESS: ____

State	**Highway Route**	**Length of Project**
______________	______________	______________

Year Constructed ________ Project Number _________________________

General Location____

1. In general, what was the problem and how severe was it?
   ____
   ____

   Rank its severity 1 – 5 (5=very severe) ___

2. Which Mix Characteristic(s) do you think caused the problem? (Check all that apply)
   Workability___ Consistency___ Shrinkage___ Strength ___ Air Content ___

   Permeability___ Other ___________________________________

Describe the nature of the problem:

____

____

3. Do you feel there was a material related cause? Yes ____ No ____

If yes, describe: ____

____

4. Do you feel there was a construction-related cause? Yes ____ No ____

If yes, describe: ____

____

Was this within the specifications and normal construction practices?

Yes _____ No _____

5. Do you feel there was an environmental related cause? Yes_____ No _____

   If yes, describe: ____

6. Did the problem persist throughout the project? Yes _____ No _____

   If no, how much of the project? ____

   What changed (Weather, certain material, etc.)? __________________________________

7. What tests were used to identify the causes? ___________________________________

   ____

8. What information / tests would have helped in identifying the problem prior to / during construction?

   ____

   ____

9. Are project-level construction records or materials information available?

   Yes ____ No ____

10. Were any post-construction investigative tests performed on the pavement? (Cores, petrography, in-place strength, etc.)

    Yes ____ No ____

    If yes, describe: ____

11. Have changes been made to your specifications or design methods to prevent a repeat of this problem, and if so what change was made?

    Yes ____ No ____

    If yes, describe: ____

B.6. Compilation of State Problem Projects

Iowa

1 = Yes
2 = No

Item	Value
Names	Todd Hanson
Title/Position	
Address	
Phone	515-232-8210
E-mail	todd.hanson@dot.state.ia.us
State	IOWA
Highway Route	I-80
Length of Project	5.47
Year Constructed	1987
Project Number	IR-80-6(126)209--12-48
General Location	
In general, what was the problem?	
Rank its severity 1-5 (5=very severe)	4
Which Mix Characteristic(s) do you think caused the problem?	
Mix Workability	True
Mix Consistency	False
Mix Shrinkage	False
Mix Strength	False
Mix Air Content	True
Mix Permeability	False
Mix Other	False
Mix Other Describe	
Describe the nature of the problem:	
Material Related Cause	1
Material Related Cause Describe	
Construction Related Cause	1
Construction Related Cause Describe	
Was this within the specifications and normal construction practices?	1

Do you feel there was an environmental related cause?	1
Environmental Related Cause Description	
Did the problem persist throughout the project?	1
If no, how much of the project:	
What changed (weather, certain material, etc.)?	
What tests were used to identify the causes?	
What information / tests would have helped in identifying the problem prior to / during construction?	
Are project level construction records or materials information available?	1
Were any post-construction investigative tests performed on the pavement? (Cores, petrography, in-place strength, etc.)	1
If yes, describe:	
Have changes been made to your specifications or design methods?	1
If yes, describe:	
Date/Time	6/27/2003 11:22:16 AM

1 = Yes
2 = No

Item	Value
Names	Todd Hanson
Title/Position	
Address	
Phone	515-232-8210
E-mail	todd.hanson@dot.state.ia.us
State	DALLAS
Highway Route	I-80
Length of Project	15.7
Year Constructed	1987
Project Number	IR-80-3(57)106--12-2548
General Location	
In general, what was the problem?	
Rank its severity 1-5 (5=very severe)	4
Which Mix Characteristic(s) do you think caused the problem?	
Mix Workability	True
Mix Consistency	False

Mix Shrinkage	False
Mix Strength	False
Mix Air Content	True
Mix Permeability	False
Mix Other	False
Mix Other Describe	
Describe the nature of the problem:	
Material Related Cause	1
Material Related Cause Describe	
Construction Related Cause	1
Construction Related Cause Describe	
Was this within the specifications and normal construction practices?	1
Do you feel there was an environmental related cause?	1
Environmental Related Cause Description	
Did the problem persist throughout the project?	2
If no, how much of the project:	
What changed (weather, certain material, etc.)?	
What tests were used to identify the causes?	
What information / tests would have helped in identifying the problem prior to / during construction?	
Are project level construction records or materials information available?	1
Were any post-construction investigative tests performed on the pavement? (Cores, petrography, in-place strength, etc.)	1
If yes, describe:	
Have changes been made to your specifications or design methods?	1
If yes, describe:	
Date/Time	6/27/2003 11:28:29 AM

1 = Yes
2 = No

Item	Value
Names	Todd Hanson
Title/Position	
Address	
Phone	515-232-8210

E-mail	todd.hanson@dot.state.ia.us
State	Pottawattamie
Highway Route	I-29
Length of Project	15.7
Year Constructed	1994
Project Number	IM-29-4(38)58--13-78
General Location	
In general, what was the problem?	
Rank its severity 1-5 (5=very severe)	4
Which Mix Characteristic(s) do you think caused the problem?	
Mix Workability	True
Mix Consistency	False
Mix Shrinkage	False
Mix Strength	False
Mix Air Content	True
Mix Permeability	False
Mix Other	False
Mix Other Describe	
Describe the nature of the problem:	
Material Related Cause	1
Material Related Cause Describe	
Construction Related Cause	1
Construction Related Cause Describe	
Was this within the specifications and normal construction practices?	1
Do you feel there was an environmental related cause?	1
Environmental Related Cause Description	
Did the problem persist throughout the project?	1
If no, how much of the project:	
What changed (weather, certain material, etc.)?	
What tests were used to identify the causes?	
What information / tests would have helped in identifying the problem prior to / during construction?	
Are project level construction records or materials information available?	1

Were any post-construction investigative tests performed on the pavement? (Cores, petrography, in-place strength, etc.)	1
If yes, describe:	
Have changes been made to your specifications or design methods?	1
If yes, describe:	
Date/Time	6/27/2003 11:34:40 AM

1 = Yes
2 = No

Item	Value
Names	Todd Hanson
Title/Position	
Address	
Phone	515-232-8210
E-mail	todd.hanson@dot.state.ia.us
State	Lee
Highway Route	US 61
Length of Project	5.92
Year Constructed	1992
Project Number	DE-RP-518-1(10)--33-56
General Location	
In general, what was the problem?	
Rank its severity 1-5 (5=very severe)	4
Which Mix Characteristic(s) do you think caused the problem?	
Mix Workability	False
Mix Consistency	False
Mix Shrinkage	False
Mix Strength	False
Mix Air Content	False
Mix Permeability	False
Mix Other	True
Mix Other Describe	
Describe the nature of the problem:	
Material Related Cause	1
Material Related Cause Describe	

Construction Related Cause	1
Construction Related Cause Describe	
Was this within the specifications and normal construction practices?	1
Do you feel there was an environmental related cause?	2
Environmental Related Cause Description	
Did the problem persist throughout the project?	1
If no, how much of the project:	
What changed (weather, certain material, etc.)?	
What tests were used to identify the causes?	
What information / tests would have helped in identifying the problem prior to / during construction?	
Are project level construction records or materials information available?	1
Were any post-construction investigative tests performed on the pavement? (Cores, petrography, in-place strength, etc.)	1
If yes, describe:	
Have changes been made to your specifications or design methods?	1
If yes, describe:	
Date/Time	6/27/2003 11:41:27 AM

Minnesota

1 = Yes
2 = No

Item	Value
Names	Douglas J. Schwartz
Title/Position	
Address	
Phone	651-779-5576
E-mail	doug.schwartz@dot.state.mn.us
State	Minnesota
Highway Route	I-35
Length of Project	8.6 miles
Year Constructed	1992
Project Number	0980-127

General Location	
In general, what was the problem?	
Rank its severity 1-5 (5=very severe)	2
Which Mix Characteristic(s) do you think caused the problem?	
Mix Workability	False
Mix Consistency	True
Mix Shrinkage	False
Mix Strength	False
Mix Air Content	True
Mix Permeability	False
Mix Other	True
Mix Other Describe	
Describe the nature of the problem:	
Material Related Cause	1
Material Related Cause Describe	
Construction Related Cause	1
Construction Related Cause Describe	
Was this within the specifications and normal construction practices?	0
Do you feel there was an environmental related cause?	2
Environmental Related Cause Description	
Did the problem persist throughout the project?	1
If no, how much of the project:	
What changed (weather, certain material, etc.)?	
What tests were used to identify the causes?	
What information / tests would have helped in identifying the problem prior to / during construction?	
Are project level construction records or materials information available?	0
Were any post-construction investigative tests performed on the pavement? (Cores, petrography, in-place strength, etc.)	2
If yes, describe:	
Have changes been made to your specifications or design methods?	1
If yes, describe:	
Date/Time	7/1/2003 3:18:00 PM

1 = Yes
2 = No

Item	Value
Names	Douglas J. Schwartz
Title/Position	
Address	
Phone	651-779-5576
E-mail	doug.schwartz@dot.state.mn.us
State	Minnesota
Highway Route	I-35
Length of Project	3.0 miles
Year Constructed	1989
Project Number	7080-42
General Location	
In general, what was the problem?	
Rank its severity 1-5 (5=very severe)	3
Which Mix Characteristic(s) do you think caused the problem?	
Mix Workability	True
Mix Consistency	True
Mix Shrinkage	True
Mix Strength	True
Mix Air Content	True
Mix Permeability	True
Mix Other	True
Mix Other Describe	
Describe the nature of the problem:	
Material Related Cause	1
Material Related Cause Describe	
Construction Related Cause	2
Construction Related Cause Describe	
Was this within the specifications and normal construction practices?	0
Do you feel there was an environmental related cause?	2
Environmental Related Cause Description	
Did the problem persist throughout the project?	1

If no, how much of the project:	
What changed (weather, certain material, etc.)?	
What tests were used to identify the causes?	
What information / tests would have helped in identifying the problem prior to / during construction?	
Are project level construction records or materials information available?	0
Were any post-construction investigative tests performed on the pavement? (Cores, petrography, in-place strength, etc.)	2
If yes, describe:	
Have changes been made to your specifications or design methods?	0
If yes, describe:	
Date/Time	7/1/2003 4:05:33 PM

1 = Yes
2 = No

Item	**Value**
Names	Douglas J. Schwartz
Title/Position	
Address	
Phone	651-779-5576
E-mail	doug.schwartz@dot.state.mn.us
State	Minnesota
Highway Route	TH 71
Length of Project	3.06 miles
Year Constructed	2000
Project Number	3412-60
General Location	
In general, what was the problem?	
Rank its severity 1-5 (5=very severe)	1
Which Mix Characteristic(s) do you think caused the problem?	
Mix Workability	False
Mix Consistency	False
Mix Shrinkage	True
Mix Strength	False

Mix Air Content	False
Mix Permeability	False
Mix Other	True
Mix Other Describe	
Describe the nature of the problem:	
Material Related Cause	1
Material Related Cause Describe	
Construction Related Cause	2
Construction Related Cause Describe	
Was this within the specifications and normal construction practices?	0
Do you feel there was an environmental related cause?	1
Environmental Related Cause Description	
Did the problem persist throughout the project?	2
If no, how much of the project:	
What changed (weather, certain material, etc.)?	
What tests were used to identify the causes?	
What information / tests would have helped in identifying the problem prior to / during construction?	
Are project level construction records or materials information available?	1
Were any post-construction investigative tests performed on the pavement? (Cores, petrography, in-place strength, etc.)	2
If yes, describe:	
Have changes been made to your specifications or design methods?	1
If yes, describe:	
Date/Time	7/1/2003 4:33:15 PM

Missouri

1 = Yes
2 = No

Item	Value
Names	Jason Blomberg
Title/Position	Sr. Research and Development Assistant
Address	Missouri Department of Transportation Central Laboratory

	1617 MO Blvd. Jefferson City, MO 65109
Phone	(573) 526-4338
E-mail	blombj@mail.modot.state.mo.us
State	Missouri
Highway Route	I-70
Length of Project	3 Miles
Year Constructed	1991
Project Number	J5I0448
General Location	Westbound lanes of I-70 in Cooper County, MO. West of Lamine River Bridge to 0.4 miles east of Rt. K.
In general, what was the problem?	This project was an bonded concrete overlay in which cracks were observed two days after placement. Areas of sand pockets and segregation failed and needed to be replaced. Approximately 5 reflective cracks/panel occurred within 90 days after placement.
Rank its severity 1-5 (5=very severe)	5
Which Mix Characteristic(s) do you think caused the problem?	
Mix Workability	True
Mix Consistency	True
Mix Shrinkage	False
Mix Strength	False
Mix Air Content	False
Mix Permeability	False
Mix Other	False
Mix Other Describe	
Describe the nature of the problem:	Workability and consistency were the problem mix characteristics. The mixes were delivered to the jobsite unmixed and segregated.
Material Related Cause	1
Material Related Cause Describe	Material related cause. Flash setting could have been occurring due the use of Type 3 cement.
Construction Related Cause	1
Construction Related Cause	Construction related cause.

Describe	Material issue caused the concrete to build up and harden in the drum and the blades of the mixer at the central batch plant causing further mixing problems.
Was this within the specifications and normal construction practices?	2
Do you feel there was an environmental related cause?	2
Environmental Related Cause Description	
Did the problem persist throughout the project?	1
If no, how much of the project:	the problem persisted throughout the project.
What changed (weather, certain material, etc.)?	
What tests were used to identify the causes?	Visual observations of unmixed material were made at the site and many loads were rejected. Unfortunately, the blades of the mixer were not checked until after project completion.
What information / tests would have helped in identifying the problem prior to / during construction?	Concrete mixing equipment needs to be checked prior to the pour and possibly during the pour if flash setting is occurring.
Are project level construction records or materials information available?	1
Were any post-construction investigative tests performed on the pavement? (Cores, petrography, in-place strength, etc.)	1
If yes, describe:	Yes, some construction and materials information is available.
Have changes been made to your specifications or design methods?	0
If yes, describe:	MoDOT is in the process of implementing new QC/QA performance related specifications for concrete paving.
Date/Time	7/10/2003 12:53:30 PM

Nebraska

1 = Yes
2 = No

Item	Value
Names	George Woolstrum
Title/Position	
Address	
Phone	402-479-4791
E-mail	gwoolstr@dor.state.ne.us
State	NE
Highway Route	Nebraska 2
Length of Project	5 miles
Year Constructed	1991
Project Number	F-2-3(1014)
General Location	
In general, what was the problem?	
Rank its severity 1-5 (5=very severe)	3
Which Mix Characteristic(s) do you think caused the problem?	
Mix Workability	False
Mix Consistency	False
Mix Shrinkage	True
Mix Strength	False
Mix Air Content	False
Mix Permeability	False
Mix Other	False
Mix Other Describe	
Describe the nature of the problem:	
Material Related Cause	1
Material Related Cause Describe	
Construction Related Cause	1
Construction Related Cause Describe	
Was this within the specifications and normal construction practices?	1
Do you feel there was an environmental related cause?	1
Environmental Related Cause Description	

Did the problem persist throughout the project?	1
If no, how much of the project:	
What changed (weather, certain material, etc.)?	
What tests were used to identify the causes?	
What information / tests would have helped in identifying the problem prior to / during construction?	
Are project level construction records or materials information available?	1
Were any post-construction investigative tests performed on the pavement? (Cores, petrography, in-place strength, etc.)	1
If yes, describe:	
Have changes been made to your specifications or design methods?	1
If yes, describe:	
Date/Time	6/24/2003 5:17:19 PM

1 = Yes
2 = No

Item	Value
Names	George Woolstrum
Title/Position	
Address	
Phone	402-479-4791
E-mail	gwoolstr@dor.state.ne.us
State	NE
Highway Route	Nebraska
Length of Project	
Year Constructed	0
Project Number	
General Location	
In general, what was the problem?	
Rank its severity 1-5 (5=very severe)	0
Which Mix Characteristic(s) do you think caused the problem?	
Mix Workability	False
Mix Consistency	False
Mix Shrinkage	False
Mix Strength	False

Mix Air Content	False
Mix Permeability	False
Mix Other	False
Mix Other Describe	
Describe the nature of the problem:	
Material Related Cause	0
Material Related Cause Describe	
Construction Related Cause	0
Construction Related Cause Describe	
Was this within the specifications and normal construction practices?	0
Do you feel there was an environmental related cause?	0
Environmental Related Cause Description	
Did the problem persist throughout the project?	0
If no, how much of the project:	
What changed (weather, certain material, etc.)?	
What tests were used to identify the causes?	
What information / tests would have helped in identifying the problem prior to / during construction?	
Are project level construction records or materials information available?	0
Were any post-construction investigative tests performed on the pavement? (Cores, petrography, in-place strength, etc.)	0
If yes, describe:	
Have changes been made to your specifications or design methods?	0
If yes, describe:	
Date/Time	6/25/2003 9:59:44 AM

1 = Yes
2 = No

Item	Value
Names	George Woolstrum
Title/Position	
Address	
Phone	402-479-4791
E-mail	gwoolstr@dor.state.ne.us
State	NE

Highway Route	Nebraska 2
Length of Project	11 miles
Year Constructed	1996
Project Number	F-2-7(1014)
General Location	
In general, what was the problem?	
Rank its severity 1-5 (5=very severe)	2
Which Mix Characteristic(s) do you think caused the problem?	
Mix Workability	False
Mix Consistency	False
Mix Shrinkage	True
Mix Strength	False
Mix Air Content	False
Mix Permeability	False
Mix Other	False
Mix Other Describe	
Describe the nature of the problem:	
Material Related Cause	1
Material Related Cause Describe	
Construction Related Cause	1
Construction Related Cause Describe	
Was this within the specifications and normal construction practices?	2
Do you feel there was an environmental related cause?	1
Environmental Related Cause Description	
Did the problem persist throughout the project?	2
If no, how much of the project:	
What changed (weather, certain material, etc.)?	
What tests were used to identify the causes?	
What information / tests would have helped in identifying the problem prior to / during construction?	
Are project level construction records or materials information available?	1
Were any post-construction investigative tests performed on the pavement? (Cores, petrography, in-place strength, etc.)	1
If yes, describe:	
Have changes been made to your specifications or design methods?	1

If yes, describe:	
Date/Time	6/25/2003 3:52:03 PM

1 = Yes
2 = No

Item	Value
Names	George Woolstrum
Title/Position	
Address	
Phone	402-479-4791
E-mail	gwoolstr@dor.state.ne.us
State	NE
Highway Route	US-77
Length of Project	5 miles
Year Constructed	1991
Project Number	F-77-1(1011)
General Location	
In general, what was the problem?	
Rank its severity 1-5 (5=very severe)	2
Which Mix Characteristic(s) do you think caused the problem?	
Mix Workability	False
Mix Consistency	False
Mix Shrinkage	True
Mix Strength	False
Mix Air Content	False
Mix Permeability	False
Mix Other	False
Mix Other Describe	
Describe the nature of the problem:	
Material Related Cause	1
Material Related Cause Describe	
Construction Related Cause	1
Construction Related Cause Describe	
Was this within the specifications and normal construction practices?	1
Do you feel there was an environmental related cause?	1

Environmental Related Cause Description	
Did the problem persist throughout the project?	1
If no, how much of the project:	
What changed (weather, certain material, etc.)?	
What tests were used to identify the causes?	
What information / tests would have helped in identifying the problem prior to / during construction?	
Are project level construction records or materials information available?	1
Were any post-construction investigative tests performed on the pavement? (Cores, petrography, in-place strength, etc.)	1
If yes, describe:	
Have changes been made to your specifications or design methods?	1
If yes, describe:	
Date/Time	6/26/2003 9:46:02 AM

1 = Yes
2 = No

Item	Value
Names	George Woolstrum
Title/Position	
Address	
Phone	402-479-4791
E-mail	gwoolstr@dor.state.ne.us
State	NE
Highway Route	US-136
Length of Project	1.4 miles
Year Constructed	1988
Project Number	F-136-7(1003)
General Location	
In general, what was the problem?	
Rank its severity 1-5 (5=very severe)	4
Which Mix Characteristic(s) do you think caused the problem?	
Mix Workability	False
Mix Consistency	False
Mix Shrinkage	False

Mix Strength	False
Mix Air Content	False
Mix Permeability	False
Mix Other	True
Mix Other Describe	
Describe the nature of the problem:	
Material Related Cause	1
Material Related Cause Describe	
Construction Related Cause	1
Construction Related Cause Describe	
Was this within the specifications and normal construction practices?	1
Do you feel there was an environmental related cause?	2
Environmental Related Cause Description	
Did the problem persist throughout the project?	1
If no, how much of the project:	
What changed (weather, certain material, etc.)?	
What tests were used to identify the causes?	
What information / tests would have helped in identifying the problem prior to / during construction?	
Are project level construction records or materials information available?	1
Were any post-construction investigative tests performed on the pavement? (Cores, petrography, in-place strength, etc.)	1
If yes, describe:	
Have changes been made to your specifications or design methods?	1
If yes, describe:	
Date/Time	6/26/2003 12:10:56 PM

North Carolina

1 = Yes
2 = No

Item	Value
Names	Thomas M. Hearne, Jr.
Title/Position	Pavement Analysis Engineer
Address	NCDOT - Pavement Management Unit

	716 West Main Street Albemarle, NC 28001
Phone	704-983-4019
E-mail	thearne@dot.state.nc.us
State	North Carolina
Highway Route	I-440
Length of Project	Estimate 1 mile (Affects the I-440 part of a 6.1 mile project including I-40)
Year Constructed	2000
Project Number	8.1404201
General Location	I-440 Beltline in Raleigh, North Carolina
In general, what was the problem?	Transverse cracks in 4"" bonded concrete overlay
Rank its severity 1-5 (5=very severe)	4
Which Mix Characteristic(s) do you think caused the problem?	
Mix Workability	False
Mix Consistency	False
Mix Shrinkage	True
Mix Strength	False
Mix Air Content	False
Mix Permeability	False
Mix Other	False
Mix Other Describe	Shrinkage of mix is a possible contributor to the problem
Describe the nature of the problem:	Transverse cracks near mid-slab in 4"" bonded concrete overlay
Material Related Cause	1
Material Related Cause Describe	Shrinkage possibly contributes to problem
Construction Related Cause	1
Construction Related Cause Describe	High temperatures during placement of thin overlay on rigid base with joint spacings varying from 18 to 25 ft. in length creates potential for problems with drying shrinkage.
Was this within the specifications and normal construction practices?	1
Do you feel there was an environmental related cause?	1
Environmental Related Cause Description	High temperatures

Did the problem persist throughout the project?	1
If no, how much of the project:	
What changed (weather, certain material, etc.)?	Cracking was not as severe when air temperature was lower
What tests were used to identify the causes?	Cores, Distress Surveys
What information / tests would have helped in identifying the problem prior to / during construction?	Good engineering judgment--high risk of failure
Are project level construction records or materials information available?	1
Were any post-construction investigative tests performed on the pavement? (Cores, petrography, in-place strength, etc.)	1
If yes, describe:	Various strength tests, compression wave velocities, distress surveys
Have changes been made to your specifications or design methods?	1
If yes, describe:	Use smaller slab lengths for overlay
Date/Time	7/14/2003 2:20:59 PM

Wisconsin

1 = Yes
2 = No

Item	Value
Names	Steven Krebs
Title/Position	Chief Pavements Engineer Wisconsin Department of Transportation
Address	3502 Kinsman Blvd. Madison, WI. 53704
Phone	608 246-5399
E-mail	steven.krebs@dot.state.wi.us
State	Wisconsin
Highway Route	Interstate 90/94
Length of Project	20 + miles
Year Constructed	1991

Project Number	Several Projects
General Location	Interstate 90/94 from STH 33 to STH 16 & 12 (Lyndon Station)
In general, what was the problem?	The problem was cracking along the transverse joint, which are skewed. Also we have discovered the concrete has delaminated/debonded to the dowel bars. Fairly severe.
Rank its severity 1-5 (5=very severe)	3
Which Mix Characteristic(s) do you think caused the problem?	
Mix Workability	True
Mix Consistency	False
Mix Shrinkage	False
Mix Strength	True
Mix Air Content	False
Mix Permeability	False
Mix Other	False
Mix Other Describe	
Describe the nature of the problem:	
Material Related Cause	1
Material Related Cause Describe	
Construction Related Cause	2
Construction Related Cause Describe	
Was this within the specifications and normal construction practices?	1
Do you feel there was an environmental related cause?	2
Environmental Related Cause Description	
Did the problem persist throughout the project?	1
If no, how much of the project:	
What changed (weather, certain material, etc.)?	
What tests were used to identify the causes?	We have done FWD testing.
What information / tests would have helped in identifying the problem prior to / during construction?	

Are project level construction records or materials information available?	1
Were any post-construction investigative tests performed on the pavement? (Cores, petrography, in-place strength, etc.)	1
If yes, describe:	
Have changes been made to your specifications or design methods?	1
If yes, describe:	
Date/Time	6/23/2003 10:36:45 AM

1 = Yes
2 = No

Item	Value
Names	Steven Krebs
Title/Position	Chief Pavements Engineer Wisconsin Department of Transportation
Address	3502 Kinsman Blvd. Madison, WI. 53704
Phone	608 246-5399
E-mail	steven.krebs@dot.state.wi.us
State	Wisconsin
Highway Route	US Highway 8
Length of Project	2 miles
Year Constructed	1992
Project Number	
General Location	Rhinelander bypass.
In general, what was the problem?	Longitudinal cracking
Rank its severity 1-5 (5=very severe)	5
Which Mix Characteristic(s) do you think caused the problem?	
Mix Workability	False
Mix Consistency	False
Mix Shrinkage	False
Mix Strength	True
Mix Air Content	False

Mix Permeability	False
Mix Other	False
Mix Other Describe	
Describe the nature of the problem:	
Material Related Cause	1
Material Related Cause Describe	
Construction Related Cause	2
Construction Related Cause Describe	
Was this within the specifications and normal construction practices?	1
Do you feel there was an environmental related cause?	1
Environmental Related Cause Description	
Did the problem persist throughout the project?	1
If no, how much of the project:	
What changed (weather, certain material, etc.)?	
What tests were used to identify the causes?	We cut beams and broke them.
What information / tests would have helped in identifying the problem prior to / during construction?	
Are project level construction records or materials information available?	2
Were any post-construction investigative tests performed on the pavement? (Cores, petrography, in-place strength, etc.)	1
If yes, describe:	
Have changes been made to your specifications or design methods?	2
If yes, describe:	
Date/Time	6/24/2003 3:52:00 PM

1 = Yes
2 = No

Item	Value
Names	James M. Parry, P.E.
Title/Position	
Address	
Phone	608-246-7939
E-mail	james.parry@dot.state.wi.us

State	Wisconsin
Highway Route	I-90/94
Length of Project	5 Miles
Year Constructed	1991
Project Number	1101-03-71
General Location	
In general, what was the problem?	
Rank its severity 1-5 (5=very severe)	5
Which Mix Characteristic(s) do you think caused the problem?	
Mix Workability	False
Mix Consistency	False
Mix Shrinkage	False
Mix Strength	False
Mix Air Content	False
Mix Permeability	False
Mix Other	True
Mix Other Describe	
Describe the nature of the problem:	
Material Related Cause	1
Material Related Cause Describe	
Construction Related Cause	2
Construction Related Cause Describe	
Was this within the specifications and normal construction practices?	1
Do you feel there was an environmental related cause?	1
Environmental Related Cause Description	
Did the problem persist throughout the project?	1
If no, how much of the project:	
What changed (weather, certain material, etc.)?	
What tests were used to identify the causes?	
What information / tests would have helped in identifying the problem prior to / during construction?	
Are project level construction records or materials information available?	2
Were any post-construction investigative tests performed on the pavement? (Cores, petrography, in-place strength, etc.)	1

If yes, describe:	
Have changes been made to your specifications or design methods?	1
If yes, describe:	
Date/Time	7/1/2003 2:51:14 PM

1 = Yes
2 = No

Item	Value
Names	James M. Parry, P.E.
Title/Position	
Address	
Phone	608-246-7939
E-mail	james.parry@dot.state.wi.us
State	Wisconsin
Highway Route	STH 35-Tower Ave-City of Superior
Length of Project	5 miles
Year Constructed	1997
Project Number	8010-07-23
General Location	
In general, what was the problem?	
Rank its severity 1-5 (5=very severe)	3
Which Mix Characteristic(s) do you think caused the problem?	
Mix Workability	False
Mix Consistency	True
Mix Shrinkage	False
Mix Strength	False
Mix Air Content	False
Mix Permeability	False
Mix Other	False
Mix Other Describe	
Describe the nature of the problem:	
Material Related Cause	1
Material Related Cause Describe	
Construction Related Cause	1

Construction Related Cause Describe	
Was this within the specifications and normal construction practices?	2
Do you feel there was an environmental related cause?	2
Environmental Related Cause Description	
Did the problem persist throughout the project?	1
If no, how much of the project:	
What changed (weather, certain material, etc.)?	
What tests were used to identify the causes?	
What information / tests would have helped in identifying the problem prior to / during construction?	
Are project level construction records or materials information available?	1
Were any post-construction investigative tests performed on the pavement? (Cores, petrography, in-place strength, etc.)	1
If yes, describe:	
Have changes been made to your specifications or design methods?	2
If yes, describe:	
Date/Time	7/1/2003 3:19:44 PM

1 = Yes
2 = No

Item	Value
Names	James M. Parry
Title/Position	
Address	
Phone	608-246-7939
E-mail	james.parry@dot.state.wi.us
State	Wisconsin
Highway Route	STH 16 - 7th Street
Length of Project	2 Miles
Year Constructed	2000
Project Number	7575-08-71
General Location	
In general, what was the problem?	

Rank its severity 1-5 (5=very severe)	4
Which Mix Characteristic(s) do you think caused the problem?	
Mix Workability	False
Mix Consistency	False
Mix Shrinkage	False
Mix Strength	False
Mix Air Content	False
Mix Permeability	False
Mix Other	False
Mix Other Describe	
Describe the nature of the problem:	
Material Related Cause	1
Material Related Cause Describe	
Construction Related Cause	2
Construction Related Cause Describe	
Was this within the specifications and normal construction practices?	1
Do you feel there was an environmental related cause?	2
Environmental Related Cause Description	
Did the problem persist throughout the project?	2
If no, how much of the project:	
What changed (weather, certain material, etc.)?	
What tests were used to identify the causes?	
What information / tests would have helped in identifying the problem prior to / during construction?	
Are project level construction records or materials information available?	1
Were any post-construction investigative tests performed on the pavement? (Cores, petrography, in-place strength, etc.)	1
If yes, describe:	
Have changes been made to your specifications or design methods?	2
If yes, describe:	
Date/Time	7/1/2003 3:54:15 PM

APPENDIX C. FIELD REPORTS FOR THE PHASE II SHADOW PROJECTS

Louisiana Field Report

Louisiana Shadow Construction Project Information

- Project No. 023-10-0038
- LADOTD, District 5
- Contractor: James Construction Group, LLC

Louisiana Shadow Construction Project Location

The Louisiana shadow project took place on US 167 in Lincoln Parish (see Figure C.1). The contractor prepared an area at the plant site for the Mobile Concrete Research Lab. This location was adjacent to the project.

Project access and plant access for sampling and testing purposes was excellent. There was no delay in transporting air void analyzer and microwave water-cement ratio samples to the Mobile Concrete Research Lab.

Figure C.1. Map of Louisiana Shadow Project Location

Sampling and Testing Activities

The research team arrived onsite March 20, 2006, and began testing project concrete March 22. The two-day delay was due to rain. Fresh concrete testing was concluded on March 30, 2006. Locations for cores were marked by the research team before departure from the project. The cores were then obtained by the contractor, after the pavement had reached opening strength, and were shipped to Ames, Iowa.

The following is an approximate summary of samples and tests conducted during the demonstration:

- Slump, flow, unit weight, temperature, and air content of fresh concrete: 6 tests
- Unit weight and air content of concrete sampled behind the paver: 1 test
- Air void analysis: 6 sampling locations, 23 tests (8 tests of material sampled ahead of the paver)
- Microwave w/c ratio: 6 tests
- Cast and test 6 in. x 12 in. cylinders for compressive strength maturity curve: 12 specimens
- Cast and test 6 in. x 6 in. x 20 in. beams for flexural strength maturity curve: 12 specimens
- Cast and test 6 in. x 12 in. cylinders for 7 day strength: 3 specimens
- Heat signature: 1 PCC test and 1 mortar test
- Heat generation (coffee cup test): 5 tests
- Initial set and final set: 1 test
- Modified false set: 1 test
- Portland cement and fly ash samples obtained for material testing in Ames (XRD, XRF, DSC, and Blaine): 5 samples
- Marked 4 in. pavement cores for testing in Ames (CTE, permeability and hardened air): 5 cores
- Project materials obtained to conduct lab mix design studies in Ames: various bulk quantities

Key Findings

- The results of the 23 AVA tests show fairly consistent but marginally low values for specific surface. Spacing factor results are consistent as well, with marginally high results. The average spacing factor for all tests is 0.0130 in.; this is within the suggested minimum and maximum limits of 0.0040 in. and 0.015 in. The average specific surface of 527 in.$^{-1}$ is within the suggested minimum and maximum limits of 400 in.$^{-1}$ and 1,100 in.$^{-1}$. No significant pattern is evident when comparing the on-vibrator samples to the between-vibrator samples. One objective of this research project is to evaluate the suggested criteria for AVA results. Our experience so far is that the AVA produces results that are conservative when compared to hardened air properties obtained using the rapid air testing apparatus.

- Air content tested ahead of the paver during the demonstration ranged from 4.5% to 6.1%, and the average air content of the six tests conducted was 5.2%. Air content was tested behind the paver at a location corresponding to one of the test locations ahead of the paver. The air content behind the paver for this location was 3.8%. The air content loss from ahead of the paver to behind the paver was 2.0%.
- Vibrator frequencies were checked twice during the demonstration testing. The vibrator frequency was 9,500 vpm for both observations.
- Visual observations of the paving process revealed average edges and surface. Water was added to the surface behind the paver, and there was significant finishing effort required to achieve a consistent surface.
- Curing compound was applied approximately 45 minutes to 1 hour after the concrete had passed through the paver. Weather conditions were mild and evaporation rates were not critical during our stay on the project. In general, curing compound should be applied as quickly as reasonable, normally about 30 minutes after the concrete passes through the paver. This timeframe is critical when ambient conditions are dry and windy.
- The combined gradation of the mix was evaluated using sieve analysis data provided by the contractor. Coarseness factors ranged from 68 to 77, and workability factors ranged from 31 to 32. The 2 in. nominal coarse aggregate may have contributed to the finishing difficulties.
- Compressive strength specimens were tested to develop a strength-maturity relationship curve. Additionally, one set of three 6 in. x 12 in. cylinders was cast during field sampling and tested at seven days. The average seven-day compressive strength of these field-cast cylinders was 3,730 psi. This mix gained strength relatively slowly when compared to other mixes tested for this project.
- One maturity sensor was placed on March 3, 2006. In-place maturity values indicate that the slab had a compressive strength maturity equivalent of 2,590 psi in seven days. Also, the maturity equivalent of 490 psi flexural strength was reached seven days after placement.

A brief summary of the weather conditions recorded by a portable weather station at the Mobile Concrete Research Lab is shown in Table C.1.

Table C.1. Weather Conditions for the Louisiana Project

Date	Min. temp. (˚F)	Max. temp. (˚F)	Min. relative humidity (%)	Max. relative humidity (%)	Min. dew point (˚F)	Max. dew point (˚F)	Max. wind speed (mph)	Total rainfall (in.)
10/26	47.9	56.2	42	69	32.9	38.2	5	
10/27	41.5	58.0	42	80	35.0	40.3	5	
10/28	36.6	57.6	39	81	31.3	37.6	7	
10/29	33.1	61.2	34	85	27.9	37.2	2	0.01
10/30	34.4	46.2	58	81	28.9	33.5	1	

Technology Transfer

During the Louisiana shadow construction project, nine visitors from the Louisiana DOTD and the contractor visited the Mobile Concrete Research Lab. Project data have been made available to stakeholders through reports, presentations, and the project website, http://www.cptechcenter.org/mco/.

Indiana Field Report

Indiana Shadow Construction Project Information

- Project No. R-27619
- INDOT Vincennes District
- Contractor: E & B Paving

Indiana Shadow Construction Project Location

The Indiana shadow project took place on the Lynch Road Extension in Vanderburgh and Warrick Counties (see Figure C.2). The contractor prepared an area approximately 1/4 of a mile from the concrete plant for the Mobile Concrete Research Lab. This location was adjacent to the project, and project and plant access for sampling and testing purposes was excellent. There was no delay in transporting AVA and microwave water-cement ratio (w/c) samples to the Mobile Concrete Research Lab.

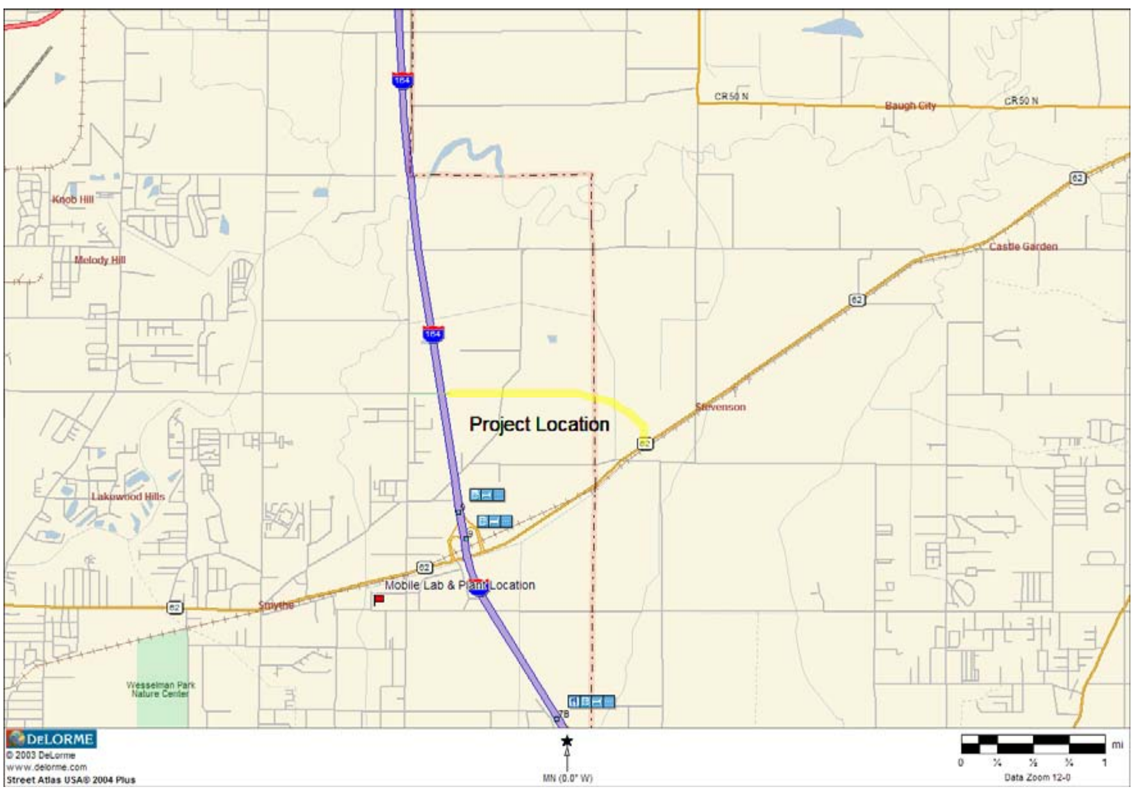

Figure C.2. Map of Indiana Shadow Project Location

Sampling and Testing Activities

The research team arrived onsite on October 26, 2005 and began testing the project concrete on October 27. Fresh concrete testing was concluded on November 2. Cores of the pavement were obtained on November 3, prior to the research team's departure from the project. The following is a summary of the samples taken and tests conducted during the demonstration:

- Slump, flow, unit weight, temperature, and air content of fresh concrete: 10 tests
- Unit weight and air content of concrete sampled behind the paver: 1 test
- Air void analysis: 9 sampling locations, 25 tests
- Microwave w/c ratio: 9 tests
- Cast and test 4 in. x 8 in. cylinders for compressive strength maturity curve: 12 specimens
- Cast and test 4 in. x 8 in. cylinders for time domain reflectometry (TDR) calibration: 10 specimens
- Cast and test 4 in. x 8 in. cylinders for 7 day strength: 3 specimens
- Heat signature:1 PCC test and 1 mortar test
- Heat generation (coffee cup test): 2 tests
- Initial set and final set: 1 test
- Modified false set: 1 test (performed in Ames on project sampled material)
- Portland cement and fly ash samples obtained for material testing in Ames (XRD, XRF, DSC, and Blaine): 5 samples
- Obtained 4 inch pavement cores for testing in Ames (coefficient of thermal expansion, permeability, and hardened air): 8 cores
- Obtained bulk project materials to conduct lab mix design studies in Ames

Key Findings

- The results of the 25 AVA tests show slightly variable results for specific surfaces, though spacing factor results are consistent. The average spacing factor for all tests is 0.0060 in., which is within the suggested maximum and minimum limits of 0.0040 in. and 0.015 in. The average specific surface of 1004 in.$^{-1}$ is within the suggested minimum and maximum limits of 400 in.$^{-1}$ and 1,100 in.$^{-1}$. No significant pattern is evident when comparing the on-vibrator samples to the between-vibrator samples.
- One objective of this research project was to evaluate the suggested criteria for AVA results. Our experience so far is that the AVA produces more conservative results than the hardened air properties obtained using the rapid air testing apparatus.
- Air content tested ahead of the paver during the demonstration ranged from 4.9% to 7.8%. The average air content of the nine tests conducted was 6.3%.
- Air content was tested behind the paver at a location corresponding to the location ahead of the paver. The air content behind the paver for this location was 5.6%. The air content loss from ahead of the paver to behind the paver was 2.2%.
- Vibrator frequencies were measured once during the demonstration testing. The vibrator frequency was 7,500 vpm, and the paver speed was approximately 5.0 fpm.
- Visual observations of the paving process revealed very good edges and surface. The finishers were not observed to have overworked the surface.
- The combined gradation of the mix was evaluated using sieve analysis data provided by the contractor. Coarseness factors ranged from 65 to 72, and workability factors ranged from 39 to 40.
- Timing of the curing compound application was observed throughout the demonstration.

The curing compound was applied approximately 45 minutes after concrete placement. In general, curing compound should be placed within 30 minutes after concrete placement whenever possible.

- Compressive strength specimens were tested to develop a strength-maturity relationship curve. Additionally, one set of three 4 in. x 8 in. cylinders was cast during field sampling and tested at seven days. The average seven-day compressive strength of these field-cast cylinders was 4,630 psi. While this research project is less concerned with strength properties than with other durability-related properties, the research team believes that a minimum strength is necessary to meet the design intent. However, our experience is that almost all rigid pavement failures are a result of properties other than concrete strength.
- One maturity sensor was placed on October 27, 2005. In-place maturity values indicate that the slab had a compressive strength maturity equivalent of 3,690 psi at 4.25 days after placement. The maturity equivalent of 550 psi flexural strength was reached at approximately 2.5 days after placement. The flexural strength-maturity relationship was developed by the contractor, E & B Paving. An American Concrete Institute equation was used to estimate the compressive strength equivalent of 550 psi flexural strength (Raphael 1984). The equation used is MR = 2.3(f´c2/3).
- Dr. Vincent P. Drnevich, P.E., from Purdue University demonstrated a TDR device. The research team worked cooperatively with the Purdue representatives in an effort to further Dr. Drnevich’s use of the TDR to measure w/c ratio and estimate strength.

Table C.2 shows a summary of the weather conditions recorded by a portable weather station at the Mobile Concrete Research Lab location. Note that the weather station malfunctioned during the project and stopped recording data on October 30 at 8:15 a.m. Weather data was collected from 3:00 p.m. on October 26 through 8:15 a.m. on October 30.

Table C.2. Weather Conditions during the Indiana Shadow Project

Date	Min. temp. (˚F)	Max. temp. (˚F)	Min. rel. humidity (%)	Max. rel. humidity (%)	Min. dew point (˚F)	Max. dew point (˚F)	Max. wind speed (mph)	Total rainfall (in.)
10/26	47.9	56.2	42	69	32.9	38.2	5	
10/27	41.5	58.0	42	80	35.0	40.3	5	
10/28	36.6	57.6	39	81	31.3	37.6	7	
10/29	33.1	61.2	34	85	27.9	37.2	2	0.01
10/30	34.4	46.2	58	81	28.9	33.5	1	

Technology Transfer

The project team has had numerous interactions with individuals in Indiana during the Indiana shadow construction project. During field testing at the shadow project, INDOT and contractor representatives visited the Mobile Concrete Research Lab. Project data have been made available to stakeholders through reports, presentations, and the project website, http://www.cptechcenter.org/mco/.

Reference

Raphael, J.M. 1984. Tensile strength of concrete. *ACI Journal* 81.2: 158–165.

Iowa Field Report

Iowa Shadow Construction Project Information

- Project No. NHSX-34-9(123)--3H-29
- Contractor: Flynn Company, Inc.
- Iowa DOT District 5, Fairfield

Iowa Shadow Construction Project Location

The project was located on US Route 34 in Des Moines County, Iowa (see Figure C.3). The contractor prepared an area approximately 1/4 of a mile from the plant for the Mobile Concrete Research Lab. This location was adjacent to the project. Project and plant access for sampling and testing purposes was excellent. There was no delay in transporting AVA and microwave water-cement (w/c) ratio samples to the Mobile Concrete Research Lab.

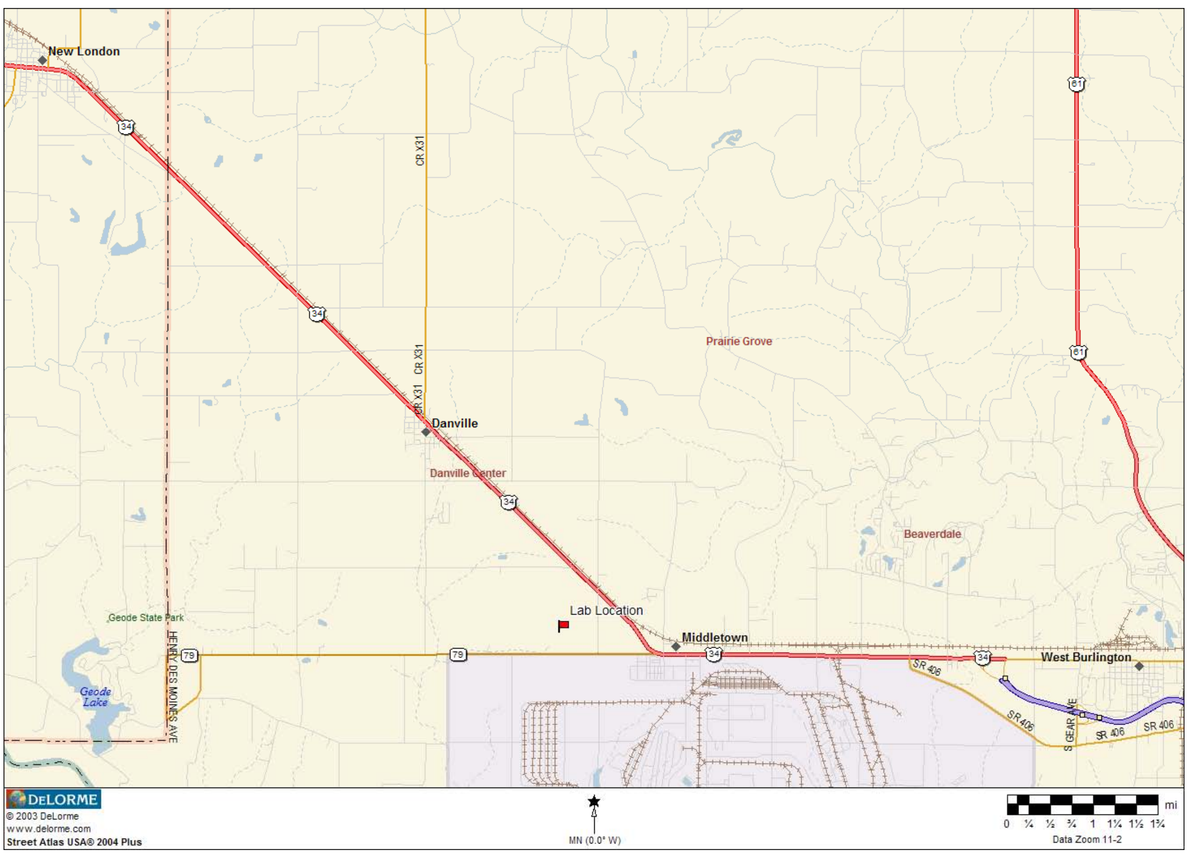

Figure C.3. Map of Iowa Shadow Project Location

Sampling and Testing Activities

The research team arrived to the site June 6, 2005, and began testing the project concrete on June 7. Fresh concrete testing was concluded on June 16. Cores of the pavement were obtained on June 15, prior to the research team's departure from the project. The following is a summary of samples and tests conducted during the demonstration:

- Slump, flow, unit weight, temperature, and air content of fresh concrete: 12 tests
- Unit weight and air content of concrete sampled behind the paver: 0 tests, because the team used contractor data
- Air void analysis: 11 sampling locations, 26 tests
- Microwave w/c ratio: 9 tests
- Wet-sieved concrete for combined gradation analysis: 1 sample
- Cast and test 4 in. x 8 in. cylinders for compressive strength maturity curve: 12 specimens
- Cast and test 4 in. x 8 in. cylinders for tensile strength maturity curve: 12 specimens
- Cast and test 4 in. x 8 in. cylinders for 7 day strength: 3 specimens
- Heat signature: 1 PCC test and 1 mortar test
- Heat generation (coffee cup test): 6 tests
- Initial set and final set: 1 test
- Modified false set: 2 tests
- Portland cement and fly ash samples obtained for material testing in Ames (XRD, XRF, DSC, and Blaine): 5 samples
- Obtained 4 inch pavement cores for testing in Ames (coefficient of thermal expansion [CTE], permeability, and hardened air): 12 cores
- Obtained bulk project materials to conduct lab mix design studies in Ames

Key Findings

- The results of the 26 AVA tests show consistent data for the specific surface. Spacing factor results are consistent as well. The average spacing factor for all tests is 0.0092 in.; this is within the suggested minimum and maximum limits of 0.0040 in. and 0.015 in. The average specific surface of 691 in.$^{-1}$ is within the suggested minimum and maximum limits of 400 in.$^{-1}$ and 1,100 in.$^{-1}$. No significant pattern is evident when comparing the on-vibrator samples to the between-vibrator samples.
- One objective of this research project is to evaluate the suggested criteria for AVA results. Our experience so far is that the AVA produces results that are more conservative that the hardened air properties obtained using the rapid air testing apparatus.
- Air content tested ahead of the paver during the demonstration ranged from 6.5% to 9.5%. The average air content of the 14 tests conducted was 8.0%.
- Air content was tested behind the paver by the contractor at three locations corresponding to locations ahead of the paver. The average air content behind the paver for these locations was 6.1%. The average air content loss from ahead of the paver to behind the paver was 2.6%. This air loss through the paver is slightly higher than results observed

from other states. However, the total air content behind the paver is higher than that of other projects tested.

- Vibrator frequencies were monitored continuously by the contractor using an auto-vibe system. The data file shows average vibrator frequencies of 6,645 vpm and 6,857 vpm, corresponding to the time/location of the workability documentation reports prepared by the research team on June 7, 2005 and June 10, 2005.
- Visual observations of the paving process revealed very good edges; the auto-float was able to fill in any voids in the surface and the finishers were not overworking the surface.
- The combined gradation of the mix was very consistent. The mix utilized an intermediate-sized aggregate. Coarseness factors ranged from 57 to 62 and workability factors ranged from 34 to 36. One wet-sieved sample was tested using a modified method of washing over the #16 sieve. The results of this test were 48/38 (coarseness/ workability). The research team is still trying to develop a modified wet sieve procedure that can be performed easily in the field as a spot check of stockpile and/or belt samples.
- Timing of the application of the curing compound was checked twice. The times were 18 min and 30 min behind the paver. These times are representative of the normal operations observed by the research team and are indicative of excellent curing operations.
- Compressive strength and tensile strength specimens were tested to develop a strength/maturity relationship curve. The average 7 day compressive strength of 4 x 8 inch cylinders was 3,740 psi. The average 7 day split tensile strength of these specimens was 315 psi. This research project is less concerned with strength properties than with other durability related properties. In the opinion of the research team, a minimum strength is necessary to meet the design intent. However, our experience is that almost all rigid pavement failures are a result of properties other than concrete strength.
- Two maturity sensors were placed from June 6 to June 10, 2005. In-place maturity values indicate that the slab had a compressive strength maturity equivalent of 2,500 psi at approximately 41 hours. The maturity equivalent of 300 psi tensile strength was reached at approximately 2.5 days (60 hrs) after placement. The difference between the two strength equivalents is a function of the mix design: admixtures, aggregate grading, aggregate particle shape, etc. It is always difficult to develop a correlation between tensile and compressive strength for a given mix with a limited number of specimens.
- A severe thunderstorm passed through the project on June 8, 2005 at approximately 12:30 p.m. The weather station at the Mobile Concrete Research Lab recorded the event. Graphs showing the weather conditions from 8:00 a.m. to 11:45 p.m. were plotted. Slab temperature, as recorded by the maturity sensor placed on June 7, 2005 at 10:20 a.m., was plotted with the weather data. The ambient temperature dropped 20.2 ˚F in 1 hour. The slab temperature dropped 9.0 ˚F in 1.5 hours. The HIPERPAV report for this period is also included in this report. Rainfall recorded was approximately 3/4 inches in 30 minutes, and the maximum wind gust was 52 mph. A brief summary of the weather conditions recorded by a portable weather station at the Mobile Concrete Research Lab location is shown in Table C.3.

Table C.3. Weather Data for the Iowa Shadow Project

Date	Min. Temp. (˚F)	Max. Temp. (˚F)	Min. Relative Humidity (%)	Max. Relative Humidity (%)	Min. Dew Point (˚F)	Max. Dew Point (˚F)	Max. Wind Speed (mph)	Total Rainfall (in.)
6/6	70.6	87.4	39	69	58.1	64.9	15	
6/7	67.9	89.7	43	79	43.0	79.0	15	
6/8	63.2	84.1	61	85	57.6	69.9	38	1.00
6/9	65.0	84.9	49	85	60.0	69.1	12	
6/10	67.1	85.1	52	86	61.9	71.4	33	0.02
6/11	65.3	85.7	54	88	61.5	70.5	18	0.01
6/12	66.0	84.9	56	88	59.8	69.1	20	0.01
6/13	68.9	82.4	56	85	62.5	68.2	17	
6/14	65.0	74.9	53	84	55.8	65.2	25	
6/15	61.8	76.3	55	78	54.9	59.5	20	
6/16	55.6	72.5	42	85	47.9	54.4	9	

Weather data is from 11:30 a.m. 6/6/2005 through 11:30 a.m. 6/16/2005

Technology Transfer

During field testing at the shadow project, 14 people visited the Mobile Concrete Research Lab from the Iowa DOT and the contractor. Project data have been made available to stakeholders through reports, presentations, and the project website, http://www.cptechcenter.org/mco/.

Kansas Field Report

Kansas Shadow Construction Project Information

- Project Nos. K-6391-01, K-4890-01 and K-4890-02
- Contractor: Clarkson Construction Company
- KDOT District 1, Topeka

Kansas Shadow Construction Project Location

The research site was an I-35 reconstruction and I-635/I-70 reconstruction project in Wyandotte County, Kansas (see Figure C.4). An area approximately 1/4 of a mile from the plant on the I-35 project was made available by the contractor for the Mobile Concrete Research Lab. This location was adjacent to the project. Project access and plant access for sampling and testing purposes was excellent.

Paving took place on five days while the Mobile Concrete Research Lab was onsite. Of those five days, the first four consisted of paving on the I-635 project and the last day was on the I-35 project. The travel time from the I-635 project back to the Mobile Concrete Research Lab was approximately 20 to 25 minutes. This distance between the Mobile Concrete Research Lab and the paving on the I-635 project presented issues in transporting concrete samples for maturity specimens, water-cement ratio (w/c) samples, and possibly AVA samples.

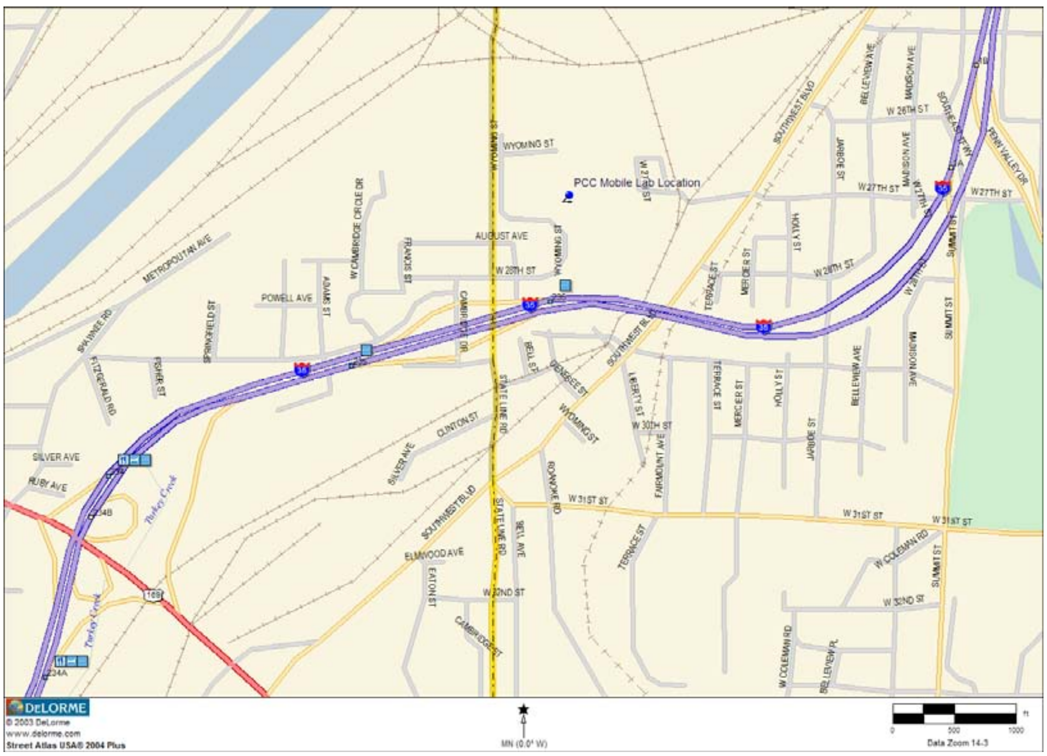

Figure C.4. Map of Kansas Shadow Project Site

Sampling and Testing Activities

The research team arrived onsite August 30, 2004, and began testing project concrete August 31. Fresh concrete testing was concluded on September 10. Cores of the pavement were obtained from the I-635 project on September 9 prior to the research team's departure from the project. The following is a summary of samples and tests conducted during the demonstration:

- Slump, unit weight, temperature, and air content of fresh concrete: 5 tests
- Unit weight and air content of concrete sampled behind the paver: 1 test (2 sampling locations; 1 test was discarded due to scale malfunction)
- Air void analysis: 5 sampling locations, 12 tests
- Microwave w/c ratio: 4 tests (3 tests from the I-635 project were delayed in testing due to transport issues)
- Heat signature: 1 PCC test and 1 mortar test (data corrupted during upload to Quadrel)
- Heat generation (coffee cup test): 5 tests
- Initial set and final set: 1 test
- Modified false set: 3 tests
- Portland cement and fly ash samples obtained for material testing in Ames (XRD, XRF, DSC, and Blaine): 5 samples
- Obtained 4 in. pavement cores for testing in Ames (coefficient of thermal expansion, permeability, and hardened air): 8 cores
- Obtained bulk project materials to conduct lab mix design studies in Ames

Key Findings

- The results of the 12 AVA tests show acceptable data for the specific surface, disregarding the one sample at 18+363, which appears to be an outlier. Spacing factor results are acceptable as well, if the outlier at 0+863 is disregarded. The average spacing factor for all tests is 0.0120 in. and 0.0109, if the apparent outlier at 0+863 is eliminated; both of these averages are within the suggested minimum and maximum limits of 0.0040 in. and 0.0150 in. The average specific surface for all tests is 584 in.$^{-1}$ and 532 in.$^{-1}$, if the apparent outlier at 18+363 is eliminated; both averages are within the suggested minimum and maximum limits of 400 in.$^{-1}$ and 1,100 in.$^{-1}$. No significant pattern is evident when comparing the on-vibrator samples to the between-vibrator samples.
- Air content tested ahead of the paver during the demonstration ranged from 4.9% to 7.0%; the average air content of the 5 tests conducted was 5.9%. The lowest air test of 4.9% was observed on September 10, 2004, within the first 90 minutes of paving on the I-35 project. The research team observed bleeding on the slab surface while taking fresh concrete samples. Pictures of the bleeding are shown in Figure C.5.

Figure C.5. Bleeding on the Slab Surface, Kansas Shadow Project

- Air content was tested behind the paver at two locations. However, the unit weight and air content test results behind the paver at the first sampling location indicate sampling or testing error. The second location tested had an air content ahead of the paver of 5.5% and 5.2% behind the paver; this indicates that the pavement was not being over-vibrated and that the entrained air was stable.
- Visual observations of the paving process revealed good edges, and the finishers were not overworking the surface. The edges did have consistent variation at the locations of the dowel baskets.
- The combined gradation of the mix was analyzed based on one set of test results provided by the contractor. The plot of the combined gradation on the 8-18 chart shows a minor spike of material retained on the #4 sieve. The workability factor of 47 indicates a sandy mix.
- A brief summary of the weather conditions recorded by a portable weather station at the Mobile Concrete Research Lab location is shown in Table C.4.

Table C.4. Weather Data for the Kansas Shadow Project

Date	Min. Temp. (˚F)	Max. Temp. (˚F)	Min. Relative Humidity (%)	Max. Relative Humidity (%)	Min. Dew Point (˚F)	Max. Dew Point (˚F)	Max. Wind Speed (mph)	Total Rainfall (in.)
8/30	65.0	83.4	48	79	56.9	64.6	8	
8/31	67.3	85.7	47	82	60.5	67.2	4	
9/1	68.3	86.5	37	73	56.4	65.2	4	
9/2	68.3	84.7	44	76	59.5	63.6	6	
9/3	67.1	85.7	42	73	57.8	65.3	7	
9/7	56.9	77.6	36	82	47.7	53.5	5	
9/8	55.7	76.8	40	76	48.0	54.0	4	
9/9	57.0	81.1	42	83	51.8	57.8	5	
9/10	63.9	78.6	47	71	53.2	58.1	6	

Weather data is from 7:15 a.m. 8/30/2004 through 10:30 a.m. 9/10/2004

Technology Transfer

During field testing at the shadow project, 54 people from the Kansas DOT and the contractor visited the Mobile Concrete Research Lab. Project data have been made available to stakeholders through reports, presentations, and the project website, http://www.cptechcenter.org/mco/.

Michigan Field Report

Michigan Shadow Construction Project Information

- Contractor: Ajax Paving Industries, Inc.
- MIDOT Metro Region

Michigan Shadow Construction Project Location

The research site consisted of two construction projects, located on I-94 and I-96 in Wayne County, Michigan (see Figure C.6). An area approximately 300 yards from the I-94 plant was utilized for the Mobile Concrete Research Lab. This location was approximately 3 miles from the I-94 project and approximately 12 miles from the I-96 project site. The contractor was alternately paving on both projects during the demonstration project testing. The distance to the I-96 project and urban traffic was problematic for AVA and water-cement ratio (w/c) testing. After this demonstration project, the research team has made an effort to avoid urban projects that potentially delay testing of the fresh concrete at the Mobile Concrete Research Lab.

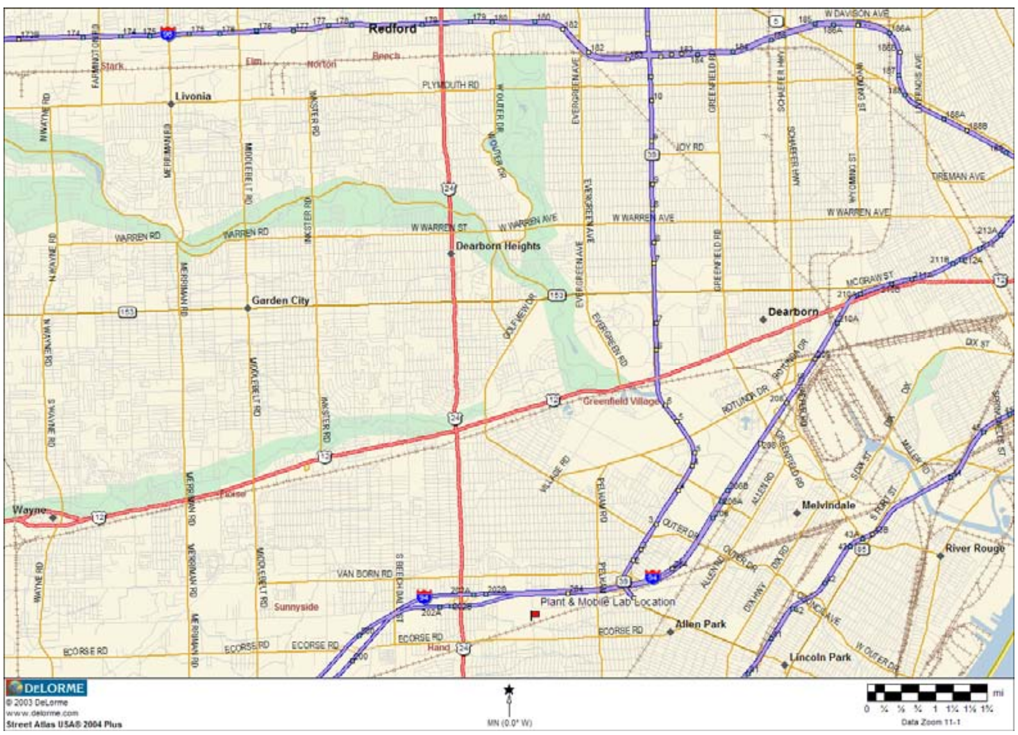

Figure C.6. Map of Michigan Shadow Project Site

Sampling and Testing Activities

The research team arrived onsite September 20, 2004 and began testing project concrete on September 21. Fresh concrete testing was concluded on September 29. Cores of the pavement were obtained on September 30 prior to the research team's departure from the project. The following is a summary of the samples and tests conducted during the demonstration:

- Slump, flow, unit weight, temperature and air content of fresh concrete: 7 tests
- Air content of concrete sampled behind the paver: 1 test
- Air void analysis: 5 sampling locations, 9 tests
- Microwave w/c ratio: 5 tests
- Cast and test 4 in. x 8 in. cylinders for compressive strength maturity curve: 12 specimens
- Cast and test 6 in. x 6 in. x 20 in. beams for flexural strength maturity curve: 12 specimens
- Cast and test 4 in. x 8 in. cylinders for 7 day strength: 3 specimens
- Heat generation (coffee cup test): 3 tests
- Initial set and final set: 2 tests
- Modified false set: 2 tests
- Portland cement and fly ash samples obtained for material testing in Ames (XRD, XRF, DSC, and Blaine): 6 samples
- Obtained 4 inch pavement cores for testing in Ames (coefficient of thermal expansion, permeability and hardened air): 6 cores
- Obtained bulk project materials to conduct lab mix design studies in Ames

Key Findings

- The results of the 9 AVA tests show consistent data for the specific surface. Spacing factor results are consistent as well. The average spacing factor for all tests is 0.0087 in.; this is within the suggested minimum and maximum limits of 0.0040 in. and 0.015 in. The average specific surface of 722 in.$^{-1}$ is within the suggested minimum and maximum limits of 400 in.$^{-1}$ and 1,100 in.$^{-1}$. When comparing the on-vibrator samples to the between-vibrator samples, there is no distinct pattern or significant difference between on-vibrator and off-vibrator tests.
- One objective of this research project is to evaluate the suggested criteria for AVA results. Our experience so far is that the AVA produces results that are more conservative than the hardened air properties obtained using the rapid air testing apparatus.
- Air content tested ahead of the paver during the demonstration ranged from 4.5% to 7.0%; the average air content of the seven tests conducted was 5.7%.
- Air content was tested behind the paver at one location corresponding to the location ahead of the paver: 6.5% ahead and 6.0% behind. The air content loss from ahead of the paver to behind the paver was 0.5% at this location; this is the lowest air loss observed to date.
- Visual observations of the paving process revealed good edges and moderate slurry/grout on the surface.
- Four different mix designs were utilized on the two projects. Two of the mixes had an intermediate-sized aggregate. Coarseness factors for the three-aggregate mix used on I-94 ranged from 67 to 68, and workability factors ranged from 35 to 36.

- One fresh sample of concrete was wet-sieved, dried, and graded; the coarseness factor for this sample was 68 and the workability factor was 32.
- Compressive strength and flexural strength specimens were tested to develop a strength/maturity relationship curve. The average two-day compressive strength of 4 x 8 inch cylinders was 2,550 psi. A set of three cylinders was also cast in the field on September 23, 2004; the average seven-day compressive strength of these specimens was 4,130 psi.
- The average two-day flexural strength of the maturity specimens was 520 psi.
- This research project is less concerned with strength properties than with other durability related properties. In the opinion of the research team, a minimum strength is necessary to meet the design intent. However, our experience is that almost all rigid pavement failures are a result of properties other than concrete strength.
- One maturity sensor was placed (September 23, 2004). Unfortunately, the sensor was damaged during construction before any data could be downloaded from it.
- A brief summary of the weather conditions recorded by a portable weather station at the Mobile Concrete Research Lab location is shown in Table C.5.

Table C.5. Weather Data for the Michigan Shadow Project

Date	Min. Temp. (˚F)	Max. Temp. (˚F)	Min. Relative Humidity (%)	Max. Relative Humidity (%)	Min. Dew Point (˚F)	Max. Dew Point (˚F)	Max. Wind Speed (mph)	Total Rainfall (in.)
9/22	52.3	86.5	27	85	45.2	54.4	7	
9/23	55.0	82.6	36	85	49.7	60.9	8	
9/24	59.6	80.9	44	84	53.8	61.5	6	
9/25	60.9	69.1	53	74	47.8	58.2	8	
9/26	54.4	74.7	27	76	36.2	53.5	6	
9/27	48.5	76.1	39	82	42.6	52.3	6	
9/28	52.2	65.6	53	84	42.1	54.3	16	
9/29	51.0	64.8	44	75	40.3	44.5	12	
9/30	43.3	52.0	71	84	38.2	43.5	2	

Weather data is from 12:00.m. 9/22/2004 through 9:15 a.m. 9/30/2004

Technology Transfer

During field testing at the shadow project, 81 visitors from the Michigan DOT and the contractor visited the Mobile Concrete Research Lab. Project data have been made available to stakeholders through reports, presentations, and the project website, http://www.cptechcenter.org/mco/.

Additionally, this demonstration project was scheduled to coincide with the Technical Advisory Committee meeting. This provided an excellent opportunity for technology transfer.

Minnesota Field Report

Minnesota Shadow Construction Project Information

- Project No. S.P. 8103-47 TH14
- Contractor: Shafer Contracting Co., Inc.
- MNDOT District 7, Mankato

Minnesota Shadow Construction Project Location

The construction project was located on Trunk Highway 14 in Waseca County, Minnesota (see Figure C.7). An area approximately 200 yards from the plant and adjacent to the project was reserved for the Mobile Concrete Research Lab. Project and plant access for sampling and testing purposes was excellent. There was no delay in transporting AVA and microwave water-cement ratio (w/c) samples to the Mobile Concrete Research Lab.

Figure C.7. Map of Minnesota Shadow Project Site

Sampling and Testing Activities

The research team arrived onsite August 29, 2005, and began testing project concrete August 29. Fresh concrete testing was concluded on September 6 due to rain. Cores of the pavement were obtained on September 8 prior to the research team's departure from the project. The following is a summary of the samples taken and tests conducted during the demonstration:

- Slump, flow, unit weight, temperature and air content of fresh concrete: 11 tests
- Air content of concrete sampled behind the paver: 1 test
- Air void analysis: 10 sampling locations, 25 tests
- Microwave w/c ratio: 10 tests
- Cast and test 4 in. x 8 in. cylinders for compressive strength maturity curve: 12 specimens
- Cast and test 6 in. x 6 in. x 20 in. beams for flexural strength maturity curve: 12 specimens
- Cast and test 4 in. x 8 in. cylinders for 7 day strength: 3 specimens
- Heat signature: 1 PCC test and 1 mortar test
- Heat generation (coffee cup test): 9 tests
- Initial set and final set: 1 test
- Modified false set: 2 tests
- Portland cement and fly ash samples obtained for material testing in Ames (XRD, XRF, DSC, and Blaine): 5 samples
- Obtained 4 inch pavement cores for testing in Ames (coefficient of thermal expansion, permeability, and hardened air): 6 cores
- Obtained bulk project materials to conduct lab mix design studies in Ames

Key Findings

- The results of the 25 AVA tests show very consistent data for the specific surface. Spacing factor results are very consistent as well. The average spacing factor for all tests is 0.0092 in.; this is within the suggested minimum and maximum limits of 0.0040 in. and 0.015 in. The average specific surface of 642 in.$^{-1}$ is within the suggested minimum and maximum limits of 400 in.$^{-1}$ and 1,100 in.$^{-1}$. When comparing the on-vibrator samples to the between-vibrator samples, the spacing factor is lower and the specific surface is higher for on-vibrator samples for 7 of the 8 test locations. This is the only field demonstration out of the 11 performed to date that exhibited a distinct pattern between on-vibrator and between vibrator samples.
- One objective of this research project is to evaluate the suggested criteria for AVA results. Our experience so far is that the AVA produces results that are more conservative than hardened air properties obtained using the rapid air testing apparatus.
- Air content tested ahead of the paver during the demonstration ranged from 6.5% to 8.5%; the average air content of the 11 tests conducted was 7.2%.
- Air content was tested behind the paver at one location corresponding to the location ahead of the paver. This test was conducted by the contractor. The air content loss from ahead of the paver to behind the paver was 2.0% at this location.
- Vibrator frequencies were monitored continuously by the contractor using an auto-vibe system (see Table C.6). These monitors were observed and recorded three times by the research team during sampling activities. These are the lowest vibrator frequencies that have been observed to date and the fastest paver speeds observed to date. The paver speed is at least partially attributable to the slab thickness of 8.5 inches, and the relatively low vibrator frequency is most likely due to the dense graded mixture.

Table C.6. Vibrator Frequencies during Paving on the Minnesota Shadow Project

Date	Station	Vibrator frequency (vpm)	Paver speed (fpm)
8-30-2005	414+60	6,200	11.5
8-31-2005	Southbound Main St. in Janesville	6,000	6.6
9-06-2005	311+75	5,750	11.5

- Visual observations of the paving process revealed good edges and minimal slurry/grout on the surface.
- The mix utilized an intermediate-sized aggregate and two coarse aggregates. Coarseness factors ranged from 60 to 67, and workability factors ranged from 37 to 41
- Timing of the application of curing compound was checked three times, at 15 min., 30 min., and 45 min. behind the paver. These times represent the normal operations observed by the research team and are indicative of acceptable curing operations.
- Compressive strength and flexural strength specimens were tested to develop a strength/maturity relationship curve. The average seven-day compressive strength of 4 x 8 inch cylinders was 4,470 psi. A set of three cylinders was also cast in the field on August 31, 2005; the average seven-day compressive strength of these specimens was 4,140 psi.
- The average seven-day flexural strength of the maturity specimens was 540 psi.
- This research project is concerned less with strength properties than with other durability related properties. In the opinion of the research team, a minimum strength is necessary to meet the design intent. However, our experience is that almost all rigid pavement failures are a result of properties other than concrete strength.
- Two maturity sensors were placed (August 29 and 30, 2005). In-place maturity values indicate that the slab reached the maturity equivalent of 500 psi flexural strength at approximately two days.
- A brief summary of the weather conditions recorded by a portable weather station at the Mobile Concrete Research Lab location is shown in Table C.7.

Table C.7. Weather Data for the Minnesota Shadow Project

Date	Min. Temp. (˚F)	Max. Temp. (˚F)	Min. Relative Humidity (%)	Max. Relative Humidity (%)	Min. Dew Point (˚F)	Max. Dew Point (˚F)	Max. Wind Speed (mph)	Total Rainfall (in.)
8/29	62.9	78.3	49	79	55.9	61.7	8	
8/30	56.5	76.7	52	85	51.6	59.6	7	
8/31	56.0	74.6	59	85	49.8	62.7	15	
9/1	49.5	80.1	31	83	44.0	53.1	21	
9/2	48.9	75.8	35	81	43.1	53.0	10	
9/3	52.9	78.1	51	80	45.9	61.7	20	
9/4	62.6	85.3	53	85	56.4	68.5	20	0.70
9/5	65.0	85.7	46	85	58.5	66.4	16	
9/6	63.5	82.8	56	87	58.3	67.4	14	0.18
9/7	57.2	70.6	67	86	52.7	65.9	17	0.45
9/8	56.3	70.6	68	87	51.5	59.5	15	0.18

Weather data is from 10:15 a.m. 8/29/2005 through 2:15 p.m. 9/8/2005

Technology Transfer

During field testing at the shadow project, 17 visitors from Mn/DOT and the contractor visited the Mobile Concrete Research Lab. Project data have been made available to stakeholders through reports, presentations, and the project website, http://www.cptechcenter.org/mco/.

Missouri Field Report

Missouri Shadow Construction Project Information

- Project No.: J3P0422, FAF-61-4(113)
- Contractor: Fred Carlson Company, Inc.
- MODOT Northeast District 3, Hannibal

Missouri Shadow Construction Project Location

The construction project was located on Rte. 27, Avenue of The Saints, in Clark County, Missouri (see Figure C.8). An area approximately 200 yards from the plant was reserved for the Mobile Concrete Research Lab. This location was adjacent to the project (see Figure C.9), and project and plant access for sampling and testing purposes was excellent. There was no delay in transporting air void analyzer and microwave water-cement ratio (w/c) samples to the Mobile Concrete Research Lab.

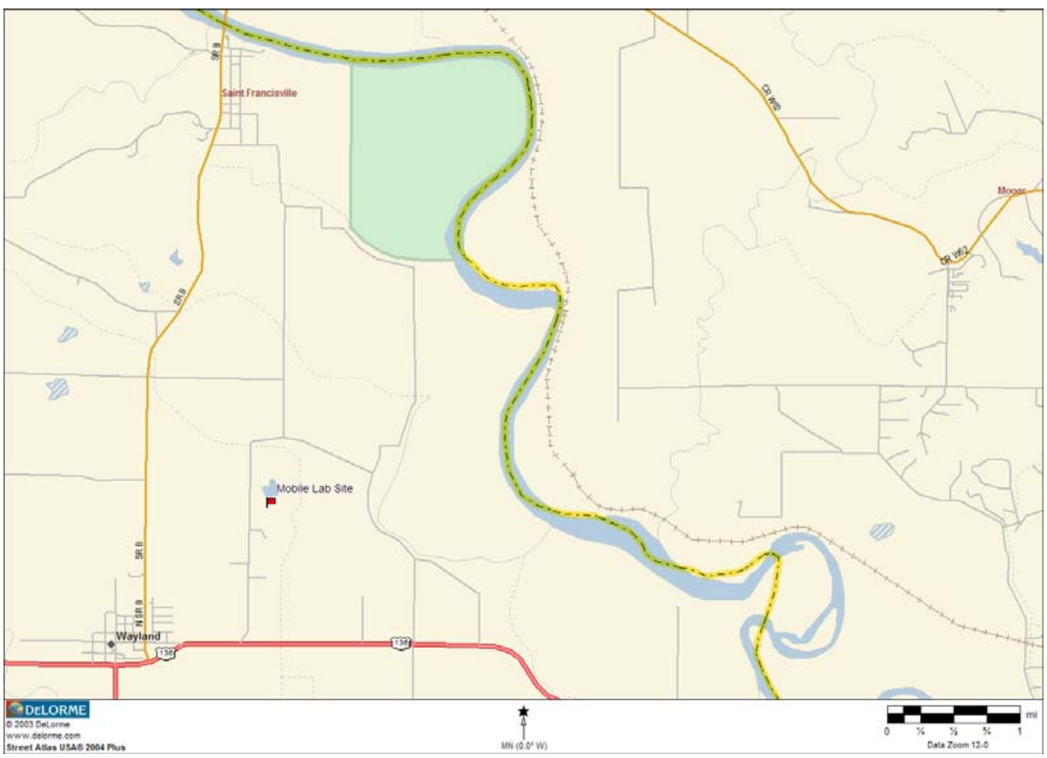

Figure C.8. Map of Missouri Shadow Project Site

Figure C.9. Missouri Shadow Project Location

Sampling and Testing Activities

The research team arrived onsite August 2, 2004, and began testing project concrete on August 3. Fresh concrete testing was concluded on August 12. Cores of the pavement were obtained on August 12 prior to the research team's departure from the project. The following is a summary of samples and tests conducted during the demonstration:

- Unit weight of fresh concrete: 7 tests
- Air content of fresh concrete: 5 tests
- Microwave w/c ratio: 1 test (0.41)
- Unit weight and air content of concrete sampled behind the paver: 1 test
- Air void analysis: 6 sampling locations, 13 tests
- Cast and test 4 in. x 8 in. cylinders for compressive strength maturity curve: 12 specimens
- Cast and test 6 in. x 6 in. x 20 in. beams for flexural strength maturity curve: 12 specimens (test data invalid)
- Heat signature: 1 PCC test
- Heat generation (coffee cup test): 5 tests
- Initial set and final set: 2 tests
- Portland cement and fly ash samples obtained for material testing in Ames (XRD, XRF, DSC, and Blaine): 7 samples
- Obtained 4 inch pavement cores for testing in Ames (coefficient of thermal expansion, permeability, and hardened air): 6 cores
- Obtained bulk project materials to conduct lab mix design studies in Ames

Key Findings

- The results of the 13 AVA tests show good results for specific surface. Spacing factor results are acceptable as well. The average spacing factor for all tests is 0.0090 inches;

this is within the suggested minimum and maximum limits of 0.0040 and 0.015 inches. The average specific surface of 613 in.$^{-1}$ is within the suggested minimum and maximum limits of 400 in.$^{-1}$ and 1,100 in.$^{-1}$. The spacing factor of the between-vibrator samples is marginally higher than the on-vibrator samples for 5 of the 6 paired sample locations.

- Air content tested ahead of the paver during the demonstration ranged from 6.0% to 10.0%; the average air content of the 5 tests conducted was 7.5%.
- Air content was tested behind the paver in one location with a result of 8.0%.
- Visual observations of the paving process revealed good edges and moderate slurry/grout on the surface.
- The mix utilized an intermediate-sized aggregate. Coarseness factors ranged from 68 to 72, and workability factors ranged from 35 to 38.
- Compressive strength and flexural strength specimens were tested to develop a strength/maturity relationship curve. The average three-day compressive strength of 4 x 8 inch cylinders was 3,040 psi. The flexural strength test results are not reported due to a testing error associated with the loading rate applied during testing.
- A brief summary of the weather conditions recorded by a portable weather station at the Mobile Concrete Research Lab location is shown in Table C.8.

Table C.8. Weather Conditions on the Missouri Shadow Project

Date	Min. Temp. (˚F)	Max. Temp. (˚F)	Min. Relative Humidity (%)	Max. Relative Humidity (%)	Min. Dew Point (˚F)	Max. Dew Point (˚F)	Max. Wind Speed (mph)	Total Rainfall (in.)
8/02	72.8	88.0	48	86	65.5	71.5	10	
8/03	68.4	94.3	57	90	65.0	78.0	11	0.03
8/04	68.4	80.1	62	90	56.5	75.2	19	1.15
8/05	60.9	76.0	46	82	51.9	59.0	12	
8/06	52.2	77.4	41	86	48.1	58.8	5	
8/09	63.9	87.4	45	89	59.2	70.0	11	
8/10	57.5	72.1	54	85	51.6	58.7	11	
8/11	53.3	67.4	45	87	42.3	52.0	14	
8/12	50.8	56.0	79	84	46.0	49.8	3	

Weather data is from 3:15 p.m. 8/02/2004 through 7:45 a.m. 8/12/2004

Technology Transfer

During field testing at the shadow project, 25 visitors from the Missouri DOT and the contractor visited the Mobile Concrete Research Lab. Project data have been made available to stakeholders through reports, presentations, and the project website, http://www.cptechcenter.org/mco/.

North Carolina Field Report

North Carolina Shadow Construction Project Information

- Contractor: McCarthy Improvement Company
- NCDOT Division 5

North Carolina Shadow Construction Project Location

The two construction projects studied were located on US 64 and I-85 in Wake County, North Carolina (see Figure C.10). Testing was performed for two days on the I-85 project and for three days on the US 64 project. The Mobile Concrete Research Lab was located adjacent to or on both projects sites. Both lab locations were suitable and allowed for timely testing of the fresh concrete and easy transport of AVA and microwave water-cement ratio (w/c) samples.

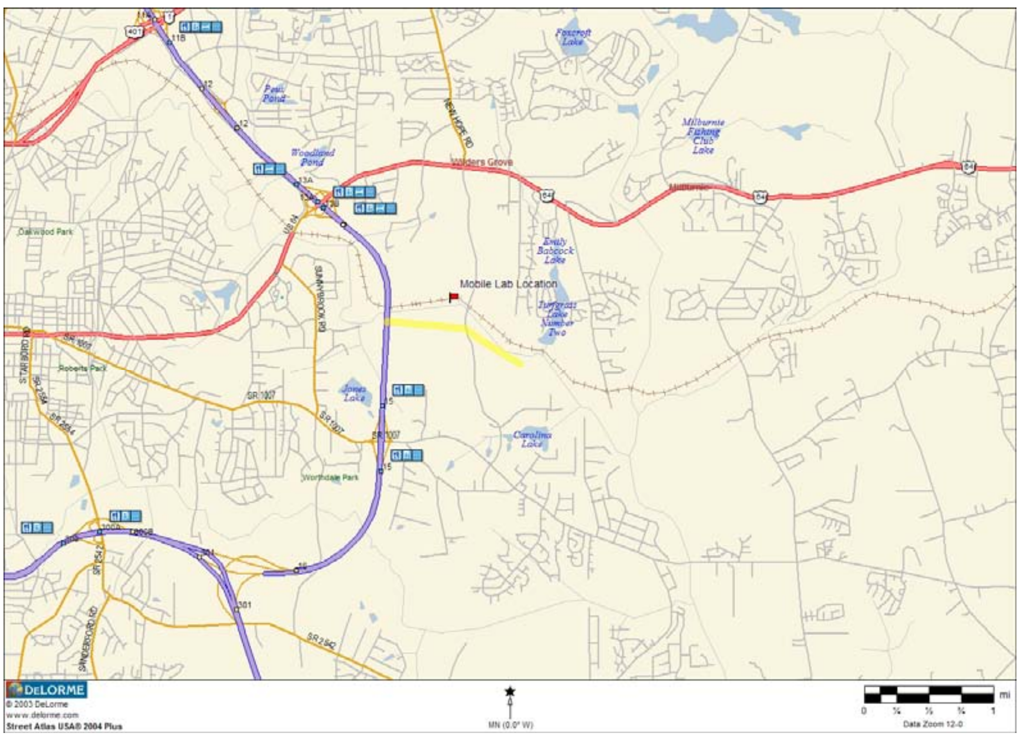

Figure C.10. Map of the North Carolina Shadow Project Site

Sampling and Testing Activities

The research team arrived onsite November 8, 2004 and began testing project concrete November 9. Fresh concrete testing was concluded on November 17. Cores of the pavement were obtained on November 18 prior to the research team's departure from the project. The following is a summary of the samples taken and tests conducted during the demonstration:

- Slump, flow, unit weight, temperature and air content of fresh concrete: 7 tests
- Air content of concrete sampled behind the paver: 1 test
- Air void analysis: 5 sampling locations, 12 tests
- Microwave w/c ratio: 7 tests
- Cast and test 6 in. x 6 in. x 20 in. beams for flexural strength maturity curve: 12 specimens
- Heat generation (coffee cup test): 1 test
- Portland cement and fly ash samples obtained for material testing in Ames (XRD, XRF, DSC, and Blaine): 3 samples
- Obtained 4 inch pavement cores for testing in Ames (coefficient of thermal expansion, permeability, and hardened air): 4 cores
- Obtained bulk project materials to conduct lab mix design studies in Ames

Key Findings

- The results of the 12 AVA tests show consistent data for the specific surface. Spacing factor results are consistent as well. The average spacing factor for all tests is 0.0086 in.; this is within the suggested minimum and maximum limits of 0.0040 in. and 0.015 in. The average specific surface of 917 $in.^{-1}$ is within the suggested minimum and maximum limits of 400 $in.^{-1}$ and 1,100 $in.^{-1}$. When comparing the on-vibrator samples to the between-vibrator samples, there is no distinct pattern or significant difference between on-vibrator and off-vibrator tests.
- One objective of this research project is to evaluate the suggested criteria for AVA results. Our experience so far is that the AVA produces results that are more conservative than hardened air properties obtained using the rapid air testing apparatus.
- Air content tested ahead of the paver during the demonstration ranged from 4.4% to 5.4%; the average air content of the 7 tests conducted was 4.8%.
- Air content was tested behind the paver at one location (4.5%) corresponding to the location ahead of the paver (3.6%). The air content loss from ahead of the paver to behind the paver was 0.9% at this location. This is lower air content and lower air loss through the paver than has been observed on other demonstration projects.
- Visual observations of the paving process revealed good edges and moderate slurry/grout on the surface.
- The mix designs used on both projects consisted of one coarse and one fine aggregate. Both mixes appeared to be gap-graded. Subsequent gradations on mix design materials show a coarseness factor of 95.3 and a workability factor of 34.4. The combination of a fine sand with a gap-graded coarse aggregate (13% passing 1/2-inch sieve) can contribute to poor workability.
- Flexural strength specimens were tested to develop a strength/maturity relationship curve. The average four-day flexural strength of the maturity specimens was 505 psi.
- This research project is concerned less with strength properties than with other durability related properties. In the opinion of the research team, a minimum strength is necessary to meet the design intent. However, our experience is that almost all rigid pavement failures are a result of properties other than concrete strength.

- One maturity sensor was placed on November 11, 2004. The in-place estimated strength at 72 hours was 435 psi.
- A brief summary of the weather conditions recorded by a portable weather station at the PCC mobile lab location is shown in Table C.9.

Table C.9. Weather Data for the North Carolina Shadow Project

Date	Min. Temp. (˚F)	Max. Temp. (˚F)	Min. Relative Humidity (%)	Max. Relative Humidity (%)	Min. Dew Point (˚F)	Max. Dew Point (˚F)	Max. Wind Speed (mph)	Total Rainfall (in.)
11/11	44.5	64.3	34	87	34.6	50.6	4	0.05
11/12	49.4	63.4	83	89	45.1	59.8	8	1.26
11/13	39.3	55.3	45	84	21.7	44.3	10	
11/14	29.5	52.3	27	83	17.1	28.3	7	
11/15	27.3	61.0	26	85	23.1	35.9	5	
11/16	32.4	59.3	36	86	28.4	41.8	2	
11/17	35.0	66.4	30	87	31.1	41.0	4	
11/18	41.5	53.5	66	86	37.6	45.7	2	

Weather data is from 8:15 a.m. 11/11/2004 through 9:00 a.m. 11/18/2004

Technology Transfer

During field testing at the shadow project, 33 visitors from the North Carolina DOT and the contractor visited the Mobile Concrete Research Lab. Project data have been made available to stakeholders through reports, presentations, and the project website, http://www.cptechcenter.org/mco/.

North Dakota Field Report

North Dakota Shadow Construction Project Information

- Project No. IM-1-094(071)137
- Contractor: Northern Improvement Co.
- NDDOT District 1, Bismarck

North Dakota Shadow Construction Project Location

The construction project was located on I-94 in Morton County, North Dakota (see Figure C.11). An area approximately 200 yards from the plant and adjacent to the project was reserved for the Mobile Concrete Research Lab. Project and plant access for sampling and testing purposes was excellent. There was no delay in transporting AVA and microwave water-cement ratio (w/c) samples to the Mobile Concrete Research Lab.

Figure C.11. Map of North Dakota Shadow Project Site

Sampling and Testing Activities

The research team arrived onsite June 20, 2005 and began testing project concrete June 21. Fresh concrete testing was concluded on June 28. Cores of the pavement were obtained on June 24 prior to the research team's departure from the project. The following is a summary of samples and tests conducted during the demonstration:

- Slump, flow, unit weight, temperature, and air content of fresh concrete: 11 tests
- Unit weight and air content of concrete sampled behind the paver: 1 test
- Air void analysis: 11 sampling locations, 24 tests
- Microwave w/c ratio: 10 tests
- Cast and test 4 in. x 8 in. cylinders for compressive strength maturity curve: 12 specimens
- Cast and test 6 in. x 6 in. x 20 in. beams for flexural strength maturity curve: 12 specimens
- Cast and test 4 in. x 8 in. cylinders for 7 day strength: 3 specimens
- Heat signature: 1 PCC test and 1 mortar test
- Heat generation (coffee cup test): 6 tests
- Initial set and final set: 1 test
- Modified false set: 1 test
- Portland cement and fly ash samples obtained for material testing in Ames (XRD, XRF, DSC, and Blaine): 5 samples
- Obtained 4 inch pavement cores for testing in Ames (coefficient of thermal expansion, permeability, and hardened air): 5 cores
- Obtained bulk project materials to conduct lab mix design studies in Ames

Key Findings

- The results of the 24 AVA tests show consistent results for the specific surface. Spacing factor results are consistent as well. The average spacing factor for all tests is 0.0099 in.; this is within the suggested minimum and maximum limits of 0.0040 in. and 0.015 in. The average specific surface of 680 in.$^{-1}$ is within the suggested minimum and maximum limits of 400 in.$^{-1}$ and 1,100 in.$^{-1}$. No significant pattern is evident when comparing the on-vibrator samples to the between-vibrator samples.
- One objective of this research project is to evaluate the suggested criteria for AVA results. Our experience so far is that the AVA produces results that are more conservative than the hardened air properties obtained using the rapid air testing apparatus.
- Four AVA tests were invalid and not included with the data. These samples could not be broken up in the test apparatus. This has been observed before, but not to this degree. One explanation may be the dense gradation of the mix and mortar. The dense-graded mix also affected the sampling behind the paver. More force than usual was required to obtain a mortar sample. This caused edge deformation and caused the research team to sample further from the edge.
- Air content tested ahead of the paver during the demonstration ranged from 6.5% to 11.3%; the average air content of the 11 tests conducted was 8.1%.
- Air content was tested behind the paver at two locations corresponding to the location ahead of the paver (see Table C.10). One of these tests was conducted by NDDOT (4.9%) and the other by Mobile Concrete Research Lab staff (8.0%). The average air content loss from ahead of the paver to behind the paver was 2.5%.

Table C.10. Air Content Data behind the Paver, North Dakota Shadow Project

Sample date/location/lab	Air ahead of the paver (%)	Air behind the paver (%)	Air loss through the paver (%)
6-21-05/928+75/NDDOT	6.6	4.9	1.7
6-28-05/850+00/ISU	11.3	8	3.3

- Vibrator frequencies were monitored continuously by the contractor using an auto-vibe system. These monitors were observed by the research team during sampling activities to be in the 7,000 (±500) vpm range.
- Visual observations of the paving process revealed good edges and minimal slurry/grout on the surface.
- The mix utilized an intermediate-sized aggregate. Coarseness factors ranged from 51 to 66 and workability factors ranged from 32 to 33.
- The timing of the application of curing compound was checked twice during paving, at 30 min. and 35 min. behind the paver. These times represent the normal operations observed by the research team and indicate good curing operations.
- Compressive strength and flexural strength specimens were tested to develop a strength/maturity relationship curve. The average six-day compressive strength of 4 x 8 inch cylinders was 2,630 psi. A set of three cylinders was also cast in the field on June 21, 2005. The average seven-day compressive strength of these specimens was 3,180 psi.
- The average five-day flexural strength of the maturity specimens was 445 psi.
- This research project is concerned less with strength properties than with other durability related properties. In the opinion of the research team, a minimum strength is necessary to meet the design intent. However, our experience is that almost all rigid pavement failures are a result of properties other than concrete strength.
- Two maturity sensors were placed (June 21 and 23, 2005). In-place maturity values indicate that the slab reached the maturity equivalent of 450 psi flexural strength at approximately six days.
- A brief summary of the weather conditions recorded by a portable weather station at the Mobile Concrete Research Lab location is shown in Table C.11.

Table C.11. Weather Data for the North Dakota Shadow Project

Date	Min. Temp. (˚F)	Max. Temp. (˚F)	Min. Relative Humidity (%)	Max. Relative Humidity (%)	Min. Dew Point (˚F)	Max. Dew Point (˚F)	Max. Wind Speed (mph)	Total Rainfall (in.)
6/20	63.2	84.5	41	75	54.1	63.6	11	0.03
6/21	62.3	81.4	57	83	54.6	67.2	24	0.07
6/22	65.5	89.7	55	84	59.5	74.3	18	
6/23	64.8	87.8	39	90	49.4	73.7	28	0.01
6/24	51.6	75.4	26	79	34.5	49.6	13	
6/25	57.3	79.8	40	76	44.1	63.0	22	
6/26	59.8	83.0	54	88	55.9	68.3	28	2.02
6/27	57.3	75.3	52	86	53.1	60.2	13	
6/28	57.6	73.7	59	85	52.8	60.4	18	

Weather data is from 8:30 a.m. 6/20/2005 through 3:45 p.m. 6/28/2005

Technology Transfer

During field testing at the shadow project, 25 visitors from the North Dakota DOT and the contractor visited the Mobile Concrete Research Lab. Project data have been made available to stakeholders through reports, presentations, and the project website, http://www.cptechcenter.org/mco/.

Ohio Field Report

Ohio Shadow Construction Project Information

- Project No. 7(20053), PID No. 25523
- Contractor: Kokosing Construction Co., Inc.
- OHDOT District 8

Ohio Shadow Construction Project Location

The research site was an I-275 widening project, SR-125 to five-mile road, in Clermont County, Ohio (see Figure C.12). An area approximately 300 feet from the plant was prepared by the contractor for the Mobile Concrete Research Lab. This location was adjacent to the project. Project and plant access for sampling and testing purposes was excellent. There was no delay in transporting AVA and microwave water-cement ratio (w/c) samples to the Mobile Concrete Research Lab.

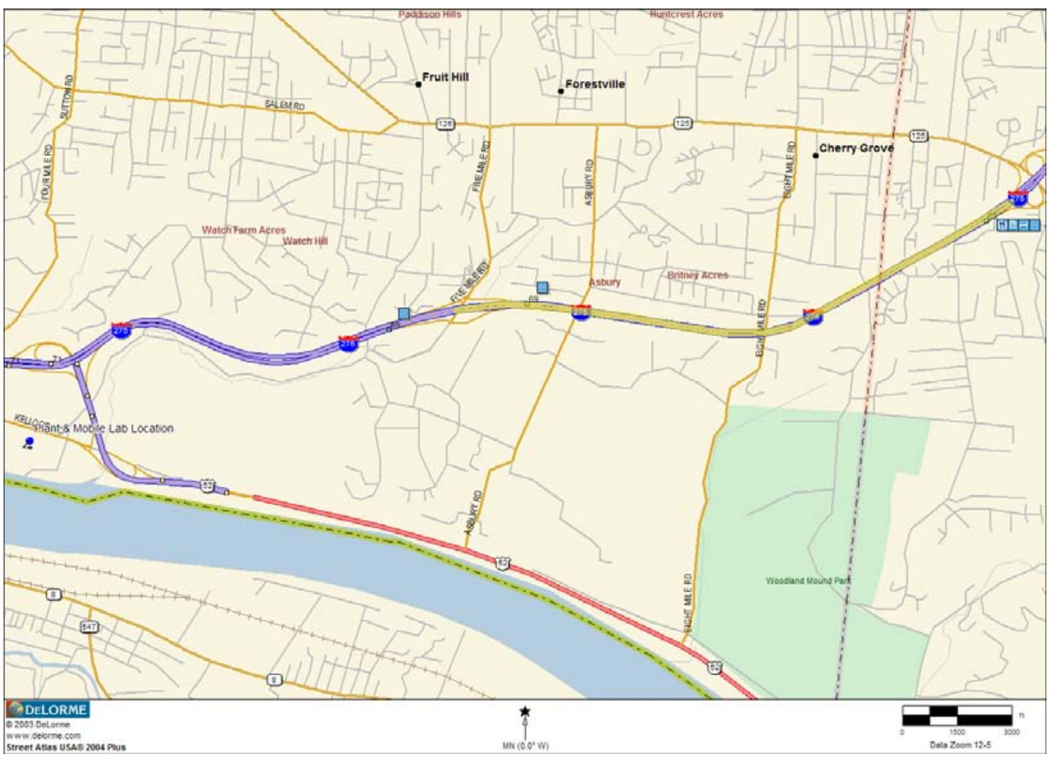

Figure C.12. Map of the Ohio Shadow Project Site

Sampling and Testing Activities

The research team arrived onsite October 17, 2005, and began testing project concrete on October 17. Fresh concrete testing was concluded on October 19. Adverse weather prevented paving and testing from October 20 through October 25. The research team left the project on

October 26 due to a previously scheduled demonstration project in Indiana. Cores of the pavement were obtained on October 25 prior to the research team's departure from the project. The following is a summary of the samples taken and tests conducted during the demonstration:

- Slump, flow, unit weight, temperature, and air content of fresh concrete: 7 tests
- Air void analysis: 5 sampling locations, 12 tests
- Microwave w/c ratio: 7 tests
- Cast and test 4 in. x 8 in. cylinders for compressive strength maturity curve: 12 specimens
- Cast and test 4 in. x 8 in. cylinders for 7 day strength: 3 specimens
- Heat signature: 1 PCC test and 1 mortar test
- Heat generation (coffee cup test): 2 tests
- Initial set and final set: 1 test
- Portland cement and fly ash samples obtained for material testing in Ames (XRD, XRF, DS, and Blaine): 5 samples
- Obtained 4 inch pavement cores for testing in Ames (coefficient of thermal expansion, permeability, and hardened air): 5 cores
- Obtained bulk project materials to conduct lab mix design studies in Ames

Key Findings

- The results of the 12 AVA tests show slightly variable data for the specific surface. Spacing factor results are variable as well. The average spacing factor for all tests is 0.0088 in.; this is within the suggested minimum and maximum limits of 0.0040 in. and 0.015 in. The average specific surface of 791 in.$^{-1}$ is within the suggested minimum and maximum limits of 400 in.$^{-1}$ and 1,100 in.$^{-1}$. No significant pattern is evident when comparing the on-vibrator samples to the between-vibrator samples.
- One objective of this research project is to evaluate the suggested criteria for AVA results. Our experience so far is that the AVA produces results that are more conservative than hardened air properties obtained using the rapid air testing apparatus.
- Air content tested ahead of the paver during the demonstration ranged from 4.8% to 7.5%; the average air content of the 7 tests conducted was 5.9%.
- Vibrator frequencies were monitored by the contractor. The research team made one observation of vibrator frequency and paver speed on October 19. The approximate average vibrator frequency was 9,400 vpm and the paver speed was approximately 5.8 fpm.
- Visual observations of the paving process revealed very good edges and surface. The finishers were not observed overworking the surface.
- The combined gradation of the mix was evaluated based on the materials gathered for a lab mix design. The coarseness factor was 78 and the workability factor was 34. The combined gradation of the mix is gap-graded from the 3/8-inch sieve to the #50 sieve.
- Timing of the application of curing compound was observed throughout the demonstration. The curing compound was applied approximately 30 to 45 minutes after the concrete placement. Whenever possible, curing compound should be placed within 30 minutes after concrete placement.

- Compressive strength specimens were tested to develop a strength-maturity relationship curve. Additionally, one set of three 4 in. x 8 in. cylinders was cast during field sampling and tested at seven days. The average seven-day compressive strength of these field cast cylinders was 4,360 psi. This research project is concerned less with strength properties than with other durability related properties. In the opinion of the research team, a minimum strength is necessary to meet the design intent. However, our experience is that almost all rigid pavement failures are a result of properties other than concrete strength.
- One maturity sensor was placed on October 17; in-place maturity values indicate that the slab had a compressive strength maturity equivalent of 3,750 psi in eight days.
- A brief summary of the weather conditions recorded by a portable weather station at the Mobile Concrete Research Lab location is shown in Table C.12.

Table C.12. Weather Data for the Ohio Shadow Project

Date	Min. Temp. (˚F)	Max. Temp. (˚F)	Min. Relative Humidity (%)	Max. Relative Humidity (%)	Min. Dew Point (˚F)	Max. Dew Point (˚F)	Max. Wind Speed (mph)	Total Rainfall (in.)
10/17	55.1	72.3	34	69	40.8	47.2	3	
10/18	48.6	77.4	28	79	40.4	51.8	1	
10/19	46.2	84.0	47	87	41.5	62.4	2	
10/20	50.5	62.9	58	82	43.6	50.3	5	0.45
10/21	49.4	53.5	81	85	44.9	48.1	4	0.74
10/22	44.9	58.3	54	86	40.1	45.1	2	0.05
10/23	41.9	49.1	79	86	36.2	44.0	1	0.25
10/24	37.3	45.5	78	85	32.9	40.0	2	0.21
10/25	43.9	49.2	62	82	36.3	39.9	1	0.11
10/26	36.5	45.8	71	85	32.1	37.8	1	

Weather data is from 11:00 a.m. 10/17/2005 through 10:45 a.m. 10/26/2005

Technology Transfer

During field testing at the shadow project, 30 visitors from the Ohio DOT and the contractor visited the Mobile Concrete Research Lab. Project data have been made available to stakeholders through reports, presentations, and the project website, http://www.cptechcenter.org/mco/.

Texas Field Report

Texas Shadow Construction Project Information

- Project No. 0314-02-047, IMD 20-4(257)
- TxDOT Ft. Worth District, Weatherford Area Office
- Contractor: W.W. Webber

Texas Shadow Construction Project Location

The Texas shadow project took place at the eastbound lanes of Interstate 20 in Palo Pinto County, Texas (see Figure C.13). A fenced in site at the SH-4 interchange was made available for the Mobile Concrete Research Lab. This location was adjacent to the project and approximately ¼ of a mile from the batch plant (see Figure C.14).

Project access and plant access for sampling and testing purposes were excellent. There was no delay in transporting AVA and microwave w/c ratio samples to the Mobile Concrete Research Lab.

Figure C.13. Map of the Texas Shadow Project Site

Figure C.14. Batch Plant near the Texas Shadow Project Site

Sampling and Testing Activities

The research team arrived at the site on April 15, 2005, and began testing project concrete on April 26. Fresh concrete testing was concluded on May 5, 2005. Cores of the pavement were obtained on May 6 immediately prior to the research team's departure from the project.

Samples taken and tests conducted during the demonstration include the following:

- Slump, flow, unit weight, temperature ,and air content of fresh concrete: 11 tests
- Unit weight and air content of concrete sampled behind the paver: 2 tests
- Air void analysis: 11 sampling locations, 29 tests
- Microwave w/c ratio: 9 tests
- Wet sieved concrete for combined gradation analysis: 1 sample
- Cast and test 4 in. x 8 in. cylinders for maturity curve: 12 specimens
- Cast and test 6 in. x 6 in. x 20 in. beams for maturity curve: 11 specimens
- Cast and test 4 in. x 8 in. cylinders for 7 day strength: 3 specimens
- Heat signature: 1 concrete test and 1 mortar test
- Heat generation (coffee cup test): 10 tests
- Initial set and final set: 1 test
- Modified false set: 6 tests
- Portland cement and fly ash samples obtained for material testing (XRD, XRF, DSC, and Blaine) in Ames: 8 samples
- 4 in. pavement cores obtained for testing (CTE, permeability and hardened air) in Ames: 6 samples
- Project materials obtained to conduct lab mix design studies in Ames: various bulk quantities

Key Findings

- The results of the 29 AVA tests show consistent results for specific surface (excluding one outlier). Spacing factor results are consistent as well. The average spacing factor for all tests is 0.0148 in.; this is very near the suggested maximum criteria of 0.015 in. The average specific surface of 464 $in.^{-1}$ is below the suggested minimum criteria of 600 $in.^{-1}$. No significant pattern is evident when comparing the on-vibrator samples to the between-vibrator samples. One objective of this research project is to evaluate the suggested criteria for AVA results. Our experience so far is that the AVA produces results that are conservative when compared to hardened air properties obtained using the rapid air testing apparatus.
- Subsequent to the Texas shadow project, it was discovered that the pressure air meter that was used was not calibrated correctly. The calibration was performed on June 7, 2005, and revealed that the air meter was measuring 2% low at that time. Unfortunately, it is impossible to adjust the Texas test results with any precision. We cannot be sure if the air meter steadily lost calibration or if the entire 2% drop occurred at one point in time. The research team has initiated new procedures that include calibration of the air meter(s) at the beginning and middle of each state shadow project. The hardened air properties obtained from project cores will be used for all conclusions obtained from the Texas shadow project. We apologize for the error and any inconvenience that this has caused TxDOT or the contractor.
- Air content was checked behind the paver twice during the project. The sampling location for the air behind the paver corresponds to the same location (same batch of concrete) as an air test ahead of the paver. A brief summary of these results is shown in Table C.13.

Table C.13. Air Content Sampling for the Texas Shadow Project

Date	Time	Air ahead (%)	Air behind (%)	Air loss through the paver (%)
4/29/2005	10:20 a.m.	5.2	3.5	1.7
5/05/2005	1:15 p.m.	2.4	2.5	-0.1

- The air loss of 1.7% on April 29, 2005, was likely caused by a combination of material variability and the vibrator frequency on the paver. Higher vibrator frequencies reduce the air content behind the paver more than lower vibrator frequencies.
- The second result on March 5, 2005, is not easily explained. Two possible explanations for this result are as follows: (1) the imprecision of the sampling and testing method masks air loss that may have occurred and/or (2) the diameters of the air bubbles that were present in the concrete were very small and were not affected by the vibrators. The important point to consider is that air loss through the paver (approximately 1.0% to 2.0%) should always be anticipated when testing the air content of concrete from samples in front of the paver.

- The mix proportions were changed on May 5, 2005. It is the experience of the research team that any time mix proportions are changed, the first three to four batches or more should be checked for air content to ensure that the new mix proportions have adequate air entrainment.
- Vibrator frequencies were measured on the project twice at 8,100 vpm and 8,000 vpm. Based on the research team’s experience, this would be considered marginally high for vibrator frequencies. Higher frequencies may reduce the long-term durability of the pavement due to low air content. However, the reduction in air content of 1.7% behind the paver is in the normal range for slip-formed pavements, and therefore the vibrator frequency does not appear to be adversely affecting the air loss. When measuring air content in front of the paver for quality control purposes, it is important to recognize that some entrained air will be lost during the paving process (approximately 1.0% to 2.0%).
- Visual observations of the paving process revealed very good edges, the auto-float was able to fill in any voids in the surface, and the finishers were not overworking the surface. Water was consistently being sprayed on the burlap directly behind the paver. This water and the fine sand in the mix created an ample amount of paste on the surface. Excessive paste on the surface can contribute to scaling, spalling, and other potential durability issues. However, this potential may be lower for a continuously reinforced pavement than for a jointed pavement.
- According to project personnel, the fine aggregate used in the mix consisted of fine natural sand that had been blended with some portion of clean crushed limestone screenings to coarsen the total fine aggregate enough to meet specification. Fine sands tend to require more water than coarser sands to obtain adequate workability. Angular particles can also present workability problems. Dense graded mixes are superior to gap graded mixes with respect to long-term durability. The research team would encourage the use of dense graded mixes whenever these materials are economically available.
- Curing of the slab ranged from 40 min. to 103 min. behind the paver. Ideally, curing should take place as soon as is practical in the paving process.
- Compressive strength and flexural strength specimens were tested for the purposes of developing a strength/maturity relationship curve. The average 7-day 1/3 point flexural strength of these specimens was 615 psi. The average 7-day compressive strength of 4” x 8” cylinders was 3,250 psi. This research project is less concerned with strength properties than with other durability-related properties. In the opinion of the research team, a minimum strength is necessary to meet the design intent. However, it is believed that almost all rigid pavement failures are a result of properties other than concrete strength.
- Three maturity sensors were placed from April 26 to May 2, 2005; in-place maturity values indicate that the slab had a maturity equivalent of 450 psi between 2 and 3 days after placement. The maturity equivalent of 2,800 psi compressive strength was reached at 4 days after placement. The difference between the two strength equivalents is a function of the mix design—admixtures, aggregate grading, aggregate particle shape, etc. It is always difficult to develop a correlation between flexural and compressive strength for a given mix with a limited number of specimens.

- A brief summary of the weather conditions recorded by a portable weather station at the Mobile Concrete Research Lab location is shown in Table C.14.

Table C.14. Summary of Weather Conditions for the Texas Shadow Project

Date	Min. temp. (˚F)	Max. temp. (˚F)	Min. relative humidity (%)	Max. relative humidity (%)	Min. dew point (˚F)	Max. dew point (˚F)	Max. wind speed (mph)	Total rainfall (in.)
4/25	59.5	82.8	25	68	41.4	56.3	13	0.00
4/26	51.9	78.3	22	69	30.5	48.7	13	0.00
4/27	50.5	88.6	25	65	37.5	50.1	15	0.00
4/28	65.3	93.4	22	51	41.9	55.8	15	0.00
4/29	50.2	74.6	46	80	39.7	61.5	11	0.00
4/30	47.9	68.8	29	70	33.9	41.6	11	0.00
5/01	40.1	74.6	32	80	33.5	45.4	8	0.00
5/02	51.3	65.6	46	64	38.0	44.6	14	0.00
5/03	48.8	65.5	43	73	39.1	43.6	8	0.02
5/04	48.8	55.9	76	86	43.5	51.8	8	1.05
5/05	56.0	76.3	52	87	52.2	58.9	9	0.38
5/06	55.1	63.2	74	85	50.4	55.0	2	0.00

Note: Weather data are from 10:15 a.m. 4/25/2005 through 8:15 a.m. 5/06/2005.

Technology Transfer

The project team has had numerous interactions with individuals in Texas before, during, and after the Texas shadow construction project. During field testing at the shadow project, six visitors (four Texas DOT representatives and two contractor representatives) visited the Mobile Concrete Research Lab. Project data have been made available to stakeholders through reports, presentations, and the project website, http://www.cptechcenter.org/mco/.

Wisconsin Field Report

Wisconsin Shadow Construction Project Information

- Contractor: James Cape & Sons Co.
- WIDOT Southwest Region

Wisconsin Shadow Construction Project Location

The construction project was located on a US-151 expansion from Dickeyville to Dodgeville, in Grant County, WI (see Figure C.15). An area on a southbound onramp was reserved for the Mobile Concrete Research Lab. This location was adjacent to the project. Project and plant access for sampling and testing purposes was excellent. There was no delay in transporting AVA and microwave water-cement ratio (w/c) samples to the Mobile Concrete Research Lab.

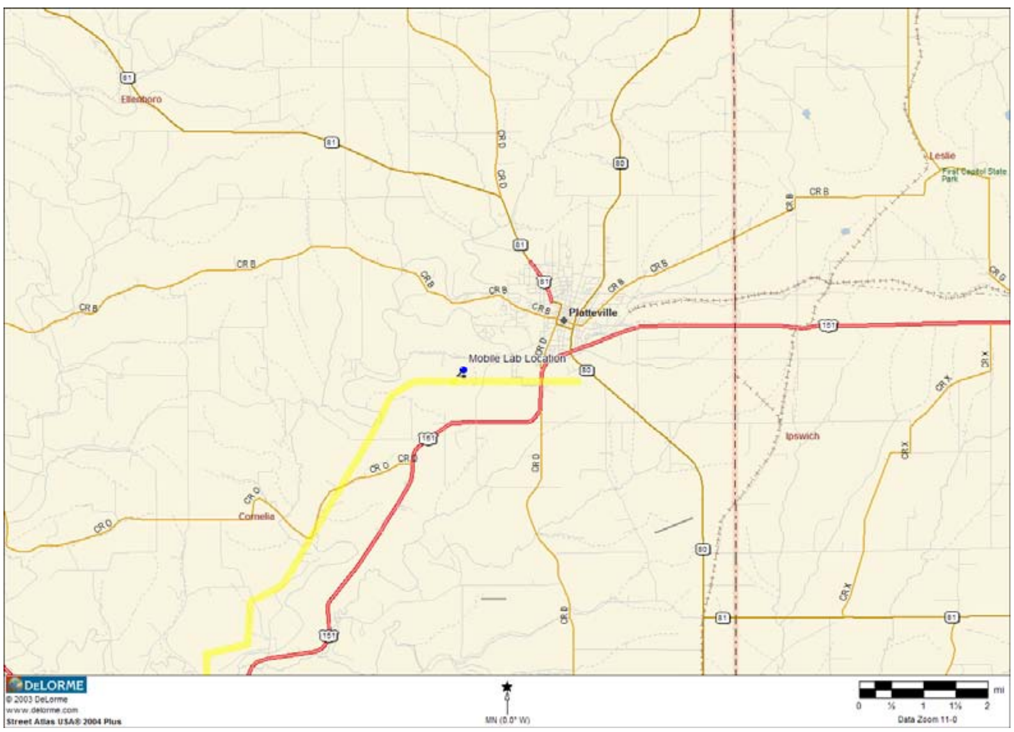

Figure C.15. Map of the Wisconsin Shadow Project Site

Sampling and Testing Activities

The research team arrived onsite October 18, 2004, and began testing project concrete on October 20. Fresh concrete testing was concluded on October 29. Cores of the pavement were obtained on October 28 prior to the research team's departure from the project. The following is a summary of the samples taken and tests conducted during the demonstration:

- Slump, flow, unit weight, temperature, and air content of fresh concrete: 10 tests
- Air content of concrete sampled behind the paver: 1 test
- Air void analysis: 8 sampling locations, 17 tests
- Microwave w/c ratio: 8 tests
- Cast and test 4 in. x 8 in. cylinders for compressive strength maturity curve: 12 specimens
- Cast and test 4 in. x 8 in. cylinders for tensile strength maturity curve: 12 specimens
- Cast and test 4 in. x 8 in. cylinders for 7 day strength: 3 specimens
- Heat generation (coffee cup test): 3 tests
- Initial set and final set: 1 test
- Modified false set: 1 test
- Portland cement and fly ash samples obtained for material testing in Ames (XRD, XRF, DSC, and Blaine): 5 samples
- Obtained 4 inch pavement cores for testing in Ames (coefficient of thermal expansion, permeability, and hardened air): 5 cores
- Obtained bulk project materials to conduct lab mix design studies in Ames

Key Findings

- The results of the 17 AVA tests show fairly consistent data for the specific surface. Spacing factor results are consistent as well. The average spacing factor for all tests is 0.0101 in.; this is within the suggested minimum and maximum limits of 0.0040 in. and 0.015 in. The average specific surface of 710 in.$^{-1}$ is within the suggested minimum and maximum limits of 400 in.$^{-1}$ and 1,100 in.$^{-1}$. No significant pattern is evident when comparing the on-vibrator samples to the between-vibrator samples.
- One objective of this research project is to evaluate the suggested criteria for AVA results. Our experience so far is that the AVA produces results that are more conservative than hardened air properties obtained using the rapid air testing apparatus.
- Air content tested ahead of the paver during the demonstration ranged from 5.0% to 6.6%; the average air content of the 10 tests conducted was 6.0%.
- Air content was tested behind the paver at one location corresponding to the location ahead of the paver (6.4%–4.7%). The air content loss from ahead of the paver to behind the paver was 1.7% at this location.
- Visual observations of the paving process revealed good edges and an above-average amount of slurry/grout on the surface.
- The mix utilized a coarse and fine aggregate. The fine aggregate contained a high fraction of #30- to #50-sized material. Coarseness factors ranged from 68 to 69, and workability factors ranged from 39 to 40.
- Compressive strength and tensile strength specimens were tested to develop a strength-maturity relationship curve. A set of three cylinders was also cast in the field on October 20; the average seven-day compressive strength of these specimens was 4,060 psi. This research project is concerned less with strength properties than with other durability related properties. In the opinion of the research team, a minimum strength is necessary to meet the design intent. However, our experience is that almost all rigid pavement failures are a result of properties other than concrete strength.

- One maturity sensor was placed on October 25. In-place maturity values indicate that the slab reached the maturity equivalent of 325 psi tensile strength in approximately one and a half days.
- A brief summary of the weather conditions recorded by a portable weather station at the Mobile Concrete Research Lab location is shown in Table C.15.

Table C.15. Weather Data for the Wisconsin Shadow Project

Date	Min. Temp. (˚F)	Max. Temp. (˚F)	Min. Relative Humidity (%)	Max. Relative Humidity (%)	Min. Dew Point (˚F)	Max. Dew Point (˚F)	Max. Wind Speed (mph)	Total Rainfall (in.)
10/18	43.8	49.5	60	78	35.3	37.8	17	0.06
10/19	43.2	49.1	79	84	37.2	43.3	14	0.16
10/20	46.4	49.5	74	83	39.8	42.4	9	
10/21	45.5	60.1	58	80	39.3	45.7	16	
10/22	47.4	60.7	79	88	41.5	56.3	23	0.13
10/23	52.8	68.4	54	87	42.3	60.1	26	0.64
10/24	40.6	65.5	36	84	35.8	42.0	17	
10/25	43.5	63.1	51	76	36.4	47.0	15	
10/26	48.2	50.8	64	86	38.2	46.8	16	0.27
10/27	47.9	53.5	80	87	43.3	47.6	12	
10/28	49.2	59.3	78	90	45.0	56.4	15	
10/29	59.6	68.3	85	91	56.7	63.6	13	

Weather data is from 2:45 p.m. 10/18/2004 through 10:00 a.m. 10/29/2004

Technology Transfer

During field testing at the shadow project, 74 visitors from the WIDOT and the contractor visited the Mobile Concrete Research Lab. Project data have been made available to stakeholders through reports, presentations, and the project website, http://www.cptechcenter.org/mco/.

Oklahoma Field Report

Oklahoma Shadow Construction Project Information

- Project No. IMY-35-1(125)000/BRIY-35-1(133), 1957604
- ODOT Division 7, Ardmore Residency
- Contractor: Duit Construction Co., Inc.

Oklahoma Shadow Construction Project Location

The Oklahoma shadow project took place on I-35 in Love County (see Figure C.16). The contractor prepared an area at the plant site for the Mobile Concrete Research Lab. This location was adjacent to the project.

Project access and plant access for sampling and testing purposes was excellent. There was no delay in transporting air void analyzer and microwave water-cement ratio samples to the Mobile Concrete Research Lab.

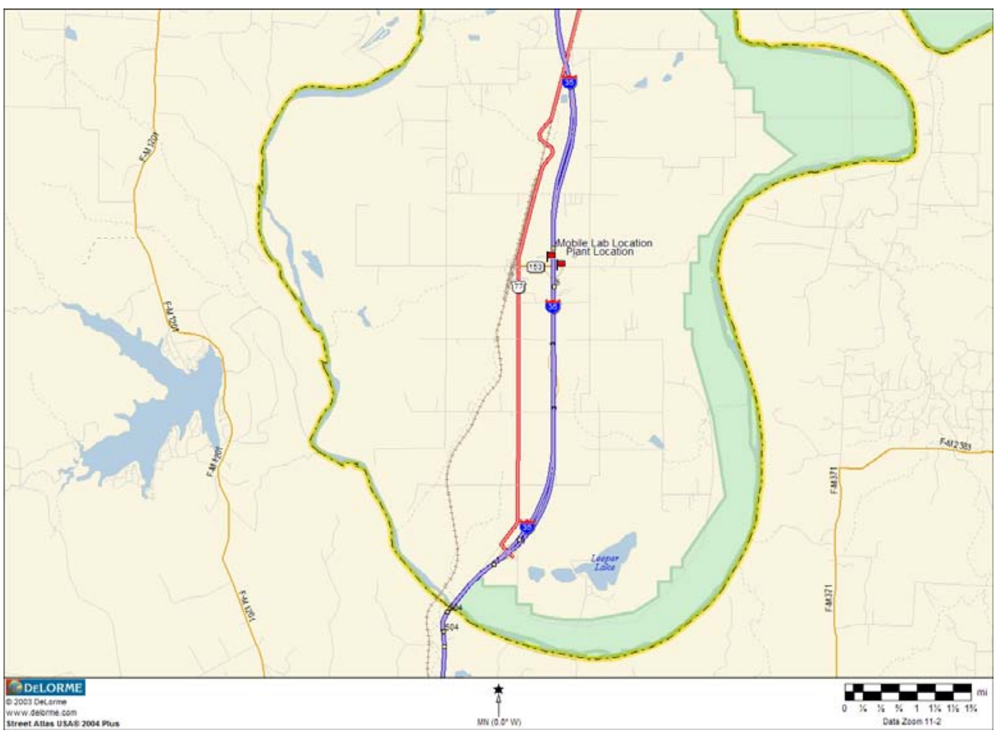

Figure C.16. Map of the Oklahoma Shadow Project Location

Sampling and Testing Activities

The research team arrived onsite April 3, 2006 and began testing project concrete April 4. Fresh concrete testing was concluded on April 12, 2006. Cores of the pavement were obtained on April 11 and April 13 prior to the research team's departure from the project.

Samples taken and tests conducted during the demonstration include the following:

- Slump, flow, unit weight, temperature, and air content of fresh concrete: 8 tests
- Air void analysis: 8 sampling locations, 29 tests (8 tests of material ahead of the paver)
- Microwave w/c ratio: 8 tests
- Cast and test 4 in. x 8 in. cylinders for compressive strength maturity curve: 12 specimens
- Cast and test 6 in. x 6 in. x 20 in. beams for flexural strength maturity curve: 12 specimens
- Cast and test 4 in. x 8 in. cylinders for seven-day strength: 3 specimens
- Heat signature: 1 PCC test
- Heat generation (coffee cup test): 5 tests
- Initial set and final set: 1 test
- Modified false set: 2 tests
- Portland cement and fly ash samples obtained for material testing in Ames (XRD, XRF, DSC, and Blaine): 5 samples
- 4 in. pavement cores for testing in Ames (CTE, permeability, and hardened air): 5 cores
- Obtained bulk project materials to conduct lab mix design studies in Ames

Key Findings

- The results of the 29 AVA tests show slightly variable values for specific surface. Spacing factor results are variable as well. The average spacing factor for all tests is 0.0095 in.; this is within the suggested minimum and maximum limits of 0.0040 in. and 0.015 in., respectively. The average specific surface of 689 in.$^{-1}$ is within the suggested minimum and maximum limits of 400 in.$^{-1}$ and 1,100 in.$^{-1}$. No significant pattern is evident when comparing the on-vibrator samples to the between-vibrator samples. One objective of this research project is to evaluate the suggested criteria for AVA results. Our experience so far is that the AVA produces results that are conservative when compared to hardened air properties obtained using the rapid air testing apparatus.
- Air content tested ahead of the paver during the demonstration ranged from 4.3% to 7.6%, and the average air content of the eight tests conducted was 5.9%.
- Visual observations of the paving process revealed excellent edges and surface. The mix was workable and was finished without excessive effort.
- Curing compound was applied approximately 45 minutes after the concrete had passed through the paver. Weather conditions were mild and evaporation rates were not critical during our stay on the project. Generally, curing compound should be applied as quickly as reasonable, normally about 30 minutes. This is most critical when ambient conditions are dry and windy.

- The combined gradation of the mix was evaluated using sieve analysis data provided by the contractor. Coarseness factors ranged from 70 to 75, and workability factors ranged from 33 to 34 for the Class A mix and 31 for the Class AP mix.
- Compressive strength specimens were tested to develop a strength-maturity relationship curve. Additionally, one set of three 4 in. x 8 in. cylinders was cast during field sampling and tested at seven days. The average seven-day compressive strength of these field-cast cylinders was 4,590 psi.
- One maturity sensor was placed on April 5, 2006. In-place maturity values indicate that the slab had a compressive strength maturity equivalent of 3,000 psi at 46 hours. Additionally, the maturity equivalent of 450 psi flexural strength was reached 34 hours after placement.
- A brief summary of the weather conditions recorded by a portable weather station at the Mobile Concrete Research Lab is shown in Table C.16.

Table C.16. Summary of Weather Conditions for the Oklahoma Shadow Project

Date	Min. temp. (˚F)	Max. temp. (˚F)	Min. relative humidity (%)	Max. relative humidity (%)	Min. dew point (˚F)	Max. dew point (˚F)	Max. wind speed (mph)	Total rainfall (in.)
04/03	60.5	70.4	40	50	41.2	44.9	7	
04/04	49.4	75.1	36	68	39.0	50.6	7	
04/05	61.3	82.8	43	80	50.0	61.8	20	0.01
04/06	65.3	83.4	14	76	26.7	63.4	18	
04/07	51.7	80.7	19	56	24.4	40.3	25	0.01
04/08	51.6	70.1	32	67	36.4	43.5	20	
04/10	55.0	77.4	35	63	40.3	50.9	13	
04/11	61.2	76.8	48	69	46.1	57.1	16	
04/12	63.9	84.3	47	70	53.8	62.2	12	
04/13	62.7	79.9	57	86	57.8	63.8	9	

Weather data is from 7:00 p.m. 04/03/2006 through 12:30 p.m. 04/13/2006

Technology Transfer

During the Oklahoma shadow construction project, 21 visitors from ODOT and the contractor visited the Mobile Concrete Research Lab. Project data have been made available to stakeholders through reports, presentations, and the project website, http://www.cptechcenter.org/mco/.

Georgia Field Report

Georgia Shadow Construction Project Information

- Project No. NH-75-1(204) 01 / B11834-04-000-0
- GADOT District 4, Area 8, Interstate Reconstruction Office, Tifton, GA
- Contractor: The Scruggs Company

Georgia Shadow Construction Project Location

The Georgia shadow project took place on I-75 in Cook County (see Figure C.17). The contractor prepared an area at the plant site for the Mobile Concrete Research Lab. This location was adjacent to the project.

Project access and plant access for sampling and testing purposes was excellent. There was no delay in transporting air void analyzer and microwave water-cement ratio samples to the Mobile Concrete Research Lab.

Figure C.17. Map of Georgia Shadow Project Location

Sampling and Testing Activities

The research team arrived onsite May 15, 2006 and began testing project concrete May 16. Fresh concrete testing was concluded on May 24, 2006. Cores of the pavement were obtained on May 24 prior to the research team's departure from the project.

Samples taken and tests conducted during the demonstration include the following:

- Slump, flow, unit weight, temperature, and air content of fresh concrete – 12 tests
- Air void analysis – 11 sampling locations, 42 tests (20 tests of material sampled ahead of the paver)
- Microwave w/c ratio – 12 tests
- Cast and test 4" x 8" cylinders for compressive strength maturity curve – 12 specimens
- Cast and test 6" x 6" x 20" beams for flexural strength maturity curve – 12 specimens
- Cast and test 4" x 8" cylinders for seven-day strength – 3 specimens
- Heat signature – 1 PCC test
- Heat generation (coffee cup test) – 5 tests
- Initial set and final set – 1 test
- Modified false set – 1 test
- Portland cement and fly ash samples obtained for material testing in Ames (XRD, XRF, DSC, and Blaine) – 6 samples
- Obtained 4" pavement cores for testing in Ames (CTE, permeability, and hardened air) – 6 cores
- Obtained bulk project materials to conduct lab mix design studies in Ames

Key Findings

- The results of the 42 AVA tests show variable values for specific surface. Spacing factor results are variable as well. The average spacing factor for all tests is 0.0121 in.; this is within the suggested minimum and maximum limits of 0.0040 in. and 0.015 in. The average specific surface of 471 in.$^{-1}$ is within the suggested minimum and maximum limits of 400 in.$^{-1}$ and 1,100 in.$^{-1}$. No significant pattern is evident when comparing the on-vibrator samples to the between-vibrator samples. One objective of this research project is to evaluate the suggested criteria for AVA results. Our experience so far is that the AVA produces results that are conservative when compared to hardened air properties obtained using the rapid air testing apparatus.
- Air content tested ahead of the paver during the demonstration ranged from 5.3% to 6.0%, and the average air content of the 11 tests conducted was 5.6%. Air content behind the paver was tested in one location that corresponded to an air content test location ahead of the paver. The air loss through the paver for this sample was 0.7% (5.6% in front and 4.9% behind). This air loss value is smaller than those of the majority of the projects tested to date. This value is a good indication that the mix was not being over vibrated.
- Visual observations of the paving process revealed excellent edges and surface. The mix was workable and was finished without excessive effort.
- Curing compound was applied approximately 45 to 60 minutes after the concrete had passed through the paver. Generally, curing compound should be applied as quickly as reasonable, normally about 30 minutes after the concrete passes through the paver. This guideline is most critical when ambient conditions are dry and windy.
- The combined gradation of the mix was evaluated using sieve analysis data provided by GADOT. The coarseness factor was 73, and the workability factor was 48. In general, the

mix contained a larger proportion of fine aggregate than the other mixes that we have evaluated in other states. Compared to a mix with a more uniform gradation, this amount of fine aggregate can lead to an increased water demand, which can lead to increased shrinkage.

- Slump and mortar flow results for the 11 samples were consistent. Slump ranged from 3/4” to 2”, with a 1” average. Flow ranged from 79% to 108%, with an average of 87%.
- Unit weight ranged from 142.6 lb/ft^3 to 145.8 lb/ft^3, and the average unit weight for 11 samples was 144.7 lb/ft^3.
- The water content of the mix was tested according to AASHTO T318. When the cementitious content was assumed to be equivalent to the mix design mass, the water to cementitious material ratio ranged from 0.41 to 0.51, and the average was 0.45.
- Set time of the mix was tested once. Initial set occurred at 5.4 hours, and final set was achieved at 7.9 hours.
- Compressive strength and flexural strength specimens were tested to develop a strength-maturity relationship curve. Additionally, one set of three 4” x 8” cylinders was cast during field sampling and tested at seven days. The average seven-day compressive strength of these field-cast cylinders was 4,030 psi.
- One maturity sensor was placed on May 16, 2006. In-place maturity values indicated that the slab had a compressive strength maturity equivalent of 2,500 psi at 37 hours. Additionally, the maturity equivalent of 435 psi flexural strength was reached 38 hours after placement.
- A brief summary of the weather conditions recorded by a portable weather station at the Mobile Concrete Research Lab site is shown in Table C.17.

Table C.17. Summary of Weather Conditions for the Georgia Shadow Project

Date	Min. Temp. (˚F)	Max. Temp. (˚F)	Min. Relative Humidity (%)	Max. Relative Humidity (%)	Min. Dew Point (˚F)	Max. Dew Point (˚F)	Max. Wind Speed (mph)	Total Rainfall (in.)
05/15	61.5	81.6	45	86	48.9	61.5	10	0.20
05/16	54.5	74.9	40	80	45.2	54.3	7	
05/17	54.8	77.7	37	84	49.3	54.0	7	
05/18	56.5	83.6	33	78	49.7	55.9	6	
05/19	62.3	87.4	28	81	48.9	59.9	8	
05/20	66.4	92.9	27	81	53.3	68.2	5	
05/21	64.7	92.7	30	86	56.2	66.4	7	
05/22	65.0	92.5	27	78	52.9	63.0	6	
05/23	66.0	93.2	30	77	56.0	65.1	4	
05/24	69.4	94.5	34	78	60.7	67.8	5	
05/25	69.9	77.4	71	85	64.8	67.6	3	

Technology Transfer

During the Georgia shadow construction project, 11 visitors from GADOT and the contractor visited the Mobile Concrete Research Lab. Project data have been made available to stakeholders through reports, presentations, and the project website, http://www.cptechcenter.org/mco/.

South Dakota Field Report

South Dakota Shadow Construction Project Information

- Project No. IM-29-1(84)37
- SDDOT Mitchell Region
- Contractor: Irving F. Jensen Co., Inc.

South Dakota Shadow Construction Project Location

The South Dakota shadow project took place in Union County on the southbound lanes of I-29 (see Figure C.18). The contractor prepared an area at the plant site for the Mobile Concrete Research Lab. This location was adjacent to the project.

Project access and plant access for sampling and testing purposes was excellent. There was no delay in transporting air void analyzer and microwave water-cement ratio samples to the Mobile Concrete Research Lab.

Figure C.18. Map of South Dakota Shadow Project Location

Sampling and Testing Activities

The research team arrived onsite September 18, 2006 and began testing project concrete September 19. Fresh concrete testing was concluded on September 27, 2006. Cores of the pavement were obtained on September 28 prior to the research team's departure from the project.

Samples taken and tests conducted during the demonstration include the following:

- Slump, flow, unit weight, temperature and air content of fresh concrete – 11 tests
- Air void analysis – 10 sampling locations, 30 tests (12 tests of material sampled ahead of the paver)
- Microwave w/c ratio – 11 tests
- Cast and test 4” x 8” cylinders for compressive strength maturity curve – 12 specimens
- Cast and test 6” x 6” x 20” beams for flexural strength maturity curve – 12 specimens
- Cast and test 4” x 8” cylinders for seven-day strength – 3 specimens
- Heat signature – 1 PCC test
- Heat generation (coffee cup test) – 3 tests
- Initial set and final set – 1 test
- Modified false set – 1 test
- Portland cement and fly ash samples obtained for material testing in Ames (XRD, XRF, DSC, and Blaine) – 5 samples
- Obtained 4” pavement cores for testing in Ames (coefficient of thermal expansion, permeability, and hardened air) – 6 cores
- Obtained bulk project materials to conduct laboratory mix design studies in Ames

Key findings

- The results of the 30 AVA tests show consistent values for specific surface. Spacing factor results are consistent as well. The average spacing factor for all tests is 0.0069 in.; this is within the suggested minimum and maximum limits of 0.0040 in. and 0.015 in. The average specific surface of 748 in.$^{-1}$ is also within the suggested minimum and maximum limits of 400 in.$^{-1}$ and 1,100 in.$^{-1}$. No significant pattern is evident when comparing the on-vibrator samples to the between-vibrator samples. Based on AVA test results, the entrained air properties of this mix are excellent.
- Air content tested ahead of the paver during the demonstration ranged from 4.8% to 7.0%, and the average air content of the 10 tests conducted was 6.3%. Air content behind the paver was tested in one location that corresponded to an air content test location ahead of the paver. The air loss through the paver for this sample was 0.7% (6.5% ahead and 5.8% behind). This air loss is typical of the projects that have been tested to date. This value indicates that the mix was not over-vibrated. The project team also evaluated a proposed procedure for determining the stability of entrained air. For this evaluation, a normal air content test was run alongside a companion air content test from the same sampling location that was hand-vibrated in a bucket (3 insertions at 10 seconds per insertion). The four vibrated samples showed variable results with respect to air loss (0.3% to 2.7%).
- Visual observations of the paving process revealed excellent edges and surface. The mix was workable and was finished without excessive effort.
- Vibrator frequencies of approximately 7,500 vpm were observed during the field sampling operations. The paver speed was approximately 5.5 ft/min.

- Excellent curing practices were observed. A double coat of curing compound was applied approximately 30 to 45 minutes after the concrete had passed through the paver.
- The combined gradation of the mix was evaluated using sieve analysis data provided by SDDOT's lab technicians. The coarseness factor ranged from 61 to 66, and the workability factor ranged from 35 to 37. In general, the mix was very well graded compared to the majority of the other projects that have been tested during this research project.
- Slump and mortar flow results were consistent. Slump ranged from 1 in. to 1.5 in., with an average of 1.25 in. Flow ranged from 80% to 104%, with an average of 88%.
- Unit weight ranged from 143.7 lb/ft^3 to 146.7 lb/ft^3, and the average unit weight for nine samples was 145.0 lb/ft^3.
- The water content of the mix was tested according to AASHTO T318. With the cementitious content assumed to be equivalent to the mix design mass, the water to cementitious material ratio ranged from 0.37 to 0.44, and the average was 0.39.
- The set time of the mix was tested once. Initial set occurred at 7.9 hours, and final set was achieved at 10.2 hours.
- Compressive strength and flexural strength specimens were tested for the purposes of developing a strength-maturity relationship curve. Additionally, one set of three 4" x 8" cylinders was cast during field sampling and tested at seven days. The average seven-day compressive strength of these field -cast, lab-cured cylinders was 4,320 psi.
- One maturity sensor was placed on September 19, 2006; in-place maturity values indicate that the slab had a compressive strength maturity equivalent of 4,000 psi in 6.17 days. Additionally, the maturity equivalent of 640 psi flexural strength was reached 5.32 days after placement.
- Table C.18 and Figures C.19–C.21 show a brief summary of the weather conditions recorded by a portable weather station at the Mobile Concrete Research Lab location.

Table C.18. Summary of Weather Conditions for South Dakota Shadow Project

Date	Min. Temp. (˚F)	Max. Temp. (˚F)	Min. Relative Humidity (%)	Max. Relative Humidity (%)	Min. Dew Point (˚F)	Max. Dew Point (˚F)	Max. Wind Speed (mph)	Total Rainfall (in.)
09/18	45.4	51.4	57	71	35.0	40.0	26	
09/19	40.2	55.4	38	77	29.4	37.5	16	
09/20	34.4	62.4	36	81	28.2	38.0	11	
09/21	49.8	56.3	51	87	36.9	52.4	16	1.20
09/22	52.0	57.2	80	88	48.6	51.9	13	0.38
09/23	49.6	56.5	76	88	45.7	51.8	18	0.08
09/24	42.1	63.5	45	87	38.2	47.2	15	
09/25	44.9	70.1	44	82	39.3	49.4	13	
09/26	44.2	82.0	25	85	37.1	50.8	17	
09/27	43.9	62.7	48	85	38.5	49.1	17	0.12
09/28	36.6	55.6	37	86	28.5	38.7	12	0.01
09/29	41.3	48.8	66	79	35.1	39.1	11	

Weather data is from 1:00 p.m. 09/18/2006 through 10:15 a.m. 09/29/2006

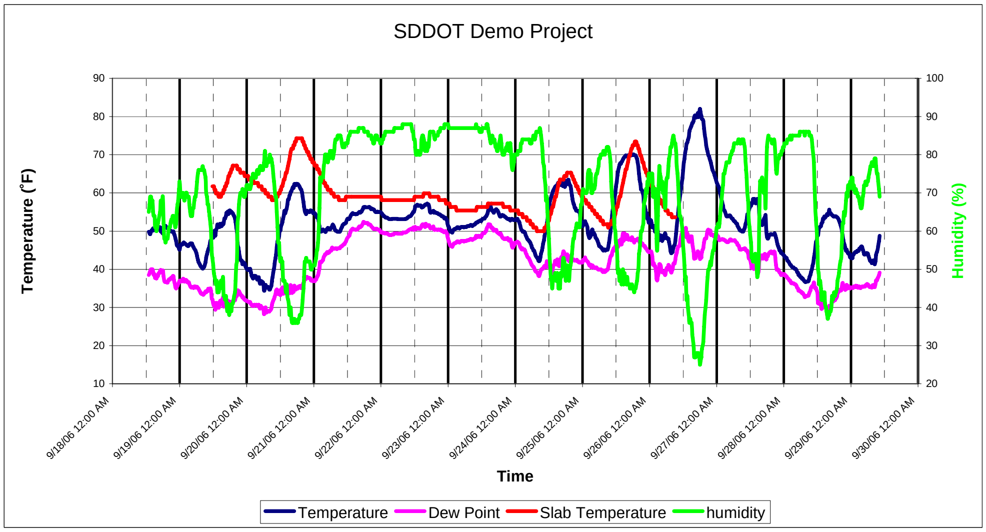

Figure C.19. Various Temperature Indicators for the South Dakota Shadow Project

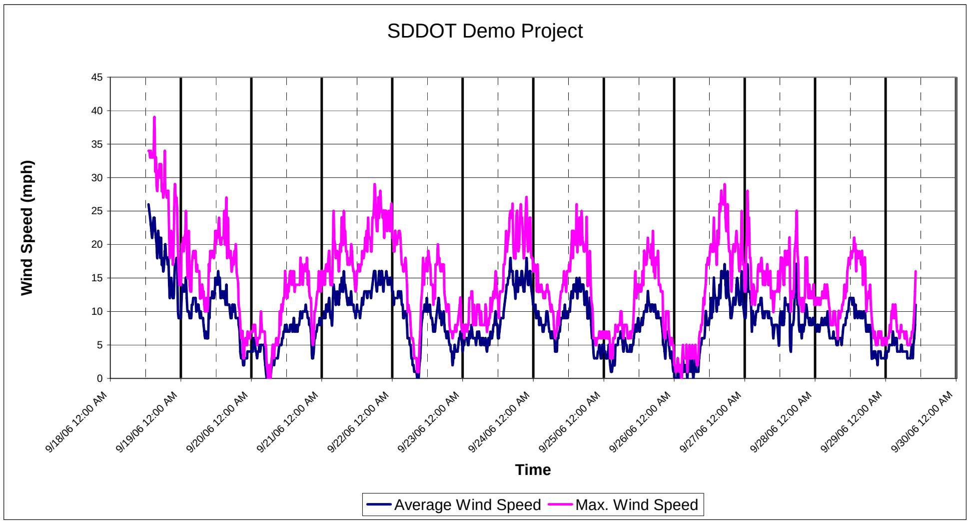

Figure C.20. Wind Speeds during the South Dakota Shadow Project

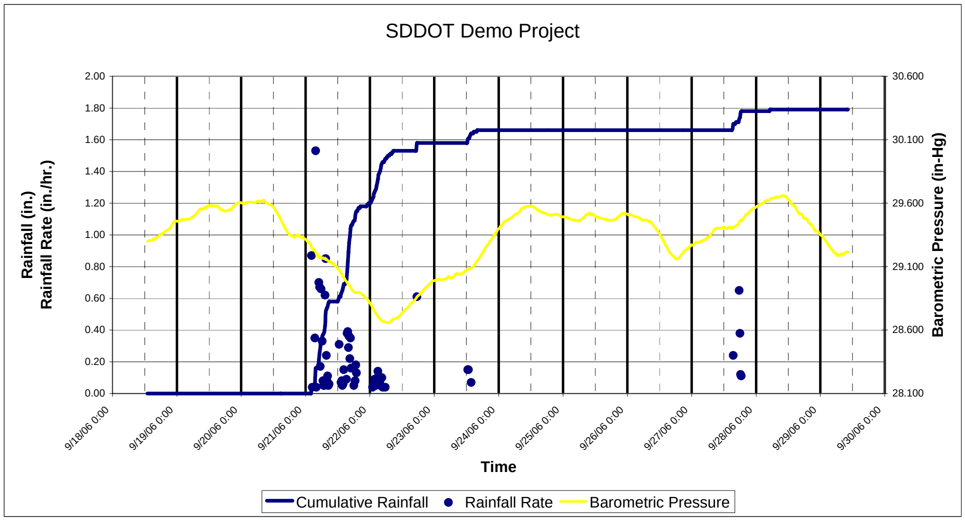

Figure C.21. Rainfall during the South Dakota Shadow Project

Technology Transfer

During the South Dakota shadow construction project, seven visitors from SDDOT and the contractor visited the Mobile Concrete Research Lab. Project data have been made available to stakeholders through reports, presentations, and the project website, http://www.cptechcenter.org/mco/.

New York Field Report

New York Shadow Construction Project Information

- Project No. H980-6008-073
- NYDOT Region 6; Hornell, NY
- Contractor: Cold Spring Construction Company

New York Shadow Construction Project Location

The New York shadow project took place in Steuben County on an interchange project between I-86 and US Route 15, Phase III (see Figure C.22). The contractor prepared an area at the plant site for the Mobile Concrete Research Lab. This location was adjacent to the project.

Project access and plant access for sampling and testing purposes was excellent. There was no delay in transporting air void analyzer and microwave water-cement ratio samples to the Mobile Concrete Research Lab.

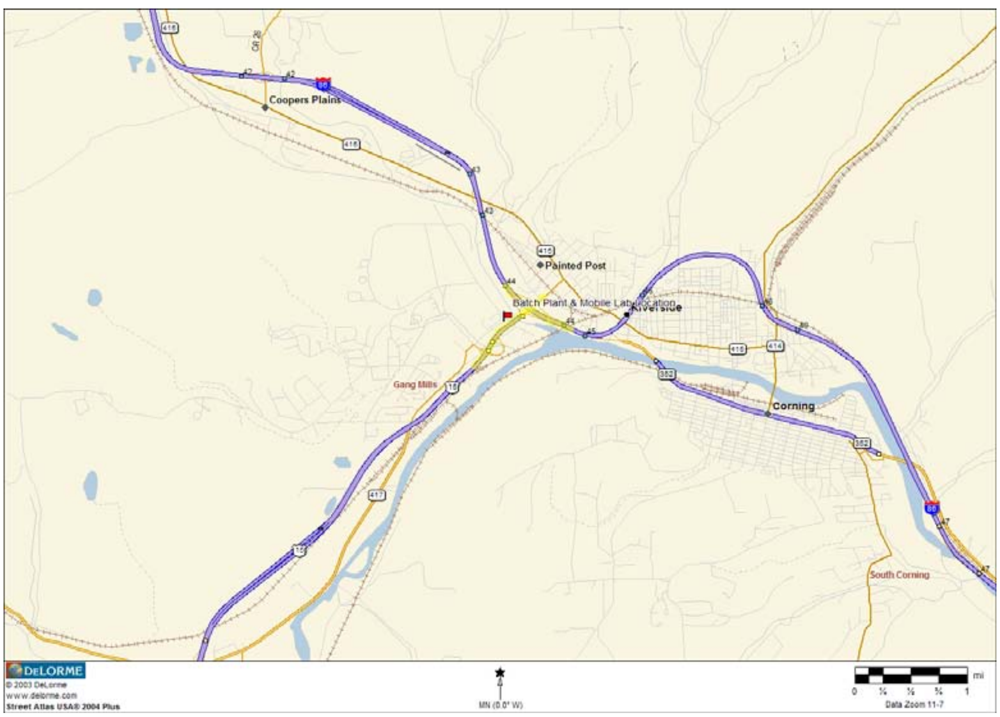

Figure C.22. Map of New York Shadow Project Location

Sampling and Testing Activities

The research team arrived onsite August 8, 2006 and began testing project concrete August 9. Fresh concrete testing was concluded on August 16, 2006. Cores of the pavement were obtained on August 17 prior to the research team's departure from the project.

Samples taken and tests conducted during the demonstration include the following:

- Slump, flow, unit weight, temperature, and air content of fresh concrete – 10 tests
- Air void analysis – 9 sampling locations, 26 tests (15 tests of material sampled ahead of the paver or at the lab trailer)
- Microwave w/c ratio – 10 tests
- Cast and test 4” x 8” cylinders for compressive strength maturity curve – 12 specimens
- Cast and test 6” x 6” x 20” beams for flexural strength maturity curve – 12 specimens
- Cast and test 4” x 8” cylinders for seven-day strength – 3 specimens
- Heat signature – 1 PCC test
- Heat generation (coffee cup test) – 3 tests
- Initial set and final set – 1 test
- Modified false set – 1 test
- Portland cement and fly ash samples obtained for material testing in Ames (XRD, XRF, DSC, and Blaine) – 4 samples
- Obtained 4” pavement cores for testing in Ames (CTE, permeability, and hardened air) – 6 cores
- Obtained bulk project materials to conduct lab mix design studies in Ames

Key Findings

- The results of the 26 AVA tests show variable values for specific surface. Spacing factor results are variable as well. The average spacing factor for all tests is 0.0092 in.; this is within the suggested minimum and maximum limits of 0.0040 in. and 0.015 in. The average specific surface of 686 $in.^{-1}$ is within the suggested minimum and maximum limits of 400 $in.^{-1}$ and 1,100 $in.^{-1}$. No significant pattern is evident when comparing the on-vibrator samples to the between-vibrator samples. The data plots show a noticeable improvement in the entrained air properties of the concrete for the pavement placed after August 11, 2006. Some of this improvement may be explained by differences in the hand pour mix design: no fly ash was added, and a different water reducer was included. However, the two slipform Class C samples after August 11, 2006 have markedly different entrained air properties than the four samples from August 9 and 11, 2006.
- Air content tested ahead of the paver during the demonstration ranged from 4.6% to 7.0%, and the average air content of the 9 tests conducted was 6.1%. Air content behind the paver was tested in one location that corresponded to an air content test location ahead of the paver. The air loss through the paver for this sample was 0.1% (6.5% in front and 6.4% behind). This air loss is smaller than that of any projects tested to date. This figure is a good indication that the mix was not over-vibrated. The project team also evaluated a proposed procedure for determining the stability of entrained air. For this evaluation, a normal air content test was run alongside a companion air content test from the same sampling location that was hand vibrated in a bucket (three insertions at 10 sec. per insertion). The three vibrated samples showed negligible air loss (0% to 0.8%).
- Visual observations of the paving process revealed excellent edges and surface. The mix was workable and was finished without excessive effort.
- Excellent curing practices were observed. Curing compound was applied approximately 30 minutes after the concrete had passed through the paver. Curing compound should be

applied as quickly as reasonable, normally about 30 minutes after the concrete passes through the paver. This guideline is critical when ambient conditions are dry and windy.

- The combined gradation of the mix was evaluated using sieve analysis data provided by NYDOT's onsite consultant. The coarseness factor ranged from 67 to 80, and the workability factor ranged from 30 to 32. In general, the mix is gap-graded from the 3/8" to the #8 sieve size. Adding an intermediate-sized aggregate could improve workability and reduce the water demand.
- Slump and mortar flow results for the 6 samples of Class C concrete for slipform use were consistent. Slump ranged from 3/4" to 1 3/4", with a 1 1/4" average. Flow ranged from 78% to 112%, with an average of 97%.
- Unit weight ranged from 139.8 lb/ft^3 to 143.6 lb/ft^3, and the average unit weight for 9 samples was 142.3 lb/ft^3.
- The water content of the mix was tested according to AASHTO T318. When the cementitious content was assumed to be equivalent to the mix design mass, the water to cementitious material ratio ranged from 0.43 to 0.53, and the average was 0.48.
- The set time of the mix was tested once. Initial set occurred at 5.1 hours, and final set was achieved at 7.1 hours.
- Compressive strength and flexural strength specimens were tested to develop a strength-maturity relationship curve. Additionally, one set of three 4" x 8" cylinders was cast during field sampling and tested at seven days. The average seven-day compressive strength of these field-cast cylinders was 3,460 psi.
- One maturity sensor was placed on August 9, 2006. In-place maturity values indicate that the slab had a compressive strength maturity equivalent of 2,470 psi at 84 hours. Additionally, the maturity equivalent of 430 psi flexural strength was reached 77 hours after placement.
- A brief summary of the weather conditions recorded by a portable weather station at the Mobile Concrete Research Lab location is shown in Table C.19 and Figures C.23–C.25.

Table C.19. Summary of Weather Conditions for New York Shadow Project

Date	Min. Temp. (˚F)	Max. Temp. (˚F)	Min. Relative Humidity (%)	Max. Relative Humidity (%)	Min. Dew Point (˚F)	Max. Dew Point (˚F)	Max. Wind Speed (mph)	Total Rainfall (in.)
08/08	55.1	75.6	38	76	45.5	49.8	8	
08/09	49.5	78.6	27	89	41.6	56.9	5	
08/10	56.9	80.5	35	86	49.8	59.2	6	
08/11	53.2	72.8	34	86	42.8	56.3	6	
08/12	47.4	73.9	29	89	38.1	49.4	5	
08/13	46.5	78.6	30	89	43.2	54.8	5	
08/14	51.3	84.1	37	90	48.2	65.4	10	0.15
08/15	61.5	80.5	32	89	47.7	65.7	9	0.02
08/16	54.1	79.8	41	90	51.2	57.2	3	
08/17	54.5	76.1	46	91	51.3	57.0	5	
05/25	69.9	77.4	71	85	64.8	67.6	3	

Weather data is from 4:45 p.m. 08/08/2006 through 12:15 p.m. 08/17/2006

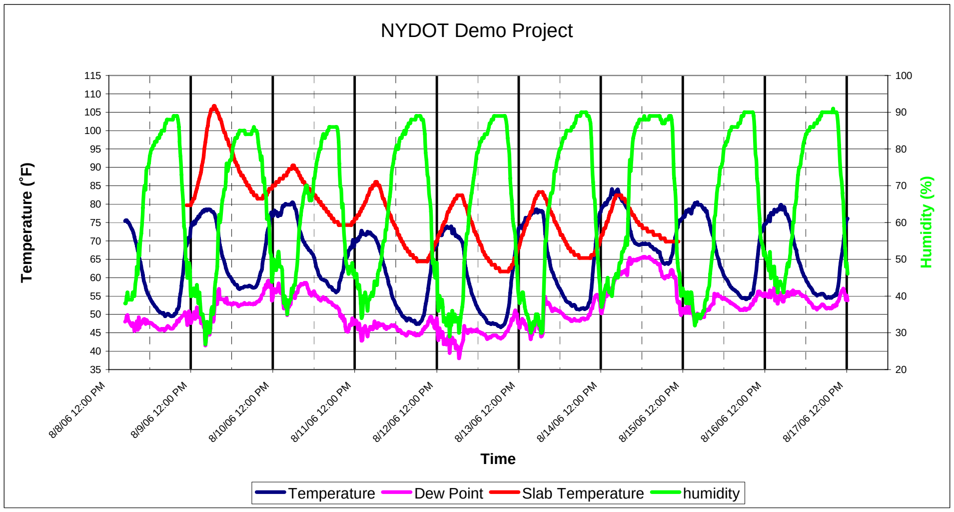

Figure C.23. Various Temperature Indicators for the New York Shadow Project

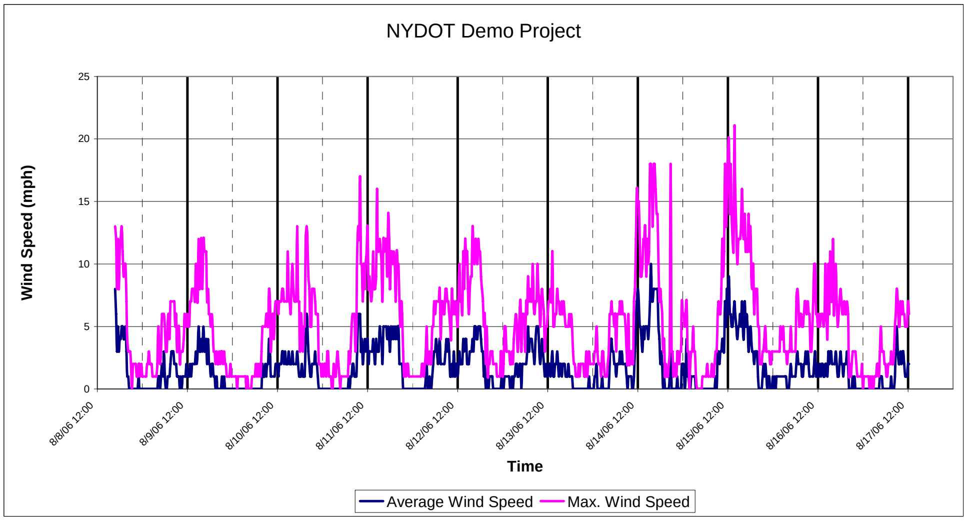

Figure C.24. Wind Speeds during the New York Shadow Project

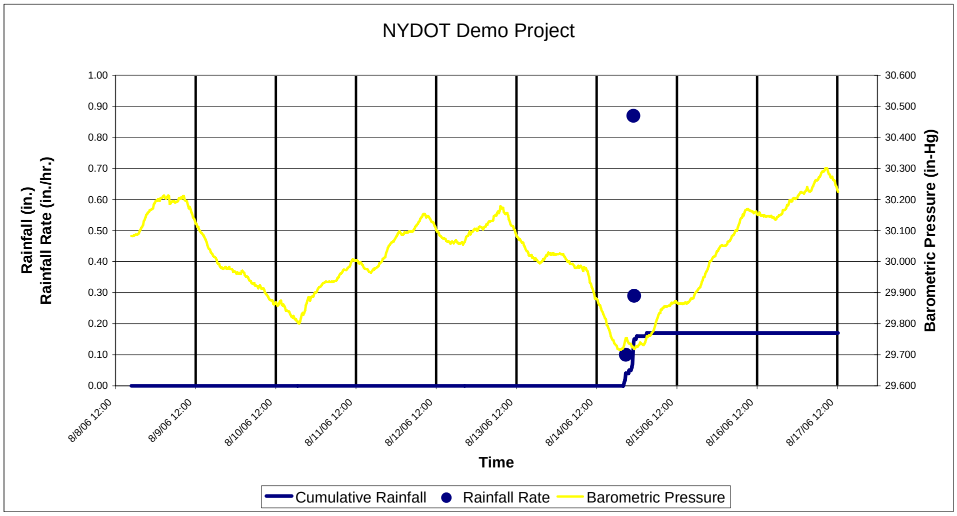

Figure C.25. Rainfall during the New York Shadow Project

TechNology Transfer

During the New York shadow construction project, nine visitors from NYDOT and the contractor visited the Mobile Concrete Research Lab. Project data have been made available to stakeholders through reports, presentations, and the project website, http://www.cptechcenter.org/mco/.

APPENDIX D. SUITE OF TESTS DEVELOPED IN PHASE I

Table D.1. Mix Design Tests

FOCAL PROPERTIES	MIX DESIGN		
	Exists	**Further Develop**	**Needed**
WORKABILITY			
Material Characteristics			
Gypsum Content	DSC/ XRD	TGA	
Sulphate Content	XRF		
Alkali Content	XRF		
Fineness	Blaine	Laser Particle Size Analyzer	
Gradation			
Gradation	Shilstone Proportions 8/18 & 45 Power		
Shape		Shape/Texture	
Durability		Iowa Pore Index	
Texture			
Compatibility			
Set Time	ASTM 187 (Vicat)	Automated ASTM 403	
Premature Stiffening	ASTM 359 (False Set)	Modified ASTM 359 Coffee Cup Test Dan Johnston Test	
Loss of Consistency			
Slump/Vibrating Slope Apparatus (VSA)	Inverted Slump	VSA	Mini VSA
Aggregate Moisture Content			
Mix Properties	Concrete Temperature	Heat Signature	
STRENGTH DEVELOPMENT			
Early Strength	Std. Strength Tests		
Long-Term Strength	Std. Strength Tests		
AIR SYSTEM			
Fresh Concrete	Pressure Meter (ASTM 231) Unit Weight	AVA	
Hardened Concrete	Linear Traverse	MO-Image Analysis MI- Image Analysis	
PERMEABILITY			
Permeability	Rapid Chloride	Rapid Migration Test	
SHRINKAGE			
Temperature Gradient	CTE (AASHTO)		
Temperature Profile			
Shrinkage Potential	Free Shrinkage Test	Restrained Shrinkage Test (AASHTO TP)	

Table D.2. Preconstruction Mix Verification Tests

FOCAL PROPERTIES	PRESCONSTRUCTION MIX VERIFICATION		
	Exists	**Further Develop**	**Needed**
WORKABILITY			
Material Characteristics			
Gypsum Content	DSC (Portable)	TGA	
Sulphate Content	XRF (Portable)		
Alkali Content	XRF (Portable)		
Fineness	Blaine		
Gradation			
Gradation	Shilstone Proportions 8/18 & 45 Power		
Shape			
Durability			
Texture			
Compatibility			
Set Time		Automated ASTM 403	
Premature Stiffening	ASTM 359	Modified ASTM 359 Coffee Cup Test Dan Johnston Test	
Loss of Consistency			
Slump/Vibrating Slope Apparatus (VSA)	Inverted Slump	VSA	Mini VSA
Aggregate Moisture Content			
Mix Properties	Concrete Temperature	Heat Signature	
STRENGTH DEVELOPMENT			
Early Strength	Maturity Curve	Temperature Match Cure	
Long-Term Strength			
AIR SYSTEM			
Fresh Concrete	Pressure Meter (ASTM 231) Unit Weight	AVA	
Hardened Concrete	Linear Traverse		New Test Image Analysis Test (Scanner)
PERMEABILITY			
Permeability			
SHRINKAGE			
Temperature Gradient	CTE (AASHTO)		
Temperature Profile	Temperature Sensors (HIPERPAV)		
Shrinkage Potential			

Table D.3. Construction Quality Control Tests

FOCAL PROPERTIES	CONSTRUCTION QUALITY CONTROL		
	Exists	**Further Develop**	**Needed**
WORKABILITY			
Material Characteristics			
Gypsum Content	DSC (Portable)		
Sulphate Content			
Alkali Content			
Fineness			
Gradation			
Gradation	Shilstone Proportions 8/18 & 45 Power	Optical Grading (Scanning)	
Shape			
Durability			
Texture			
Compatibility			
Set Time			
Premature Stiffening			
Loss of Consistency			
Slump/Vibrating Slope Apparatus (VSA)	Inverted Slump		Mini VSA
Aggregate Moisture Content			Coarse Aggregate Moisture Monitor
Mix Properties		Heat Signature Automated Concrete Temp.	
STRENGTH DEVELOPMENT			
Early Strength	Maturity Temperature (Slab)	Temperature Match Cure	
Long-Term Strength			
AIR SYSTEM			
Fresh Concrete	Pressure Meter (ASTM 231) Unit Weight		Simple AVA
Hardened Concrete			New Test Image Analysis Test (Scanner)
PERMEABILITY			
Permeability			Curing/Moisture Test
SHRINKAGE			
Temperature Gradient			
Temperature Profile	Temperature Sensors (HIPERPAV)		
Shrinkage Potential			

APPENDIX E. SUITE OF TESTS DEVELOPED IN PHASE II

Suite of Tests

24OCT2006

Material and Construction Optimization for Prevention of Premature Pavement Distress in PCC Pavements – TPF-5(066)	Project Stage: Mix Design	Project Stage: Pre-Construction Mix Verification	Project Stage: Quality Control/Acceptance
Workability			
Combined Grading			
Slump and Slump Loss			- test slump at the paver to track consistency
Mortar Flow	? - need more field data to justify		
Set Time			? - calorimetry or other method
Vibrator Monitoring			- automatic monitoring system
Cementitious Heat Generation - Coffee Cup			- monitor daily to identify changes
Strength Development			
Concrete Strength - 3, 7 and 28 day		- 3 day only	? - use 3 day or 7 day tests
Microwave Water Content			
Heat Signature (calorimetry)			? - need affordable equipment & max. 36 to 48 hr. test
Strength - Maturity Relationship			- embed sensor in the pavement (am & pm)
Air Entrainment			
Unit Weight			
Air Content			- quantify loss through the paver
Air Void Analyzer	Use AVA or hardened air during the mix design stage to check entrained air properties		- need guidance on what frequency is necessary
Hardened Air Properties			
Permeability			
Rapid Chloride Penetration			
Permeable Voids (boil test)	? - is this a viable alternative that should be considered		
Shrinkage			
Coefficient of Thermal Expansion			
HIPERPAV	- run simulations at estimated weather extremes for probable ranges of input values		- what happens when cracks are predicted but none appear, how conservative can we afford to be?

Note: The tests included in this table were recommended as a result of the Phase II research activities.

APPENDIX F. OTHER PHASE III DELIVERABLES

Testing Guide

A testing guide for both agency and contractor personnel was produced. This guide outlines a suite of tests that will characterize material properties and concrete properties to assure long-term durability through real-time testing. Details from individual tests are provided, including reasons for conducting the tests, when to use the tests, the information they supply, and the necessary details of the tests themselves.

This field reference guide identifies the common problems that arise during construction, the tests that should be performed to understand said problems, and the recommended tests to solve the problems. The guide is useful to agency personnel in updating specifications through required tests that both test the appropriate properties and yield results in real time. The guide aids both contractors and inspection personnel in identifying causes for and solutions to construction problems.

AVA HyperDocument

A user's guide for the AVA was produced that incorporates the experience gained through the shadow projects in an easy-to-follow procedural guide. The guide includes a step-by-step "how to" instructions and helpful hints for the inexperienced user and a quick reference guide for subsequent use. Imbedded DVD videos and figures detail the operation of the equipment and supplement the user's guide.

Coffee Cup Video

A DVD narrated video showing the coffee cup test being conducted was produced and is available.