Materials and Mix Optimization Procedures for PCC Pavements

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16. Abstract

Severe environmental conditions, coupled with the routine use of deicing chemicals and increasing traffic volume, tend to place extreme demands on portland cement concrete (PCC) pavements. In most instances, engineers have been able to specify and build PCC pavements that met these challenges. However, there have also been reports of premature deterioration that could not be specifically attributed to a single cause. Modern concrete mixtures have evolved to become very complex chemical systems. The complexity can be attributed to both the number of ingredients used in any given mixture and the various types and sources of the ingredients supplied to any given project. Local environmental conditions can also influence the outcome of paving projects.

This research project investigated important variables that impact the homogeneity and rheology of concrete mixtures. The project consisted of a field study and a laboratory study. The field study collected information from six different projects in Iowa. The information that was collected during the field study documented cementitious material properties, plastic concrete properties, and hardened concrete properties. The laboratory study was used to develop baseline mixture variability information for the field study. It also investigated plastic concrete properties using various new devices to evaluate rheology and mixing efficiency. In addition, the lab study evaluated a strategy for the optimization of mortar and concrete mixtures containing supplementary cementitious materials.

The results of the field studies indicated that the quality management concrete (QMC) mixtures being placed in the state generally exhibited good uniformity and good to excellent workability. Hardened concrete properties (compressive strength and hardened air content) were also satisfactory. The uniformity of the raw cementitious materials that were used on the projects could not be monitored as closely as was desired by the investigators; however, the information that was gathered indicated that the bulk chemical composition of most materials streams was reasonably uniform. Specific minerals phases in the cementitious materials were less uniform than the bulk chemical composition. The results of the laboratory study indicated that ternary mixtures show significant promise for improving the performance of concrete mixtures. The lab study also verified the results from prior projects that have indicated that bassanite is typically the major sulfate phase that is present in Iowa cements. This causes the cements to exhibit premature stiffening problems (false set) in laboratory testing. Fly ash helps to reduce the impact of premature stiffening because it behaves like a low-range water reducer in most instances. The premature stiffening problem can also be alleviated by increasing the water–cement ratio of the mixture and providing a remix cycle for the mixture.

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MATERIALS AND MIX OPTIMIZATION PROCEDURES FOR PCC PAVEMENTS

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EXECUTIVE SUMMARY

This research project investigated important variables that impact the homogeneity and rheology of concrete mixtures. The project consisted of a field study and a laboratory study. The field study collected information from six different projects in Iowa. The information that was collected during the field study documented cementitious material properties, plastic concrete properties, and hardened concrete properties. The laboratory study was used to develop baseline mixture variability information for the field study. It also investigated plastic concrete properties using various new devices to evaluate rheology and mixing efficiency. In addition, the lab study evaluated a strategy for the optimization of mortar and concrete mixtures containing supplementary cementitious materials.

The results of the field studies indicated that the quality management concrete (QMC) mixtures being placed in the state generally exhibited good uniformity and good to excellent workability. Hardened concrete properties (compressive strength and hardened air content) were also satisfactory. The uniformity of the raw cementitious materials that were used on the projects could not be monitored as closely as was desired by the investigators; however, the information that was gathered indicated that the bulk chemical composition of most materials streams was reasonably uniform. Specific minerals phases in the cementitious materials were less uniform than the bulk chemical composition. This suggests that some manufacturing processes could be improved to provide a more uniform materials stream to the construction projects. Of the six projects that were monitored, only one contractor reported mixture-related problems. However, testing indicated that the cementitious materials were functioning adequately and that the problem was more aptly associated with the extreme weather conditions (heat index approximately 110 degrees) and a relatively harsh mixture.

The results of the laboratory study indicated that ternary mixtures show significant promise for improving the performance of concrete mixtures. The optimization strategy that was evaluated during this study was only partially successful and additional work will be needed to verify the findings presented in this report.

The lab study also verified the results from prior projects that have indicated that bassanite ($CaSO_4 \bullet ½H_2O$) is typically the major sulfate phase that is present in Iowa cements (both portland cements and blended cements). This causes the cements to exhibit premature stiffening problems (false set) in laboratory testing. Fly ash helps to reduce the impact of premature stiffening because it behaves like a low-range water reducer in most instances. The premature stiffening problem can also be alleviated by increasing the water–cement ratio of the mixture and providing a remix cycle for the mixture.

INTRODUCTION

Background

The routine production of durable concrete pavements has always been a challenging task. Severe environmental conditions, coupled with the routine use of deicing chemicals and increasing traffic volume, tend to place extreme demands on portland cement concrete (PCC) pavements. In most instances, engineers have been able to specify and build PCC pavements that met these challenges. However, there have also been reports of premature deterioration that could not be specifically attributed to a single cause. Such deterioration often appeared to be the result of problems that arose because of plastic concrete problems (mixture incompatibilities) and/or construction practices (construction-related distress or CRD).

Modern concrete mixtures have evolved to become very complex chemical systems. The complexity can be attributed to both the number of ingredients used in any given mixture and the various types and sources of the ingredients supplied to any given project. Local environmental conditions can also influence the outcome of paving projects. Hence, research is needed on characterizing basic concrete materials (i.e., uniformity before and after mixing), identifying potential incompatibility problems, and optimizing mixture proportion because these are key issues to increasing the durability of concrete pavements.

For example, Figure 1 illustrates a problem that was noted on a section of I-29 in western Iowa. The District Engineer had noted some early deterioration on specific sections of the pavement and took core samples to evaluate the concrete. Visual inspection suggested that the top half of the concrete core appeared to have a lighter color than the bottom half of the core. Subsequent petrographic examination of the core indicated that the top half of the core had a water–cement ratio of about 0.6, while the bottom half of the core had a water–cement ratio of about 0.4. How could this anomaly have occurred?

In addition, the strong push towards the use of supplementary cementitious materials (SCMs) in the concrete industry has raised concerns about product homogeneity and performance. These two concerns are not totally independent because lack of homogeneity can obviously complicate field operations and this can impact performance. Homogeneity concerns pertain to both the raw cementitious materials (portland cements, blended cements, and fly ash) and to the efficiency of field mixing. Homogeneity of raw materials is typically evaluated via uniformity requirements in the base material specifications (see ASTM C 595 and 618). Such requirements are often only monitored by the user because the materials are typically certified by the manufacturer. Bulk chemical composition for portland cements and fly ash often gives a good indication of material homogeneity; however, such measurements are less meaningful for blended cements because the blending process tends to obscure changes in either of the base materials. For example, Table 1 summarizes a problem that was observed with blended cement that was delivered to a job site (Job 3). The table clearly shows that this project received blended cement that contained significantly less slag than was anticipated. How will this impact constructability (the trial mixtures were made using a totally different cementitious material) and the ultimate durability (service life) of the pavement? Future uniformity requirements will hopefully progress to the level of measuring actual mineral phases or glass components to give a more precise estimate of the uniformity of the active ingredient(s) in the material. It is also important to notice that the materials supplier typically did a very good job of controlling the slag content of the blended cements used in all of the other jobs (the Type IS cement should have contained 35% slag, the average observed slag content was 34%). Was the discrepancy observed in the cementitious material delivered to Job 3 really a materials blending issue or was it simply a transportation error?

Concrete uniformity needs to be evaluated in both the plastic state (freshly mixed) and the hardened state (core specimens). The important plastic properties have been described in detail by Daniel and Lobo (2005) as they pertain to ready-mixed concrete. For the purpose of this research, these properties have also been considered to be useful in documenting the plastic properties of low-slump pavement concrete. Core specimens are needed to document the hardened concrete properties because these give a better indication of how the concrete should perform in the field. This is due to the fact that construction practices can have a significant impact on the amount of entrained air that is incorporated in the mixture. Poor hardened air contents have been linked to premature distress in Iowa pavements (Jones 1991, Stutzman 1999, and Schlorholtz 2000).

Figure 1. Example of a water–cement ratio anomaly in concrete from I-29 in western Iowa

Table 1. Example of a problem noted with blended cements delivered to Iowa projects

Sample	Cementitious Material	% slag, measured by XRD
Job 1	Blended – Type IS	30
Job 2	Blended – Type IS	38
Job 3	Blended – Type IS	3
Job 4	Blended – Type IS	33
Job 5	Type I/II	-1 (reported as zero)
average % slag for Jobs 1, 2, and 4 =		**34**

Purpose and Scope

The purpose of this research project was to provide reasonable answers to the questions that were posed in the previous section. As the Iowa Department of Transportation (Iowa DOT) continues to use SCMs in pavement and structural concrete, such answers will provide a more rational basis for explaining discrepancies between theoretical performance (ideal, laboratory) and actual field performance (service life). In addition, the test results will help to document the uniformity of materials and concrete used on a series of different field projects. The ultimate goal of this research project was to provide contractors and engineers with a set of guidelines that simplify and specify the process of producing affordable and durable PCC pavements. The guidelines should provide details on optimization of concrete mixing procedures when supplementary cementitious materials and other admixtures are used to modify the properties of concrete. The scope of this project was limited to (1) materials commonly used by the Iowa DOT and (2) job sites in the state of Iowa. Hence, the guidelines will only pertain to the state of Iowa. Broader and more robust guidelines are being developed by a pooled fund study TPF 5(066) that has a broader scope. The specific objectives for this project can be summarized as follows:

- Define the characteristics of a “good” concrete mix as it relates to the mixture supplied to the slipform paver on grade.
- Investigate effects of the key parameters of concrete mixing on fresh concrete properties, such as uniformity and workability, under laboratory conditions that replicate different material combinations, mixing times, and mixing methods.
- Develop guidelines for proper optimization of materials and mixing method/time to obtain the best performing concrete pavement with a given set of performance criteria and available materials.

Hence, the reader needs to understand that the title of this particular project really did a poor job of describing the major thrust of the research. Very little of the research was directed at “optimization” of concrete mixtures. Instead, most of the effort was to be directed at documenting the uniformity of raw materials, plastic concrete properties, and hardened concrete. This is explained in detail in the next section of this report.

RESEARCH APPROACH

This research project investigated important variables that impact the homogeneity and rheology of concrete mixtures. The project consisted of a field study and a laboratory study. The field study collected information from six different projects in Iowa. The information that was collected during the field study documented cementitious material properties, plastic concrete properties, and hardened concrete properties. The laboratory study was used to develop baseline mixture variability information for the field study. It also investigated plastic concrete properties using various new devices to evaluate rheology and mixing efficiency. In addition, the lab study evaluated a strategy for the optimization of concrete mixtures containing supplementary cementitious materials. Each particular task conducted during the study will be presented in more detail below. It is important to note that some of the tasks that were present in the original proposal had been modified by later communications between the investigators and the Federal Highway Administration (FHWA). Letters documenting the discussions and the changes in the Research Approach are given in Appendix A. The overall thrust of the research project was not changed during the discussions; rather, the research tasks were changed (focused) to increase the chance of producing meaningful test results.

Field Study

The field study was conducted to establish the uniformity of concrete reaching the slipform paver at six different job sites. This research was similar to a study reported by Cable and McDaniel in 1998 (HR-1066). However, their study was aimed at evaluating the influence of mixing time on only a few mixtures (basically a standard DOT mix design and a mix design proposed by the contractor). In this project, the contractor was able to choose the mix design (a QMC mixture) for the project. The results of HR-1066 indicated that the within-batch (single-haul unit) uniformity of mixtures obtained from a sixty-second mixing cycle was typically pretty good. Hence, this research program attempted to concentrate more on the between-batch uniformity of concrete mixtures and how this might be influenced by raw materials. The tests that were used to evaluate the fresh concrete were similar to those used in HR-1066; however, setting time was included in the testing repertoire for several of the field sites. All efforts were made to ensure that the testing was conducted without interfering with the flow of work at the jobsite. This meant that all of the tests could not be conducted at all of the field sites. A summary of the tests that were conducted is given in Table 2. In addition, none of the contractors liked the idea of double sampling (i.e., immediately after mixing and then on grade) that was proposed in Table 2 because they thought that this would slow the paving process. Hence, all field samples were only taken near the paver.

Laboratory Study

A laboratory study was conducted to supplement information obtained from the field study (see Table 3). Laboratory mixes (basically Iowa DOT C-3 mix designations) were used to estimate the ultimate precision levels that could be expected from the field study. Also, the use of new mix control technology (a moisture sensor) and different mixing cycles were evaluated via laboratory scale experimentation. A vibrating slope apparatus (VSA) was used to evaluate the workability of many different laboratory concrete mixtures. One task evaluated if mortar and paste specimens could be effectively used to optimize SCM dosage for concrete mixtures. Finally, the laboratory study investigated the fundamental reasons why certain combinations of cement, fly ash, and/or slag cause workability or premature stiffening problems.

Table 2. Summary of tests conducted in the field study

Problem or Task	Tests to be Conducted	Expected Result(s)
Questionable raw material uniformity	Bulk chemistry Bulk mineralogy (+sulfate minerals) Moisture content Paste/mortar tests as needed	Document variability of raw materials
Questionable fresh concrete uniformity	Density Compressive strength Coarse aggregate content Air content (plastic on grade; hardened from pavement core)	Document uniformity of freshly mixed concrete. Document loss of entrained air voids during the construction process.
Questionable workability	Slump test Vibrating slope apparatus (VSA) Temperature of concrete Setting time of mortar	Document workability immediately after mixing and then just prior to paving

Table 3. Summary of tasks conducted in the laboratory study

Problem or Task	Tests to be Conducted	Expected Outcome
Estimate “ultimate” concrete uniformity	Air content (plastic) Density Water content 7-day compressive strength	Document “ideal” variability of well-mixed concrete
Investigate new mix control technology (moisture sensor)	Evaluated batching sequence and mixing time in a laboratory (pan) mixer that was fitted with a moisture sensor	Document devices that are available and the results of laboratory trials
Mixture proportioning—also includes a brief study of why some mixtures behave poorly in certain instances	Various AASHTO or ASTM paste, mortar, and concrete tests as required Vibrating slope apparatus (VSA) Calorimetry (heat signature testing)	Document incompatible mixtures and relate to field experience Document a strategy for optimizing mixtures containing supplementary cementitious materials

EQUIPMENT AND PROCEDURES

This project utilized a wide variety of standard and specialized test methods. All of the methods will be described in the following sections. For brevity, the standard methods will simply be cited and any deviations from the standard techniques will be described.

Laboratory Test Methods

Materials Analysis & Research Laboratory (MARL)—Chemical Methods

The MARL used X-ray techniques to measure the bulk chemistry and mineralogy of the different samples of supplementary cementitious materials (fly ash and slag) that were used for this study. These X-ray techniques were to measure the bulk chemistry and mineralogy of portland cements, blended cements, fly ash, and slag samples.

A Philips PW 2404 X-ray spectrometer (XRF) was used for the bulk chemical determinations that were made during this study. The spectrometer was equipped with a rhodium target X-ray tube. All measurements were corrected for tube drift via a monitor sample (AUSMON-silicate minerals reference monitor). Specimens were typically presented to the spectrometer as fused disks (flux to sample ratio = 5.00); however, slag assays and some of the cement uniformity tests were conducted using pressed pellets (8.00 grams of sample mixed with 2.5 grams of binder). This was done to enhance the sensitivity for sodium, potassium, and sulfur because these elements have been found to be correlated to prior field problems. This alternate sample preparation method also alleviated any concerns about volatility of these particular elements during the fusion process. The spectrometer was calibrated using National Institute of Standards and Technology (NIST) grade certified reference materials for the fused disk technique and Cement and Concrete Reference Laboratory (CCRL) proficiency samples for the cement pellets.

A Siemens D 500 X-ray diffractometer (XRD) was used to determine the mineralogy of various samples. The diffractometer was equipped with a copper X-ray tube and a diffracted beam monochromater. Test specimens were prepared by back-loading the material into one-inch diameter (25 mm) sample holders. Data collections parameters (i.e., step size and counting time) were selected based on the crystallinity of the sample that was being analyzed.

A TA-Instruments differential scanning calorimeter (DSC, Model 2910) was used to analyze the hydraulic cement samples for gypsum ($CaSO_4$-$2H_2O$) and bassanite ($CaSO_4$-$\frac{1}{2}H_2O$) content. A typical experiment was conducted on a 10-milligram specimen that was heated from 35°C to about 300°C using a heating rate of 15 degrees per minute. All specimens were hermetically sealed in aluminum sample pans prior to analysis. Nitrogen gas was purged through the system to avoid oxidation of the DSC cell. The method was calibrated using a series of synthetic standards that were manufactured from pure gypsum, bassanite, and a portland cement clinker that contained neither of the minerals.

Materials Analysis & Research Laboratory (MARL)—Physical Test Methods

The MARL contains all of the testing equipment required to mix, cure, and test paste and mortar specimens for compliance with ASTM C 618. The MARL participates in the Cement and Concrete Reference Laboratory (CCRL) pozzolan proficiency sample testing program and the CCRL laboratory inspection program. The most recent CCRL laboratory inspection was conducted on September 28, 2004.

One task in this study was aimed at evaluating the use of paste and mortar mixtures to select optimum SCM dosages for subsequent testing in concrete mixtures. This was done to help minimize the amount of effort that is required to make better use of permeability-reducing materials like fly ash and slag. Paste and mortar tests tend to be quick and do not require large amounts of materials. Hence, a study was conducted to see if this strategy was plausible.

Pastes for the study were mixed in accordance with ASTM C 305. Enough water was added to each mixture to reach normal consistency (as per ASTM C 187). Pastes were tested for setting time (ASTM C 191) and semi-adiabatic temperature rise (calorimetric tests similar to a heat signature test). The temperature rise tests were conducted in 665 mL dewar flasks. Paste specimens, consisting of 200 grams of cementitious material at normal consistency, were placed in disposable plastic vials along with an I-button for temperature measurement. The dewar flasks were then closed with a styrofoam lid and hydration (specimen temperature) was monitored for about 1.5 days.

Mortars were mixed in accordance with ASTM C 305. Enough water was added to each mixture to attain a flow of 110% ± 5%. Mortar specimens were cast to allow for measuring compressive strength and drying shrinkage. Strength tests were conducted on mortar cubes in accordance with ASTM C 109. Tests were conducted after moist curing for 3, 7, 28, 56, and 180 days. The unrestrained drying shrinkage characteristics of various mixtures were measured using prismatic bar specimens (nominal dimensions of 25 by 25 by 300 mm (1 by 1 by 11.25 inches), with an effective gage length of 250 mm (10 inches)). This is in general agreement with ASTM C 157; however, two discrepancies were noted. First, the moist curing period prior to drying was only seven days (rather than the 28 days that is often used for SCMs). Secondly, the humidity could not be maintained at the 50% ± 5% because the room dehumidifier could not keep up during the first few weeks of the experiment.

Premature stiffening tests, often called false set tests, were conducted using a procedure similar to that given in ASTM C 359. This procedure, which will be referred to as the “modified C 359,” utilized a shorter mixing cycle (one minute at speed 1) than the procedure described in ASTM C 359. This test method has been used in a previous study (Schlorholtz 2000) and has been observed to be more rigorous than the standard C 359 test method. This was deemed appropriate due to the rather short mix cycles that are used in pavement concrete mixtures. Briefly, the test method uses a modified Vicat apparatus to evaluate the premature stiffening behavior of mortar specimens. Four penetration measurements were taken during the first 10 minutes after water was added to the mixture. The mortars were then subjected to a remix cycle to evaluate if the premature stiffening was caused by flash set or false set. Mortars exhibiting false set typically exhibit high penetration values immediately after the remix cycle. For the purpose of this research program, the mortar specimens were subjected to one additional penetration measurement 15 minutes after the remix cycle. This was done to lengthen the observation period to approximately 30 minutes after the water was added to the mixture (this is in reasonable agreement with the maximum haul time for concrete that is allowed by the Iowa DOT).

Setting time tests (ASTM C 403) were conducted on specific mortar mixtures. Tests were conducted on mortar samples containing various cements and cement-fly ash mixtures. Most tests were conducted at ambient laboratory temperature (23˚C ± 2˚C); however, several tests were conducted at 37˚C. This was done in effort to simulate the field conditions that were experienced on specific job sites. Experiments were also run to provide comparison test results from the main apparatus (Acme penetrometer, H-4133) with a pocket penetrometer (Humboldt MFG., H-4134). This correlation was only applicable to initial set determinations and it was needed to compensate for zero offset errors noted in the field. The zero offset errors were related to extreme temperatures experienced at a job site. Apparently, the hydraulic system of the Acme penetrometer contained some air which made the zero point of the apparatus temperature sensitive. The anomaly was not apparent at normal operating (laboratory) temperatures.

Image analysis was used to determine the air void parameters of the hardened concrete. The tests were conducted using the MARL standard operating practice that had been developed in an earlier research project (Schlorholtz 1996). A Hitachi variable pressure scanning electron microscope (SEM) was used to collect digital images of the various test specimens. The digital images were then subjected to image analysis to determine entrained air content and the apparent void-size distribution of air voids in the mortar fraction of the concrete.

Core specimens or compressive strength cylinders were sampled for SEM analysis by sectioning with a Buehler LAPRO slab saw. The saw was equipped with a 457 mm (18 inch) diameter notched-rim diamond blade. Reagent grade propylene glycol was used as the lubricant-coolant during the cutting process. Test specimens were cut from the top and bottom of the core or cylinder by making a cut approximately 25 mm (1 inch) below the top and above the bottom surfaces, respectively. Hence, the nominal section area that was available for analysis on any given specimen was about 81 cm^2 (12.6 in^2, in reasonable accordance with ASTM C 457, assuming a nominal coarse aggregate size of 25 mm (1 inch)). The sections were then prepared for analysis using an Allied variable speed grinder/polisher. The grinder/polisher was equipped with a 300 mm (12 inch) diameter wheel. Fixed grit diamond grinding disks (Diagrid, nominal grit sizes of 260 microns, 70 microns, 15 microns, and 6 microns) were used throughout the study.

Portland Cement Concrete Research Laboratory (PCC Lab)

All of the concrete mixtures were made in the PCC Lab at Iowa State University. The lab contains all of the equipment needed to mix, cure, and test concrete test specimens. Concrete was mixed and test specimens were molded in accordance with ASTM C 192. Concrete slump was tested in accordance with ASTM C 143. Slump loss test was conducted thirty minutes after the initial slump determination. Air content was tested in accordance with ASTM C 231 (Type B meter). The density of the concrete was determined by weighing the base of the air pot prior to conducting the air content test. After the air content test was finished, the material in the base of the air pot was washed through a 4.75 mm (#4) mesh sieve. The coarse aggregate retained on the sieve was then allowed to reach a saturated surface dry (SSD) condition and then weighed on a laboratory bench scale. Compressive strength was determined in accordance with ASTM C 39 using 102 by 203 mm (4 by 8 inch) cylinders; unbonded capping pads were used to constrain the test specimens during the compressive strength determinations. Compressive strength test specimens were cured in a fog room for various periods of time (3, 7, 28, and 56 days were most commonly used) until they were broken in unconfined compression on an ELE CT-761B compression testing machine. The testing machine is calibrated on a yearly basis by the Calser Corporation.

A vibrating slope apparatus (VSA) was evaluated during this study. The VSA (denoted as #3) and the computer control/data interpretation system were borrowed from the Federal Highway Administration (FHWA). The VSA was used to evaluate the workability of concrete from many laboratory mixtures and a job mixture produced at a single field site. The operating details are rather lengthy and for simplicity are summarized in Appendix B.

Field Sampling and Test Methods

Field tests consisted of uniformity tests, setting time tests, and hardened air content tests. All of the tests were conducted on a concrete sample that was taken from an agitator delivery unit dumping directly into a wheel barrow or when dump trucks were used to deliver concrete to the paver; four five-gallon pails of concrete were scooped directly from the pile on the grade (directly below the belt placer). In both instances, plastic concrete samples of about 0.05 cubic meters (1.5 to 2 cubic feet) were obtained; this was in reasonable agreement with the sample volume suggested by ASTM C 94. Sampling of agitator haul units could be conducted randomly during the day. However, samplers were allowed access to the concrete on the grade only during the routine QMC quality assurance testing that was being conducted by the contractor and the Iowa DOT.

The uniformity tests measured concrete temperature (ASTM C 1064), slump, slump loss, air content, density, and compressive strength. The field test procedures were identical to the lab test procedures that were described earlier in this report, with only a few exceptions. One notable exception was that concrete compressive strength cylinders that were molded in the field were cured under lime water until they reached an age of 28 days. This was done in an attempt to allow the concrete specimens containing blended cement to achieve higher compressive strengths. It also helped to minimize the impact of early curing differences that are commonly observed in cylinders cast and then allowed to set and harden overnight in the field.

Hardened air content tests were typically conducted on core samples. However, in some instances air content tests were also conducted on concrete cylinders that were cast from field concrete. Core samples having a nominal diameter of 102 mm (4 inches) were extracted from each site by Iowa DOT personnel. All of the cores represented the full depth of the pavement slab unless noted otherwise. Of these two different types of specimens (cores versus cylinders), the core specimens should be considered to provide the most realistic estimates of the hardened air content of the pavement. This is due to the fact that they were subjected to consolidation by vibrators on the slipform paver.

FIELD SITES

Six sites were selected for the field testing program. Details are summarized in Table 4. The various sites were spread across the state and represented work conducted by four different contractors. No jobs from southwest Iowa were included in the study. Rather, an additional job from northwest Iowa (Highway 60) was selected to contrast the use of portland cement (Site 4) versus blended cement (Site 6). The job sites were located within about 20 miles of each other and the concrete mixtures used the same sources of coarse aggregate and fly ash. Hence, this was an excellent opportunity to contrast the different cement types and different contractors.

Table 4. Field sites visited during this project

Site	Location	DOT designation	Cementitious materials details	Contractor
1	Hwy 151 Jones County	NHSX-151-4(85) – 3H-53	Type I(SM) + 15% Class C ash	Fred Carlson Co.
2	Hwy 5 Marion County	STP-5-3(19) – 2C-63	Type I(SM) + 15% Class C ash	Fred Carlson Co.
3	I-35 SB Hamilton County	IM-35-6(94)140 – 13-40	Type I(S) + 15% Class C ash	Fred Carlson Co.
4	Hwy 60 Plymouth County	NHSX-60-1(21) – 3H-75	Type I/II + 20% Class C ash	Irving F. Jensen Co.
5	Hwy 34 Des Moines County	NHSX-34-9(123) – 3H-29	Type I(SM) + 20% Class C ash	Flynn Company
6	Hwy 60 Sioux County	NHSX-60-2(55) – 3H-84	Type I(SM) + 20% Class C ash	Cedar Valley Construction Co.

RESULTS AND DISCUSSION

The test results and subsequent discussion of implications of the results will be presented in this section. Supporting information that was gathered from the field or produced from laboratory investigations has been appended to this report.

Literature Survey

The literature survey that was conducted for this project is given in Appendix C. The literature survey indicated that uniformity measurements and associated performance limits have already been described in great detail by Daniel and Lobo (2005). These tests, and the associated precision values, will be used as preliminary guides to evaluate the uniformity of field mixtures. Additional precision information will also be developed in the laboratory phase of this study. Since Cable and McDaniel (1998) have already conducted extensive research on the within-batch uniformity of DOT mixtures, the field study will concentrate on the between-batch uniformity and how that may be related to fluctuations in raw materials. The literature survey also indicated that moisture sensor technology is already used in specific concrete applications; however, this technology has not migrated to the stationary mixers commonly used to construct pavements. Hence, research evaluating moisture sensors and mixing techniques is required.

Summary of Field Test Results

Site 1 (Highway 151)

Highway 151 in Jones County was the first field site monitored. Only raw cementitious materials properties, 28-day compressive strength, and hardened air content were monitored at this site. Information about the plastic air content (before and after the paver), density, and water–cement ratio were provided by the contractor. This contractor used a Rex Model S central batch plant (stationary mixer) that dispensed concrete into agitator trucks (most commonly used) or dump trucks for delivery to the grade. The contractor did not report any difficulties (mixing or workability problems) with the concrete mixture formulation that was used on this job.

Bulk chemical assays of the cementitious materials used on the project are summarized in Tables 5 and 6. The XRF method described earlier in this report (fused disk technique) was used. The test results for the blended cement (Lafarge, Type I(SM)) are expressed on an as-received basis. The test results for fly ash (Class C from Louisa generating station) are expressed on a dry basis. Slag content of the blended cement was estimated using XRD. The gypsum content and bassanite content were estimated using DSC. Bulk chemistry and slag content of the blended cement were reasonably uniform over the duration of the sampling period. Bulk chemistry of the fly ash was also relatively uniform. However, the mineralogy of the blended cement and fly ash exhibited more variation than was evident in the bulk assays. For example, the gypsum content of the blended cement had a coefficient of variation that was roughly twice as large as was observed for the bulk SO_3 content. In addition, the ratio of gypsum to bassanite (Gyp/Bas) changed significantly over the duration of the sampling period.

The results of compressive strength tests are illustrated in Figure 2. The tests were conducted on cylinders cast on the grade (moist-cured for 28 days prior to testing). Test specimens were cast at two different times (morning and afternoon) on three different days (8/18, 8/21, and 8/25/03). Mortar strength tests (standard C 109 cubes) were also conducted on the blended cement that was used in the project, and that information is also plotted in Figure 2. In general, the compressive strength tended to drop over the duration of the project and the variation between morning and afternoon test specimens tended to decrease. The cube test results tended to mimic the trend that was observed in the cylinders.

Table 5. Cement assays from Site 1 (expressed on an as-received basis)

Oxide, mass %	**CMT 8/15**	**CMT 8/18**	**CMT 8/19**	**CMT 8/20**	**CMT 8/21**	**CMT 8/22**	**CMT 8/25**
SiO_2	22.18	22.22	22.87	22.36	22.12	23.08	22.78
Al_2O_3	5.78	5.77	5.74	5.82	5.82	5.84	5.59
Fe_2O_3	3.15	3.19	2.96	3.12	3.20	2.93	2.97
CaO	58.15	58.56	57.54	58.24	58.24	57.45	57.73
MgO	4.38	4.41	4.65	4.45	4.48	4.77	4.66
SO_3	3.00	3.04	3.08	3.04	3.08	3.17	3.09
Na_2O	0.11	0.12	0.12	0.12	0.11	0.12	0.11
K_2O	0.59	0.57	0.56	0.62	0.59	0.58	0.61
TiO_2	0.35	0.35	0.36	0.35	0.36	0.36	0.42
P_2O_5	0.09	0.09	0.09	0.09	0.09	0.09	0.08
SrO	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Mn_2O_3	0.47	0.47	0.48	0.48	0.46	0.48	0.46
LOI, %	0.97	0.98	1.00	0.91	1.00	1.04	0.98
Slag, %	16	17	18	20	20	21	20
Gypsum, %	2.25	1.97	1.78	1.62	1.27	1.76	1.91
Bassanite, %	1.47	1.37	0.79	1.92	1.84	1.17	1.26
Ratio Gyp/Bas	1.52	1.44	2.27	0.85	0.69	1.51	1.52

Table 6. Fly ash assays from Site 1 (expressed on a dry basis)

Oxide, mass %	**FA 8/15**	**FA 8/18**	**FA 8/19**	**FA 8/20**	**FA 8/21**	**FA 8/22**	**FA 8/26**
SiO_2	34.59	39.15	39.82	38.31	38.08	37.06	40.89
Al_2O_3	17.57	17.52	17.95	17.81	18.13	17.86	18.39
Fe_2O_3	5.76	6.70	6.50	6.38	6.05	6.09	6.10
sum	57.92	63.38	64.27	62.50	62.26	61.01	65.38
CaO	27.65	23.64	23.89	24.97	25.29	25.39	22.89
MgO	5.23	4.59	4.70	4.90	4.94	4.97	4.37
SO_3	2.57	1.81	1.83	2.01	2.01	2.02	1.71
Na_2O	1.80	1.54	1.58	1.65	1.71	1.70	1.67
K_2O	0.34	0.60	0.56	0.51	0.49	0.48	0.59
TiO_2	1.58	1.47	1.51	1.52	1.50	1.48	1.47
P_2O_5	0.80	0.90	0.93	0.93	1.06	1.11	1.05
SrO	0.47	0.41	0.42	0.44	0.46	0.47	0.41
Mn_2O_3	0.04	0.03	0.03	0.03	0.03	0.03	0.02
BaO	0.78	0.71	0.72	0.74	0.77	0.78	0.70
Moisture, %	0.07	0.01	0.07	0.02	0.05	0.01	0.02
LOI, %	0.25	0.20	0.18	0.19	0.15	0.16	0.19

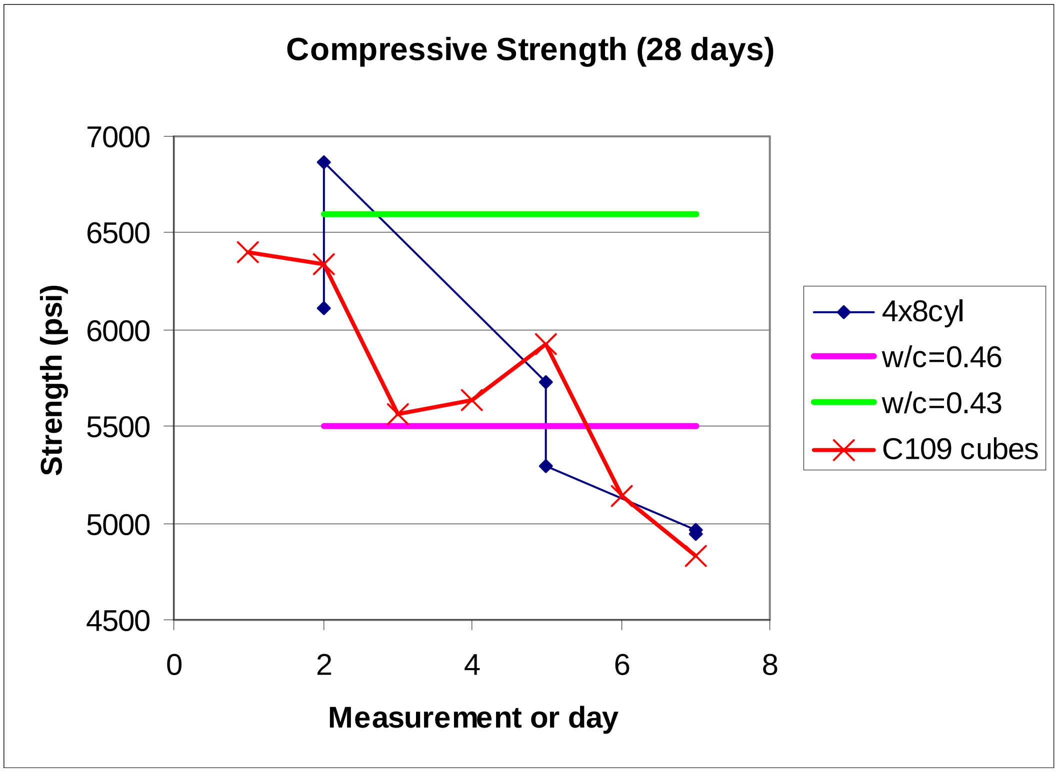

Figure 2. Illustration of compressive strength versus time for Site 1

Test results for the plastic air content and hardened air content are illustrated in Figures 3 and 4, respectively. The plastic air content was measured before and after the paver. The hardened air content was measured on cores that had been extracted from the pavement. Typically, the contractor reported plastic air contents ranging from about 7.5% to 9% (before the paver). About two to three percent air was lost during the paving process (note the "after paver" values shown in Figure 3). The plastic air content remained relatively uniform over the duration of the project. The hardened air content of the core specimens was measured on a slice taken from near the top and bottom of the core. Hence, two determinations were conducted on each core specimen. The bulk hardened air content of the core can be calculated by taking the average of the two values and then adjusting for the coarse aggregate content of the mixture. The bulk hardened air contents of the cores were 5.7% (placed 8/19/2003) and 7.0% (placed 8/20/2003). These values were in reasonable agreement with the plastic air contents that were measured after the paver.

The cumulative void-size distribution curves can be used to compare how well the field concrete matches similar mixtures that had been prepared in a laboratory (ideal batching and mixing conditions). For convenience, two bold lines have been placed on the cumulative void-size distribution curves shown in Figure 4. The lower curve, which terminates at a cumulative mortar air content of about 2%, represents a lab concrete that failed the cyclical freezing and thawing test given in ASTM C 666 (method B). This concrete exhibited an expansion of about 0.6% after 300 cycles of freezing and thawing and is indicative of a concrete with a very poor air-void distribution curve. The bold curve that has a cumulative mortar air content of about 9% represents a "good" air-void distribution curve. This concrete exhibited negligible expansion (0.03%) when subjected to over 1000 cycles of cyclical freezing and thawing.

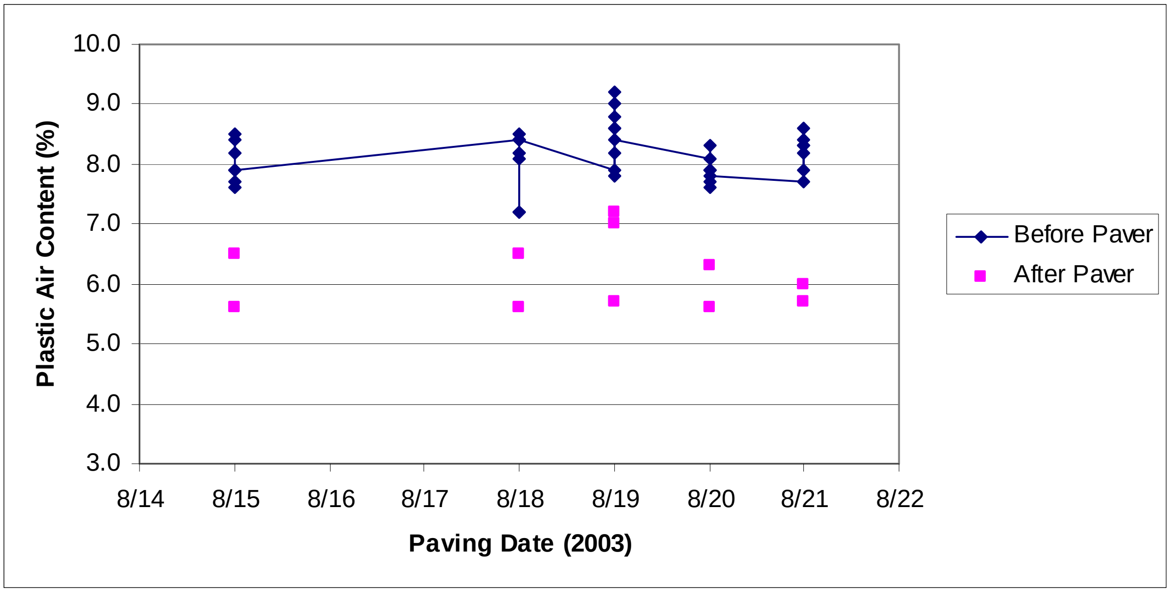

Figure 3. Plastic air content (via pressure-meter, supplied by the contractor) for Site 1

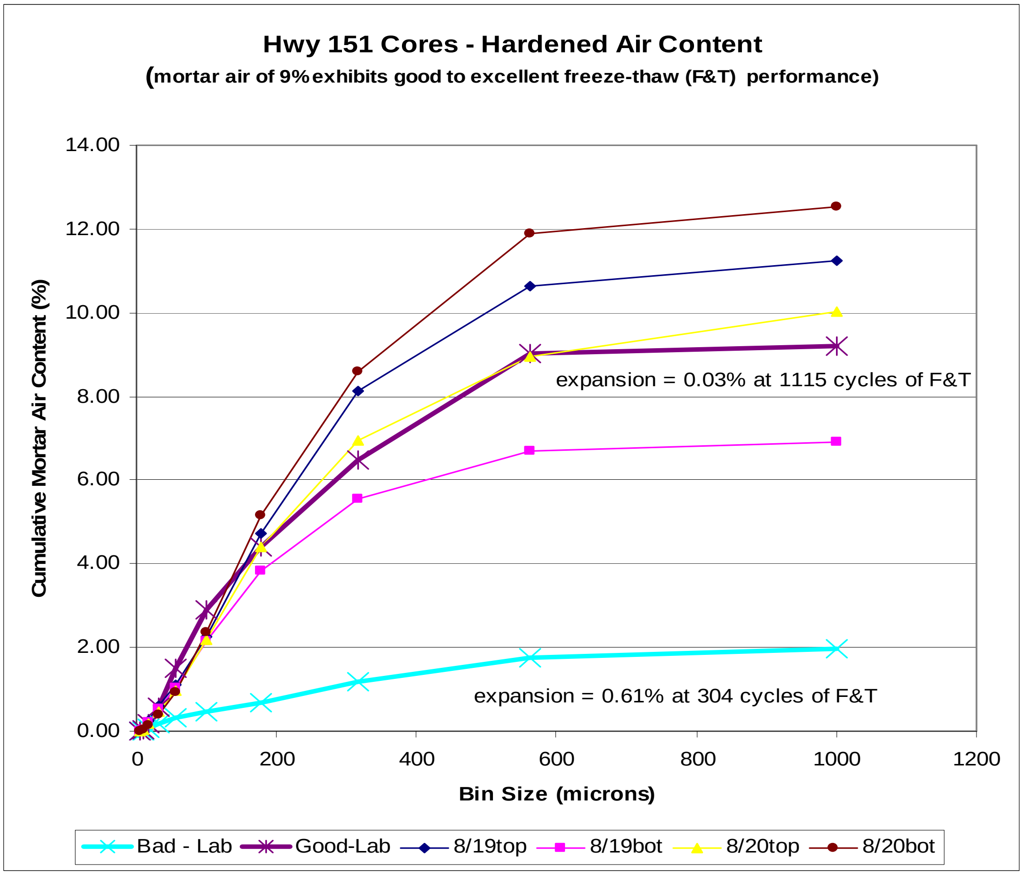

Figure 4. Hardened air content of cores extracted from Site 1

Cumulative void-size distribution curves that plot above the "good" curve should exhibit good freeze-thaw durability (assuming durable aggregates were used). In contrast, curves that plot below the "good" curve are deficient in entrained air voids. Prior experience has indicated that it is desirable to have a cumulative mortar air content of at least 6% when a bin size of 316 microns is reached. This represents about 3.8% of entrained air (expressed on an Iowa DOT C-3 concrete mix basis). In addition, the last segment of the cumulative void distribution curve should be nearly flat (the line segment from about 500 to 1000 microns). This segment of the curve gives an indication of the amount of small entrapped-air voids present in the specimen. These entrapped-air voids do little to protect the specimen from frost damage; however, they can give a false sense of security because they drastically increase the air content of the mixture.

Site 2 (Highway 5)

Highway 5 in Marion County was the second field site monitored. Bulk samples of cementitious materials were not obtained from this site because the samples were lost when the contractor moved the batch plant to a new location (Site 3). This move was conducted after completing paving in the late afternoon. On the following day, when researchers returned to get the samples that had been accumulated, the samples could not be found. A visit was made to Site 3 to see if the samples had been taken with the batch plant; however, they must have been discarded during the move. This contractor used a Rex Model S batch plant that typically dispensed concrete into agitator trucks for delivery to the grade. The haul distance from the mixer to the paver was short (only about a mile or two). The contractor did not report any difficulties (mixing or workability problems) with the concrete mixture formulation that was used on this job.

Site 2 was visited twice for collecting uniformity information. The first visit to the site was on 9/18/2003 and the second visit was on 9/23/2003. The concrete properties that were measured at this site included concrete temperature, plastic air content, unit weight, slump and slump loss (at 30 minutes), workability as estimated using the vibrating slope apparatus (VSA), 28-day compressive strength, and hardened air content.

The results obtained at Site 2 are summarized in Table 7. Field conditions were excellent for paving. Day one had temperatures in the mid to high seventies, with a relative humidity of about 55%. Day two was cooler (the noon-time temperature was only 70°F), with a relative humidity of about 30%. The temperature measurements that were conducted on the plastic concrete mimicked the ambient conditions. Slump and slump loss were nearly constant at about two inches and one inch, respectively. Air content was reasonably steady at about 8.5% (give or take about 1%). The compressive strength of test cylinders was higher on day 1 than on day 2; however, all values were easily greater than 5000 psi, so no strength problems were evident. Unit weight exhibited a correlation to air content and compressive strength (just as one would expect). The last sample of the day (Sample I in Table 7) was lower than the rest.

The first three loads on day 1 were subjected to workability testing using the VSA. The results of the test are illustrated in Figure 5. All three of the tests produced very similar results. Load A had a workability index (WI) of 0.1, load B had a WI of 0.08 and load C had a WI of 0.07. These test results will be discussed in greater detail later in this report.

The hardened air content of the core extracted from the pavement was 8.4% (expressed as concrete air, based on an Iowa DOT C-3 mixture). The cumulative void-size distribution curves from the core are illustrated in Figure 6. The rapidly rising upper limb of the curve indicated that there was a significant amount of entrapped air in the concrete. When the air content was recalculated by ignoring these entrapped voids, the hardened air content dropped to 7.4%.

Table 7. Summary of test results from Highway 5 (Pleasantville bypass)

Day	Sample	Concrete Temp. °F	Slump (inches)	Air (%)	Slump at 30 min (inches)	Slump loss (inches)	Strength at 28 days (psi)	Unit wt (pcf)
1	A	81.3	2.00	8.5	Not meas'd	Not meas'd	6860	140.6
1	B	78.3	2.25	8.0	1.00	1.25	6690	141.8
1	C	78.8	2.00	8.5	0.75	1.25	6630	141.0
2	D	68.0	1.75	8.7	0.75	1.00	5880	139.8
2	E	69.1	2.00	9.0	1.00	1.00	5640	139.8
2	F	67.7	2.00	8.2	0.75	1.25	5470	141.8
2	G	71.5	2.25	9.5	0.75	1.50	5690	138.2
2	H	70.5	2.25	9.7	0.75	1.50	5260	138.2
2	I	71.4	1.50	6.7	0.50	1.00	6540	143.0

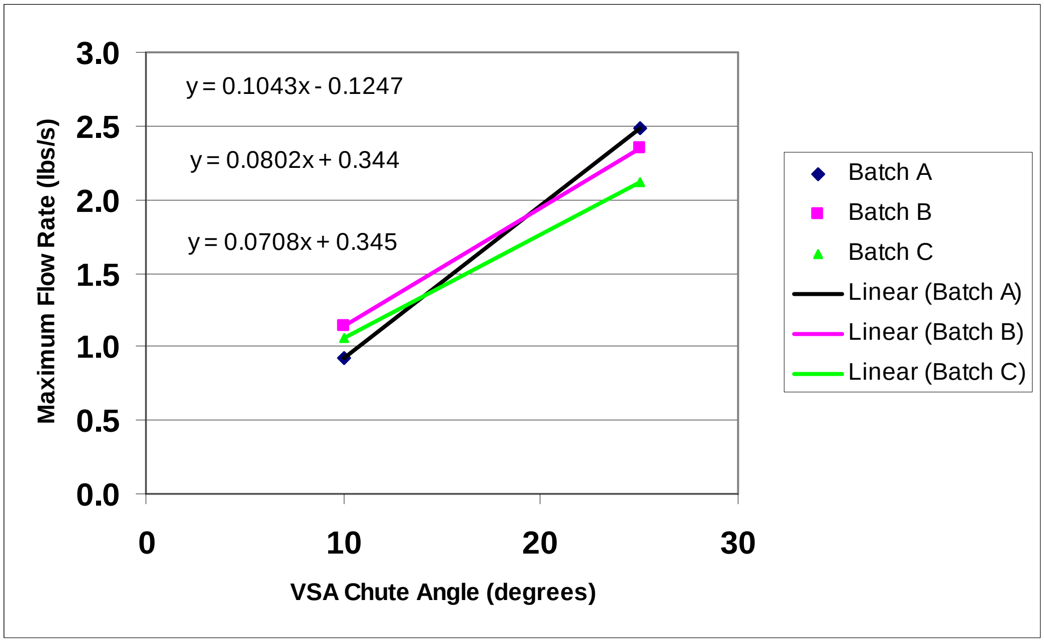

Figure 5. VSA test results from field Site 2 (Pleasantville bypass)

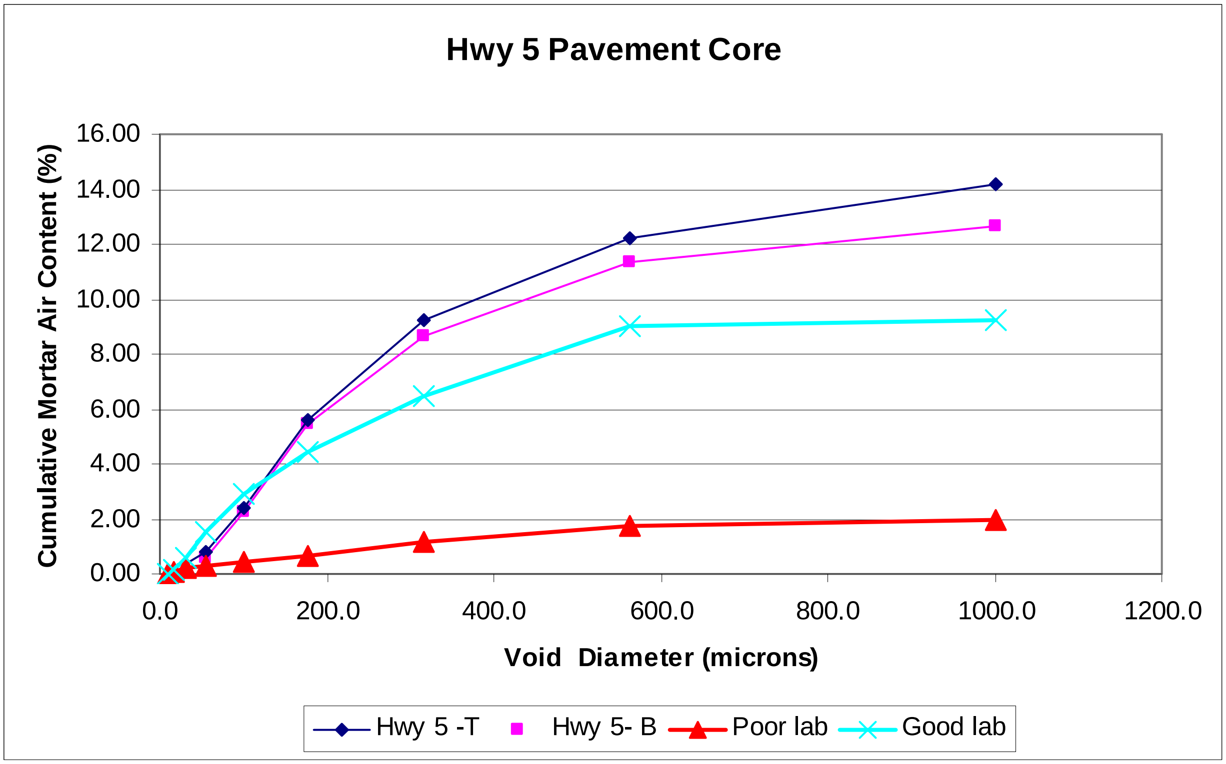

Figure 6. Hardened air content of a core extracted from Site 2 (T=top, B=bottom)

Site 3 (I-35 South Bound)

I-35 South Bound (SB) in Hamilton County was the third field site monitored. Only raw cementitious materials properties and hardened air content were monitored at this site. The contractor expressed concerns about allowing researchers access to this job because of the tight site conditions and associated safety concerns. Information about the plastic air content (before and after the paver), density, and water–cement ratio were provided by the contractor. This contractor used a Rex Model S batch plant that typically dispensed concrete into agitator trucks for delivery to the grade. The contractor did not report any difficulties (mixing or workability problems) with the concrete mixture formulation that was used on this job.

Bulk chemical assays of the cementitious materials used on the project are summarized in Tables 8 and 9. The XRF method described earlier in this report (fused disk technique) was used. The test results for the blended cement (Lehigh, Type I(S)) are expressed on an as-received basis. The test results for fly ash (Class C from Port Neal 4 generating station) are expressed on a dry basis. Slag content of the blended cement was estimated using XRD. The gypsum content and bassanite content were estimated using DSC. Bulk chemistry and slag content of the blended cement were reasonably uniform over the duration of the sampling period. Bulk chemistry of the fly ash was also relatively uniform. However, the mineralogy of the sulfate minerals present in the blended cement was again noted to be primarily composed of bassanite rather than gypsum (note the low Gyp/Bas ratios given in Table 8).

Test results for the plastic air content and hardened air content are illustrated in Figures 7 and 8, respectively. The plastic air content was measured before and after the paver. The hardened air content was measured on a core that had been extracted from the pavement. Typically, the contractor reported plastic air contents ranging from about 6.5% to 8.5% (before the paver). However, the values from the last day of paving were very erratic (ranged from 6% to 11%). The air content after the paver was more uniform and tended to range from about 6% to 7%. The bulk hardened air content of the core was 8.6% (concrete air based on a C-3 mix design). This value appeared to be inflated because of the high value obtained from the bottom of the core (see Figure 8). The top of the core had a hardened air content of 6.6%.

Table 8. Cement assays from Site 3 (expressed on an as-received basis)

Oxide, mass %	Cement 1002AM	Cement 1002PM	Cement 1003AM	Cement 1003PM	Cement 1006AM
SiO_2	24.21	24.43	24.57	24.28	24.34
Al_2O_3	8.76	8.94	9.08	8.81	8.85
Fe_2O_3	1.75	1.75	1.75	1.75	1.76
CaO	52.99	53.91	54.08	54.38	54.37
MgO	5.04	4.81	4.87	4.98	4.97
SO_3	3.29	3.30	3.36	3.40	3.40
Na_2O	0.18	0.18	0.20	0.20	0.19
K_2O	0.54	0.53	0.51	0.54	0.56
TiO_2	0.59	0.59	0.60	0.59	0.60
P_2O_5	0.05	0.05	0.05	0.05	0.05
SrO	0.04	0.04	0.04	0.05	0.05
Mn_2O_3	0.26	0.24	0.24	0.23	0.23
LOI, %	1.67	0.33	0.27	0.37	0.41
Slag %	35	36	38	34	32
Gypsum, %	3.07	0.82	0.48	0.41	0.42
Bassanite, %	1.07	2.46	2.86	2.21	2.31
ratio gyp/bass	2.9	0.3	0.2	0.2	0.2

Table 9. Fly ash assays from Site 3 (expressed on a dry basis)

Oxide, mass %	Fly Ash 1002AM	Fly Ash 1003AM	Fly Ash 1006AM
SiO_2	32.22	32.57	32.83
Al_2O_3	19.07	19.29	19.64
Fe_2O_3	6.93	7.14	7.06
sum	58.22	59.00	59.52
CaO	27.71	27.05	26.95
MgO	4.89	4.82	4.84
SO_3	2.94	2.86	2.72
Na_2O	1.87	1.77	1.76
K_2O	0.33	0.35	0.38
TiO_2	1.13	1.12	1.13
P_2O_5	1.58	1.55	1.58
SrO	0.48	0.48	0.48
BaO	0.81	0.80	0.79
Moisture, %	0.22	0.21	0.20
LOI, %	0.55	0.53	0.49

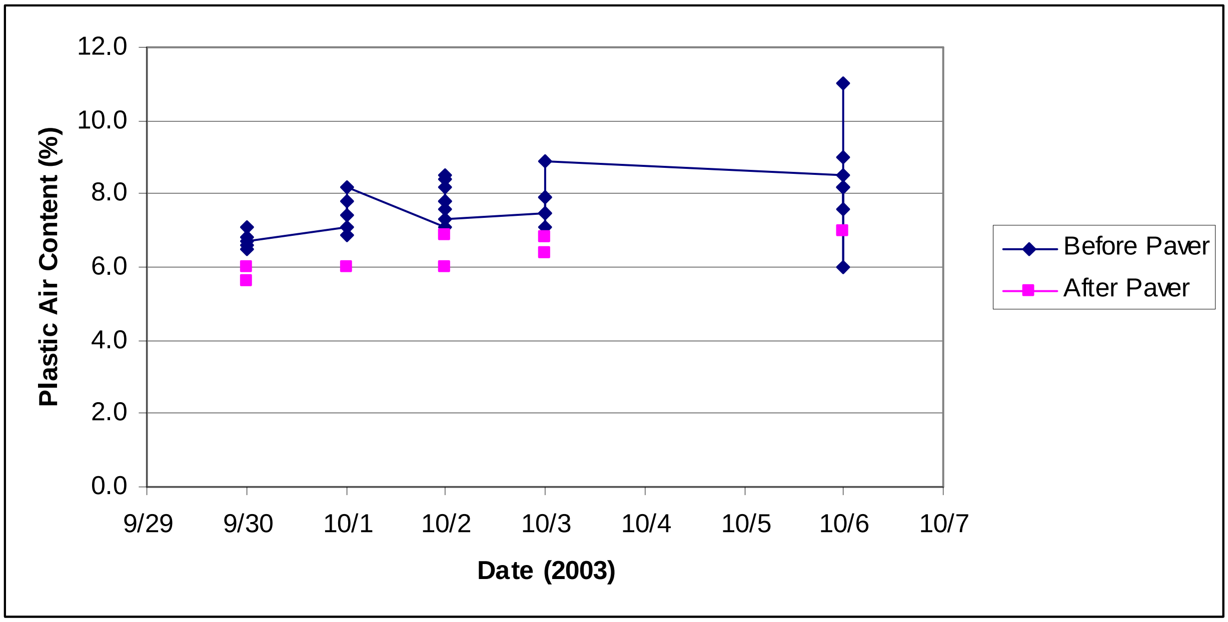

Figure 7. Plastic air content for Site 3 (via pressure-meter, supplied by the contractor)

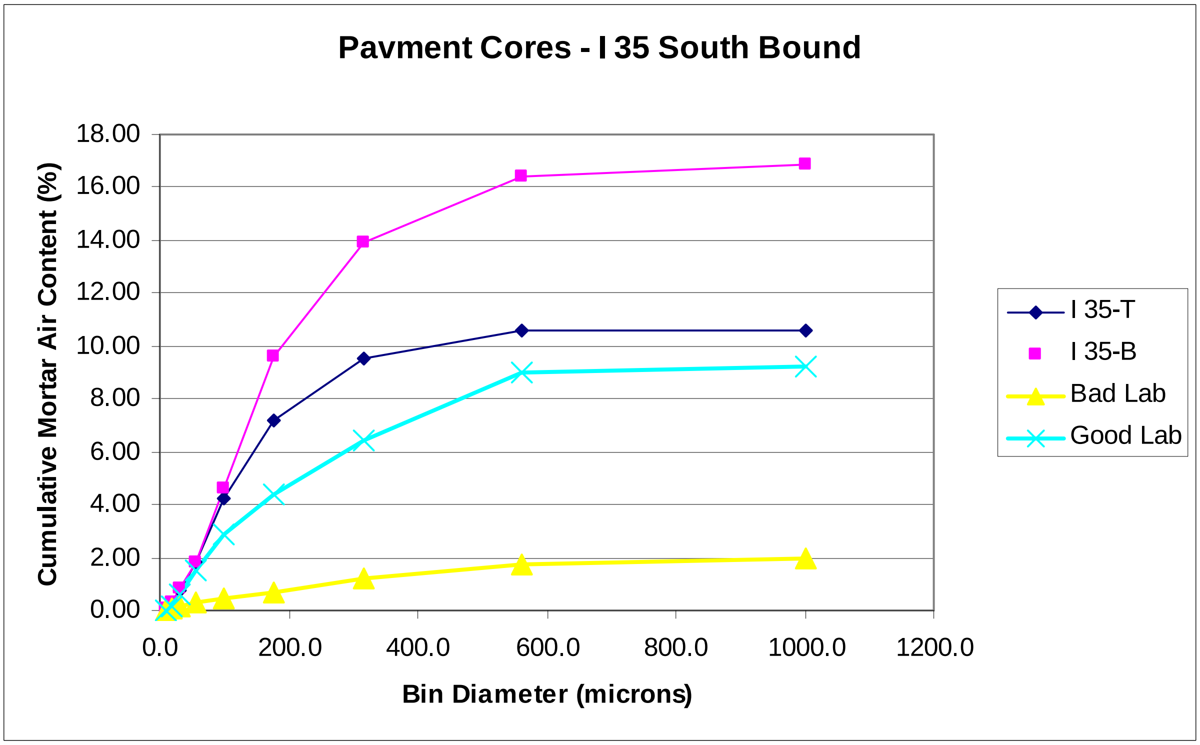

Figure 8. Hardened air content of a core extracted from Site 3 (T=top, B=bottom)

Site 4 (Highway 60)

Highway 60 in Plymouth County was the fourth field site monitored. The contractor used a stationary mixer that typically dispensed concrete into flow-boy trucks (12 cubic yards) for delivery to the grade. The contractor did note some difficulties (workability problems) with the concrete mixture formulation that was used on this job. He indicated that the mixture tended to be harsh (too rocky, lack of mortar), and this tended to make the concrete hard to finish. He also commented that he was considering the use of a retarder because the mixture appeared to be loosing workability or setting quicker than expected. The haul distance from the mixer to the grade was about 4 to 5 miles.

Site 4 was visited for two days (7/21/2005 and 7/22/2005). However, very little paving was conducted during the first day because the mixer broke down (roller failure). The mixer was fixed during the afternoon and concrete production was started early the next morning. The concrete properties that were measured at this site included concrete temperature, plastic air content, unit weight, slump, coarse aggregate content, mortar set-time, and 28-day compressive strength.

Bulk chemical assays of the cementitious materials used on the project are summarized in Tables 10 and 11. The XRF method described earlier in this report (fused disk technique) was used. The test results for the portland cement (Ash Grove, Type I/II) are expressed on an as-received basis. The test results for fly ash (Class C from Port Neal 4 generating station) are expressed on a dry basis. The slag content of the cement was determined to be negligible (<5% using XRD). The gypsum content and bassanite content were estimated using DSC. This cement contained roughly equal amounts of gypsum and bassanite, plus it also contained some anhydrite. It was not possible to comment on the variability of the cementitious materials at this site (lack of samples).

Table 10. Cement assays from Sites 4, 5, and 6 (expressed on an as-received basis)

Oxide, mass %	**Site 4 072205-AM**	**Site 5 072705-AM**	**Site 6 081805-PM**	**Site 6 081905-AM**	**Site 6 081905-PM**
SiO_2	20.60	23.16	24.29	24.47	24.32
Al_2O_3	4.17	5.60	5.99	5.99	5.92
Fe_2O_3	3.25	2.73	1.91	1.92	1.91
CaO	62.97	58.07	57.56	57.64	57.47
MgO	3.03	4.46	3.88	3.91	3.87
SO_3	2.72	2.99	3.14	3.19	3.17
Na_2O	0.16	0.13	0.18	0.17	0.17
K_2O	0.64	0.67	0.52	0.53	0.52
TiO_2	0.23	0.32	0.27	0.27	0.27
P_2O_5	0.07	0.09	0.06	0.06	0.06
SrO	0.09	0.05	0.04	0.04	0.04
Mn_2O_3	0.07	0.54	0.15	0.16	0.15
LOI, %	1.52	0.72	1.17	1.17	1.19
Slag, %	< 5	21	24	25	22
Gypsum, %	1.12	1.44	0.85	0.92	0.82
Bassanite, %	1.25	1.2	2.52	2.08	2.37
Ratio Gyp/Bas	0.90	1.20	0.34	0.44	0.35

Table 11. Fly ash assays from Sites 4 and 6 (expressed on a dry basis)

Oxide, mass %	Site 4, 072205-AM	Site 6, 081805-PM	Site 6, 081905-AM
SiO_2	34.03	33.97	35.06
Al_2O_3	18.79	18.60	18.57
Fe_2O_3	6.74	6.23	6.25
sum	59.56	58.80	59.88
CaO	26.80	26.81	26.22
MgO	4.81	4.68	4.71
SO_3	2.11	2.61	2.49
Na_2O	1.74	1.71	1.69
K_2O	0.39	0.36	0.37
TiO_2	1.55	1.59	1.59
P_2O_5	1.01	1.00	1.00
SrO	0.47	0.48	0.48
BaO	0.79	0.80	0.77
Moisture, %	0.04	0.09	0.13
LOI, %	0.18	0.37	0.38

The test results for concrete samples obtained at Site 4 are summarized in Table 12. Field conditions were brutal at this site. Day one had temperatures in the mid to high eighties, with a relative humidity of about 55%. Day two was hotter (the noon-time temperature was 91°F, reaching the high-nineties by mid-afternoon), with a relative humidity of about 68%. This caused heat index values to hover near 105°F to 110°F. Wind speed was relatively calm (5 to 10 mph, some gusts to 15 mph were recorded by early afternoon). The temperature measurements that were conducted on the plastic concrete mimicked the ambient conditions. Slump was about two inches and air content was reasonably steady at about 7.5% (give or take about 0.5%). The coarse aggregate content of the mixture was about 42%, which was within 1% of the nominal value given for the mix design. The air-free unit weight of the concrete was easily within the 1.6% (relative error) allowed by the uniformity criteria.

The setting time tests were conducted using the pocket penetrometer because the pressure gauge of the Acme penetrometer was highly erratic. This discrepancy, basically a zero point problem, was due to the extreme temperatures and lack of shade on the job site. The pocket penetrometer was only able to measure the initial set time; hence, lab tests were conducted using job materials to shed more light on the potential for rapid setting of the field concrete. The initial set times that were obtained in the field ranged from about 5 to 6 hours. These did not appear to be abnormally short considering the conditions at the site.

The compressive strength of test cylinders ranged from about 4800 to 5500 psi. The low value was obtained from concrete that had been sampled from the first batch of the morning. The average of the three sets of cylinders was 5280 psi, so the low value just failed to meet the uniformity criterion of ±7.5% as given in ASTM C 94. This criterion actually only applies to 7-day compressive strength, and this uniformity failure will be re-evaluated using the test results generated in the laboratory phase of this testing program.

Table 12. Summary of test results from Sites 4, 5, and 6

Site	Sample	Concrete Temp. °F	Slump (inches)	Air (%)	Slump @ 30 min (inches)	Slump loss (inches)	% Coarse Agg. (SSD)	Unit wt (pcf)
4	A	88.9	2.00	7.8	Not meas'd	Not meas'd	42.0	140.9
4	B	90.1	1.50	7.2	Not meas'd	Not meas'd	Not meas'd	141.8
4	C	91.6	2.00	7.2	Not meas'd	Not meas'd	42.4	141.8
5	A	82.5	2.00	6.0	1.25	0.75	39.8	143.1
5	B	85.1	1.00	5.2	0.50	0.50	40.5	144.8
5	C	83.3	1.75	6.1	0.75	1.0	39.2	143.6
6	A	85.7	1.75	7.7	1.00	0.75	44.4	141.6
6	B	78.3	1.75	7.8	1.12	0.63	45.7	141.8

Site	Sample	Initial Set Time (hrs)	Final Set Time (hrs)	Start Time	Unit wt, air-free mortar (pcf)	Strength at 28 days (psi)	Comments
4	A	5.8	Not meas'd	7:20 AM	145.5	4772	First load of day
4	B	4.8	Not meas'd	10:20 AM	Not calc'd	5510	
4	C	Not meas'd	Not meas'd		145.1	5550	
5	A	5.4	7.5	9:00 AM	148.1	5460	
5	B	4.2	6.5	12:05 PM	148.9	6260	First load after break down
5	C	4.3	6.1	1:30 PM	149.3	5930	
6	A	3.7	4.8	1:40 PM	145.6	5340	
6	B	4.9	6.2	7:50 AM	145.5	5400	

Site 5 (Highway 34)

Highway 34 in Des Moines County was the fifth field site monitored. The contractor was paving ramps at this site using the QMC mixture that had been used for mainline paving. This contractor used a CON-E-CO LO-PRO batch plant that typically dispensed concrete into dump trucks for delivery to the grade. The haul distance from the mixer to the grade was about 5 miles. The contractor did not report any difficulties (mixing or workability problems) with the concrete mixture formulation that was used on this job. However, the contractor did express some concern about the number of material changes that had occurred over the course of the project. Most of the concern was due to the lack of fly ash available for the project (three different sources had been used) and the difficulty of getting intermediate aggregate.

Site 5 was visited for two days (7/26/2005 and 7/27/2005). However, no samples of concrete were taken during the first day because of rain. The rain subsided by late evening and concrete production and paving started the next morning. The concrete properties that were measured at this site included concrete temperature, plastic air content, unit weight, slump, coarse aggregate content, mortar set time, 28-day compressive strength, and hardened air content.

A bulk chemical assay of the blended cement used on the project is summarized in Table 10. The XRF method described earlier in this report (fused disk technique) was used. The test results for the portland cement (Lafarge, Type I(SM)) are expressed on an as-received basis. The slag content of the cement was determined using XRD. The gypsum content and bassanite content were estimated using DSC. This cement contained roughly equal amounts of gypsum and bassanite, plus it also contained some anhydrite. It was not possible to comment on the variability of the cementitious materials at this site (lack of samples).

The test results obtained at Site 5 are summarized in Table 12. Other than the heavy rain on the first day, field conditions were excellent at this site. Temperatures on day 2 were in the low to mid seventies, with a relative humidity of about 55%. Wind speed was relatively calm (5 to 10 mph). The temperature measurements that were conducted on the plastic concrete tended to be about 10 degrees above ambient conditions. Slump was about two inches, and air content was reasonably steady at about 6.0% (give or take about 1%). The coarse aggregate content of the mixture was about 40%, which was within 1% of the nominal value (39.2%) given for the mix design. The air-free unit weight of the concrete was easily within the 1.6% (relative error) allowed by the uniformity criteria. Some leniency has been granted to the test results obtained for the sample denoted as B. This is because the paver broke down for about two hours in the mid-morning (i.e., between samples A and B). The batch plant was cycled down during the delay and then started up again when the paver was fixed. The sample denoted as B was taken from first load delivered to the grade after the paver was fixed.

Setting time tests were conducted on the mortar fraction of the concrete by using the Acme penetrometer. Test results for initial set times ranged from about 4 to 5 hours. Final set times ranged from about 6 to 7.5 hours.

The compressive strength of test cylinders ranged from about 5460 to 6260 psi. The average of the three sets of cylinders was 5880 psi, so the low value just met the uniformity criterion of ±7.5% as given in ASTM C 94.

Test results for the hardened air content of cylinders and cores are illustrated in Figures 9 and 10, respectively. The values for plastic air content (see Table 12) tended to be lower than those that were obtained from other projects. In addition, the contractor was observing plastic air contents in the range of about 7% to 8% (before the paver). Since our test results for plastic air content appeared to be low, it was decided to check the hardened air content of a few cylinders that had been prepared at the site. These values could be compared to the plastic air contents that were measured on site. The average bulk hardened air content of the cylinders was 6.6% (concrete air based on a C-3 mix design), which was in reasonable agreement with the plastic air content (average = 5.8%). The average value for the hardened air content was slightly high because of the high value obtained from cylinder D (see Figure 9). The bulk hardened air content of a few cores that were extracted from the pavement was 6.4% (concrete air based on a C-3 mix design). These particular specimens represented the top sections of pavement cores. It appears that the entrained air content of this pavement was slightly lower than at some of the other sites (compare Figures 4, 8, and 10); however, the air-void distribution curves indicated that the pavement should exhibit good resistance to cyclical freezing and thawing.

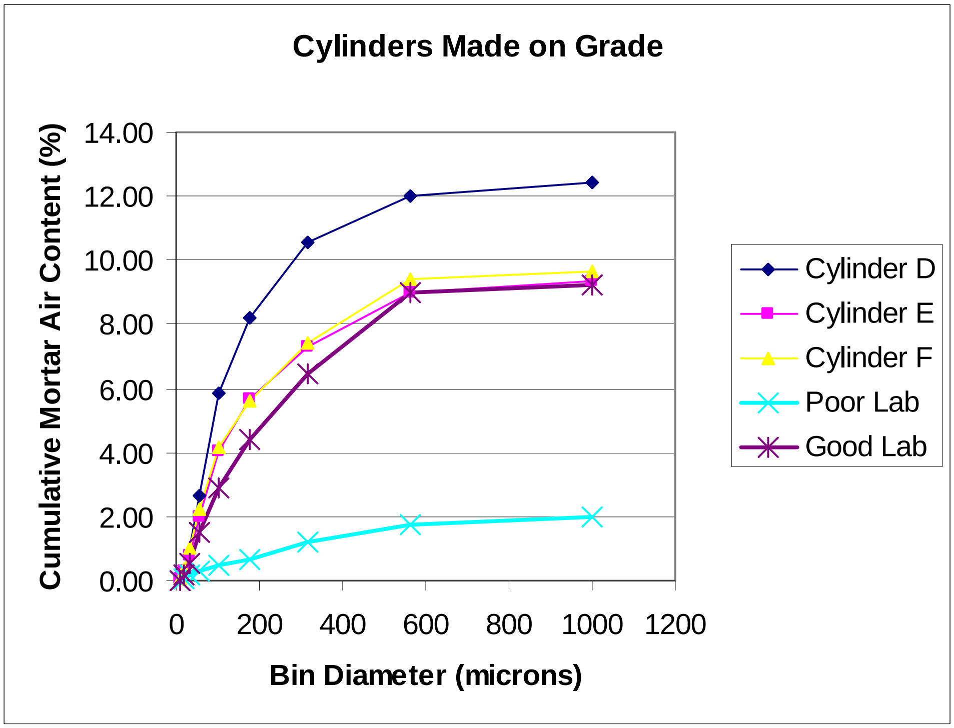

Figure 9. Hardened air content of cylinders from Site 5

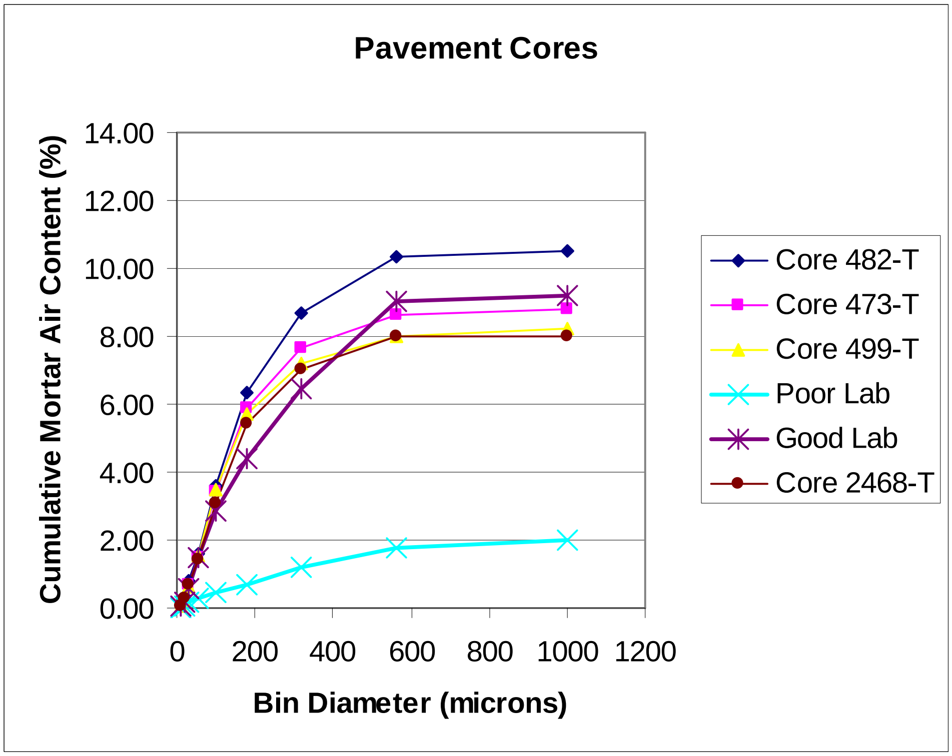

Figure 10. Hardened air content of cores extracted from Site 5 (T = top)

Site 6 (Highway 60)

Highway 60 in Sioux County was the last field site monitored. This contractor used a Vince Hagan batch plant that typically dispensed concrete into dump trucks for delivery to the grade. The haul distance from the mixer to the grade was about 4 miles. The contractor did not report any difficulties (mixing or workability problems) with the concrete mixture formulation that was used on this job. In fact, the contractor was very pleased with the mixture that was being placed at this site.

Site 6 was visited for two days (8/18/2005 and 8/19/2005). Time constraints and site conditions only allowed researchers to evaluate two samples of concrete from this site. The concrete properties that were measured at this site included concrete temperature, plastic air content, unit weight, slump, coarse aggregate content, mortar set time, and 28-day compressive strength.

Bulk chemical assays of the cementitious materials used on the project are summarized in Tables 10 and 11. The XRF method described earlier in this report (fused disk technique) was used. The test results for the blended cement (Holcem, Type I(SM)) are expressed on an as-received basis. The test results for fly ash (Class C from Port Neal 4 generating station) are expressed on a dry basis. Slag content of the blended cement was estimated using XRD. The gypsum content and bassanite content were estimated using DSC. Bulk chemistry and slag content of the blended cement were reasonably uniform over the duration of the sampling period. Mineralogy of the blended cement was also relatively constant. Again, bassanite was the primary sulfate mineral present in the blended cement.

The test results obtained at Site 6 are summarized in Table 12. Field conditions were seasonal at this site. Day one had temperatures in the low eighties, with a relative humidity of about 60%. Day two was similar (temperature was 78°F by 10AM), with a relative humidity of about 79%. Wind speed was calm (4 to 6 mph). The temperature measurements that were conducted on the plastic concrete mimicked the ambient conditions. Slump was about 1.75 inches and air content was reasonably steady at about 8% (give or take about 0.5%). The coarse aggregate content of the mixture was about 45%, which was within 2% of the nominal value (43%) given for the mix design. The air-free unit weight of the concrete was easily within the 1.6% (relative error) allowed by the uniformity criteria.

The setting time tests were conducted using theAcme penetrometer. The initial set times ranged from about 4 to 5 hours. The final set times ranged from about 5 to 6 hours. These values appeared to be in reasonable agreement with tests that were conducted at the other sites.

The compressive strength of test cylinders was nearly constant at about 5400 psi. The average of the two sets of cylinders was 5370 psi, so they easily met the uniformity criterion of ±7.5% as given in ASTM C 94.

Summary of Laboratory Study

The thrust of the lab study was to investigate several key areas that are difficult to evaluate in the field. This included an experiment that evaluated the testing error that can be attributed to the various uniformity tests. A similar evaluation was also conducted on portland cement samples obtained from the Iowa DOT. This was done to supplement the information that was gathered from the field projects because contractors generally did not sample bulk materials at an adequate frequency. A series of experiments were conducted to evaluate how a moisture sensor could be used to measure mixing efficiency in real time. And finally, the last experiments consisted of tests aimed at identifying workability problems and testing a strategy for the optimization of supplementary cementitious materials in mortar and concrete mixtures.

The raw materials that were used in the laboratory studies included portland cement (Holcim Type I and Lafarge Type I/II), fly ash from Ottumwa generating station (Class C), and slag from Holcim (grade 100). The bulk chemical composition of the raw materials is given in Tables 13 and 14. Several samples of Holcim cement and two samples of fly ash from Ottumwa Generating station were used over the course of this study. Each new batch was checked to make sure that it produced physical and chemical test results that were reasonably consistent.

Concrete mixtures were generally proportioned using an Iowa DOT C-3-20C mixture as a starting point (see Table 15). These mixtures contain about 6.5 bags of cement per cubic yard. Fly ash and/or slag were substituted for cement on an equivalent mass basis and fine aggregate was removed from the mix to compensate for the increase in volume caused by the use of the supplementary cementitious materials. Fine aggregate consisted of a natural sand from south of Ames, IA (Hallet's south pit), and coarse aggregate was a crushed limestone from Ames Mine (Martin Marietta Mine, just north of Ames, IA). Unless stated otherwise the coarse aggregate was always soaked overnight and then dried to saturated surface dry (SSD). The fine aggregate was allowed to air dry overnight at ambient lab conditions and the batch water was corrected (increased) to account for the absorption of the sand.

Table 13. Cement assays for the lab work (expressed on an as-received basis)

Oxide, mass %	Holcim Sample 1	Holcim Sample 2	Holcim Sample 3	Lafarge Type I/II
SiO_2	20.80	20.52	19.32	20.60
Al_2O_3	5.55	5.38	5.28	4.13
Fe_2O_3	2.25	2.20	2.28	3.01
CaO	64.24	63.37	64.70	62.97
MgO	1.91	2.36	2.49	3.12
SO_3	2.96	2.82	2.70	2.88
Na_2O	0.19	0.16	0.16	0.06
K_2O	0.50	0.61	0.49	0.67
TiO_2	0.26	0.24	0.22	0.40
P_2O_5	0.48	0.26	0.40	0.10
SrO	0.05	0.05	0.05	0.05
Mn_2O_3	0.05	0.04	0.06	0.49
LOI, %	0.82	1.70	1.69	1.11

Table 14. Fly ash and slag assays for the lab studies (fly ash expressed on a dry basis)

Oxide, mass %	Ottumwa fly ash Sample 1	Ottumwa fly ash Sample 2	Holcim Slag (expressed on an as-rec'd basis)
SiO_2	34.96	35.54	37.25
Al_2O_3	19.86	18.55	9.20
Fe_2O_3	5.40	5.64	0.90
sum	60.22	59.73	…
CaO	24.95	26.34	37.10
MgO	Not reported	5.14	10.31
SO_3	Not reported	2.21	Not measured
Na_2O	3.20	2.33	0.32
K_2O	0.53	0.38	0.43
TiO_2	Not reported	1.55	0.45
P_2O_5	Not reported	0.96	0.02
SrO	Not reported	0.55	0.04
BaO	Not reported	0.78	Not measured
S	Not measured	Not measured	1.08
Moisture, %	0.0	0.0	Not measured
LOI, %	0.3	0.2	Not measured

Table 15. Summary of nominal concrete mixture proportions and coarse aggregate gradation

Constituent	Absolute volume	Mass per cubic yard (lbs)
Cement (Type I/II)	0.091	484
SCM (at 20% replacement)	0.023	121
Water	0.154	260
Fine Aggregate (SSD)	0.302	1329
Coarse Aggregate (SSD)	0.370	1669
Air	0.060	
Total	1.000	

Coarse Aggregate Grading

Sieve Opening	*% Retained*
3/4" (19.0 mm)	10
1/2" (12.7 mm)	40
3/8" (9.5 mm)	25
# 4 (4.76 mm)	25

Documentation of Cement Variability and Mixture Uniformity

The goal of this section is to provide estimates of the testing error associated with the chemical and physical measurements that were conducted during this study. The testing error can then be stripped from the overall variability of the measurement to provide a better estimate of the "true" variability of the bulk material. ASTM C 1451 was used to evaluate the testing error associated with the physical measurements. In addition, the statistical nomenclature given in C 1451-99 was used for this report; however, the term “mean” will be used interchangeably with the term “average” throughout the text and tables. A slightly different strategy will be used to evaluate the testing error of the chemical measurements. However, the final calculations will be the same because it will be assumed that the variation of a measurement (s^2) is composed two parts. One component of error is related to fluctuations in materials properties (s_c^2), while the other component is related to testing error (s_e^2). Mathematically, this can be stated as $s^2 = s_c^2 + s_e^2$. Ultimately, the precision values (expressed in the form of a standard deviation, i.e., the square root of the variance) will be used to ascertain the uniformity of the bulk cement and concrete that was measured during the field portion of this research program.

Chemical testing was performed to document the variability that could be expected in bulk cements used in Iowa. It is acknowledged that the variation observed in portland cement may be a poor representation of the variability of a blended cement; however, this information helps to provide guidance on the variability issue. For example, would it be realistic to expect less variability from blended cements than for portland cements? The Iowa DOT supplied split samples of portland cements sampled during 2003 and 2004. Only the test results from 2004 will be discussed in this report. The cements were tested for bulk chemical composition via XRF (fused disk for major elements, pressed pellets for alkali and sulfate) and many were studied using X-ray diffraction. The gypsum and bassanite contents of the cement were measured using DSC because this method typically has better detection limits than X-ray diffraction and it is also much faster (about 15 minutes per sample).

CCRL 134 was used to estimate the variability in the pressed pellet XRF technique. This method was used to measure bulk sodium, potassium and sulfur (expressed as oxides) in the cement samples so researchers did not have to be concerned with potential loss of these volatile elements during the fused disk method. In addition, the sensitivity (analyte intensity for a given concentration) of the pressed pellet technique is greater than the fused disk method so the measurements tend to be more precise. Five replicate specimens were made and analyzed. The results of the tests are summarized in Table 16. The statistics for the measurements are summarized at the bottom of the table. These statistics will be used to represent the within-lab precision of the testing error (testing standard deviation, s_e) associated with the determination of sodium, potassium and sulfur. The alkali equivalent (total alkali expressed as % Na_2O) is also given in the table because many mill reports only routinely report that value.

The strategy used to define the testing error associated with the gypsum and bassanite determinations was more complicated than the one that was used for alkali and sulfur. Since no standard reference materials were available (other than the standards that were created to calibrate the DSC test method) three different cement samples were used. The cement samples were selected to cover a wide range of gypsum/bassanite ratio. Each sample was then run three or four times and the appropriate statistics were calculated (see Table 17). The statistics were inspected for uniformity, and, seeing no major discrepancies, the data was pooled together to produce a better estimate of the testing error (Taylor 1990).

Table 16. Summary of test results and statistics for the testing error for Na, K, and S

Sample	**Na2O (%)**	**K2O (%)**	**SO3 (%)**	**total alkali as %Na2O**
CCRL 134-1	0.18	0.59	3.38	0.57
CCRL 134-2	0.19	0.59	3.41	0.57
CCRL 134-3	0.19	0.59	3.41	0.57
CCRL 134-4	0.19	0.60	3.41	0.58
CCRL 134-5	0.18	0.59	3.40	0.57
Statistic mean	0.185	0.592	3.403	0.575
std dev (s_e)	0.002	0.002	0.011	0.003
CV, %	1.04	0.37	0.32	0.56
d2s	0.005	0.006	0.031	0.009
d2s%	2.94	1.04	0.91	1.59

Table 17. Summary of test results and statistics for the testing error for gypsum and bassanite

Producer #		**%Gypsum**	**%Bassanite**	**Ratio Gyp/Bas**
1		0.22	2.47	
1		0.24	2.75	
1		0.29	2.66	
1		0.28	2.14	
	Statistics for 1			
	mean	0.26	2.50	0.10
	std dev	0.03	0.27	
	CV%	12.53	10.72	
2		1.62	1.90	
2		1.39	1.72	
2		1.55	1.95	
2		1.64	2.00	
	Statistics for 2			
	mean	1.55	1.89	0.82
	std dev	0.11	0.12	
	CV%	7.34	6.34	
3		3.27	1.58	
3		3.38	1.31	
3		3.46	1.19	
	Statistics for 3			
	mean	3.37	1.36	2.48
	std dev	0.09	0.20	
	CV%	2.78	14.67	
Pooled	Standard Deviation (estimate for s_e)	0.09	0.21	
Estimates	D2S	0.24	0.58	

A summary of the statistics calculated for the cement samples provided by the DOT is given in Table 18. An estimate of the standard deviation corrected for testing error (s_c) is also given in the table. The number in brackets next to the mean from each producer denotes the number of samples that were included in the calculations. The table containing all the raw data is given in Appendix 4. There are several things to note in Table 18. First, for the chemical assays measured using XRF the testing error had a negligible impact on the overall variation that was observed - the compositional error predominated. Similar results were noted for the variation in the gypsum and bassanite contents; however, the impact due to testing error was now noticeable (but it was still small). Finally, the cements from different producers exhibited reasonably similar variability in the bulk chemical compositions but this was not true for the mineralogical compositions. The gypsum and bassanite contents exhibited significant variation at specific cement plants.

Table 18. Summary of statistics for the cement samples provided by the DOT

Producer #	Statistic	Na_2O (%)	K_2O (%)	SO_3 (%)	total alkali as %Na_2O	Gypsum (%)	Bassanite (%)	Ratio (Gyp/Bas)
1	Mean (n=5)	0.111	0.568	2.584	0.485	0.560	0.902	0.648
1	std dev	0.008	0.009	0.032	0.013	0.131	0.181	0.218
1	s_c	0.008	0.009	0.030	0.013	0.095	…	
2	Mean (n=6)	0.143	0.498	2.580	0.471	2.044	1.796	1.179
2	std dev	0.009	0.008	0.045	0.004	0.191	0.300	0.309
2	s_c	0.009	0.008	0.044	0.003	0.168	0.214	
3	Mean (n=7)	0.158	0.452	2.884	0.456	0.427	3.439	0.116
3	std dev	0.017	0.036	0.176	0.019	0.540	0.494	0.132
3	s_c	0.017	0.036	0.176	0.019	0.532	0.447	
4	Mean (n=7)	0.085	0.087	2.807	0.142	2.987	1.617	2.122
4	std dev	0.014	0.029	0.081	0.029	1.088	0.572	1.298
4	s_c	0.014	0.029	0.080	0.029	1.084	0.532	
5	Mean (n=7)	0.092	0.593	2.895	0.483	1.166	1.670	0.842
5	std dev	0.019	0.039	0.061	0.034	0.310	0.567	0.518
5	s_c	0.019	0.039	0.060	0.034	0.297	0.527	
6	Mean (n=5)	0.137	0.448	2.724	0.432	0.380	2.988	0.142
6	std dev	0.026	0.049	0.051	0.039	0.327	0.471	0.141
6	s_c	0.026	0.049	0.050	0.039	0.314	0.422	

A series of laboratory mixtures were made in an effort to estimate the variability of the uniformity tests that were used on this project. The tests were performed on five concrete mixes using three different variations of an Iowa DOT C-3 mixture (i.e., five replicates using three different mixtures for a total of 15 individual batches). The first mixture was a normal C-3 mixture without any fly ash or slag. The second mixture was a C-3-20C, and the last mixture contained a low-range water reducer (C-3WR). Nominal mixture proportions and coarse aggregate gradation were summarized earlier (see Table 15). Cementitous materials used for the mixtures consisted of Holcim cement (sample 2) and Ottumwa fly ash (sample 1). The variation for each test was pooled to provide a better estimate of the single-lab precision. The test results are tabulated in Appendix 4. A summary of the statistics calculated from the data are given in Table 19. The standard deviation of the testing error for two tests, namely the unit weight and the coarse aggregate content, was not included in the table because the calculated values appeared to be in error (i.e., the values calculated for s_e were greater than s). This suggests that there may have been some sampling problems for these two tests.

Table 19. Summary of statistics from the laboratory concrete uniformity tests

Test	Mean	Observed standard deviation (s)	Observed CV (%)	Calculated d2s	Standard deviation of testing error (s_e)	CV (%) of testing error	C 94 tolerance
Slump (inches)	2.52	0.483	19.17	1.35	0.299	11.87	1
Air (%)	5.57	0.225	4.04	0.63	0.114	2.05	1
Unit Weight (pcf)	145.1	0.709	0.49	1.99	…	…	…
Water Content (%)	12.21	0.402	3.29	1.13	0.285	2.33	…
Coarse Agg. (%)	45.1	0.920	2.04	2.58	…	…	6%
7-day Strength (psi)	5822	172.2	2.96	482	80.8	1.39	7.5%

Moisture Sensor for Mixing Efficiency

A moisture sensor was used to evaluate how mixing time and mixing procedure influenced the moisture content of concrete. The objective of this portion of the research was to determine if this type of technology could enhance the production of well-mixed concrete. This preliminary study was limited to laboratory concrete mixtures.

The moisture sensor was obtained from Hydronix Limited (Hyrdro-Probe Orbiter), and was installed in the pan mixer used for this study (see Figure 11). The output from the moisture sensor was transmitted over an RS 485 line to a computer utilizing a Windows 2000 operating system. The moisture sensor was calibrated using concrete sand that had been conditioned to various moisture contents. This allowed researchers to obtain real time (four measurements per second) estimates of moisture content directly from the concrete as it was being mixed. Recent papers by Wang and Hu (2005) and Zhang (2005) describe the background and underlying principles of moisture sensors. Figure 12 illustrates how the output can be used to monitor moisture content as a function of mixing time. All three of the batches of concrete were mixed using a process that will be referred to as “one step mixing.” This process consisted of placing all ingredients in the mixer, then adding the water and turning on the mixer. Initially the moisture content of the batch fluctuates wildly (see Figure 12). After about 35 seconds of mixing, the moisture has been distributed uniformly throughout the batch and the moisture content reading becomes stable. Once the moisture reading stabilized, additional mixing time had little impact on the output of the sensor (compare A, B, and C in Figure 12). Practical concerns, such as wear on the sensor due to aggregate impact, generally limited the total amount of mixing time evaluated during this study.

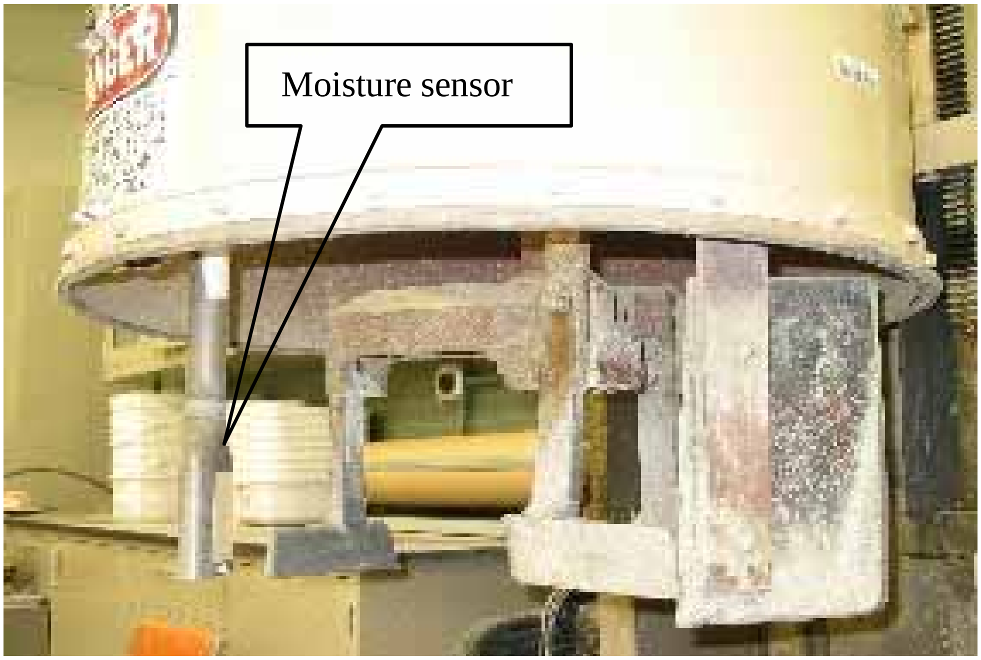

Figure 11. The moisture sensor that was used in this study

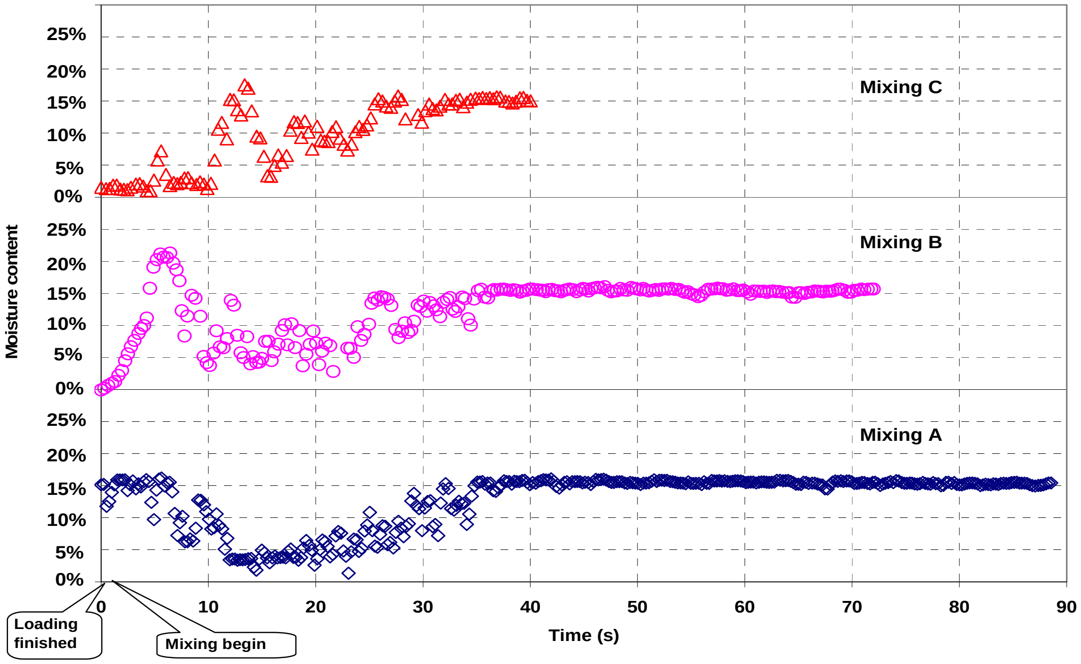

Figure 12. Illustration of output from the moisture sensor

Two testing programs were conducted to evaluate how the moisture sensor could be used to monitor the effectiveness of different mixing procedures. The first testing program evaluated four different mixing procedures while the second testing program evaluated three mixing procedures.

The first testing program used four different mixing procedures. The procedures are summarized below. Mixing time for this preliminary study was defined as the time interval from the start of mixing to the plateau of the moisture content–time curve.

(1) One-step mixing consisted of putting all the materials into the mixer, followed by adding all the water and then starting the mixer.

(2) Multi-step mixing consisted of adding materials to the mixer in a manner similar to that used at a batch plant. First, coarse aggregate was added to the mixer followed immediately by half the water for the batch. The materials were mixed until the moisture content stabilized and then the fine aggregate was added to the mixture. Again, the materials were allowed to mix until the moisture content stabilized and then the cement was added. After the moisture content of the mixture stabilized, the last of the water was added to the batch.

(3) Slurry mixing consisted of adding the cement to the mixer first, immediately followed by the water. The mixer was then turned on and mixing continued until the moisture content stabilized. Then the coarse and fine aggregate were added to the mixture.

(4) Multi-step#2 mixing was similar to that described above for multi-step mixing. However, the moisture content of the mixture was not allowed to stabilize prior to adding the various ingredients. Hence, it only took about 50 seconds to charge the mixer with all of the materials.

Concrete mixture proportions were again based on a nominal C-3 mix design. Only portland cement (Lafarge Type I/II, see Table 13) was used in this preliminary study. Hallet sand and Ames Mine limestone were used the aggregates for the mixtures. The gradation of the coarse aggregate was scalped to one-half inch maximum size so that the moisture sensor could be positioned closer to the bottom of the pan mixer. The water–cement ratio of the mixture was increased to 0.45 to compensate for the change in aggregate gradation.

The results of the preliminary study are summarized in Table 20. Mixing times varied widely because of the way that the materials were added to the mixer. Adding the materials incrementally greatly increased the total mixing time, especially if the operator waited until the moisture content stabilized before adding the next ingredient. The one-step mixing procedure produced stable moisture content readings in the concrete mixture in the least amount of time (see Figure 13). The moisture content for all of these mixture should have been identical (i.e., a fixed water–cement ratio was used for the study); however, the third mix exhibited a moisture content that was over one percent lower than the other mixes. The exact reason for this anomaly is not known but perhaps it could be related to cement paste sticking to the sides of the mixer (this mixture started from a slurry of cement and water).

Slump and VSA tests produced results that were in general agreement with each other. However, both sets of test results were clustered (mixes 2, 3, and 4 had nearly identical results) so that no reliable trends could be discerned. The exact meaning of the various VSA terms will be explained in the next section of this report.

Table 20. Summary of test results from the preliminary moisture sensor study

Mix#	Mixing Procedure	Total mixing time (seconds)	Moisture content from sensor (%)	Slump (inches)	VSA $T_{\text{loss 10}}$ (seconds)	VSA $T_{\text{20\% loss 10}}$ (seconds)	VSA Flow rate (lb/s)
1	One-step	45	15.8	2.5	1.2	12.5	1.6
2	Multi-step	260	15.8	1.5	1.6	25	0.80
3	Slurry	70	14.6	1.5	2.5	27	0.74
4	Multi-step#2	110	15.8	1.8	1.4	23	0.87

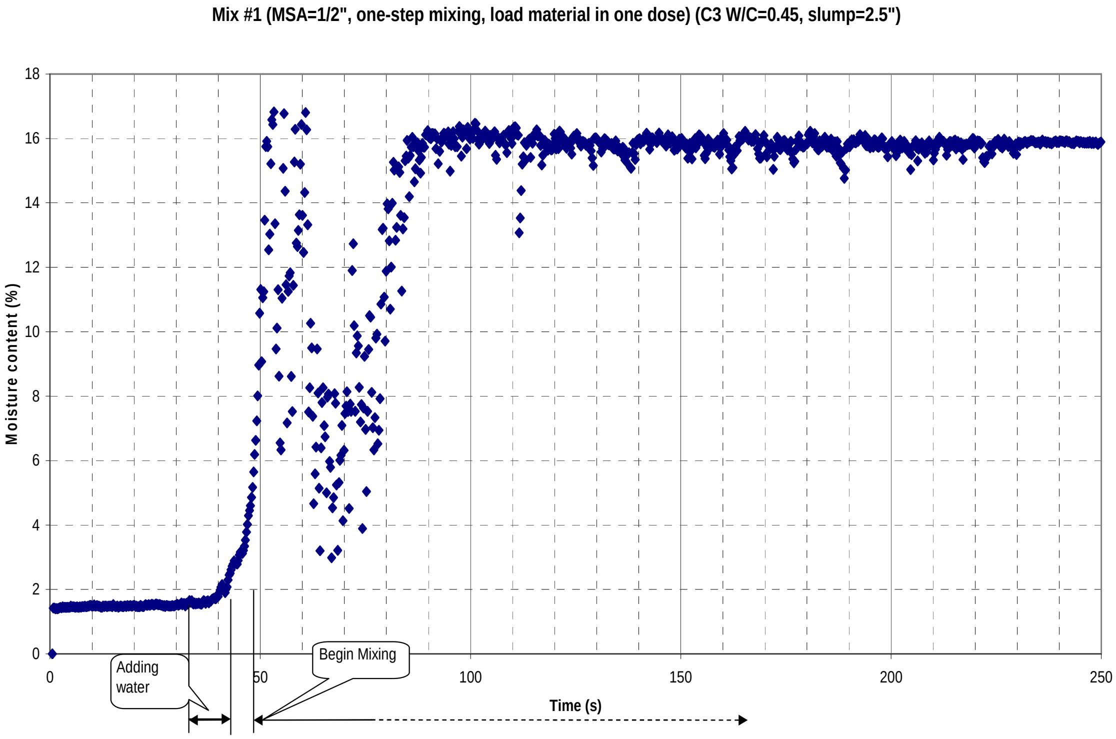

Figure 13. Illustration of the output from the moisture sensor for Mix#1

The second round of moisture sensor testing used three different mixing procedures. The one-step procedure and the multi-step procedure were defined above. For this round of mixtures the one-step method was extended for 30 seconds (Mix#1) and 50 seconds (Mix#2) after reaching the plateau of the moisture content - time curve. The third mixing technique (multi-step) was identical to the method that was described above. Concrete mixture proportions were based on a C-3-20S mix design with a water–cement ratio of 0.43. Holcim cement (sample 3) and Holcim slag (see Table 13) were used in this study. The aggregates that were used were the same as described above; the gradation of the coarse aggregate is given in Table 15.

The results of the second moisture sensor experiments are given in Table 21. Figures 14 and 15 illustrate the results obtained from the one-step and the multi-step mixing procedures. The dark lines in the figures denote a moving average (based on four points) which helps to reduce the scatter in the data. The test results were in good agreement with those that were obtained in the preliminary study. The one-step mixing process had the lowest total mixing time. All three mixing processes produced concrete with similar slump (about 2.5 inches) and compressive strength (about 3000 psi.).

Table 21. Summary of test results from the second moisture sensor study

Mix#	Mixing Procedure	Total mixing time (seconds)	Moisture content from sensor (%)	Slump (inches)	3-day compressive strength (psi)
1	One-step +30	65	15.4	2.2	3040
2	One-step + 50	91	15.4	2.5	3050
3	Multi-step	165	15.0	2.5	3070

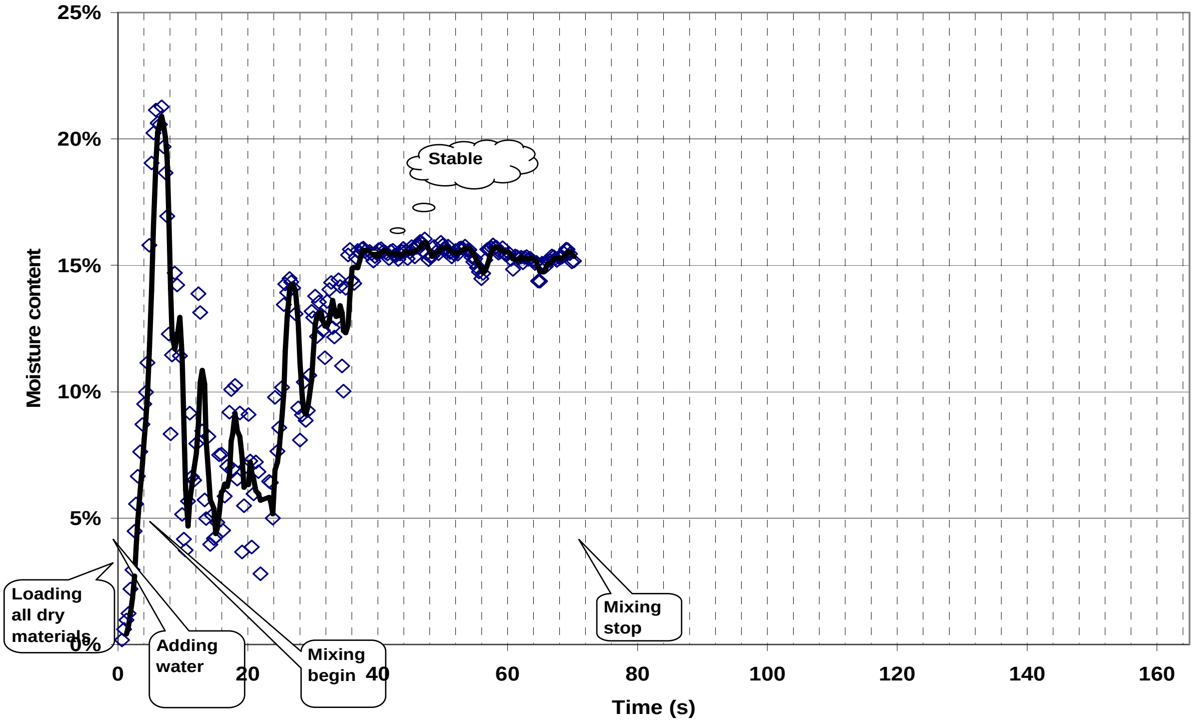

Figure 14. Illustration of the one-step mixing procedure used for mixes 1 and 2

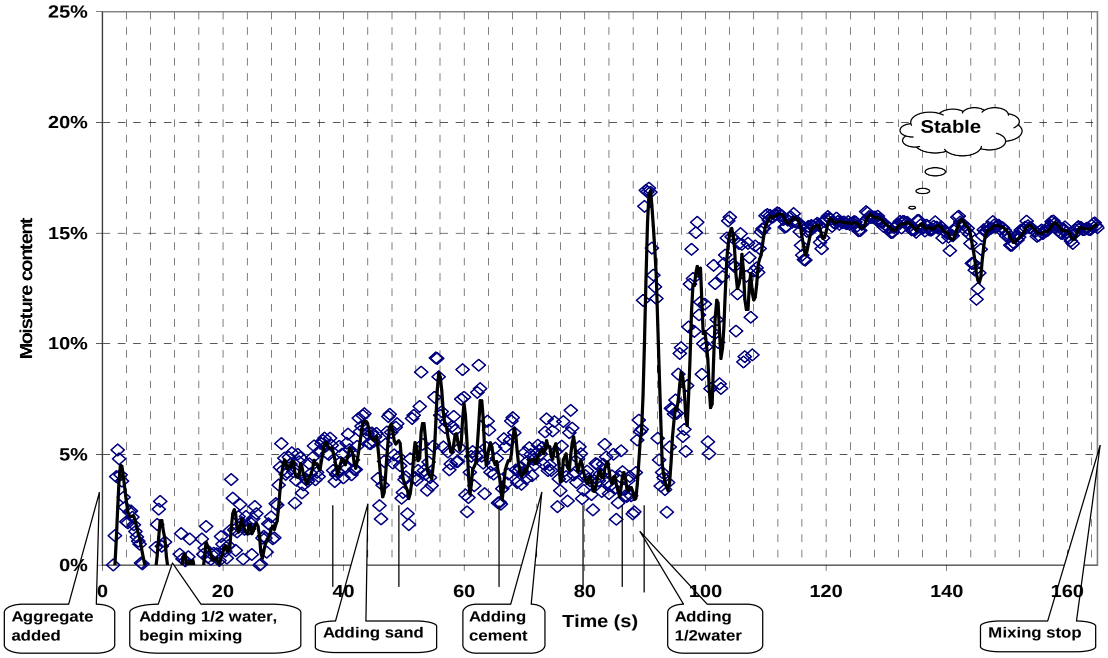

Figure 15. Illustration of the multi-step mixing procedure used for mix 3

Documentation of Plastic Properties

The plastic properties of both mortars and concrete mixtures were evaluated in this project. The thrust of the evaluation was to understand why certain mixtures exhibited poor plastic properties and to attempt to identify fundamental materials properties that were related to the poor behavior. When cementitious materials are mixed with sand to form a mortar, or with sand and rock to make concrete, the underlying assumption is that the mixture will remain plastic (i.e., workable) until it has reached its final resting place. Only then should the mixture begin to set and harden. For the purpose of this project, premature stiffening was evaluated using a modified ASTM C 359 test. Workability of concrete mixtures was evaluated using the slump test and the vibrating slope apparatus. In addition, the mortar setting time test (ASTM C 403) was used to evaluate mortars samples that were made with cementitious materials taken from specific field sites.

The modified C 359 tests have been described in detail in a previous study (Schlorholtz 2000), and the test procedure was described earlier in this report. The important variables in the test method include the total water content of the mortar (water–cement ratio is normally fixed at 0.30, but it is important to experiment with this variable), the type of sulfate minerals present in the cement, and the reactivity of the aluminate phase(s) present in the cement and Class C fly ash. Typical test results for a Type I portland cement that exhibits severe false set are given in Figure 16. The results indicate that even a modest increase in water–cement ratio (0.30 to 0.32) can help to alleviate the rapid loss of penetration that was observed when the mortar was remixed and then allowed to sit undisturbed for 15 minutes. Considerably more water is needed to alleviate the early false set tendencies of this particular cement. Similar test results can be obtained by reducing the water demand of the mixture. For example, Figure 17 illustrates the influence of increasing fly ash replacement on the false set behavior of the cement. This particular fly ash behaves like a low-range water reducer and allows all of the mixtures to perform better at the “normal” water–cement ratio of 0.30.

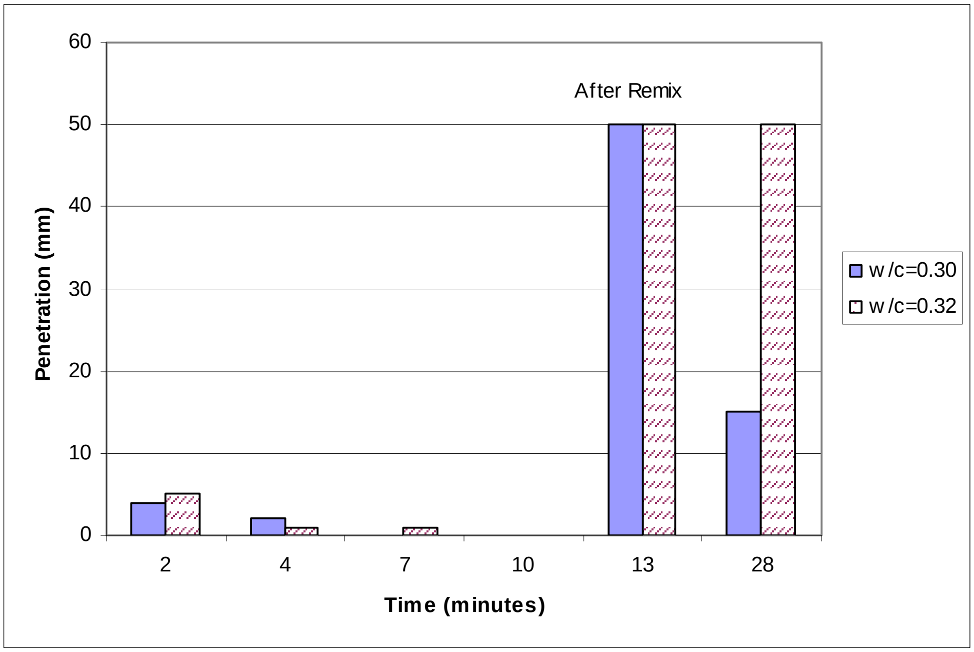

Figure 16. Illustration of severe false set in a portland cement sample

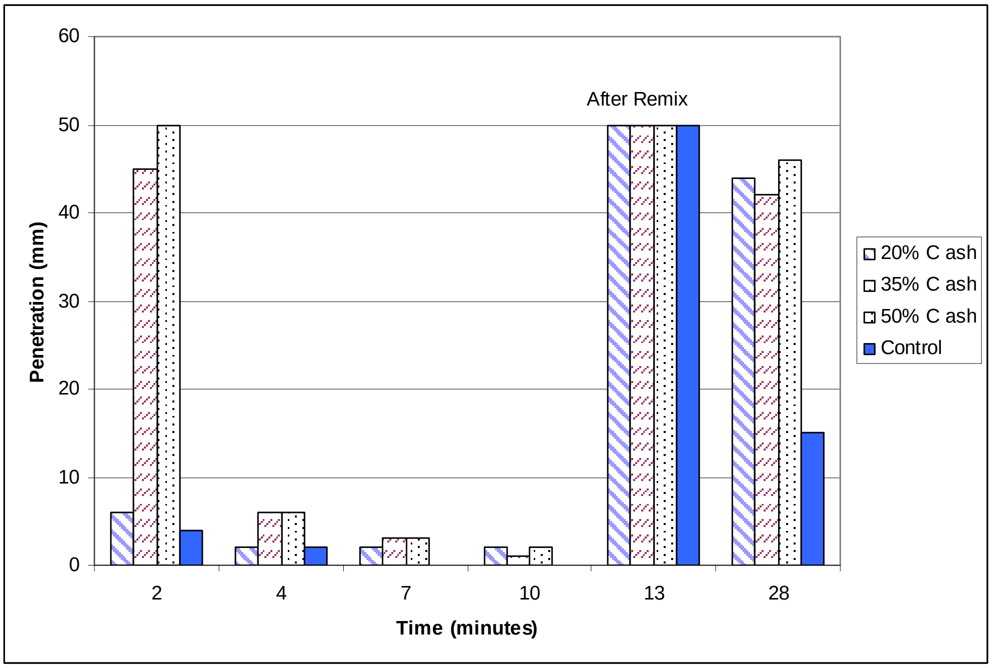

Figure 17. Illustration of how fly ash can influence the false set behavior of a mixture

For the purpose of illustration, it is advantageous to sum up the penetration readings to produce a single numerical value that represents the false set potential of any given mixture of materials. Some information is lost in the process (for example, one cannot specifically say when the cement began to loose penetration or if it regained penetration after the remix), but it allows many more test results to be viewed at one time. It also allows one to plot different variables on the x-axis to see how they correlate to the penetration values. If a mixture behaved in an ideal manner, then the sum of the penetration values would equal 300 (6 penetrations at 50 mm each). As the sum of the penetrations decreases, the mixture exhibits more severe false set. The field cement samples, obtained from sites 1, 3, 4, 5, and 6, represent typical cementitious materials used in Iowa. Only Site 4 used a portland cement; all of the remaining sites used blended cement (either Type I(SM) or Type I(S)). All of the mixtures used fly ash as an additional cementitious material that was added at the mixer. Figure 18 illustrates the false set tendencies of the field cement samples, and Figure 19 illustrates the false set tendencies of the cement–fly ash combinations. The gypsum/bassanite ratio for the various cements is plotted on the x-axis. The general trend noted in both figures is the increase in sum of the penetration values as the gypsum/bassanite ratio increases. There did appear to be one outlier in the data set. Adding fly ash to the mixture increased the penetration values, and many of the samples exhibited penetration values that exceeded 250 mm when the gypsum/bassanite ratio was greater than 1. This was a major improvement in the plastic properties of the mortars—they nearly reached the ideal behavior of 300 mm of penetration over the entire 28-minute duration of the test.

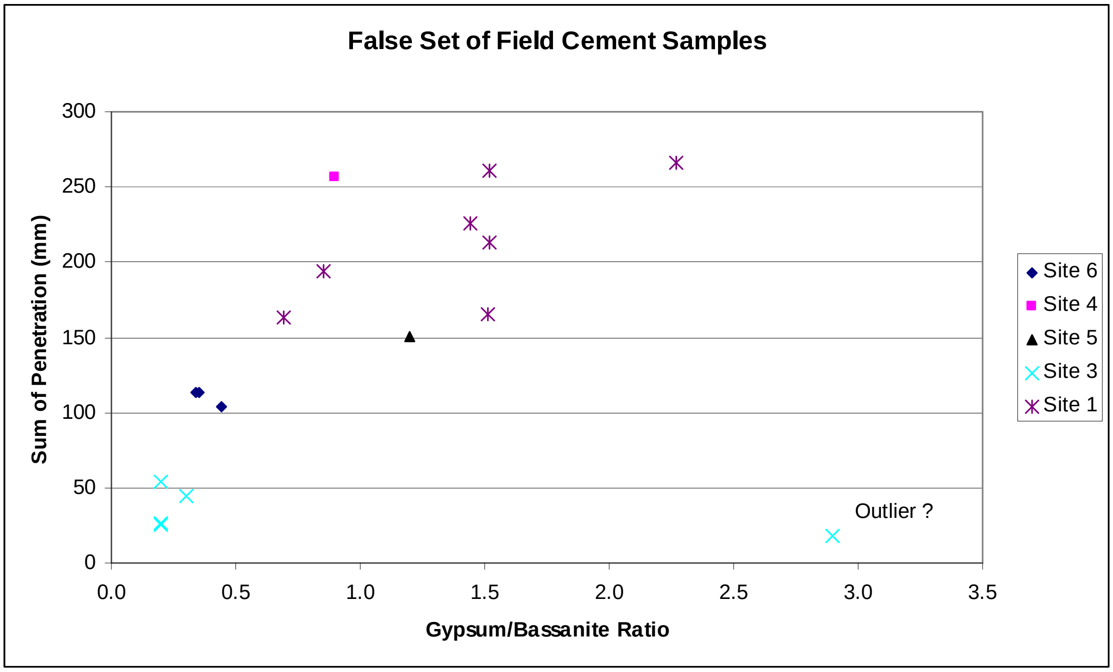

Figure 18. False set potential of the field cement samples that were collected in this study

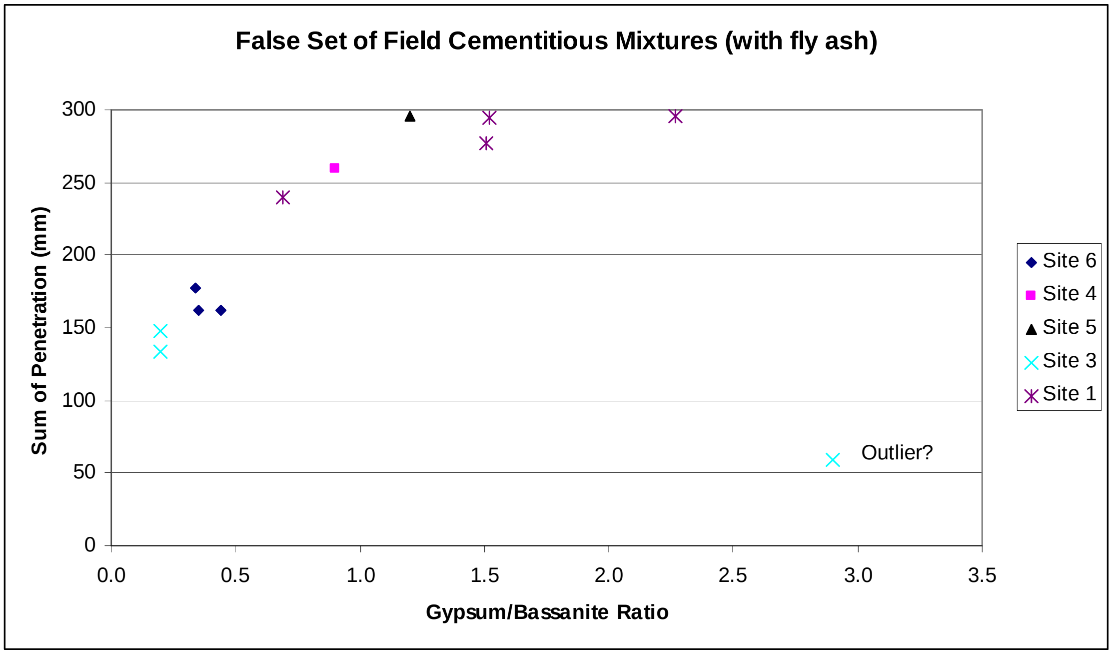

Figure 19. False set potential of the field cementitious material samples collected for this study

The workability of field concrete is normally monitored using the slump test. However, a new test method, the vibrating slope apparatus (VSA), was evaluated during this project. The VSA was developed by Wong et al. (2001) in an attempt to provide a better tool to characterize the rheological properties of stiff (low-slump, about 3 inches or less) concrete mixtures. Since pavement mixtures are usually slipformed (slump of about 1 inch at the paver), the VSA test was appealing because it had the potential to enhance researcher's ability to measure the workability of the concrete. Approximately 50 concrete mixtures were tested using the VSA during this study (the test method is given in Appendix B, and a summary of the tests is given in Appendix D). Five of the tests were conducted on real concrete mixtures in the field (at Site 2); however, only three of these tests provided useful information (calibration problems voided two of the tests). Field test results have already been illustrated in Figure 5. The basic method used by Wong et al. (2001) to interpret the data was to determine the maximum mass flow rate of the concrete at two (or more) different chute angles. An illustration of the raw data that was used to determine the maximum flow rate for batch A is given in Figure 20. The top flow curve was obtained at a chute angle of 25° and the bottom curve was obtained at a chute angle of 10° (the data was fitted with a high-order polynomial (dashed line) to aid interpretation). The workability index (W) was defined as the slope of the line (fitted to only two or three points) and the yield offset was defined as the intercept (extrapolated) with the y-axis (refer back to Figure 5).

Recent papers by Koehler et al. (2004) and Wang et al. (2005) have discussed many details of the VSA test. Both papers have discussed the advantages and disadvantages of the VSA technique. For convenience, these have been summarized in Table 22. Koehler et al. (2004) stated concerns about the assumptions that were made during the theoretical development of the test because their preliminary VSA tests failed to indicate any relationship between the yield offset (measured using the VSA) and slump. Work for this study indicated a weak (but significant) relationship between yield offset and slump (Wang et al. 2005); however, this trend only became apparent when average values from triplicate measurements were used. Re-evaluation of the data from Wong et al. (2001) was inconclusive because there was too much scatter in the data. Hence, it appears that variability is complicating the interpretation of data from the VSA. Part of the variability is due to the time required to complete the two tests that are needed to calculate the workability index. The slump loss tests that were conducted at Site 2 indicated that the concrete mixtures were losing about 1 inch of slump during the 30-minute monitoring period. Hence, one would expect that the second (or third) VSA test would also be influenced by this loss of workability. This would produce a bias in the test method.

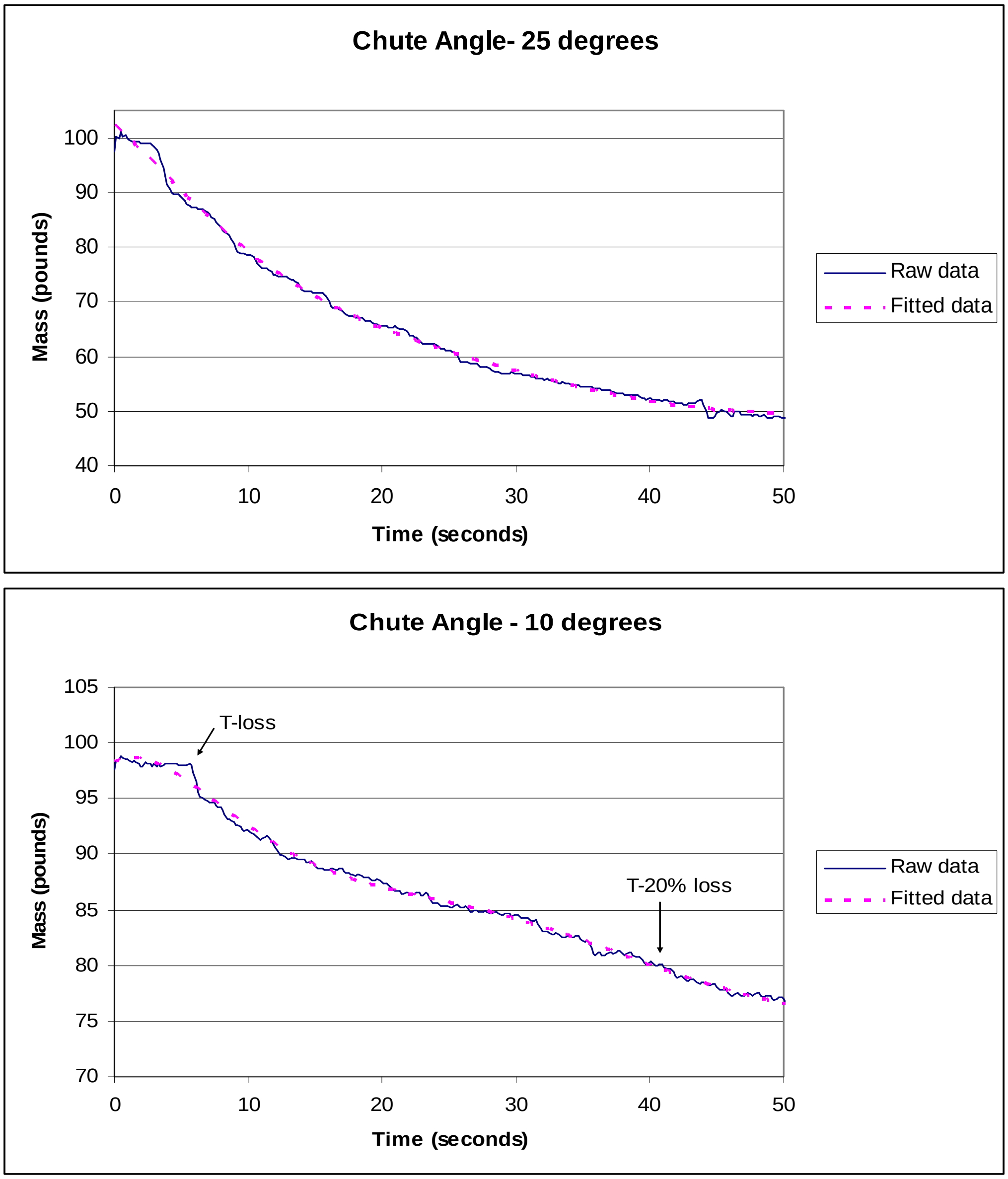

Figure 20. Flow curves from the vibrating slope apparatus (field batch A, Site 2)

Table 22. Advantages and disadvantages of the vibrating slope apparatus (VSA)

Advantages	Disadvantages
• Able to see flow differences between concrete mixtures with identical slumps • Vibration is used to create a dynamic test that is a better simulation of real field placement conditions • Test is computerized so that documentation is automatic and re-evaluation of data is possible	• Test requires too much concrete • Test takes too long to perform if multiple angles are measured • Variability of test results is large • Apparatus is large and difficult to take to the field

Both sets of researchers have proposed changes to the VSA test method to help alleviate some of the disadvantages listed in Table 22. Koehler et al. (2004) proposed the ICAR flow energy method and Wang et al. (2005) proposed new parameters taken from the raw data (flow rate) curves.

The ICAR flow energy method consists of two steps. The first step evaluates the minimum amount of energy (vibration) needed to cause the concrete to flow (Ei), and the second step determines the flow rate at a specific energy (QE). These two new parameters can be determined with the existing VSA by using only a single chute angle; this helps to alleviate the concerns about sample size and testing time. However, the determination of Ei is not very objective and additional testing will be needed to see how this impacts test results that are already highly variable.

The new parameters proposed by Wang et al. (2005) were denoted as T-loss and T-20% loss (refer to Figure 20 and note that the new parameters are typically only used for the 10° chute angle). The T-loss parameter was defined as the time (in seconds) at which concrete starts to fall out of the VSA chute. Note that the raw data curve is used to define this time parameter because the fitted data always smoothes out this important information. The T-loss parameter is somewhat similar to Ei (given above); however, it can be obtained with the current VSA procedure. The T-20% loss term was defined as the time (in seconds) that it took for 20% of the concrete to flow out of the chute. Since the flow rate out of the VSA chute is roughly linear up to T-20% loss, the average flow rate (FRavg) can be calculated by (0.2 * initial mass)/(T-20% loss – T-loss). The authors show that there is a good relationship between inverse flow rate and inverse workability index.

At present, there is no clear consensus on the applicability of the VSA to measuring the flow properties of plastic concrete. The test method has both strengths and weaknesses and, to date, most researchers have chosen to concentrate on the weaknesses. It would be best to assemble a panel of the interested researchers to compare the basic testing strategies that have been devised and work to find consensus on both the theoretical background and subsequent calculations for the VSA. At the same time, researchers could work on a good experimental plan that could be used to evaluate the variability issue. This will need to be done if this test apparatus is ever going to be standardized for general use.

Additional set-time testing was conducted to supplement the information that was obtained from the field studies. Experimentation was specifically directed at the information and materials that had been obtained from Site 4. The Acme penetrometer malfunctioned at this site due to the excessive temperatures that were encountered. A pocket penetrometer was used in the field to estimate the time of initial set of the mortar. Hence, a series of mortar mixtures were made to (1) determine the initial and final set times of cement and cement–fly ash mortars that were composed of materials obtained from the jobsite, (2) evaluate the influence of temperature on the test results, and (3) check the repeatability of the test method and how the pocket penetrometer test results correlate to the Acme penetrometer.

The results of the study are summarized in Table 23. The tests were conducted at two temperatures, 24°C (75°F) and 38°C (100°F), in an attempt to better simulate field conditions at Site 4. The sand for the elevated temperature mixtures was heated overnight at 38°C (100°F) to help boost the initial temperature of the mixtures. All of the setting time specimens were covered with plastic lids between penetration measurements; this was done to avoid moisture loss due to evaporation. The laboratory test results for the mixtures containing fly ash had initial set times ranging from about 3.5 to 5 hours and final set times ranging from about 5.5 to 7.5 hours. The initial set times were in rough agreement with the values that had been determined in the field. It was noted that the set time for mixtures placed during the early morning typically tended to be delayed by about 0.5 to 1 hour, as compared to the other mixtures. This trend was noted at all the sites where setting time tests were conducted. The pocket penetrometer appeared to provide reasonable estimates of initial set time. However, the penetration values become unreliable above about 600 psi (see Figure 21) when compared to the Acme penetrometer.

Table 23. Summary of test results from the laboratory setting time determinations

Cement–Type	Fly Ash, %	Temperature, °F	Initial Set (hours)	Final Set (hours)
Ash Grove–I/II	none	75	3.1	4.8
Ash Grove–I/II	20	75	5.0	7.4
Ash Grove–I/II	20	100	3.7	5.6
Holcim–I	none	75	3.6	5.2
Holcim–I	none	75	3.6	5.4
Holcim–I	none	100	3.0	4.4
Holcim–I	none	100	2.8	4.2

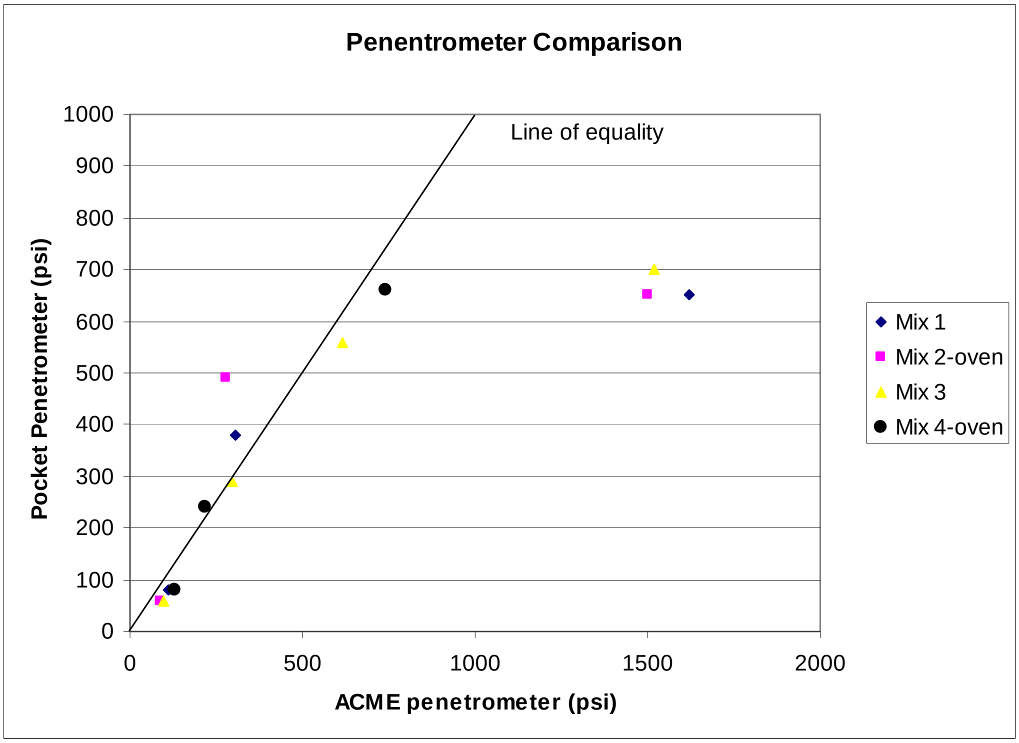

Figure 21. Correlation between the pocket penetrometer and the Acme penetrometer

Strategy for Optimizing the Use of Supplementary Cementitious Materials

An experiment was designed to evaluate a strategy for optimizing SCM dosages in binary and ternary mixtures. The goal of the experiment was to see if the optimum SCM dosages obtained from the paste and mortar tests would correspond with optimum SCM dosages in concrete mixtures. For the purpose of this study, the test response that was optimized was the compressive strength. However, a wide variety of different tests were conducted on the paste and mortar mixtures during the study.

The mass fractions of the cementitious materials used in the paste and mortar mixtures are indicated by the open circles shown in Figure 22. The ternary system investigated in this study consisted of portland cement (Holcim Type I, sample 2, see Table 13 for the chemical composition), Class C fly ash (sample 1, see Table 14), and slag (Holcim grade 100, see Table 14). The dosage of SCM was varied from 0% (the control mixture, located at the left apex of the ternary diagram shown in Figure 22) to 75% replacement. SCM was used to replace cement on an equivalent mass basis and no attempt was made to compensate for the change in the volume of the mixture that accompanied increasing SCM dosage. The mixtures were not chosen at random. Instead, three base mixtures, denoted at A (25% ash plus 75% slag), B (50% ash plus 50% slag, and C (75% ash and 25% slag) were used for the study. In addition, binary mixtures of cement and fly ash or cement and slag were also made for the study. A total of 26 individual mixtures were made for the study. Paste mixtures were tested for normal consistency, setting time, and semi-adiabatic temperature rise. Mortar mixtures were tested for water requirement, compressive strength at various curing times (lime-water curing), and linear shrinkage.

Concrete mixtures were proportioned using an Iowa DOT C-3 base mixture (refer to Table 15 for nominal mixture details and coarse aggregate gradation). The materials used in the concrete mixtures consisted of portland cement (Holcim Type I, sample 3, see Table 13 for the chemical composition), Class C fly ash (sample 2, see Table 14), and slag (Holcim grade 100, see Table 14). Mixture proportions were changed to evaluate SCM dosages from 0% (a control mixture) to 70% replacement. The fine aggregate content of the concrete mixtures was adjusted to compensate for the increase in volume caused by increasing SCM replacement for portland cement. The water–cementitious material ratio was varied to hold the slump of the mixtures constant at about 50 ± 25 mm (2 ± 1 inch). The concrete mixtures consisted of a control mixture, two binary mixtures, and three ternary mixtures (see the X's on Figure 22). The concrete mixtures were made in triplicate (typically on different days) to allow researchers to average test results and to evaluate repeatability of the test results. The plastic concrete mixtures were tested for air content, slump, slump loss, and unit weight. The compressive strength of concrete cylinders was determined after 7, 28, and 56 days of moist curing in a fog room.

All of the test results obtained from the paste, mortar, and concrete tests are summarized in Appendix D. For convenience, subsets of the mortar and concrete test results are summarized in Tables 24 and 25, respectively. This was done to simplify the process of comparing test results obtained from similar (but not identical) binary and ternary mixtures. It is important to note that all of the mortar test data was used to build the strength model that will be described later.

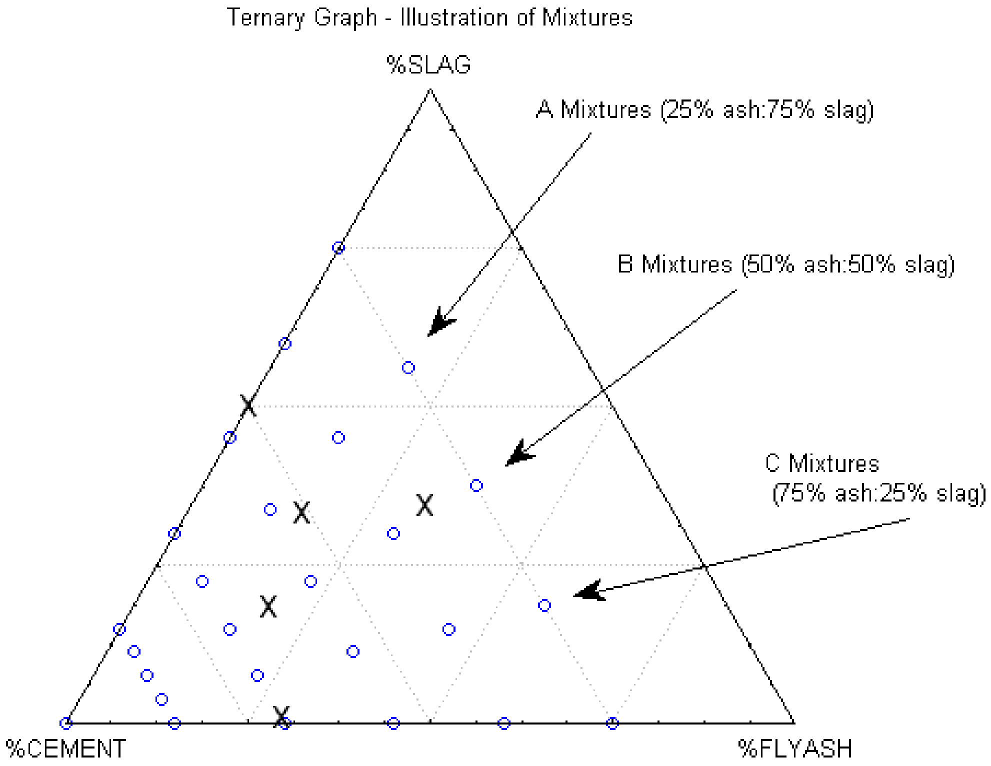

Figure 22. Illustration of the paste, mortar, and concrete mixtures made for the study

Table 24. Subset of test results obtained from specific mortar mixtures

Mix#	Cement (%)	Fly Ash (%)	Slag (%)	w/cm ratio	7-day strength (psi)	28-day strength (psi)	65-day strength (psi)	180-day strength (psi)
0	100	0	0	0.53	5570	6500	6540	6570
2	70	30	0	0.48	4360	6500	6850	7070
13	55	22.5	22.5	0.49	3390	6240	7860	9080
18	55	11.2	33.8	0.51	3630	6870	7620	9360
23	55	0	45	0.51	3620	6860	7840	9020
15	25	37.5	37.5	0.47	1200	2830	5210	8760

Table 25. Subset of test results obtained from concrete mixtures

Mix#	Cement (%)	Fly Ash (%)	Slag (%)	w/cm ratio	Slump (inches)	Air (%)	Strength (psi)		
							7 day	28 day	56 day
1	100	0	0	0.42	1.9	6.7	5510	6600	6930
2	70	30	0	0.38	2.2	6.0	6260	7670	7980
3	60	20	20	0.39	1.9	5.7	5600	7710	8480
4	50	15	35	0.40	2.0	5.8	5110	7650	8340
5	50	0	50	0.42	1.5	5.4	4950	7640	8080
6	30	35	35	0.37	1.4	5.6	3390	6700	7960

Also, the strength data was expressed in terms of relative strength (normalized to the strength of the Type I portland cement control mixture) before building the strength models. This was done in an attempt to remove the impact of the different specimen types (cubes versus cylinders) that were used to determine compressive strength. The normalization process also helped to constrain the regression coefficients within reasonable bounds so that readers could compare the coefficients in a simpler manner. It is important to realize that the modeling procedure used in this study was not rigorous; rather, it simply attempted to provide visual (conceptual) depictions of how the test response varied within the range of composition that was studied. Graphs depicting the relative strength of mortar and concrete test specimens versus dosage of supplementary cementitious material are given in Figures 23 and 24, respectively. In general, the two graphs show similar trends between relative strength and SCM dosage. However, note that the vertical scales in the two figures are not the same. It is apparent that the mortar specimens produced a wider range of test results than the concrete specimens.

The ternary diagrams shown in Figures 25, 26, and 27 illustrate the models that were produced when a quadratic regression model (with cross-product terms) was used to calculate relative mortar strength versus cementitious material composition. The x-axis (left apex of the ternary diagram) denotes the control mixture (100% portland cement). The y-axis denotes the fly ash axis (right apex of the ternary diagram; however, no mixture was composed of 100% fly ash). The z-axis denotes the slag content of the mixture (the top of the ternary diagram represents 100% slag; however, this mixture was not made in the study). The relative mortar strength, denoted as "v" in the equation near the top of the figures, can be calculated by using the mass fractions of cement, fly ash, and slag in the mixture. The relative strengths were broken into seven intervals that were about 10% apart and color coded to enhance the visualization of the test results. The entire area of the ternary diagram was color coded even though SCM replacements greater than 75% were not included in this study; hence, the reader should be very cautious about using information in those regions of the ternary diagrams.

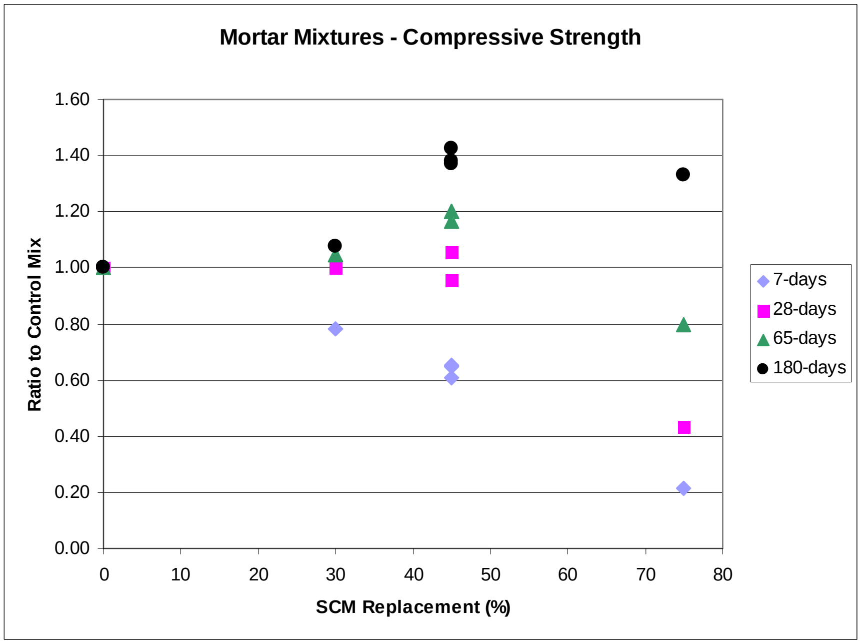

Figure 23. Relative strength of mortar cubes versus %SCM for various curing times

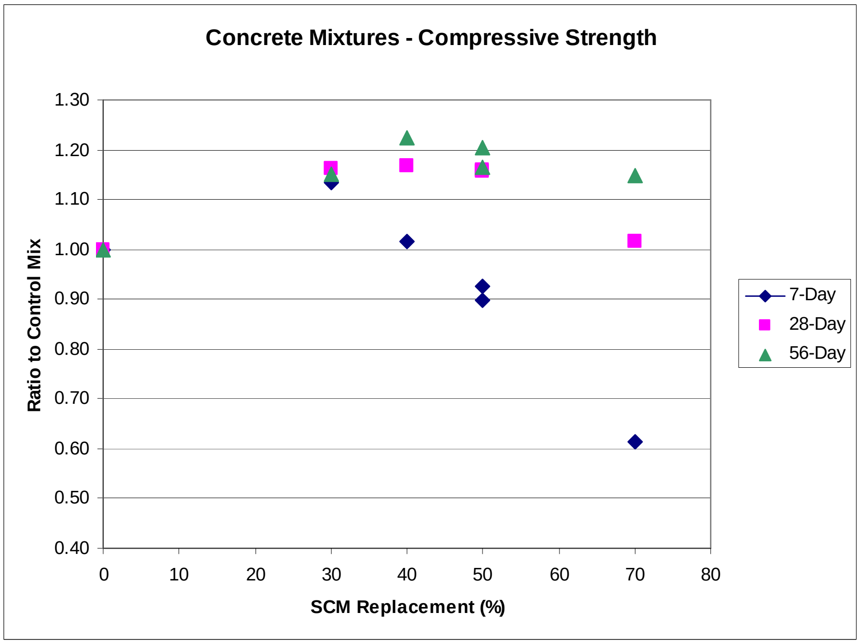

Figure 24. Relative strength of concrete cylinders versus %SCM for various curing times

Figure 25 shows the model after 7-days of moist curing. The brown and yellow colors denote the regions of higher mortar strength. At this curing time, the optimum strength values were very near to the cement apex of the diagram. Note that the SCM dosage had to be less than about 20% to produce relative strengths in excess of 90% (actually 0.883 as a decimal fraction) of the control mixture. After 65 days of moist curing, the optimum mortar strengths had shifted to the slag axis of the ternary diagram (see Figure 26, again the brown and yellow colors highlight the higher strength regions). Finally, after 180 days of moist curing, the optimum strength (the brown-colored region) had created a broad plateau near the left center of the ternary diagram. This suggested that long-term strength was strongly related to slag content (range of about 25% to 70% slag) and fly ash content (range of about 0% to 30% fly ash). However, can the strength models generated from the mortar data produce reliable estimates of concrete strength?

The results obtained from inserting the concrete mix proportion data into the compressive strength models are given in Table 25. The predicted 7-day strengths tended to be about 30% (0.30) lower than the measured strengths. A reasonable correlation was observed between the measured and predicted strengths (see Figure 28). This indicates that the predictive ability of the model could be improved by incorporating a scale factor that could compensate for the sensitivity of the mortar test results. The predicted 56-day strengths were typically within about ±15% (0.15) of the measured values (with the exception of the mixture with 70% SCM replacement). This is not bad agreement for such a simple model. Keep in mind that it only took about one week of lab time to make all of the mortar test mixtures. In contrast, it took nearly two weeks of hard work to complete the concrete mixtures (6 mixes at 3 repetitions each). In addition, when the repeatability of the concrete mixtures is taken into account (see Appendix D for the statistics), agreement to better than ±10% would be an illusion.

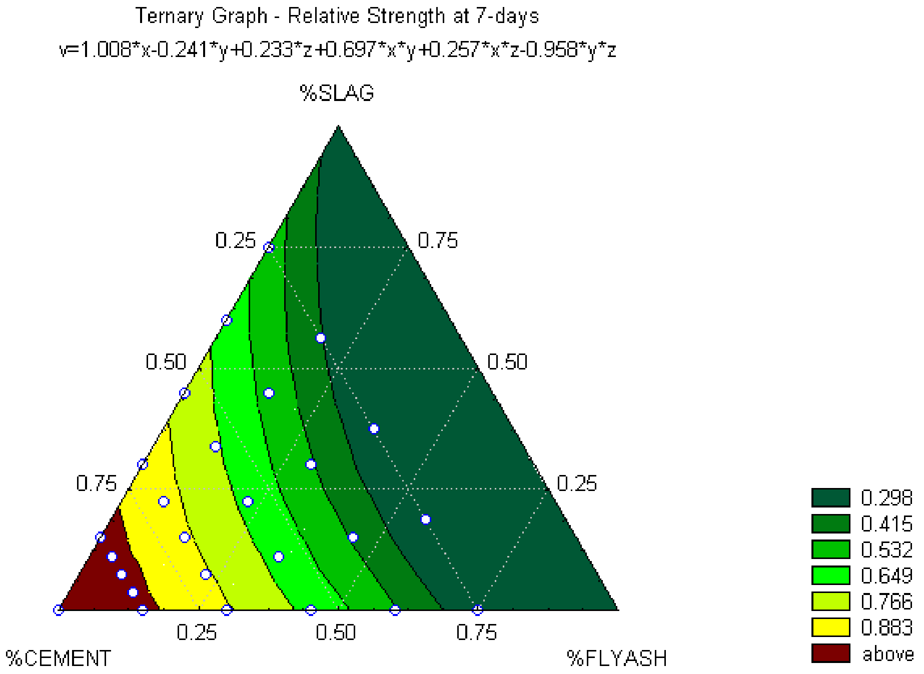

Figure 25. Ternary diagram illustrating relative mortar strength after 7 days of curing

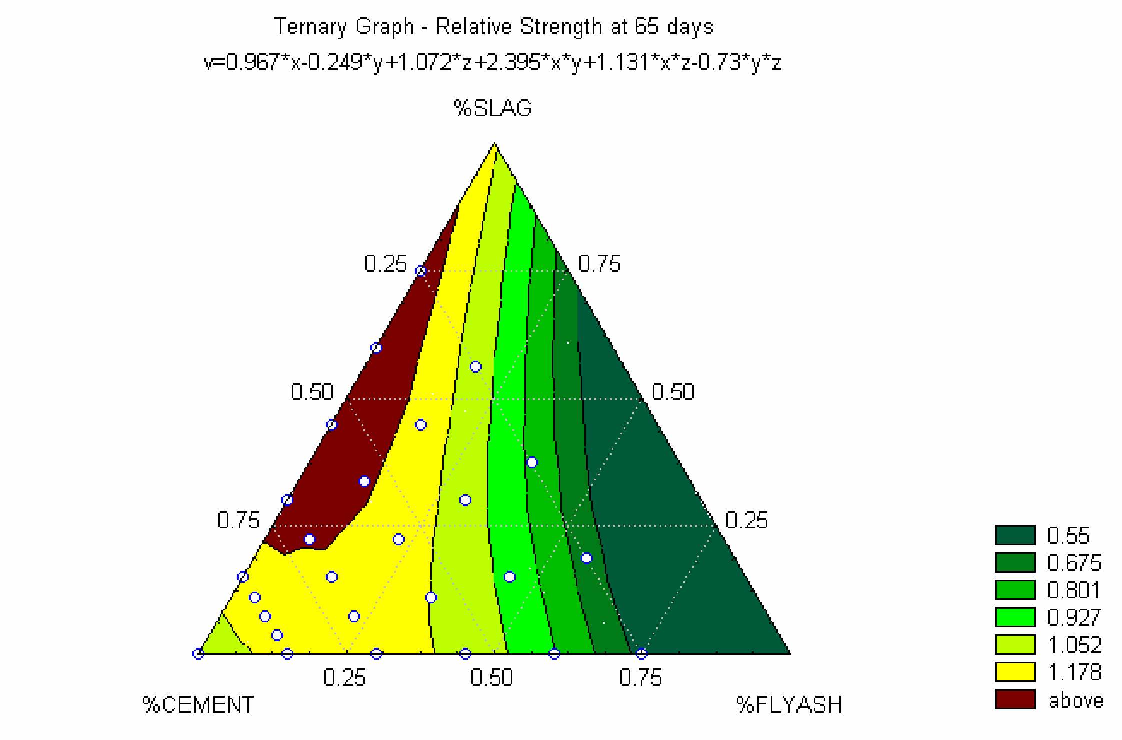

Figure 26. Ternary diagram illustrating relative mortar strength after 65 days of curing

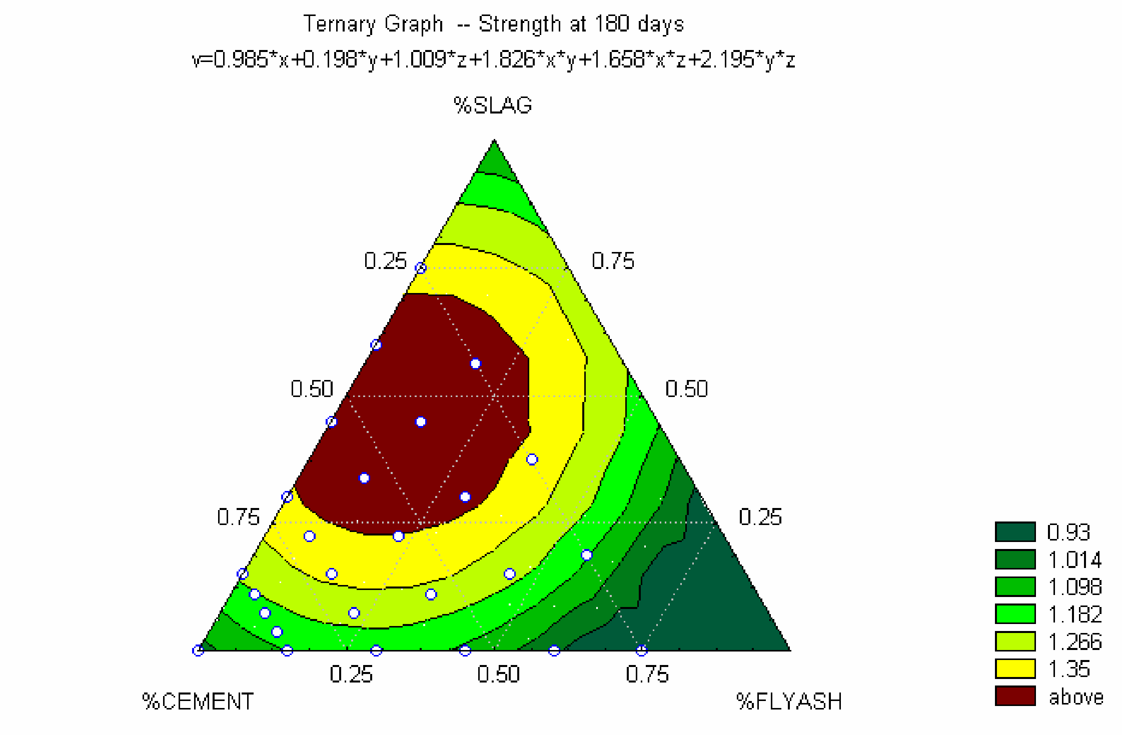

Figure 27. Ternary diagram illustrating relative mortar strength after 180 days of curing

Table 26. Summary of compressive strength (relative to control mix) obtained from the models

Mix #	SCM (%)	Cement (Mass fraction)	Fly ash (Mass fraction)	Slag (Mass fraction)	Measured 7-day	Predicted 7-day	Measured 56-day	Predicted 56-day
2	30	0.70	0.30	0.00	1.14	0.780	1.15	1.105
3	40	0.60	0.20	0.20	1.02	0.679	1.22	1.139
4	50	0.50	0.15	0.35	0.93	0.596	1.20	1.161
5	50	0.50	0.00	0.50	0.90	0.685	1.17	1.302
6	70	0.30	0.35	0.35	0.61	0.282	1.15	0.859

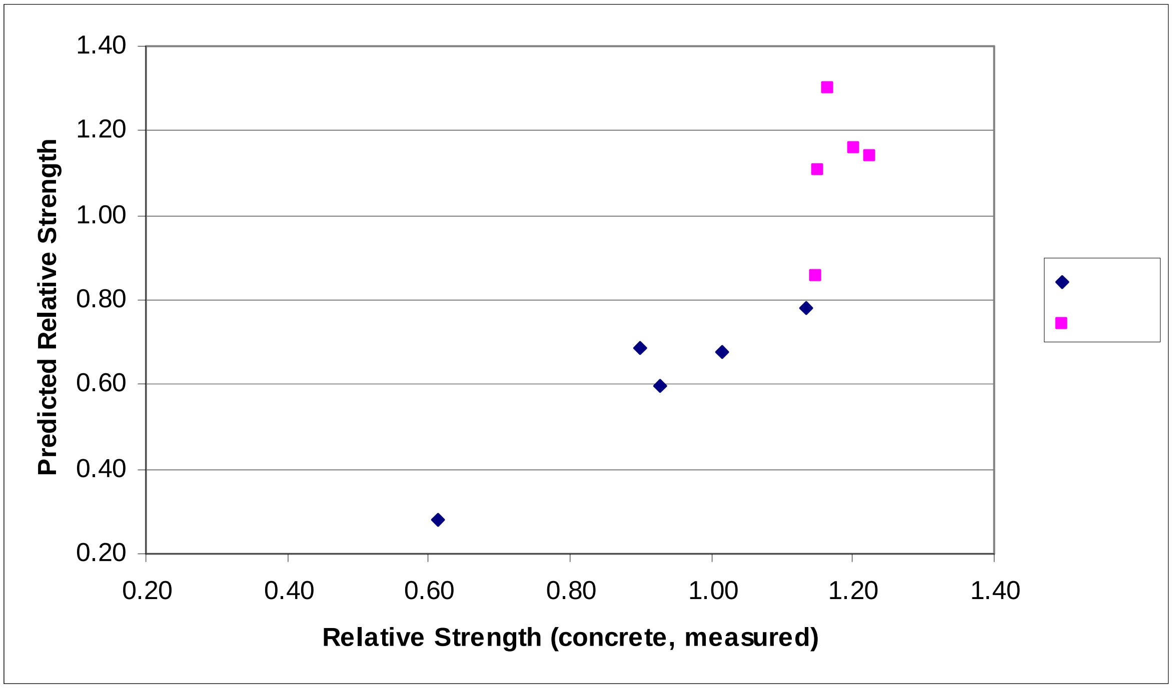

Figure 28. Predicted strength versus measured compressive strength for the concrete specimens

Another factor may also be complicating the interpretation of the test results. When the concrete mixture formulations were selected for the study, the researchers did not anticipate that the optimum strength region would become as broad as was noted earlier (refer to Figure 27). The five binary and ternary mixtures that were made tended to be located near the strength plateau (compare Figures 22 and 27). This tended to produce compressive strength test results that were all similar (with the exception of the control mixture, they were all with about ±7% of one another by 56th day of moist curing). This was not anticipated when the mixtures were selected because the researchers thought that by varying the SCM dosage from 30% to 70% a wide variety of test responses would be obtained. However, the test results can also be interpreted as indicating that the optimum strength obtained from the mortar study is similar to the optimum observed for concrete specimens. More experimentation is needed to verify this interpretation.

Compressive strength was not the only variable that was monitored during the mortar study. Many of the other tests that were conducted produced interesting results. For example, a good correlation was observed between water to cementitious material ratio used for the mortar mixtures (produced at constant flow) and the concrete mixtures (produced at constant slump). This trend is illustrated in Figure 29. It is always difficult to pinpoint the water needed to produce concrete of a specified slump, especially when no prior test mixtures had been made and when the batch proportions indicate that you have to add 40% of something that you normally do not use. In this instance, most technicians would prefer to make a series of mortar mixtures (a couple of hours of work) versus a series of trial batches (typically about one day of work).

The results obtained from the paste studies also exhibited interesting correlations to some of the mortar tests. For example, the semi-adiabatic temperature rise of paste specimens exhibited a linear relationship to the compressive strength of mortar specimens. The relationship was well defined at 3 days of moist curing, but was much less pronounced after 7 days (see Figure 30). Similar trends were noted with the areas under the thermal curves. The relationship between temperature rise and compressive strength became less apparent when the hydraulic properties of the slag started to make a significant contribution to the strength gain of the test specimens. However, it is important to note that the semi-adiabatic temperature rise tests tended to reach the maximum temperature after about 8 to 14 hours after mixing; hence, an estimate of the 3-day mortar strength could be obtained after only about half a day.

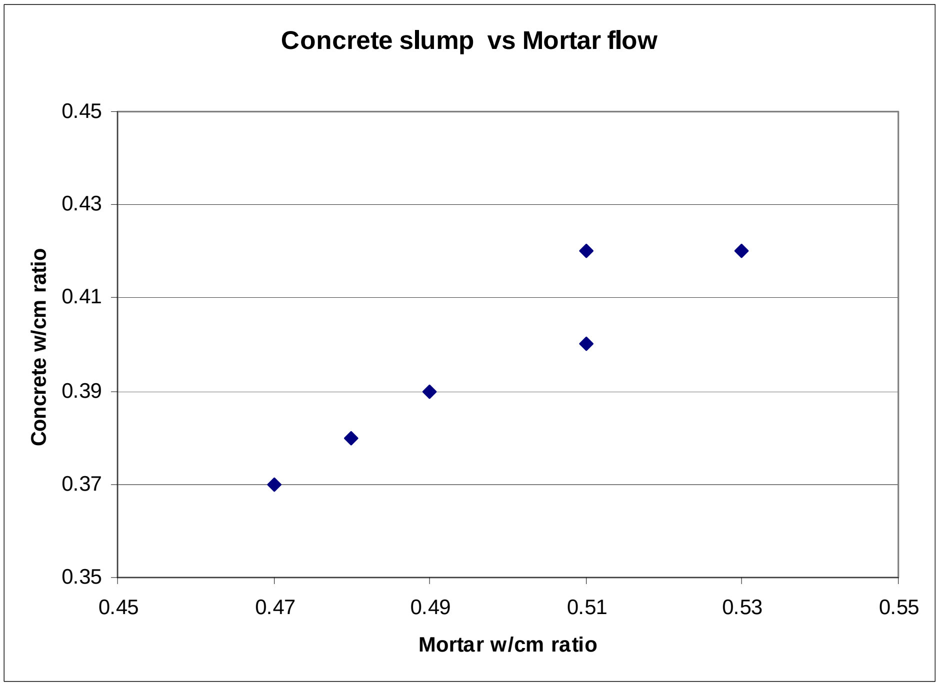

Figure 29. Relationship for the water to cementitious material ratio for the concrete and mortar specimens made for this study

Drying shrinkage can also be a concern as the cement content of a mixture increases. Normally, a change in the gradation of the coarse aggregate is used to control the shrinkage of concrete; however, one can also select cementitious materials that are less prone to shrinkage. For example, the drying shrinkage of mortar specimens is illustrated in Figures 31 and 32. The test results have again been normalized to the test result obtained from the control mortar. This was done to simplify the interpretation of the figures. Values that plot above the value observed for the control cement (1.00) tend to increase the drying shrinkage of the mortar. In contrast, values that plot below the value obtained for the control cement tend to decrease the drying shrinkage. Historically, fly ash has consistently been observed to lower the drying shrinkage of cementitious systems (Crow and Dunstan 1981). This trend is again illustrated in Figure 31 (ignoring the influence of the slag on the mixtures). If one treats the system more precisely and explicitly considers all of the binary and ternary blends that were made for this study, then the relationship given in Figure 32 is observed. The A, B, and C denote the fly ash/slag combinations that were described earlier (i.e., A=25% fly ash + 75% slag, B=50% fly ash + 50% slag, and C=75% fly ash + 25% slag). In this figure, it is apparent that slag is really behaving like a cement and tends to increase shrinkage (most probably because of the increasing volume of cementitious material in the specimens). However, the important detail to note in Figure 32 is that ternary mixtures can be formulated to entirely compensate for the shrinkage effect. We only need to know what we want. That is the reason why Halstead (1990) indicated that ternary mixtures would play such an important part in the development of concrete mixtures that exhibit performance properties that far exceed those normally obtained with only portland cement.

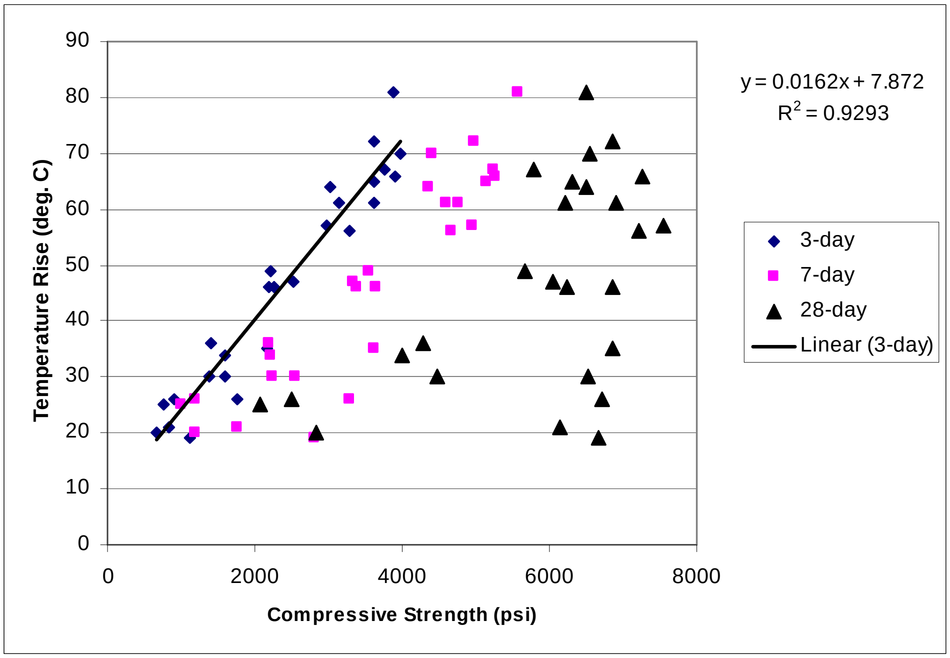

Figure 30. Temperature rise of cement pastes versus the compressive strength of mortar specimens

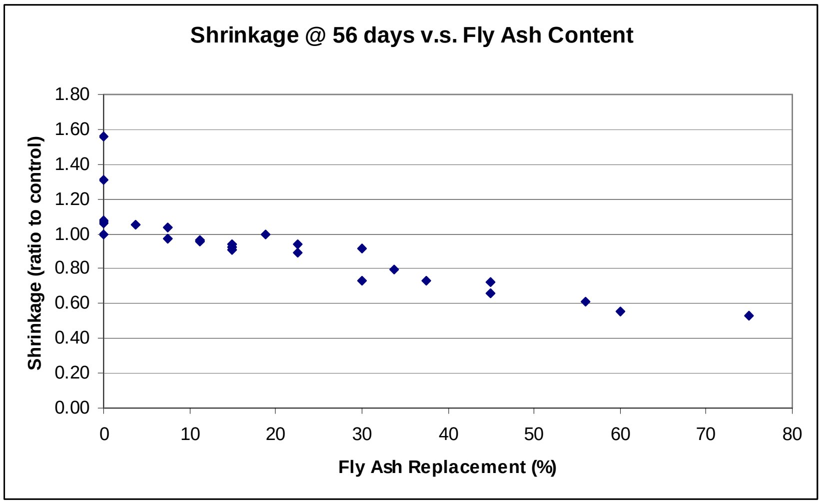

Figure 31. Influence of fly ash replacement on the relative shrinkage of mortar bars

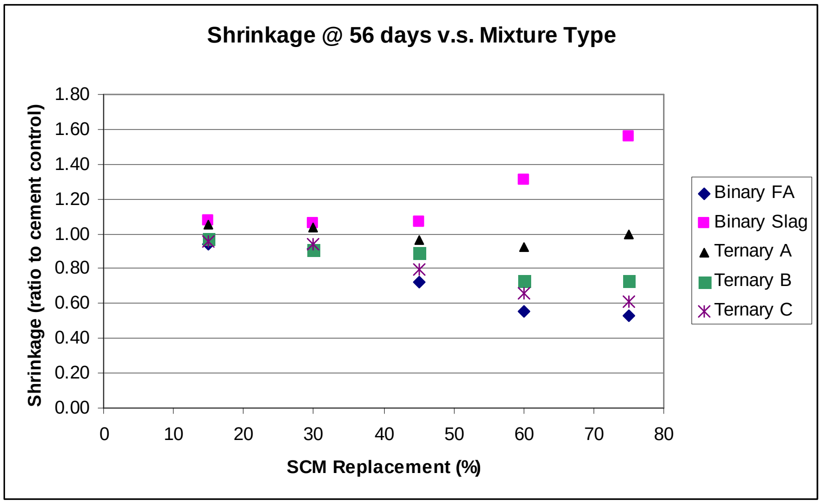

Figure 32. Illustration of how ternary mixtures impact the shrinkage of mortar bars

Further Discussion

Three specific objectives for this research project were stated earlier in this report. The first objective was to document the characteristics of a "good" concrete mix as it relates to Iowa slipform paving projects. The second objective was to conduct a laboratory evaluation of how different mixing methods and material combinations impact the uniformity and workability of concrete. Finally, the last objective was to develop guidelines for the proper optimization of materials and mixing method/time to obtain the best performing concrete pavement with a given set of performance criteria and available materials.

The first objective was accomplished. Data collected from the six field sites, although it was sporadic, provided enough information to document the characteristics of a "good" paving mix.

All six of the projects that were visited appeared to be successful. Difficulties or delays were most commonly caused by weather (rain) or mechanical breakdowns and no materials or mixing problems were noted during the visits.

A “good” paving mix normally reached the belt placer with a slump of about 44 to 50 mm (1.75 to 2 inches). This was placed on the grade and then trimmed to fit the paver. By the time the paver reached the concrete, it probably had a slump of about 19 to 25 mm (0.75 to 1 inch); this was estimated using the slump-loss information that was collected for the study. The plastic air content of the concrete (taken after the belt placer) typically ran from about 6% to 9%; however, these values are not that important. Rather, the air content after the paver is the critical measurement and that value was not measured by the researchers. Information supplied by the contractor indicated that the air content of the concrete after the paver typically was about 6% ± 1% (which is in good agreement with the requirements for frost resistance as suggested by current practice). The concrete mixture will have a water–cement ratio in good agreement with current practice for slab-on-grade concrete ($w/c < 0.45$, but it typically was about 0.40 to 0.43 for the projects monitored in this study). Finally, the aggregate grading will be optimized to provide good workability and little chance of segregation during placement.

The materials variability concerns that were mentioned earlier in this report (refer to the Background section), were not supported by the information that was gathered for this study. Much effort was expended in the laboratory phase of this study at defining the magnitude of the testing variation for the methods that were used. This was done so that the variation of the bulk material stream and the concrete stream could be estimated more accurately. The testing error was small for the bulk chemical (XRF) determinations; hence, the uncorrected standard deviation can be used as a reasonable estimate of the error in the chemical composition. The testing error for the gypsum and bassanite determinations was considerably larger than for the other chemical determinations. For example, Table 27 summarizes the chemical analysis statistics for the three major sources of blended cement that are commonly available in Iowa (the statistics were calculated using the field data presented earlier in this report). These test statistics are very similar to the statistics calculated for the portland cements used in Iowa (refer back to Table 18). Hence, one may conclude that for the elements (expressed as oxides) and compounds presented in Table 27, the magnitude of the variation is similar to that which one would expect from a normal portland cement. The slag content of the blended cements typically varied by about 5% to 10% (relative error), and the measured mean values were close to the nominal values that had been requested. The chemical composition of the fly ash samples varied considerably more than of the cement (see Table 28, again calculated using the field data), but most major oxides still exhibited coefficients of variation that were less than about 5% or 6%. From a practical standpoint, it is difficult to say if material changes of this magnitude will have a noticeable impact on the final concrete mixture. Keep in mind that fly ash is only used to replace about 15% to 20% of the cement in Iowa DOT pavement mixtures. Perhaps what contractors have really been complaining about is more closely related to changes in the source of the fly ash rather than the variation that is observed in any single source of ash. This is really an availability issue.

Table 27. Summary of blended cement statistics for the field sites visited during this study

Statistic	Na_2O, %	K_2O, %	SO_3, %	Slag %	Gypsum, %	Bassanite, %
Hwy 151 (n=7)						
Mean	0.11	0.59	3.07	19.0	1.79	1.40
Std. deviation	0.00	0.02	0.05	1.81	0.31	0.39
CV, %	4.19	3.56	1.76	9.53	17.01	27.95
s_c	0.004	0.021	0.053	…	0.292	0.331
I-35 cement (n=5)						
Mean	0.19	0.53	3.35	35.0	1.04	2.18
Std. deviation	0.01	0.02	0.05	2.03	1.15	0.67
CV, %	5.57	3.15	1.60	5.79	110.31	30.66
s_c	0.010	0.017	0.053	…	1.144	0.635
Hwy 60 cement (n=3)						
Mean	0.17	0.52	3.17	23.7	0.86	2.32
Std. deviation	0.00	0.01	0.02	1.53	0.05	0.22
CV, %	1.65	1.23	0.74	6.45	5.94	9.63
s_c	0.002	0.006	0.021	…	…	0.077

Table 28. Summary of fly ash statistics for the field sites visited during this study

Statistic	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	SO_3 (%)	Na_2O (%)	K_2O (%)	LOI (%)
Hwy 151 (n=7)								
Mean	38.27	17.89	6.23	24.82	1.99	1.66	0.51	0.19
Std. deviation	2.05	0.30	0.32	1.56	0.28	0.09	0.09	0.03
CV, %	5.35	1.70	5.11	6.27	14.17	5.12	17.12	16.11
I-35 fly (n=3)								
Mean	32.54	19.33	7.04	27.24	2.84	1.80	0.35	0.52
Std. deviation	0.30	0.29	0.10	0.41	0.11	0.06	0.03	0.03
CV, %	0.93	1.50	1.47	1.51	3.88	3.32	7.54	5.48
Hwy 60 (n=3)								
Mean	34.35	18.65	6.41	26.61	2.41	1.72	0.37	0.31
Std. deviation	0.61	0.12	0.29	0.34	0.26	0.03	0.01	0.11
CV, %	1.78	0.62	4.49	1.27	10.83	1.64	3.73	35.15

As was noted above, one of the problems associated with the use of supplementary cementitious materials is availability. A typical road construction project consumes massive quantities of raw materials. Cement (or blended cement) is a manufactured product that can be produced and stored in adequate quantities for any given project. Slag and fly ash are different because they are both by-products from major industrial processes. Iowa has chosen to minimize the slag availability issues by employing blended cements on their projects. This places the slag availability issue clearly in the hands of the cement manufacturer, who can deal with it as they see fit (vertical integration in the materials industry has greatly simplified this issue). However, the availability of fly ash can be a problem at certain times of the year. Historically, the fly ash industry has struggled to provide long-term storage for their product. Hence, market demands can easily deplete the short-term storage volumes that are available. This forces marketing agencies to utilize multiple sources of fly ash to feed a single project. This may (or may not, depending on prior experience) cause some problems for the contractor because different sources of material have the potential to change how the concrete mixture behaves. Ultimately, the contractor must still slipform any concrete that reaches the paver (the road must go on) and they view rapidly changing materials as a risk.

The second objective was also accomplished. Laboratory experimentation with the vibrating slope apparatus and the moisture sensor was generally successful. The test results indicated that these additional techniques can be employed to measure concrete workability and moisture content. However, both techniques will require a considerable amount of additional development before they become routinely used in the construction industry.

The final objective—the development of guidelines—was not accomplished. The reason that this objective was not accomplished was because of lack of clarity in the proposal when it was rewritten (focused) to accommodate the comments of reviewers. As the project progressed, it became apparent that the objective was outside the scope of the research program. This project was limited to the documentation and evaluation of raw materials and construction methods currently used in Iowa. The field study did not allow researchers to interfere with the mixture proportions, concrete mixing cycle, or construction practices that were used by the various contractors. In addition, the optimization experiments that were conducted for this study only pertained to laboratory mixtures. Hence, it would be inappropriate to base guidelines based on such limited information. The Material and Construction Optimization for Prevention of Premature Pavement Distress in PCC Pavements project (TPF-5(066)) has a much broader scope and should be able to produce more robust guidelines. In addition, other researchers have already been working to formulate guidelines for the use of supplementary cementitious materials in bridge decks (NCHRP Project Number 18-08A). When these guidelines have been thoroughly reviewed and published, they may easily be adapted to serve as guidelines for pavement concrete.

SUMMARY AND CONCLUSIONS

A study has been conducted that investigated fundamental properties of concrete paving mixtures that are commonly used by the Iowa Department of Transportation. The thrust of the study was aimed at identifying mixture problems and attempting to see if they were related to discrepancies in the properties of the bulk cementitious materials. Uniformity tests were conducted to inspect for between-batch mixing problems (variability) and workability problems.

The project consisted of a field study and a laboratory study. The field study collected information from six different projects in Iowa. The information that was collected during the field study documented cementitious material properties, plastic concrete properties, and hardened concrete properties. The laboratory study was used to develop a baseline for mixture variability information that was obtained from the field study. It also investigated plastic concrete properties using a vibrating slope apparatus (to evaluate rheology) and a moisture sensor (to evaluate mixing efficiency). In addition, the lab study also evaluated a strategy for establishing optimum mixtures of portland cement, Class C fly ash, and slag.

Observations and conclusions formulated from this study can be summarized as follows:

1. No problems were noted during the visit to Site 1 (Highway 151 in Jones County). The cementitious materials used on this project consisted of a Type I(SM) blended cement with 15% replacement of Class C fly ash. Plastic air content before the paver ranged from about 7% to 9%. Plastic air content after the paver ranged from about 5.5% to 7%. Hardened air content obtained from pavement cores ranged from about 7% to 12% (expressed as mortar air). The compressive strength of concrete cylinders broken at 28 days ranged from about 5000 to 6900 psi. Materials obtained from the project were relatively uniform. However, a perturbation in the sulfate components (gypsum and bassanite) was noted during the middle of the project. This perturbation did not have a major impact on the premature stiffening tests that were conducted during the lab study.
2. No problems were noted during the visit to Site 2 (Highway 5 in Marion County). The cementitious materials used on this project consisted of a Type I(SM) blended cement with 15% replacement of Class C fly ash. Plastic air content before the paver ranged from about 7% to 10%. Hardened air content obtained from a pavement core was about 13% (expressed as mortar air). The compressive strength of concrete cylinders broken after 28 days of moist curing ranged from about 5300 to 6900 psi. No cementitious materials were obtained from this project because the samples were lost (confusion between the researchers and the batch plant operator) when the contractor moved the batch plant to Site 3.
3. Researchers were not allowed to measure plastic concrete properties on Site 3 (I-35 south bound in Hamilton County) because of concerns voiced by the contractor (tight site conditions and associated safety concerns). The contractor indicated that the plastic air content before the paver ranged from about 6.5% to 11%. The plastic air content after the paver ranged from about 5.5% to 7%. The hardened air content obtained from a pavement core was about 13% (expressed as mortar air). The cementitious materials used on this project consisted of a Type

I(S) blended cement with 15% replacement of Class C fly ash. Materials obtained from the project were relatively uniform. However, the blended cement contained bassanite ($CaSO_4 \bullet \frac{1}{2}H_2O$) as the primary sulfate mineral throughout most of the project. This had a major impact on the premature stiffening tests that were conducted during the lab study. All the samples of blended cement exhibited severe false set during the premature stiffening tests. Addition of 15% fly ash to the cementitous material improved the test results (i.e., the mixture was less prone to false set); however, this site still exhibited the poorest test results that were observed during the study.

4. A mechanical problem (main roller failure on the mixer drum) occurred during the visit to Site 4 (Highway 60 in Plymouth County), and this limited the amount of information that was obtained from the site. The cementitious materials used on this project consisted of a Type I/II cement with 20% replacement of Class C fly ash. The uniformity of the cementious materials could not be determined because the contractor only provided a single sample of cement and fly ash from this site. Plastic air content (before the paver) ranged from about 7% to 8%. The compressive strength of concrete cylinders broken at 28 days ranged from about 4800 to 5500 psi. The contractor voiced concerns about rapid setting of the concrete mixture that was used at this site. However, mortar penetration tests conducted at this site indicated that initial set occurred after approximately 5 hours. Laboratory tests were also conducted with the samples of cement and fly ash provided by the contractor. The lab tests indicated that the cement did set rather quickly (initial set at about 3 hours and final set at about 5 hours). The cement–fly ash combination set considerably slower (initial set at about 5 hours and final set at about 7 hours). When the temperature of the cement–fly ash mortar was increased to better reflect field conditions, the setting time decreased (initial set was at about 4 hours and final set at about 6 hours). The sulfate content of the cement appeared to be balanced (i.e., roughly equal amounts of gypsum and bassanite), and this cement and cement–fly ash combination did not exhibit premature stiffening. Hence, the laboratory testing indicated that the cement–fly ash combination should have performed adequately. The field problems were most probably related to the extreme temperatures that were noted at this site. The workability of the mixture could have been improved by a minor change in gradation (more intermediate aggregate) and the use of appropriate hot weather concrete practices.
5. A weather problem (heavy rain) and a paver breakdown (left track problem) occurred during the visit to Site 5 (Highway 34 in Des Moines County). No mixture problems were reported by the contractor and none were observed during the site visit. The cementitious materials used on this project consisted of a Type I(SM) blended cement with 20% replacement of Class C fly ash. The uniformity of the cementious materials could not be determined because the contractor only provided a single sample of cement for the project. Plastic air content before the paver ranged from about 5% to 6%. Hardened air content obtained from pavement cores ranged from about 8% to 10% (expressed as mortar air). The 28-day compressive strength of concrete cylinders ranged from about 5500 to 6300 psi. Mortar set time tests were conducted in the field at this site. The test results indicated that the initial set times ranged from 4 to 5 hours, and the final set times ranged from about 6 to 7.5 hours.

6. No problems were noted during the visit to Site 6 (Highway 60 in Sioux County). The cementitious materials used on this project consisted of a Type I(SM) blended cement with 20% replacement of Class C fly ash. Materials obtained from the project were quite uniform. The predominant sulfate phase present in the blended cement was bassanite and this caused the cement to exhibit severe false set in laboratory mixtures. The cement–fly ash combination was less prone to false set; however, this mixture performed much like that obtained from Site 3. The contractor did not mention any plastic concrete problems associated with the mixture. In fact, the contractor indicated that this mixture was superior to anything he had used recently. The researchers also failed to detect any plastic concrete problems at this site. Plastic air content (before the paver) was about 8%. Slump was constant at about 1.75 inches, and slump loss was about 0.75 inches in 30 minutes. The 28-day compressive strength of concrete cylinders was about 5400 psi. Mortar set time tests were conducted in the field at this site. The test results indicated that the initial set times ranged from 4 to 5 hours, and the final set times ranged from about 5 to 6 hours.
7. The field study failed to find substantial differences between concrete mixtures delivered by different types of concrete delivery trucks. Agitator trucks were used extensively at the first three sites, while dump trucks were used extensively at the last two sites. Concrete properties (slump, slump-loss, and air content) tended to be similar at all of these field sites. Hence, this study supports the recommendation made my Cable and McDaniel (1998) that dump trucks should be allowed to function as concrete delivery units.
8. The field study indicated that mortar set times varied with the time of day that the mixture was placed. Mixtures placed early in the morning tended to set and harden slower than mixtures placed during the afternoon. This can cause a delay in set time of over one hour. Typical setting times for the Type I(SM) + 20% Class C fly ash mixtures tended to reach initial set after about 4 to 5 hours and final set after about 5 to 7.5 hours.
9. The variability of blended cements obtained from the field study was in reasonable agreement with the variability of portland cement samples obtained from the Iowa DOT during calendar year 2004.
10. Two of the three cement plants in Iowa tend to produce cements that contain significant amounts of bassanite ($CaSO_4 \cdot \frac{1}{2}H_2O$) and this tends to make the cements prone to premature stiffening (false set) in laboratory tests. Blended cements manufactured with these cements still exhibit the premature stiffening problem. The field study did not indicate any plastic concrete problems associated with the use of these false setting cements. However, in most instances, fly ash was used in conjunction with the blended cement. The use of fly ash or an increase in water–cementitious material ratio helps to eliminate the false set problem in laboratory mixtures. This may be an explanation for why most contractors insist on using fly ash with these blended cements.
11. The laboratory concrete uniformity tests that were conducted for this study produced test results that were in good agreement with the testing tolerances given in ASTM C 94.
12. A moisture sensor was effectively used to evaluate how mixing time and mixing procedure impacted the plastic and hardened properties of laboratory mixtures. The study indicated that real-time measurements of the moisture content of a

concrete or mortar mixture can be obtained quickly and easily. Hence, it is recommended that additional studies should be performed to develop the concept of using moisture sensors in concrete production for pavements. The concept should be expanded to evaluate the use of the moisture sensors to determine the moisture content of aggregates (fine aggregate will be easy, but coarse aggregate could be challenging) and the concrete mixture. This would ultimately allow for a much better control of the water–cement ratio of the mixture and should improve the overall consistency of the engineering properties and durability of the concrete.

13. A vibrating slope apparatus (VSA) was used to test the workability of laboratory and field concrete mixtures (only Site 2). The VSA was able to detect changes in the workability of laboratory mixtures (mostly Iowa DOT C-3 mixtures) when changes were made in the water–cement ratio or the dosage of water reducer. The three field mixtures that were tested produced nearly identical VSA test results and this was in good agreement with slump measurements that were conducted at the site. However, there is much disagreement between various researchers about the current test method and data reduction strategy for the VSA. These details will need to be addressed before the method can be standardized. Hence, it is recommended that a panel of interested researchers and engineers should be formed to review the current status of this test apparatus and to reach a consensus on the collection, proper presentation, and interpretation of the test results.
14. The use of mortar mixtures to identify optimum dosages of supplementary cementitious materials (limited to fly ash and slag in this study) was reasonably successful. A series of 25 binary and ternary mixtures were made during the study. A control mixture (portland cement control mortar) was used to normalize the test results obtained from the various mixtures. Compressive strength was the variable that was optimized for this study. The compressive strength of mortar cubes was monitored versus time and simple models were constructed from the data. Short-term strength models (seven days or less of curing) indicated the importance of portland cement in the mixture. Long-term strength models (greater than 28 days) indicated that slag and fly ash started to play increasingly important roles in strength development. The model developed from the 180-day compressive strength data indicated a broad optimum (greater than 35% above the control strength) that was comprised of portland cement, about 20% to 60% slag, and 0% to 30% fly ash.
15. A series of six concrete mixtures were made to see if the models constructed from mortar specimens could be used to predict the strength of concrete specimens. The concrete mixtures were chosen to simulate some existing Iowa DOT mixture formulations (i.e., 20% slag + 20% fly ash and 35% slag + 15% fly ash) plus a few additional mixtures. A control mixture containing only portland cement was used to normalize the test results obtained from the various specimens. The results obtained from the 7-day test specimens were encouraging (although a scale factor was needed to compensate for the sensitivity of the mortar test results). The results obtained from the 56-day test specimens were too close together to make any firm conclusions.
16. The mortar test results indicated that drying shrinkage was strongly related to the cementitious components in the mixture. Slag tended to increase the drying shrinkage (especially at high dosages), while fly ash tended to reduce drying

shrinkage. Hence, a ternary mixture could be formulated that compensated for the shrinkage effects caused by cement and slag.

Closing Comments

The Iowa DOT appears to have entered a very promising era in their production of concrete pavements. Much work was expended in the development and implementation of the QMC mixture program. Since no evidence of premature distress has been observed in the last decade, it appears that the problem has been resolved. In my opinion, this recovery is due to the return of common sense and the adherence to the fundamentals of good concrete. Plastic concrete is back—the concrete mixtures routinely contain an adequate volume of entrained-air voids (with an excellent distribution of bubble sizes). Gradations have been improved to minimize the potential for segregation and shrinkage. Excessive vibration during placement has been eliminated. Personnel at the Iowa DOT deserve the credit for all of these improvements. Now it is time to return to the two questions that were posed earlier in this report. What could have caused the anomaly shown in Figure 1 and the discrepancy in cement composition that was documented in Table 1? Data presented in this report has indicated that both of these errors are very infrequent. Hence, they can be classified as blunders. These types of blunders have become less probable because the DOT implemented changes that improved mixture design (the basis of the blunder shown in Figure 1) and the frequency of testing. It is sufficient to say that prior to the year 2000, no test method existed that could be used to measure the amount of slag that was present in a blended cement. Today such measurements are of a routine nature. Concrete and concrete materials are products that need to be tested to ensure that they conform to specified parameters.

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APPENDIX A: CLARIFICATION OF PROJECT DETAILS

FHWA Concerns about initial proposal (dated July 2002)

From: Bing Wong, Agreement Officer's Technical Representative
To: Dale Harrington, Director
Center for PCC Pavement Technology, ISU
Subject: Draft Research Proposal
Materials and Mix Optimization Procedures for PCC Pavements
Cooperative Agreement. DTFH 61-01-X-00042

Our group has reviewed the subject proposal from ISU and has the following comments:

1. General comments:

The draft research proposal needs to clearly describe the problems to be addressed and a comprehension of the complexities of concrete production in the field.

Mixture uniformity is a physical problem of blending liquid and solid materials such that the resulting material is as homogenous as possible. Extensive work in this area has resulted in the procedures for assessing uniformity contained in Annex A1 of ASTM C94. Mass/ft^3, air content, slump, coarse aggregate content, mortar volume, and compressive strength from the tow portions of the batch is compared. During the short period of mixing, little, if any chemical activity is taking place in the concrete. Thus, physical tests are considered the best indication of mixture homogeneity.

Attempts are being made to use rheology to characterize the workability and placeability of concrete, especially flowing and self-compacting concrete that behaves much like a liquid. Low slump paving concrete does not resemble a liquid, thus it is unlikely that rheology theory will describe its properties any better than slump. Chemical and heat signature testing should be considered to identify incompatibilities between cementitious materials and admixtures, other environmental, production, and transport issues that after the hydration characteristics.

2. Problem Statement

Again, the draft research proposal needs to show the relationship of admixture technology and hydration of cementitious materials. It is suggested that the contractors involved in this project consider and address the problems due to inadequate mixing.

3. Objectives

- Specific objective one: Type of haul vehicle and placing techniques can have a big impact on loss of plastic properties. Research should include agitating and non-agitating haul equipment.
- Specific objective two: Research and field experience have shown that it is extremely difficult to simulate production mixing at the laboratory scale. Mixer action and synergy of mass is not the same in a small mixer versus an 8 cubic yard plant mixer.

4. Outline of Proposal Research

We suggest that this project be split into two separate studies, a large scale field project to address the uniformity issue, and laboratory investigations, followed by field verification work to asses the slump loss and other chemical related issues.

The first Task should be a thorough literature review. A great deal of information related to both issues are in the literature. Mixer uniformity and mixing issues were studied by NRMCA at a full-scale concrete batch plant. Publications by Gaynor, Meninger, and Mullarky detail the findings. As you already know, many researchers have addressed slump loss and air loss in fresh concrete.

5. Field study

This portion of the study is relevant if it builds on the work done by Cable, is based on a statistically designed family of batching and mixing variables, and utilizes physical testing to assess uniformity.

6. Laboratory study

Laboratory study should focus on slump loss and chemical related issues. Small scale laboratory studies will not provide workable solutions to plant scale uniformity problems. Mixture control technology must also be proven in the field. Moisture sensors and analog slump meters based on both electrical and hydraulic principles are in use today, but are not totally reliable. Ultimately, any laboratory findings must be validated in the field on full-scale equipment.

7. Rheometer

The draft research proposal needs to demonstrate how the research project will determine the variables that impact homogeneity and rheology of concrete mixtures. As indicated in the COE research report (FHWA-RD-00-025), April 2001, “Portland-Cement Concrete Rheology and Workablity: Final Report,” it is difficult to measure workability of low slump mixtures. See TFHRC website for report—www.tfhrc.gov/pavement/pdfs/00025.pdf. We understand that there is no rheometer available in the market.

8. We suggest the establishment of expert panels to guide the work

If call us or email us to discuss this further

ISU response to FHWA Concerns

From: Scott Schlorholtz, PI, Proposed Research Project Date: 7/30/2002
To: Bing Wong, Agreement Officer's Technical Representative
Federal Highway Administration
Subject: Response to comments pertaining to a research proposal entitled
"Materials and Mix Optimization Procedures for PCC Pavements"
Cooperative Agreement: DTFH 61-01-X-00042
Amplified Work Plan for the proposed project

The ISU research group has reviewed the comments documented by the FHWA in an email dated 6/17/2002. The following responses and/or clarifications pertain to the eight comment headings used in the FHWA document. For brevity, only the comment headings have been reproduced in this document. The original FHWA comments have been included as a separate attachment (see ISUproposal.doc). The original proposal has also been attached to this email (see MIX OPTIMIZATION PROPOSAL …doc).

1) **General Comments:** We agree that the proposal did a poor job of explaining the overall thrust of the research project. The following clarifications help to focus the proposed research project. These clarifications will be referred to as an "**amplified work plan.**" The amplified work plan that is summarized below falls within the current scope of the main proposal; hence, both documents will guide the work.

   The routine production of durable concrete pavements has always been a challenging task. Severe environmental conditions, coupled with the routine use of deicing chemicals and increasing traffic volume, tend to place extreme demands on portland cement concrete (PCC) pavements. In most instances, engineers have been able to specify and build PCC pavements that met these challenges. However, there have also been reports of premature deterioration that could not be specifically attributed to a single cause. Such deterioration often appeared to be the result of problems that arose because of plastic concrete problems (mixture incompatibilities) and/or construction practices.

   Modern concrete mixtures have evolved to become very complex chemical systems. The complexity can be attributed to both the number of ingredients used in any given mixture and the various types and sources of the ingredients supplied to any given project. Local environmental conditions can also influence the outcome of paving projects. Hence, research is needed on characterizing basic concrete materials (i.e., uniformity before and after mixing), identifying potential incompatibility problems, and optimizing mixture proportion because these are key issues to increasing the durability of concrete pavements.

   The focus of the proposed research project is to specifically address the characterization, uniformity, and optimization issues. The project will consist of field and laboratory studies that are described below (also refer to the attached proposal). The scope of the proposed project is very limited because it will only pertain to materials and processes commonly used in Iowa. This helps to reduce the workload to a size that is achievable for the level of funding that has been requested.

Amplified Work Plan

Field Study: The thrust of the field study will be to measure the homogeneity of the raw materials and the fresh concrete from any particular jobsite. Specific details related to the field portion of the project are summarized in Table 1. Petrographic techniques will be used to measure the air content of cores extracted from the pavement slab. The measurements will be used to set a baseline for the uniformity of concrete produced in the field in Iowa. The measurements will be compared to existing specifications (i.e., ASTM C 94 or CRD-C 55). Workability will be evaluated using the slump test and the vibrating slope apparatus (VSA, if this device can be acquired for the project). It is anticipated that 5 or 6 field projects will be studied during the research project.

Table A.1. Summary of proposed field study

Problem or Task	Tests to be conducted	Expected Result(s)
Questionable raw material uniformity	Bulk chemistry Bulk mineralogy (+sulfate minerals) Moisture content Paste/mortar tests as needed	Document variability of raw materials
Questionable fresh concrete uniformity	Air content (plastic) Density Water content 7-day compressive strength Coarse aggregate content Air content (plastic on grade; hardened, from pavement core)	Document uniformity of freshly mixed concrete. Document loss of entrained air voids during the construction process.
Questionable workability	Slump test Vibrating slope apparatus (VSA) Temperature of concrete	Document workability immediately after mixing and then just prior to paving

Laboratory Study: The thrust of the lab study will be to supplement and refine information obtained from the field study. The lab study will also be used to practice and refine experimental techniques prior to conducting the field study. Raw materials obtained from the field will be used in portions of the lab study.

Table A.2. Summary of proposed laboratory study

Problem or Task	Tests to be conducted	Expected Outcome
Estimate “ultimate” concrete uniformity	Air content (plastic) Density Water content 7-day compressive strength	Document “ideal” variability of well mixed concrete
Investigate new mix control technology (moisture sensors)	Depends on number of devices and their availability	Document devices that are available and the results of laboratory trials
Mixture proportioning – also includes a brief study of why some mixtures behave poorly in certain instances	Various AASHTO or ASTM paste, mortar and concrete tests as required Vibrating slope apparatus (VSA) Calorimetry (heat signature testing)	Document incompatible mixtures and relate to field experience Document a strategy for optimizing mixtures containing supplementary cementitious materials

2) **Problem Statement:** The problem statement simply states why we think we have a problem. We have yet to prove that mixing is not adequate or if we have an admixture incompatibility problem. That will hinge on the outcome of the study.

3) **Objectives:**
   a) Specific objective 1 – Yes, we will attempt to include agitating and non-agitating haul vehicles in the field study by selecting projects or contractors that have this type of equipment.
   b) Specific objective 2 – Yes, this is correct – the objective has not been stated clearly. We meant to state that the lab study would be conducted using materials that were used in the field portion of the study. These materials would be used to simulate the **best uniformity** that could be expected from the field study. We agree that "field concrete" is nearly impossible to simulate in a lab mixer.

4) **Outline of the Proposal Research:** The proposed research plan is currently split into two studies. However, both studies will attempt to employ similar materials so that the results will remain applicable to Iowa concrete construction. Yes, a literature survey will be performed as a part of the research program.

5) **Field study:** The field study will attempt to build on the research conducted by Cable and his co-workers. However, statistical design of the field study will be difficult because we will be constrained to mixtures that the contractors currently produce. All attempts will be made to select as broad of a range of variables as is possible to enhance the statistical validity of the project.

6) **Laboratory study:** The lab study is not being conducted to provide workable solutions to field concrete problems. We proposed to use the lab study to ascertain the ultimate precision obtainable in well-mixed concrete. We also proposed to test moisture sensors in a laboratory environment. If successful, the lab testing of the sensors would be validated using field studies at a later stage of the project. Finally, we proposed to develop a strategy for optimizing the use of supplementary cementitious materials (specifically fly ash and ground granulated blast furnace slag) in concrete mixtures. This would include a brief look at admixture incompatibilities since they may severely influence constructability.

7) **Rheometer:** We acknowledge your concerns about the availability of a rheometer for the project. Hence, the rheometer **will not** be purchased for this project. Both the field and the lab studies will be expanded to include the use of the vibrating slope apparatus (VSA). Initially, we plan to borrow the VSA from the FHWA; however, we also anticipate fabricating a VSA during the course of the project. An updated budget has been attached to this document. The updated budget provides $25,000 for the fabrication of a VSA.

8) **Panel of experts to guide the work:** We always look forward to having a panel of experts help to guide our research efforts. Jon Mullarky and Toy Poole would be excellent people to help guide this project (depending on their availability).

APPENDIX B: VIBRATING SLOPE APPARATUS (VSA) OPERATING DETAILS

Standard Operating Procedure for the VSA (Vibrating Slope Apparatus)

Figure B.1. VSA setup

Zero Adjustment

Remove the gate and clamps from the VSA, and make sure the chute is level. With no load on the VSA, check each load cell input voltage and output using a multi-meter, use small flathead screwdriver to adjust the corresponding OFFSET screw into the required range.

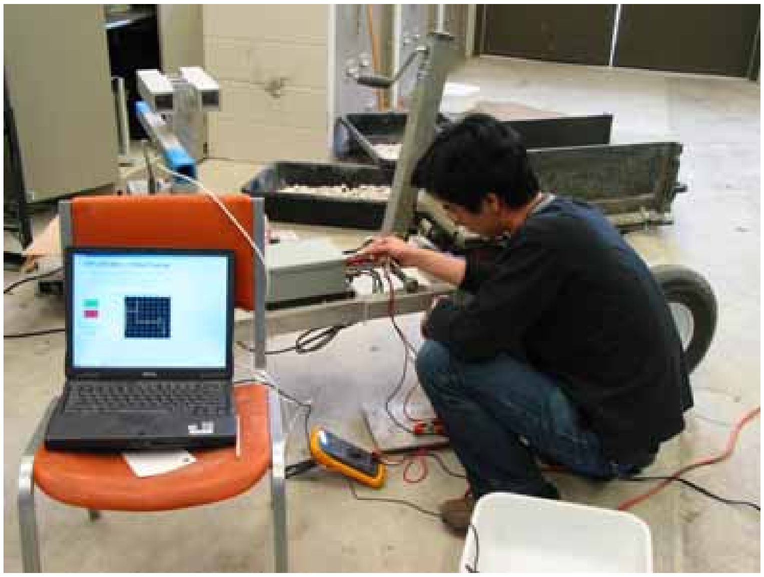

Figure B.2. Zero setting

Calibration

Perform calibration, add weights incrementally, recording the voltage reading each time (if desired, remove weights incrementally as well, again recording the voltage readings), calculate the calibration factor. Calibration factor should range between 95 and 105 lb/v.

Figure B.3. Calibration

Before Testing

- **Check VSA chute gate and location:**
    - Check that chute angle is zero (level).
    - Check that chute is securely fastened to base with wing-nuts.
    - Check that gate can be freely removed from the chute. Place the gate on the chute and clamp securely with two orange squeeze-clamps.
    - Check that VSA is located in a reasonably smooth and level location for testing, check that cotter pins are removed from the support brackets, and push the brackets down.
- **Add concrete:**
  Wet the chute prior to filling with concrete. Add concrete to the chute in one lift, level the concrete approximately 4 inches below the top of the box (run the “Run VSA,” set the variable speed knob to zero, and observe the weight from the screen, recommended weight of the sample is 110 to 120 lbs). Distribute concrete as evenly as possible when placing in the chute.
- **Consolidate:**
  To consolidate the concrete using the VSA, turn the variable speed knob all the way to the right (setting = 100). Use the program “VSA Vib” on the computer; vibrate until the concrete is consolidated in the chute, typically about 10 seconds. Click “Stop vibrator” when done.

Figure B.4. Before vibration

Figure B.5. After vibration

Test

To measure weight loss versus time and to calculate maximum flow rate, perform the following steps:

1. Raise chute to desired angle (if not done already).
2. Check that variable speed control knob is set at desired output (usually full power, all the way to the right).
3. Remove gate (if not done already).
4. Make sure the vibrator power is ON.
5. Run the software, enter required information, or make selections as follows:
   - Enter calibration factor (lb/v), if necessary
   - Select order of curve fit for weight vs. time data (dropdown box with choices ranging from 2 to 7, normally set as 7)
   - Select delay before data acquisition starts (dropdown box with choices ranging from zero to 5 seconds)—default is 2 seconds, normally set as 0
   - Select chute angle—use slider or click on up/down arrows to select angle
   - If desired, enter a test description
2. After completing the entries/ selections, click on the "start" button to begin data acquisition.
3. Monitor the progress of the test on the real-time weight vs. time plot (left side of the screen). Stop the data acquisition when at least half of the concrete had flowed out, or

when the concrete flow becomes negligible (usually 45–60 seconds after starting acquisition).

4. Save the data as designed, click “yes” to run another test, or click “no” to exit the program.
5. Run two test at different angle for same batch, normally 10 and 25 degrees are recommended to be chosen.
6. Run data reduction program to calculate workability index.

Figure B.6. VSA ready to run

Figure B.7. VSA, beginning of test

Figure B.8. VSA, end of test

After Testing

- Turn off the computer, electronics box, and vibrator power.
- Disconnect components from AC power.
- Disconnect the white cable connecting the computer to the Data Acquisition box (leave load cell input/output cables connected).
- Clean chute thoroughly. (Be sure to protect electronics box, data acquisition boxes, computer, and cable connections from water, use plastic to cover if necessary.)

APPENDIX C: REVIEW OF THE LITERATURE—LITERATURE SURVEY ON CONCRETE MIXING AND UNIFORMITY

Introduction

Concrete is a mixture composed of different ingredients. In its simplest form, this includes coarse and fine aggregates, cement, and water; however, modern concrete mixtures may contain a plethora of ingredients (multiple cementitious materials, multiple chemical admixtures, and an intermediate aggregate, to name just a few). Concrete mixing is essential for the complete blending of the various materials. The ultimate goal of the mixing process is to produce a homogeneous mixture that exhibits consistent engineering properties. A review of mixers, mixing procedures, and the influence of mixing on the workability and performance of portland cement concrete (PCC) is given in this literature survey.

Concrete Mixing and Optimization

All concrete should be mixed thoroughly until it is uniform in appearance, with all ingredients evenly distributed throughout the batch. When concrete has been adequately mixed, samples taken from different portions of a batch should meet the uniformity specification limits given in ASTM C 94 (e.g., samples should have essentially the same density, air content, slump, coarse aggregate content, and compressive strength). Therefore, both equipment and mixing methods need to be evaluated to ascertain whether they are capable of effectively mixing ingredients to produce uniform concrete mixtures for any given job.

Concrete Mixers

A variety of concrete mixers are available on the market today. They generally can be divided into three categories: drum mixers, pan mixers, and continuous mixers. Each of these mixers can be further classified as batched or continuous, free-falling or forced movement, and stationary or portable. Details of mixers, such as location, shape and angle of mixing blades, shape of the mixing chamber, rotation speed, and horsepower, are determined empirically to meet the needs of different jobs. Different types of concrete mixers are also required for different concrete mixtures. For any given concrete mixture, more than one combination of these factors will probably result in uniform mixing in the shortest amount of time. However, it is not easy to estimate mixing times without empirical tests because the underlying mechanism is not sufficiently understood.

Charonnat and Beitzel (1997) studied the efficiency of concrete mixers to qualify mixers through evaluating the homogeneity of the mix. The study included terms that characterize mixing, mixing cycle, and qualification procedures used to characterize the mixer and testing conditions. Qualification procedures and parameters, including water content, fine-element content, large-element content, and air content, used to characterize a mixer, testing conditions, and the performance criteria were described in the article.

Ferraris (2001) summarized concrete mixing methods and concrete mixers. The paper gives an overview of the various types of mixing methods and concrete mixers commercially available in the concrete industry. Batch mixers and continuous mixers were studied in more detail. Mixing processes, including loading method, discharge method, mixing time, and mixing energy, were studied. The research also recommended a method to evaluate the efficiency of a mixer through determining the homogeneity of the concrete produced, and it stated that a direct measure of the homogeneity of the concrete produced should be the most reliable method for characterizing a mixer. The direct measurement should rely on the determination of the concrete composition, such as distribution of the various constituents (e.g., air content, etc.) present in various samples taken during the discharge cycle. The composition method was recommended for standardization by RILEM (Réunion Internationale des Laboratoires et Experts des Matériaux).

Mixing time

The mixing time required should be based on the ability of the mixer to produce uniform concrete throughout the batch and from batch to batch. According to ASTM C 94, the mixing time should be counted from the time all the solid materials are in the mixer. The time required to achieve this depends primarily on the design of the mixer and basic material characteristics. Inadequate mixing typically results in lower strengths and greater variations in batch-to-batch or within-batch measurements. However, overly long times do not improve the quality of concrete and severely limit the output of the batching plant. Unusually long mixing times may cause some breakdown of softer aggregates and may cause erratic air contents, which may be highly dependent on the type of admixture(s) used in the mixture. Hence, common sense suggests the need for both a minimum and a maximum mixing time. However, due to productivity concerns voiced by the contractor, the minimum mixing time is normally the one of practical importance.

Cable and McDaniel (1998) carried out a research project that evaluated concrete performance related to mixing time, including hardened air content and distribution, potential segregation in the hauling units (dump trucks), concrete consolidation quality at the paving site, workability of the concrete after mixing, and the amount of coarse aggregate retained on a #4 sieve after washing. The authors concluded that mixing times of 60 seconds or greater would have a positive influence on the physical characteristics of the concrete. They recommended that a 60-second minimum mixing time be retained for all mixer types at this time. The research also indicated that reduced mixing times for alternative types of mixers can be applied only in specific circumstances.

Beitzel (1981) studied the effect of the mixing time on the quality of the mixing. In his research, the uniformity of distribution of sample characteristics, such as water content, power content, residue of remaining size fraction on the 2 mm screen, and residue of remaining size fractions on the 16 mm screen, were specially investigated. The results showed that, after a specific mixing time, an optimum point for the mixing efficiency occurs in the curve for the different characteristics. He concluded that because the longer mixing time affects the uniformity of distribution more than the minimum mixing time, it is necessary to set upper limits as well as lower limits for the mixing time.

Kirca (2002) stated that the slump loss caused by prolonged mixing can be overcome by re-tempering with water to restore the initial workability. Results showed that the addition of water to readjust the slump to match the initial slump of the mixture tended to cause lower compressive strengths because of the change in water-cement ratio. The decrease in the compressive strength of concrete re-tempered with superplasticizer (SP) was less than that of concrete re-tempered with water.

Mixing procedures

ASTM documents C 94 and C 192 contain guidance for traditional mixing procedures for field and laboratory concrete, respectively. Different procedures are given for stationary mixers and ready-mix concrete (transit mixers). Laboratory concrete is typically mixed using a 3-3-2 mix cycle. This indicates that the lab concrete mixture will be mixed for three minutes, allowed to sit undisturbed (rest) for three minutes, and then mixed for two more minutes. However, the current thrust towards concrete with better engineering properties, high-performance concrete, (HPC) typically requires the use of a variety of admixtures and/or supplementary cementitious materials; hence, these new mixtures pose some mixing problems for both field and laboratory concrete. This has caused some researchers to evaluate multiple mixing cycles and the ways they impact concrete workability and performance.

Gaynor (1996) studied a uniformity problem in truck-mixed concrete. The problem was related to color variations in the concrete mixture (head packs and cement balls were also noted). He found that mixing speed and loading procedure were the two most important factors that affect uniformity. He suggested that 20 to 22 revolutions per minute were preferred in truck-mixer, and one-fourth of the water should be added to the mixture as the last ingredient to ensure uniform mixing.

Chang and Peng (2001) studied the influence of mixing procedures on properties of HPC. In this investigation, six mixing methods were used to evaluate the flowability of HPC. Properties of the fresh and hardened concrete were measured. The results indicated that adding SPs in water in a single dose and allowing sufficient mixing time can help enhance the function of SPs in mixing. Based on the test results, an efficient and economical method for making HPC was proposed (most applicable for low binder content). In addition, the investigation noted that a horizontal twin shaft concrete mixer appeared to perform better than a drum-type mixer in terms of less mixing time required. This has implications for greater economy in operation and a larger throughput.

Research has shown that the time of the addition of admixture also influences the properties of concrete. Aiad et al. (2002) claimed that the lower the amount of high-range water-reducing admixture (HRWRA) absorbed by cement paste, the lower the amount of water needed for constant fluidity. The results showed that delaying the admixture addition increased the cement paste workability when compared to the workability of cement paste with admixture added at the beginning of concrete mixing. Okkenhaug and Gjorv (1992) studied the effect of delaying the addition of air-entraining admixtures (AEA). The results showed that adding the AEA at the beginning of mixing, together with the mixing water, produced a much higher total air content. However, the best air void system was produced when the AEA was added at the end of the mixing procedure, after a more uniform and well-dispersed mix had been established.

Multi-step mixing method

Multi-step mixing is sometimes considered for improving the properties of concrete. The process of two-step concrete mixing involves the advance preparation of a cement paste or slurry that is then mixed with aggregate to produce concrete. The process of three-step concrete mixing involves (1) the advance preparation of a cement paste, (2) the production of grout paste and sand, and (3) the production of concrete with coarse aggregate. The purpose of multi-step mixing is presumably to achieve efficient hydration of cement through more intimate contact between cement particles and water, which is achieved in the vigorous blending of cement paste.

Rejeb (1995; 1996) has collected and analyzed the multi-step mixing methods in several countries, including high-energy mixing method (U.S.), high-speed slurry mixing method (Canada), Tiernow method (Russia), sand enveloped with cement method (Japan), Triefe method (Belgium), two-step concrete mixing in Germany, three-step concrete mixing in Poland, and multi-step concrete mixing in the U.K. He concluded that the method of first mixing the binder and then adding aggregate can reduce the amount of water and cement needed in the process while increasing strength. Results by Rejeb suggest that, at 28 days of age, concrete mixed using the two-step method showed about 8%–17% higher compressive strengths than the concrete mixed using a normal method (see Tables 1 and 2).

Table C.1. Properties of normal concrete (from Rejeb 1996)

Water–cement ratio	Slump (cm)	Compressive strength (MPa)	Standard deviation (MPa)	Variation coefficient (%)
0.40	3.5	45.20	1.68	3.71
0.45	17.5	40.38	1.68	4.16
0.50	24.0	36.76	1.59	4.32

Table C.2. Properties of concrete mixed using the two-step mixing method using an ultramixer and a normal mixer (from Rejeb 1996)

Mixing method	Water-cement ratio	Slump (cm)	Compressive strength (MPa)	Standard deviation	Variation coefficient (%)
Pre-mixing of cement paste	0.40	4.5	50.97	2.52	4.94
	0.45	18.5	46.22	1.55	3.35
	0.50	24.5	42.17	1.94	4.60
Pre-mixing of grout	0.40	3.5	51.73	1.84	3.55
	0.45	18.0	47.15	1.43	3.03
	0.50	24.0	43.04	2.06	4.78

Tamimi (1994) developed a mixing technique in which concrete was produced by adding water at two separate times, producing sand-enveloped-with-cement (SEC) concrete. The results showed that up to 25% higher compressive strengths with a significant decrease in bleeding capacity at the early stages could be achieved. The investigations also revealed that this mixing method provided continuous filling of the porous interfacial transition zone between cement and concrete with hydration products, resulting in a high gel-space ratio when compared with one-time water-added and conventionally mixed concrete. The mixing method allowed tighter packing of hydration products with more intergrowth and interlocking, which improved the bond between the aggregate and cement paste. This caused micro-hardness of the concrete (see Figure 1).

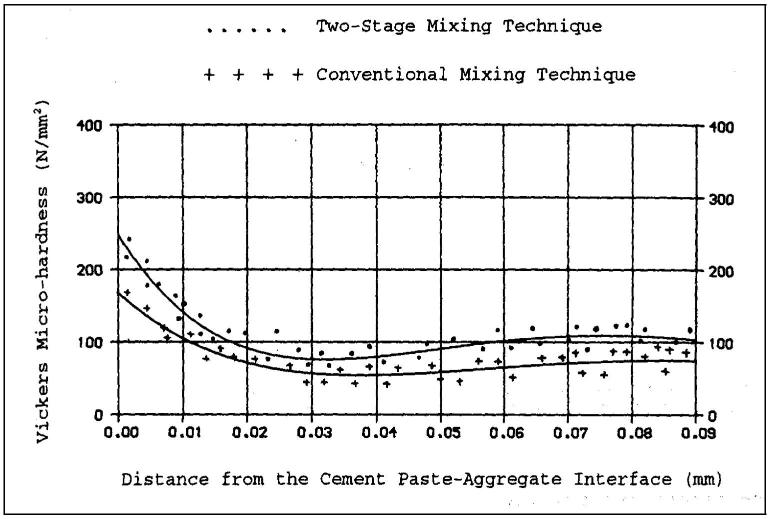

Figure C.1. Micro-hardness at age of 28 days and 0.45 W–C ratio (from Tamimi 1994)

Rougeron and Tagnit-Hamou (1996) confirmed the effect of the SEC mixing technique on concrete properties. From their results, it appeared that the effects of the SEC mixing technique are effective on short-term compressive strength only.

Uniformity Metrics

Standard methods

Parameters considered in these tests are coarse aggregate content, unit weight of the air-free mortar, water content, and air content. Standard methods for estimating concrete uniformity consist of compressive strength tests (ASTM C31), slump tests (ASTM C143), air content tests (ASTM C231), and wash-out tests (ASTM C94).

Because of the complexity of concrete materials, mix proportions, and mixing equipment and procedures, it is recommended that no single value can reflect the uniformity of concrete. Ferraris (2001) pointed out that the uniformity or homogeneity of concrete can be monitored by measuring the performance of specimens prepared with concrete taken from different parts of the mixer or at different times during the discharge. Properties such as slump, density, air content, and compressive strength might be used to access concrete performance. However, this is an indirect method and not sensitive enough. The measure of the concrete homogeneity can be achieved by determining the distribution of the various solid constituents, coarse aggregate, fine aggregate, and cement paste throughout the mixture. The average of all the measurements collected form each test can be converged into a coefficient of variation (CV, ratio of standard deviation to the average). Standard method, ASTM C94, describes how to prepare samples and how to estimate the uniformity of freshly mixed concrete.

Chemical methods and physical methods are often used to determine the moisture content of concrete. This can indicate the uniformity of the fresh concrete. Kelly and Vail (1968) used a chemical method for determining the cement and water content of concrete onsite. In this method, which involves measuring the dilution of a standard amount of chloride solution when added to a concrete mix, the net water content in concrete can be determined. The total operation time of this method is around seven minutes. The test was standardized by ASTM as Test Methods for Determining Water Content of Freshly Mixed Concrete (C 1079).

Nagi and Whiting (1994) developed a method to determine the water content of as-delivered fresh concrete using a microwave oven. In this method, a relatively high-power microwave (900W) equipped with a turntable was used to provided uniform drying. A sample of fresh concrete weighing approximately 1.5 kg is used; the drying is separated into two five-minute steps; and samples are taken out, broken, and ground using the edge of a scraper and a pestle to expose a larger surface area to complete the drying process after the first five minutes of drying.

Non-Standard Methods

A wide variety of test methods have been developed to monitor the water-cementitious materials ratio or water content of concrete. The methods described in this section have yet to be standardized.

Naik and Ramme (1989) developed a method to determine the water-cement ratio of concrete based on a buoyancy principle. In this method, water content can be found based on the weight of fresh concrete in air and under water, the specific gravity of aggregate and cement, and the aggregate-to-cement ratio of the concrete mixture. This technique relies greatly on accurate specific gravity and absorption data, and extreme care is needed in performing the test in order to obtain acceptable results.

Petrou (2000) developed a unique method for monitoring aggregate settlement in concrete based on tagging theory. Using nuclear medicine techniques, real-time images of aggregate settlement due to vibration are obtained. These images are used to study the rheological properties of the vibrated concrete mix. The technique developed allows the experimental verification of a number of assumptions regarding the rheology of fresh concrete and the implications of the accepted rheological model of fresh concrete. Additionally, the effects of vibration on aggregate settlement are clearly shown, including the effects resulting from the location of the vibrator and the size and density of the aggregate.

Moisture sensors have been developed that can be used to measure the water present in a concrete mixture. With the proper feedback loop, such techniques can exhibit significant improvements in the control of the uniformity of concrete mixing. Briefly, moisture in a concrete mixture can be monitored based on the principle of microwave energy absorption (Boscolo 1993). Water absorbs approximately 100 to 500 times as much (dependent on frequency) microwave energy as the same quantity of dry materials. The microwave absorption technique provides an accurate method for measuring moisture in concrete. Assenheim (1993) described a basic theory of a microwave moisture sensor system used in concrete. The method presumes a measurement of two different absorption parameters of the mixture material, which can overcome the problem with density-dependent properties.

Hydronix, a sensor manufacturer, developed a single-head sensing system based on electromagnetic theory (Board 1997). The sensor radiates the low-power field of microwave energy into concrete materials and detects the energy absorbed. The moisture sensor can be used in both a concrete mixer and aggregate bin to monitor the moisture contents via microwave reflection.

Mixing Energy Track

Soga et al. (1986) used a special device to measure the electric power consumption during concrete mixing. The characteristics of fresh concrete were greatly affected by the type of mixer, mixing method, and mixing time. From the results of the experiments, it was confirmed that the most effective factors for the amount of mixing energy are mixing time and the revolutions of the mixer, and that the quality of fresh concrete can be estimated based on the amount of mixing energy.

Charonnat (1996) pointed out that, for the mixing of concrete, the objective is to produce a homogeneous concrete and to guarantee this homogeneity each time a new batch of concrete is produced. To attain this objective, it is first necessary to know the capacities of the mixer. The article proposes a qualification procedure with reference to the recommendation of RILEM TC 150, “Efficiency of Concrete Mixers.” It is necessary to determine the mixing cycle that yields the expected performance, with the aim of optimizing the mixing time and plant wear. This is the reason for the initial test, which is used to fix precise, acceptable values for the various mixing parameters. The evolution of homogenization in the course of the production cycle is tracked by displaying the mixing energy. The application of this concept, through choosing a good mixer, checking the attainment of the objective, and assuring permanent monitoring of the mixing operation, serves to ensure the transparency of the mix production operation.

T. Nishizaki et al. (1999) used the electric current of the mixer to manage self-compactability, which varies due to fluctuations in the material quality in production, particularly the change in the fine aggregate surface moisture. The water content is adjusted to correct a deviation in the level of the electric current toward a predetermined target value at the end of the mixing operation. Mixing power in terms of electric current is monitored for every batch and used to confirm uniformity and/or change concrete workability.

Workability Measurement of Pavement Concrete

Although the slump cone test is widely used, the method is not suitable for measuring concrete with low flowability, that is, no-slump (or almost no-slump) concrete. The Vebe consistometer is a suitable test for determining differences in the consistency of very dry mixes. However, it is only applicable to concretes with a maximum aggregate size of less than 40 mm (1.5 inches). The vibrating slope apparatus (VSA) was developed by the Federal Highway Administration to provide additional information about the workability of low-slump concrete. The VSA can be used to evaluate the workability of pavement concrete, which generally has a slump less than two inches. Where the slump measures a static yield stress, workability is a function of the effort required to move the concrete under applied force, which is especially required in the placement of low-slump concrete.

The VSA measures the rate of discharge of concrete from a chute placed at two different slopes under a constant speed of vibration. The peak discharge rates are used to calculate a workability index, *W*, according to the equation

$$W = (R_2 - R_1)/(A_2 - A_1) \tag{1}$$

Where W is simply the slope of the line formed by plotting the peak discharge rate as a function of chute angle for the two test runs, R_1 and R_2 are the maximum flow rate at two different chute angles, and A_1 and A_2 are the two angles.

Implications for Research (Literature Review Summary)

In summary, mixing efficiency is greatly affected by both the procedure and type of mixer used. Choosing a suitable mixing method (charge method) and mixing time will be the most effective way to improve mixing efficiency.

Multi-step mixing methods have proven to be effective because they improve the microstructure of concrete and the interfacial transition zone. Delaying the addition of some chemical admixtures is also a widely used method for improving the properties of fresh concrete.

Sufficient mixing time is necessary for producing a uniform the concrete mixture, but an unnecessarily prolonged mixing time may be harmful to concrete; prolonged mixing may cause some breakdown of the softer aggregates and may decrease the air content.

Several methods had been developed to estimate the workability and uniformity of a concrete mixture, but special methods that accurately reflect mixing efficiency need to be developed. The moisture sensor is a promising tool for in situ estimation of moisture contents in different parts of the concrete inside the mixer, and hence can be used to reflect the uniformity of concrete inside the mixer. A combination of standard and non-standard methods, such as a moisture sensor, can effectively reflect the uniformity inside the concrete mixer, but a suitable procedure and estimation method are needed because measuring uniformity will include many factors.

REFERENCES FOR THE LITERATURE STUDY

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APPENDIX D: RAW DATA FROM LAB STUDY

Table D.1. Summary of results from the chemical testing program for cement uniformity

Sample	**Na2O (%)**	**K2O (%)**	**SO3 (%)**	**total alkali as %Na2O**	**Gypsum (% G)**	**Bassanite (% B)**	**Ratio (G/B)**
A-35	0.11	0.58	2.59	0.50	0.45	1.20	0.375
A-71	0.13	0.58	2.54	0.51	0.44	0.83	0.530
A-153	0.11	0.56	2.57	0.47			
A-269	0.11	0.57	2.63	0.48	0.53	0.89	0.596
A-325	0.11	0.57	2.60	0.48	0.63	0.71	0.887
A-224	0.11	0.56	2.57	0.48	0.75	0.88	0.852
average	0.111	0.568	2.584	0.485	0.560	0.902	0.648
std dev	0.008	0.009	0.032	0.013	0.131	0.181	0.218
CV, %	7.31	1.57	1.23	2.72	23.35	20.10	33.65
M 1	0.16	0.48	2.54	0.47			
M 11	0.14	0.50	2.53	0.47	1.94	1.90	1.021
M 120	0.15	0.50	2.61	0.47	2.22	1.39	1.597
M 162	0.14	0.50	2.57	0.47	2.21	1.58	1.399
M 219	0.15	0.50	2.65	0.47	2.08	2.01	1.035
M 267	0.13	0.51	2.58	0.47	1.77	2.10	0.843
average	0.143	0.498	2.580	0.471	2.044	1.796	1.179
std dev	0.009	0.008	0.045	0.004	0.191	0.300	0.309
CV, %	5.96	1.70	1.76	0.75	9.34	16.72	26.21
L 25	0.17	0.42	2.67	0.45	0.17	3.00	0.057
L 169	0.17	0.42	2.64	0.45	0.23	2.80	0.082
L 213	0.17	0.42	2.93	0.44	0.26	3.60	0.072
L 309	0.14	0.47	2.90	0.45	0.11	3.26	0.034
L 344	0.18	0.48	2.96	0.49	0.22	3.29	0.067
L 363	0.15	0.44	3.15	0.44	0.36	4.14	0.087
L 382	0.14	0.51	2.94	0.47	1.64	3.98	0.412
average	0.158	0.452	2.884	0.456	0.427	3.439	0.116
std dev	0.017	0.036	0.176	0.019	0.540	0.494	0.132
CV, %	10.60	8.06	6.10	4.12	126.51	14.37	113.83
C 66	0.08	0.06	2.79	0.11	2.23	1.84	1.212
C 111	0.08	0.07	2.87	0.12	2.74	2.70	1.015
C 174	0.09	0.09	2.70	0.15	1.44	1.42	1.014
C 228	0.09	0.14	2.73	0.18	3.40	1.64	2.073
C 290	0.08	0.10	2.85	0.15	3.11	1.66	1.873
C 354	0.11	0.09	2.78	0.17	3.03	0.96	3.156
C 383	0.07	0.07	2.93	0.11	4.96	1.10	4.509
average	0.085	0.087	2.807	0.142	2.987	1.617	2.122
std dev	0.014	0.029	0.081	0.029	1.088	0.572	1.298
CV, %	17.08	33.01	2.89	20.30	36.44	35.37	61.19

Table D.1. (*continued*)

Sample	**Na2O (%)**	**K2O (%)**	**SO3 (%)**	**total alkali as %Na2O**	**Gypsum (% G)**	**Bassanite (% B)**	**Ratio (G/B)**
F 3	0.12	0.57	2.77	0.49	0.92	2.05	0.449
F 9	0.07	0.56	2.88	0.44	1.46	1.06	1.377
F 14	0.10	0.60	2.92	0.49	0.65	2.57	0.253
F 24	0.07	0.56	2.93	0.44	1.22	1.82	0.670
F 110	0.12	0.60	2.96	0.51	1.13	1.64	0.689
F 266	0.08	0.60	2.90	0.48	1.22	1.64	0.744
F 329	0.09	0.67	2.92	0.53	1.56	0.91	1.714
average	0.092	0.593	2.895	0.483	1.166	1.670	0.842
std dev	0.019	0.039	0.061	0.034	0.310	0.567	0.518
CV, %	20.80	6.61	2.09	7.11	26.57	33.95	61.53
H 69	0.13	0.46	2.68	0.43	0.56	2.82	0.199
H 131	0.17	0.40	2.76	0.44			
H 113	0.15	0.37	2.72	0.39	0.10	3.28	0.030
H 13	0.12	0.46	2.68	0.42	0.19	2.85	0.067
H 8	0.11	0.46	2.73	0.41	0.87	2.38	0.366
H 26	0.11	0.47	2.82	0.42	0.18	3.61	0.050
H 2	0.17	0.53	2.69	0.51			
average	0.137	0.448	2.724	0.432	0.380	2.988	0.142
std dev	0.026	0.049	0.051	0.039	0.327	0.471	0.141
CV, %	18.94	11.03	1.87	8.91	85.98	15.78	99.29

Table D.2. Summary of VSA tests that were conducted during the study

Date	Batch No.	Files as shown in raw data	Batch description	Slump (in.)
2..25	C3+WR-1	c3-s-wr10-0min and c3-s-wr25-0min	C3+WR	3.25
2..25	C3+WR-2RM	c3-s-wr10-20min and c3-s-wr25-20min	C3+WR 20 min after remixing	1.5
2..25	C3+WR-3RM	c3-s-wr10-40min and c3-s-wr25-40min	C3+WR 40 min after remixing	1.25
2..26	C3-1-1	c3-10-0min and c3-25-0min	C3-old	2.5
2..26	C3-1-2RM	c3-10-20min and c3-25-20min	C3-old 20 min after remixing	1.75
2..26	C3-1-3RM	c3-10-40min and c3-25-40min	C3-old 40 min after remixing	1.25
3..11	C3-2-1	c3-10-0min and c3-25-0min	C3-new	1.25
3..11	C3-2-2RM	c3-10-20min and c3-25-20min	C3-new 20 min after remixing	1
3..11	C3-2-3RM	c3-10-40min and c3-25-40min	C3-new 40 min after remixing	0.75
3..13	C3+2WR	c3 2wr 10 0min and c3 2wr25 0min	C3+2WR	1.75
3..18	C3+4WR	c3 4wr 10 0min and c3 4wr25 0min	C3+4WR	2.75
3..18	C3+2HRWR-1	c3 2hrwr 10 0min and c3 2hrwr25 0min	C3+2HRWR-1	3.75
3..18	C3+2HRWR-2RM	c3 2hrwr 10 20min and c3 2hrwr25 20min	C3+2HRWR20 min after remixing	1.75
4..01	C3-W/C=0.43-0.5"	c3-1-10 and c3-1-25	C3-W/C=0.43-1	0.5
4..01	C3-W/C=0.43-1"	c3-2-10 and c3-2-25	C3-W/C=0.43-2	1
4..01	C3-W/C=0.43-0.75"	c3-3-10 and c3-3-25	C3-W/C=0.43-3	0.75
4..03	C3-W/C=0.47-1.75"	c3-1-10 and c3-1-25	C3-W/C=0.47-1	1.75
4..03	C3-W/C=0.47-2"	c3-2-10 and c3-2-25	C3-W/C=0.47-2	2
4..03	C3-W/C=0.47-2.25"	c3-3-10 and c3-3-25	C3-W/C=0.47-3	2.25
4..28	C3-W/C=0.51-4.75"	c3-wc51-1-10 and c3-wc51-1-25	C3-W/C=0.51-1	4.75
4..28	C3-W/C=0.51-6"	c3-wc51-2-10 and c3-wc51-2-25	C3-W/C=0.51-2	6
4..28	C3-W/C=0.51-6"	c3-wc51-3-10 and c3-wc51-3-25	C3-W/C=0.51-3	6
5..14	C3-W/C=0.47-3.5"	c3-wc51-1-10 and c3-wc51-1-25	C3-W/C=0.47-4	3.5
5..14	C3-W/C=0.47-3.75"	c3-wc51-2-10 and c3-wc51-2-25	C3-W/C=0.47-5	3.75
5..21	C3-W/C=0.47-5	wc47 5.21-1-10 and wc47 5.21-1-25	C3-W/C=0.47-6	5
5..21	C3-W/C=0.47-4.75"	wc47 5.21-2-10 and wc47 5.21-2-25	C3-W/C=0.47-7	4.75
5..21	C3-W/C=0.47-3.75"	wc47 5.21-3-10 and wc47 5.21-3-25	C3-W/C=0.47-8	3.75
5..23	C3-W/C=0.47-5"	wc47 5.23-1-10 and wc47 5.23-1-25	C3-W/C=0.47-9	5
5..23	C3-W/C=0.47-7"	wc47 5.23-2-10 and wc47 5.23-2-25	C3-W/C=0.47-10	7
5..23	C3-W/C=0.47-6"	wc47 5.23-3-10 and wc47 5.23-3-25	C3-W/C=0.47-11	6
5..23	C3-W/C=0.47-6"	wc47 5.23-4-10 and wc47 5.23-4-25	C3-W/C=0.47-12	6
5..23	C3-W/C=0.47-6.25"	wc47 5.23-5-10 and wc47 5.23-5-25	C3-W/C=0.47-13	6.25
5..23	C3-W/C=0.47-5.5"	wc47 5.23-6-10 and wc47 5.23-6-25	C3-W/C=0.47-14	5.5
6..17	C3+WR-3.5"	c3&wr1-10 and c3&wr1-25	C3+WR-3.5"	3.5
6..17	C3+WR-3"	c3&wr2-10 and c3&wr2-25	C3+WR-3"	3
6..17	C3+WR-3.5"	c3&wr3-10 and c3&wr3-25	C3+WR-3.5"	3.5
6..18	C3-2"	6-18 C3-1-10 and 6-18 C3-1-25	C3-2"	2.00
6..18	C3-2.5"	6-18 C3-2-10 and 6-18 C3-2-25	C3-2.5"	2.50
6..18	C3-2"	6-18 C3-3-10 and 6-18 C3-3-25	C3-2"	2.00
6..19	C3+2WR-4.5"	c3&2wr1-10 and c3&2wr1-25	C3+2WR-4.5"	4.50
6..19	C3+2WR-3.25"	c3&2wr2-10 and c3&2wr2-25	C3+2WR-3.25"	3.25
6..19	C3+2WR-3.5"	c3&2wr3-10 and c3&2wr3-25	C3+2WR-3.5"	3.50
6..20	C3+3WR-5.5"	c3&3wr1-10 and c3&3wr1-25		5.50
6..20	C3+3WR-5.75"	c3&3wr2-10 and c3&3wr2-25		5.75
6..20	C3+3WR-3"	c3&3wr3-10 and c3&3wr3-25		3.00
7..23	C3 1.6 ft3	7-23 c3 1-10-1and 7-23 c3 1-10-2	1.6 ft^3	2.5

Table D.2. (*continued*)

Date	Batch No.	Files as shown in raw data	Batch description	Slump (in.)
7..23	C3 2 ft3	7-23 c3 2-10-1and 7-23 c3 2-10-2, 3	2 ft^3	2.25
7..28	Mortar-1	mortar_7.28	W/C=0.5, S/C=2.5	10
7..28	Mortar-2	mortar_7.28_2	W/C=0.5, S/C=2.5	10
7..30	C3-1/2"	7-30-C3small-1-10	1/2" MSA Aggregate	2.75
7..30	C3-1/2"	7-30-C3small-2-10	1/2" MSA Aggregate	3.25
7..30	C3-1/2"	7-30-C3small-3-10	1/2" MSA Aggregate	3.5
8..5	C3-mixing 1	8-5-1-10	MSA=1/2", one-step mixing, load material in one dose) (C3 W/C=0.45, slump=2.5")	2.5
8..5	C3-mixing 2	8-5-2-10	MSA=1/2", multi-steps, load material seperately) (C3 W/C=0.45, slump=1.5")	1.5
8..6	C3-mixing 3	8-6 mix3	MSA=1/2", 2 steps, slury+agg mixing) (C3 W/C=0.45, slump=1.5")	1.5
8..8	C3-mixing 4	8-8mix4-10-1	MSA=1/2", multi-step mix, load in 50") (C3 W/C=0.45, slump=1.75"	1.75
8..12	C3	c3 1-10degree		2
8..12	C3 (rest 30min)	c3 2-10degree		1.5
8..12	C3-C	c3c 1-10degree		3
8..12	C3-C (rest 30min)	c3c 2-10degree		1.75
8..12	C3-F	c3f 1-10degree		3
8..12	C3-F (rest 30min)	c3f 2-10degree		2.75
8..13	C3-WR	c3-wr-1		1.75
8..13	C3-WR (rest 30min)	c3-wr-2		1.25
8..13	C3-WR-C	c3-wr-c-1		3.25
8..13	C3-WR-C (rest 30min)	c3-wr-c-2		2.25
8..13	C3-WR-F	c3-wr-f-1		3.75
8..13	C3-WR-F (rest 30min)	c3-wr-f-2		3
8..15	C3-30C	c3+30C-1	W/C=0.42, C3, 30% class C FA replacement	6.75
8..15	C3-30C (rest 30min)	c3+30C-2	W/C=0.42, C3, 30% class C FA replacement	6.75
8..15	C3-30F	c3+30F-1	W/C=0.41, C3, 30% class F FA replacement	3.5
8..15	C3-30F (rest 30min)	c3+30F-2	W/C=0.41 C3, 30% class F FA replacement	3.5

Table D.3. Summary of the premature stiffening tests (modified C 359 tests)

Cement Type	Cement (g)	Slag (g)	Fly Ash Type	Fly Ash (g)	Water (g)	P1 (Initial)	P2 (4 min)	P3 (7 min)	P4 (10 min)	P5 (Remix)	Mix Sum	P6 (15 after remix)	Total Sum
Holcim	600	0	none	0	180	5	3	2	1	50	61	11	72
Holcim A	600	0	none	0	180	4	2	0	0	50	56	15	71
Holcim B	600	0	none	0	180	5	1	1	0	50	57	11	68
Holcim	600	0	none	0	190	12	1	1	0	50	64	50	114
Holcim A	600	0	none	0	190	5	1	1	0	50	57	50	107
Holcim B	600	0	none	0	190	6	1	0	0	50	57	50	107
LAF I/II	600	0	none	0	180	50	50	39	14	50	203	49	252
MMOPT 8/15	600	0	none	0	180	50	45	14	8	50	167	46	213
MMOPT 8/18	600	0	none	0	180	50	45	23	12	50	180	46	226
MMOPT 8/19	600	0	none	0	180	49	47	42	31	50	219	47	266
MMOPT 8/20	600	0	none	0	180	50	28	10	10	50	148	46	194
MMOPT 8/21	600	0	none	0	180	50	8	5	5	50	118	45	163
MMOPT 8/22	600	0	none	0	180	50	9	5	5	50	119	46	165
MMOPT 8/25	600	0	none	0	180	50	46	36	31	50	213	48	261
MMOPT 8/19	510	0	FA 8/19	90	180	50	50	50	46	50	246	50	296
MMOPT 8/21	510	0	FA 8/21	90	180	50	48	24	20	50	192	48	240
MMOPT 8/22	510	0	FA 8/22	90	180	50	50	42	35	50	227	50	277
MMOPT 8/25	510	0	FA 8/26	90	180	50	50	49	46	50	245	50	295
Continental	600	0	none	0	180	15	6	6	6	8	41	6	47
Continental	600	0	none	0	180	10	7	4	5	8	34	4	38
Continental	600	0	none	0	190	48	38	9	8	42	145	10	155
Holcim A	480	0	FA 8/15	120	180	6	2	2	2	50	62	44	106
Holcim A	390	0	FA 8/15	210	180	45	6	3	1	50	105	42	147
Holcim A	300	0	FA 8/15	300	180	50	6	3	2	50	111	46	157
Continental	600	0	none	0	180	4	4	2	1	7	18	3	21
Continental	480	0	FA 8/15	120	180	14	14	10	10	40	88	20	108
Continental	390	0	FA 8/15	210	180	50	48	34	18	42	192	40	232
Continental	300	0	FA 8/15	300	180	45	40	35	21	40	181		
Continental	300	0	FA 8/15	300	180	50	50	44	32	50	226	50	276
Continental	360	120	FA 8/15	120	180	40	25	15	9	45	134	24	158
Continental	270	210	FA 8/15	120	180	27	19	11	8	44	109	18	127
Continental	270	120	FA 8/15	210	180	50	50	39	17	50	206	50	256
Continental	600	0	none	0	195	33	32	22	14	50	151	27	178
Continental	600	0	none	0	195	44	34	15	11	50	154	32	186
Continental	600	0	none	0	210	50	47	43	40	50	230	50	280
I35SBCMT1002A	600	0	none	0	180	5	4	2	2	2	15	3	18
I35SBCMT1002P	600	0	none	0	180	6	4	2	2	22	36	9	45
I35SBCMT1003A	600	0	none	0	180	7	3	3	3	26	42	12	54
I35SBCMT1003P	600	0	none	0	180	3	3	4	1	9	20	5	25
I35SBCMT1006A	600	0	none	0	180	5	1	1	1	11	19	7	26
I35SBCMT1002A	510	0	I35SB1002A	90	180	15	10	7	4	16	52	7	59
I35SBCMT1003A	510	0	I35SB1003A	90	180	44	4	2	2	50	102	46	148
I35SBCMT1006A	510	0	I35SB1006A	90	180	26	5	5	3	50	89	45	134
BC1-Holcim	480	120	none	0	180	4	1	1	0	48	54	6	60
BC2-Holcim	390	210	none	0	180	5	2	1	1	39	48	8	56

Table D.3. (*continued*)

Cement Type	Cement (g)	Slag (g)	Fly Ash Type	Fly Ash (g)	Water (g)	P1 (Initial)	P2 (4 min)	P3 (7 min)	P4 (10 min)	P5 (Remix)	Mix Sum	P6 (15 after remix)	Total Sum
BC3-Holcim	300	300	none	0	180	5	2	2	2	18	29	8	37
CMTIFJ072205	600	0	none	0	180	50	48	19	40	50	207	50	257
CMTFlyn012705	600	0	none	0	180	44	6	6	4	50	110	41	151
CMTCV081805P	600	0	none	0.00	180	6	5	4	4	50	69	44	113
CMTCV081905P	600	0	none	0	180	6	4	5	4	50	69	44	113
CMTCV081905P	600	0	none	0	180	4	3	3	3	50	63	41	104
CMTCV081905P	480	0	CV081905A	120	180	50	5	3	4	50	112	50	162
CMTCV081905P	480	0	CV081905A	120	180	50	7	4	4	50	115	47	162
CMTCV081805P	480	0	CV081805P	120	180	50	16	6	5	50	127	50	177
CMTflyn072705	480	0	OGS112103	120	180	50	49	43	18	50	210	50	260
CMTIFJ072205	480	0	IFJ072205	120	180	50	50	48.5	47	50	245.5	50	295.5

Table D.4. Summary of results from the paste testing program of the ternary mix experiment

Mix #	Cement (%)	SCM (%)	SCM Type	w/cm ratio	Set-time IS (minutes)	Set-time FS (minutes)	Temp rise deg (˚F)	Time to peak (minutes)	Area under curve
1	85	15	FA	0.260	220	290	67	502	27338
2	70	30	FA	0.245	232	330	64	528	35751
3	55	45	FA	0.231	242	360	49	648	31823
4	40	60	FA	0.214	138	210	36	700	23720
5	25	75	FA	0.198	66	173	26	770	18598
6	85	15	C	0.182	203	270	70	533	42899
7	70	30	C	0.248	210	285	61	513	35573
8	55	45	C	0.238	204	270	47	602	31653
9	40	60	C	0.226	143	255	34	644	22539
10	25	75	C	0.217	165	300	25	712	17785
11	85	15	B	0.203	234	270	72	489	40481
12	70	30	B	0.255	256	315	61	523	39914
13	55	45	B	0.254	255	330	46	650	33911
14	40	60	B	0.249	287	360	30	632	22271
15	25	75	B	0.238	242	360	20	702	15677
16	85	15	A	0.229	215	285	65	481	36832
17	70	30	A	0.258	225	285	56	556	36888
18	55	45	A	0.265	241	300	46	606	36875
19	40	60	A	0.260	265	315	30	618	25685
20	25	75	A	0.269	295	390	21	648	18133
21	85	15	Slag	0.266	203	270	66	475	38281
22	70	30	Slag	0.262	221	285	57	526	40582
23	55	45	Slag	0.269	234	300	35	579	27717
24	40	60	Slag	0.269	233	308	26	655	24855
25	25	75	Slag	0.272	246	338	19	655	18939
C	100	0	Control	0.280	205	274	81	435	39784

Table D.5. Summary of results from the mortar testing program of the ternary mix experiment

Mix#	Cement (%)	SCM (%)	SCM Type	w/cm ratio	3-day strength (psi)	7-day strength (psi)	28-day strength (psi)	65-day strength (psi)	180-day strength (psi)	56-day shrinkage (μ-strain)
1	85	15	FA	0.50	3772	5239	5794	7074	7158	885
2	70	30	FA	0.48	3025	4355	6501	6852	7071	863
3	55	45	FA	0.46	2223	3541	5666	6830	7349	679
4	40	60	FA	0.44	1406	2182	4282	5362	5907	523
5	25	75	FA	0.42	902	1180	2497	3945	5562	501
6	85	15	C	0.50	3981	4398	6556	7047	6871	899
7	70	30	C	0.49	3620	4601	6898	7580	8655	884
8	55	45	C	0.48	2518	3324	6056	6949	9010	752
9	40	60	C	0.48	1594	2223	3994	5401	7958	624
10	25	75	C	0.45	751	1011	2070	2770	6005	578
11	85	15	B	0.52	3622	4984	6849	7478	7865	918
12	70	30	B	0.51	3135	4769	6218	7612	7825	859
13	55	45	B	0.49	2263	3391	6236	7863	9081	838
14	40	60	B	0.48	1370	2248	4475	6142	8701	691
15	25	75	B	0.47	675	1202	2828	5207	8762	690
16	85	15	A	0.53	3608	5140	6304	6569	7575	990
17	70	30	A	0.52	3287	4657	7206	7876	8025	977
18	55	45	A	0.51	2185	3634	6869	7616	9358	907
19	40	60	A	0.50	1584	2556	6526	7658	9932	872
20	25	75	A	0.49	831	1758	6150	7665	10244	941
21	85	15	Slag	0.53	3909	5255	7267	7447	8751	1013
22	70	30	Slag	0.52	2986	4954	7559	8398	8758	1003
23	55	45	Slag	0.51	2161	3624	6864	7838	9024	1007
24	40	60	Slag	0.51	1766	3293	6717	8900	9184	1233
25	25	75	Slag	0.50	1109	2807	6659	7479	8100	1471
C	100	0	Control	0.53	3881	5571	6500	6536*	6573	943

notes: the cubes for mixes 24 and 25 were broken at 73 days

*the cubes for the control mix were broken at 56 days and are the average of 4 different trials (all within 3% relative error)

Table D.6. Summary of results from the concrete testing program of the ternary mix experiment

Mix#	**Mix**	**Slump (in.)**		**Slump**	**AEA**	**Unit wt.**	**Air%**	**Strength (psi)**			**w/cm**
	(pc-ash-slag)	**0min**	**30min**	**loss**	**(ml/100lb)**	**(pcf)**		**7 day**	**28 day**	**56 day**	
1-1	100-0-0	1.75	1.25	0.50	30.0	140.4	7.0	5154	6093	6450	0.415
1-2	100-0-0	2.00	1.50	0.50	25.0	142.0	6.0	5717	6592	7215	0.420
1-3	100-0-0	2.00	1.25	0.75	25.0	142.2	7	5670	7115	7129	0.420
	average	**1.92**	**1.33**	**0.58**	**26.67**	**141.53**	**6.67**	**5513.50**	**6600.00**	**6931.17**	**0.42**
	std dev	**0.14**	**0.14**	**0.14**	**2.89**	**0.99**	**0.58**	**312.65**	**510.88**	**418.89**	**0.00**
	CV, %	**7.5**	**10.8**	**24.7**	**10.8**	**0.7**	**8.7**	**5.7**	**7.7**	**6.0**	**0.7**
2-1	70-30-0	2.50	1.50	1.00	25.0	141.8	6.2	5747	7180	7584	0.38
2-2	70-30-0	2.00	1.50	0.50	25.0	142.2	5.9	6694	7862	8209	0.38
2-3	70-30-0	2.00	1.50	0.50	25.0	142.4	5.9	6337	7976	8132	0.38
	average	**2.17**	**1.50**	**0.67**	**25.00**	**142.13**	**6.00**	**6259.17**	**7672.56**	**7975.11**	**0.38**
	std dev	**0.29**	**0.00**	**0.29**	**0.00**	**0.31**	**0.17**	**478.21**	**430.34**	**340.87**	**0.00**
	CV, %	**13.3**	**0.0**	**43.3**	**0.0**	**0.2**	**2.9**	**7.6**	**5.6**	**4.3**	**0.0**
3	60-20-20	2.00	1.75	0.25	24.0	142.2	6.2	5466	7457	8457	0.39
3-2	60-20-20	2.00	1.25	0.75	24.0	142.8	5.5	5291	7765	8381	0.39
3-3	60-20-20	1.75	1.00	0.75	24.0	143.8	5.5	6034	7910	8598	0.39
	average	**1.92**	**1.33**	**0.58**	**24.00**	**142.93**	**5.73**	**5596.83**	**7710.61**	**8478.50**	**0.39**
	std dev	**0.14**	**0.38**	**0.29**	**0.00**	**0.81**	**0.40**	**388.16**	**231.42**	**109.84**	**0.00**
	CV, %	**7.5**	**28.6**	**49.5**	**0.0**	**0.6**	**7.0**	**6.9**	**3.0**	**1.3**	**0.0**
4	50-15-35	2.50	1.75	0.75	27.5	141.8	6.4	4981	7250	8189	0.405
4-2	50-15-35	2.00	1.50	0.50	27.5	141.6	5.8	5128	7711	8188	0.405
4-3	50-15-35	1.50	1.00	0.50	27.5	143.6	5.3	5221	7979	8640	0.405
	average	**2.00**	**1.42**	**0.58**	**27.50**	**142.33**	**5.83**	**5109.67**	**7646.78**	**8338.50**	**0.41**
	std dev	**0.50**	**0.38**	**0.14**	**0.00**	**1.10**	**0.55**	**120.74**	**368.88**	**260.67**	**0.00**
	CV, %	**25.0**	**27.0**	**24.7**	**0.0**	**0.8**	**9.4**	**2.4**	**4.8**	**3.1**	**0.0**
5	50-0-50	1.75	1.25	0.50	30.0	143.2	5.0	5351	7865	8359	0.42
5-2	50-0-50	1.50	1.00	0.50	40.0	142.0	5.5	4612	7458	7901	0.42
5-3	50-0-50	1.25	1.00	0.25	45.0	142.4	5.8	4892	7595	7988	0.42
	average	**1.50**	**1.08**	**0.42**	**38.33**	**142.53**	**5.43**	**4951.33**	**7639.22**	**8082.67**	**0.42**
	std dev	**0.25**	**0.14**	**0.14**	**7.64**	**0.61**	**0.40**	**373.06**	**206.91**	**243.23**	**0.00**
	CV, %	**16.7**	**13.3**	**34.6**	**19.9**	**0.4**	**7.4**	**7.5**	**2.7**	**3.0**	**0.0**
6	30-35-35	1.75	1.25	0.50	40.0	142.8	6.2	3464	6702	7878	0.37
6-2	30-35-35	1.25	0.75	0.50	40.0	142.8	5.4	3261	6478	7840	0.37
6-3	30-35-35	1.25	0.75	0.50	40.0	143.0	5.3	3438	6920	8173	0.37
	average	**1.42**	**0.92**	**0.50**	**40.00**	**142.87**	**5.63**	**3387.50**	**6700.00**	**7963.50**	**0.37**
	std dev	**0.29**	**0.29**	**0.00**	**0.00**	**0.12**	**0.49**	**110.75**	**221.17**	**181.99**	**0.00**
	CV, %	**20.4**	**31.5**	**0.0**	**0.0**	**0.1**	**8.8**	**3.3**	**3.3**	**2.3**	**0.0**