

# Materials and Mix Optimization Procedures for PCC Pavements

National Concrete Pavement  
Technology Center



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**March 2006**

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<b>16. Abstract</b> 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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## 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 mineral 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 ( $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ ) 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**

<b>Sample</b>	<b>Cementitious Material</b>	<b>% slag, measured by XRD</b>
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)
<b>average % slag for Jobs 1, 2, and 4 =</b>		<b>34</b>

## **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**

<b>Problem or Task</b>	<b>Tests to be Conducted</b>	<b>Expected Result(s)</b>
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**

<b>Problem or Task</b>	<b>Tests to be Conducted</b>	<b>Expected Outcome</b>
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 monochromator. Test specimens were prepared by back-loading the material into one-inch diameter (25 mm) sample holders. Data collection 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 ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) and bassanite ( $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ ) 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.

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  $110\% \pm 5\%$ . 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  $50\% \pm 5\%$  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 ( $23^{\circ}\text{C} \pm 2^{\circ}\text{C}$ ); however, several tests were conducted at  $37^{\circ}\text{C}$ . 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  $81\text{ cm}^2$  ( $12.6\text{ in}^2$ , 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<sub>3</sub> content. In addition, the ratio of gypsum to bassanite (Gyp/Bas) changed significantly over the duration of the sampling period.

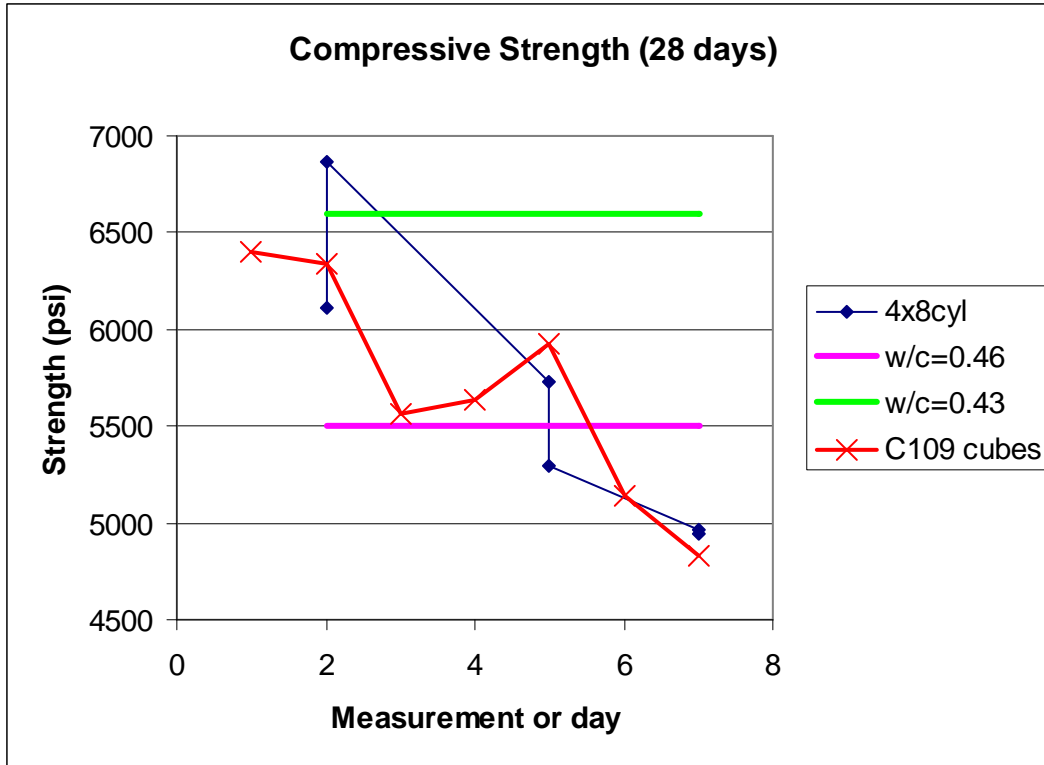
The results of compressive strength tests are illustrated in Figure 2. The tests were conducted on cylinders cast on the grade (moist-cured for 28 days prior to testing). Test specimens were cast at two different times (morning and afternoon) on three different days (8/18, 8/21, and 8/25/03). Mortar 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 <sub>2</sub>	22.18	22.22	22.87	22.36	22.12	23.08	22.78
Al <sub>2</sub> O <sub>3</sub>	5.78	5.77	5.74	5.82	5.82	5.84	5.59
Fe <sub>2</sub> O <sub>3</sub>	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 <sub>3</sub>	3.00	3.04	3.08	3.04	3.08	3.17	3.09
Na <sub>2</sub> O	0.11	0.12	0.12	0.12	0.11	0.12	0.11
K <sub>2</sub> O	0.59	0.57	0.56	0.62	0.59	0.58	0.61
TiO <sub>2</sub>	0.35	0.35	0.36	0.35	0.36	0.36	0.42
P <sub>2</sub> O <sub>5</sub>	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 <sub>2</sub> O <sub>3</sub>	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 <sub>2</sub>	34.59	39.15	39.82	38.31	38.08	37.06	40.89
Al <sub>2</sub> O <sub>3</sub>	17.57	17.52	17.95	17.81	18.13	17.86	18.39
Fe <sub>2</sub> O <sub>3</sub>	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 <sub>3</sub>	2.57	1.81	1.83	2.01	2.01	2.02	1.71
Na <sub>2</sub> O	1.80	1.54	1.58	1.65	1.71	1.70	1.67
K <sub>2</sub> O	0.34	0.60	0.56	0.51	0.49	0.48	0.59
TiO <sub>2</sub>	1.58	1.47	1.51	1.52	1.50	1.48	1.47
P <sub>2</sub> O <sub>5</sub>	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 <sub>2</sub> O <sub>3</sub>	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.

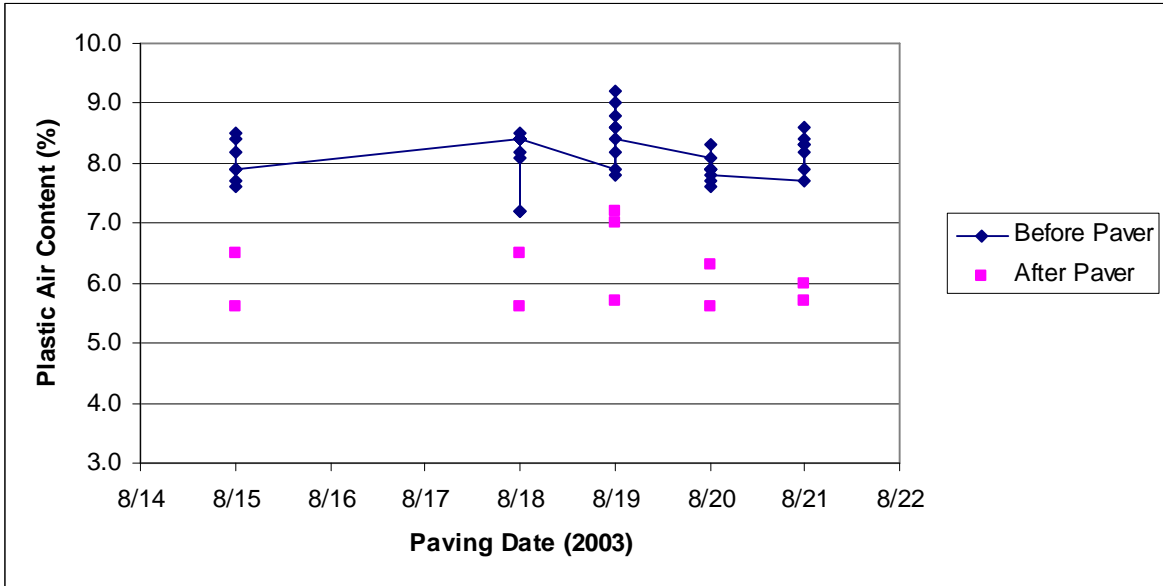


Figure 3. Plastic air content (via pressure-meter, supplied by the contractor) for Site 1

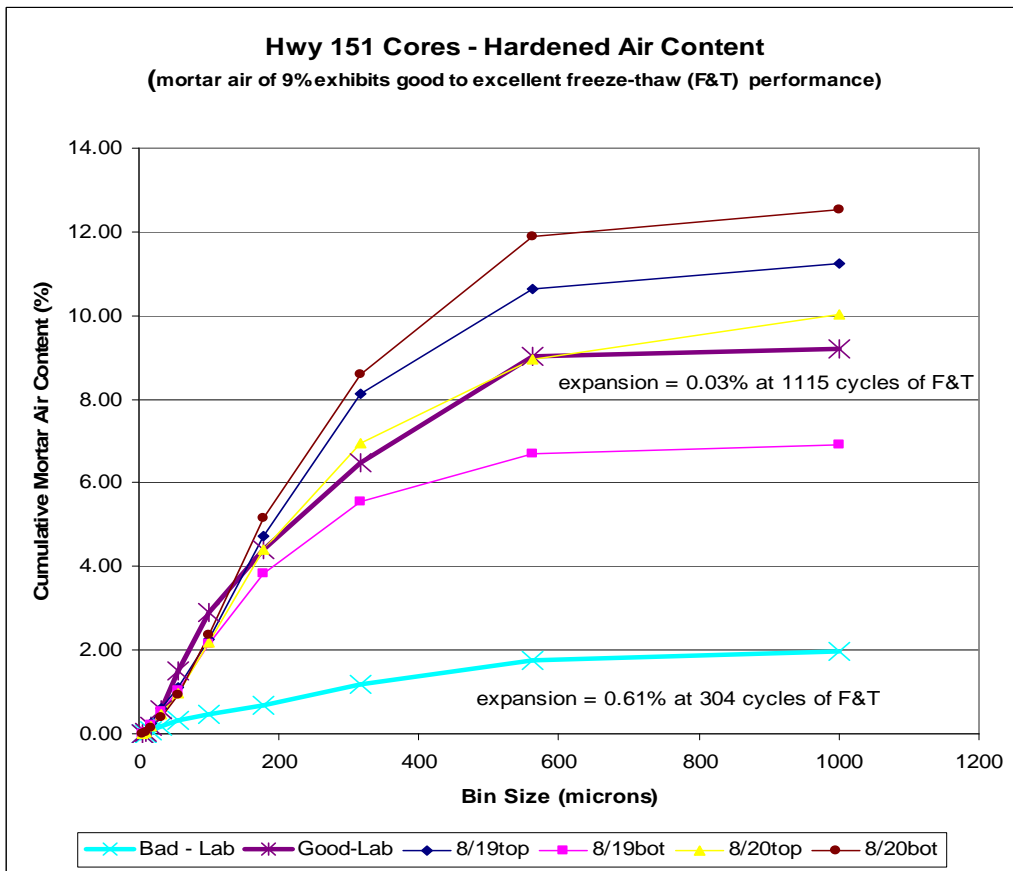


Figure 4. Hardened air content of cores extracted from Site 1

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.

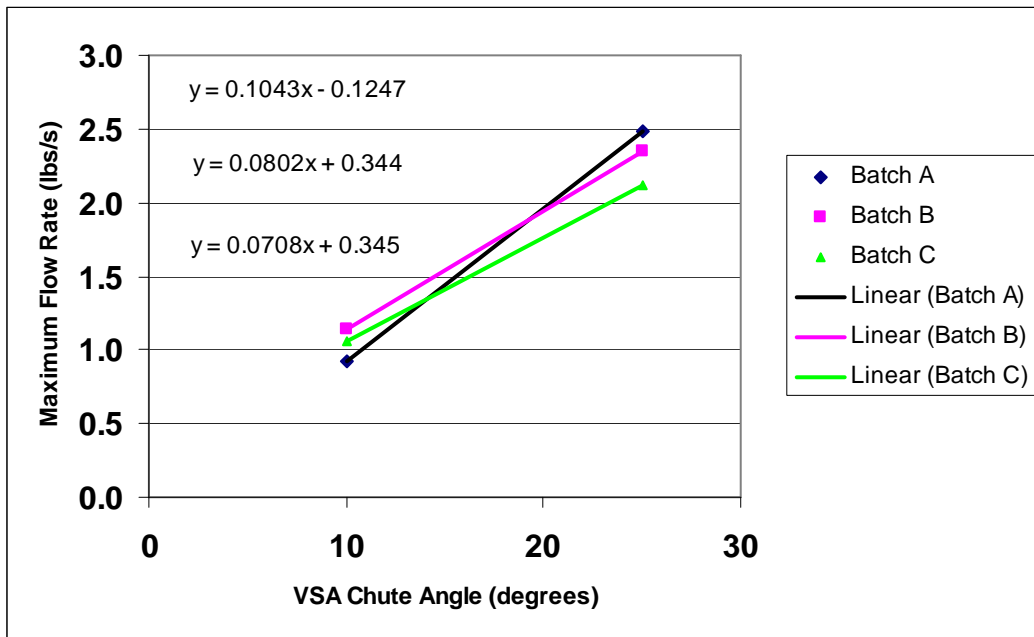
The results obtained at Site 2 are summarized in Table 7. Field conditions were excellent for paving. Day one had temperatures in the mid to high seventies, with a relative humidity of about 55%. Day two was cooler (the noon-time temperature was only 70°F), with a relative humidity of about 30%. The 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.

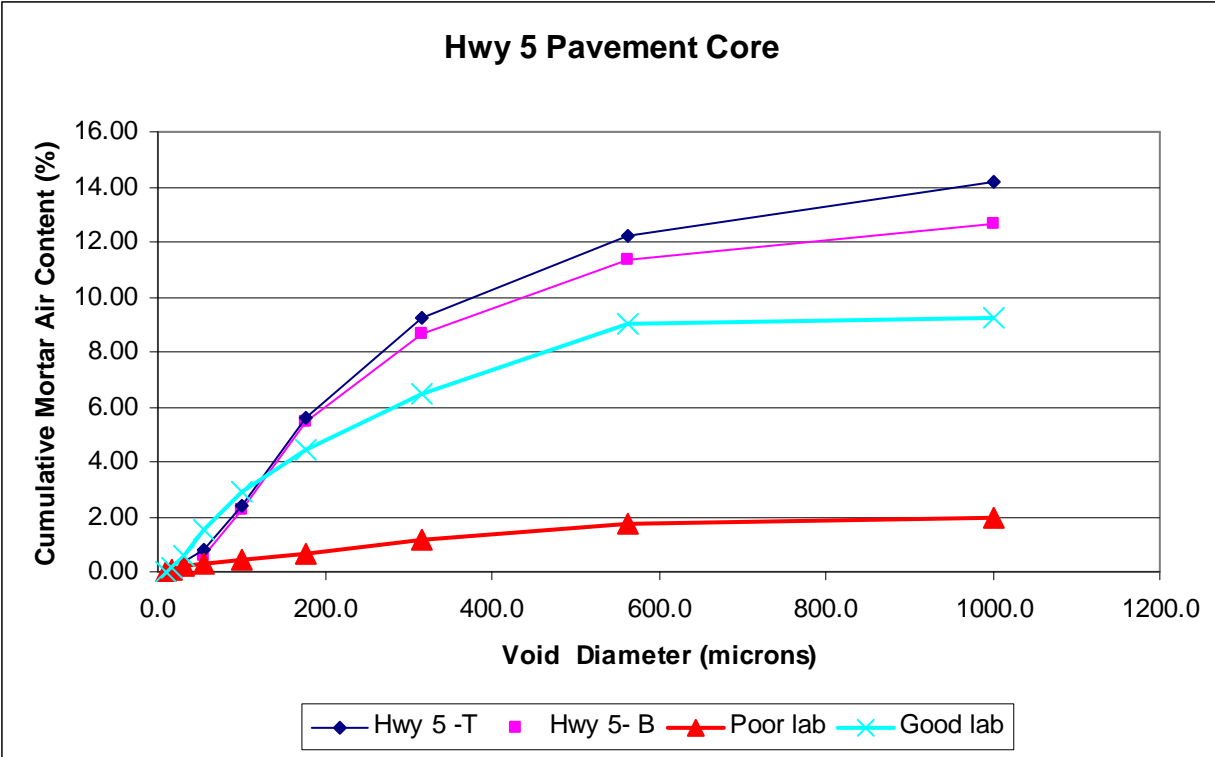
The hardened air content of the core extracted from the pavement was 8.4% (expressed as concrete air, based on an Iowa DOT C-3 mixture). The cumulative void-size distribution curves from the core are illustrated in Figure 6. The rapidly rising upper limb of the curve indicated that there was a significant 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 <sub>2</sub>	24.21	24.43	24.57	24.28	24.34
Al <sub>2</sub> O <sub>3</sub>	8.76	8.94	9.08	8.81	8.85
Fe <sub>2</sub> O <sub>3</sub>	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 <sub>3</sub>	3.29	3.30	3.36	3.40	3.40
Na <sub>2</sub> O	0.18	0.18	0.20	0.20	0.19
K <sub>2</sub> O	0.54	0.53	0.51	0.54	0.56
TiO <sub>2</sub>	0.59	0.59	0.60	0.59	0.60
P <sub>2</sub> O <sub>5</sub>	0.05	0.05	0.05	0.05	0.05
SrO	0.04	0.04	0.04	0.05	0.05
Mn <sub>2</sub> O <sub>3</sub>	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 <sub>2</sub>	32.22	32.57	32.83
Al <sub>2</sub> O <sub>3</sub>	19.07	19.29	19.64
Fe <sub>2</sub> O <sub>3</sub>	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 <sub>3</sub>	2.94	2.86	2.72
Na <sub>2</sub> O	1.87	1.77	1.76
K <sub>2</sub> O	0.33	0.35	0.38
TiO <sub>2</sub>	1.13	1.12	1.13
P <sub>2</sub> O <sub>5</sub>	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



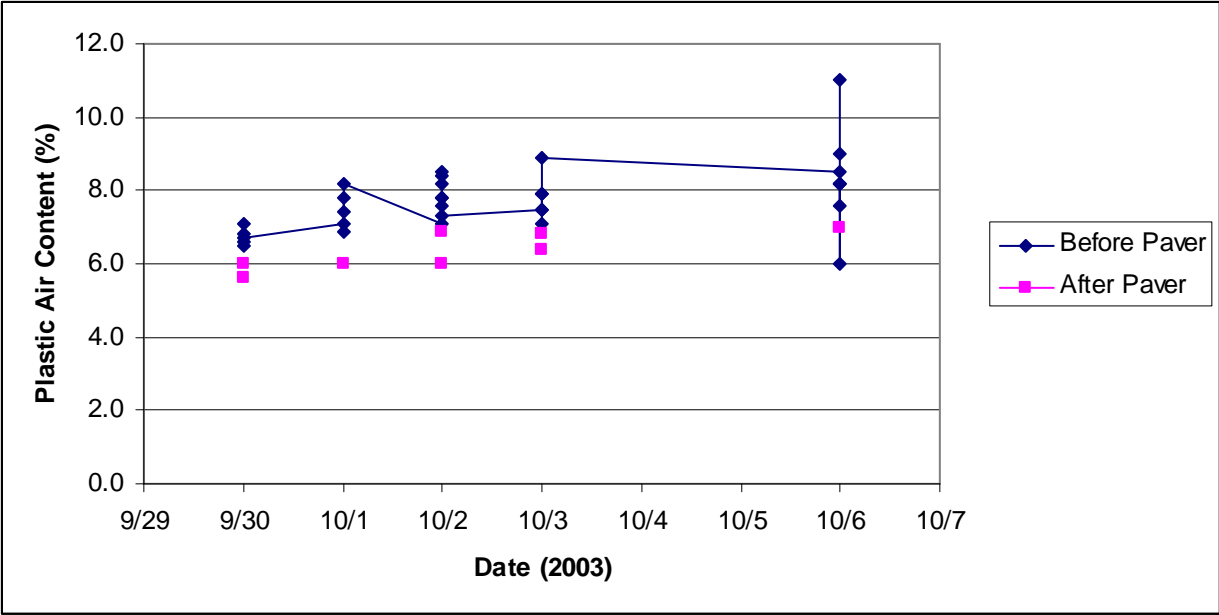


Figure 7. Plastic air content for Site 3 (via pressure-meter, supplied by the contractor)

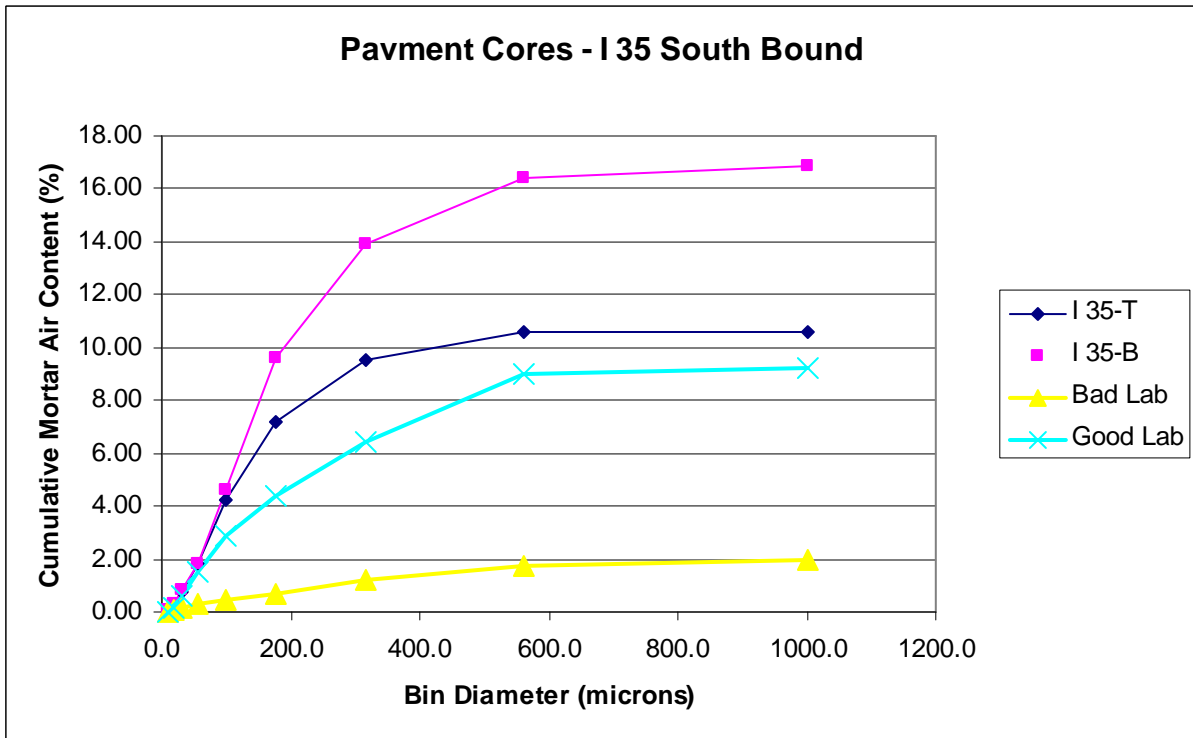


Figure 8. Hardened air content of a core extracted from Site 3 (T=top, B=bottom)

*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 losing 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)**

<b>Oxide, mass %</b>	<b>Site 4 072205-AM</b>	<b>Site 5 072705-AM</b>	<b>Site 6 081805-PM</b>	<b>Site 6 081905-AM</b>	<b>Site 6 081905-PM</b>
SiO <sub>2</sub>	20.60	23.16	24.29	24.47	24.32
Al <sub>2</sub> O <sub>3</sub>	4.17	5.60	5.99	5.99	5.92
Fe <sub>2</sub> O <sub>3</sub>	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 <sub>3</sub>	2.72	2.99	3.14	3.19	3.17
Na <sub>2</sub> O	0.16	0.13	0.18	0.17	0.17
K <sub>2</sub> O	0.64	0.67	0.52	0.53	0.52
TiO <sub>2</sub>	0.23	0.32	0.27	0.27	0.27
P <sub>2</sub> O <sub>5</sub>	0.07	0.09	0.06	0.06	0.06
SrO	0.09	0.05	0.04	0.04	0.04
Mn <sub>2</sub> O <sub>3</sub>	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 <sub>2</sub>	34.03	33.97	35.06
Al <sub>2</sub> O <sub>3</sub>	18.79	18.60	18.57
Fe <sub>2</sub> O <sub>3</sub>	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 <sub>3</sub>	2.11	2.61	2.49
Na <sub>2</sub> O	1.74	1.71	1.69
K <sub>2</sub> O	0.39	0.36	0.37
TiO <sub>2</sub>	1.55	1.59	1.59
P <sub>2</sub> O <sub>5</sub>	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  $\pm 7.5\%$  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	First load after break down
5	B	4.2	6.5	12:05 PM	148.9	6260	
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  $\pm 7.5\%$  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.

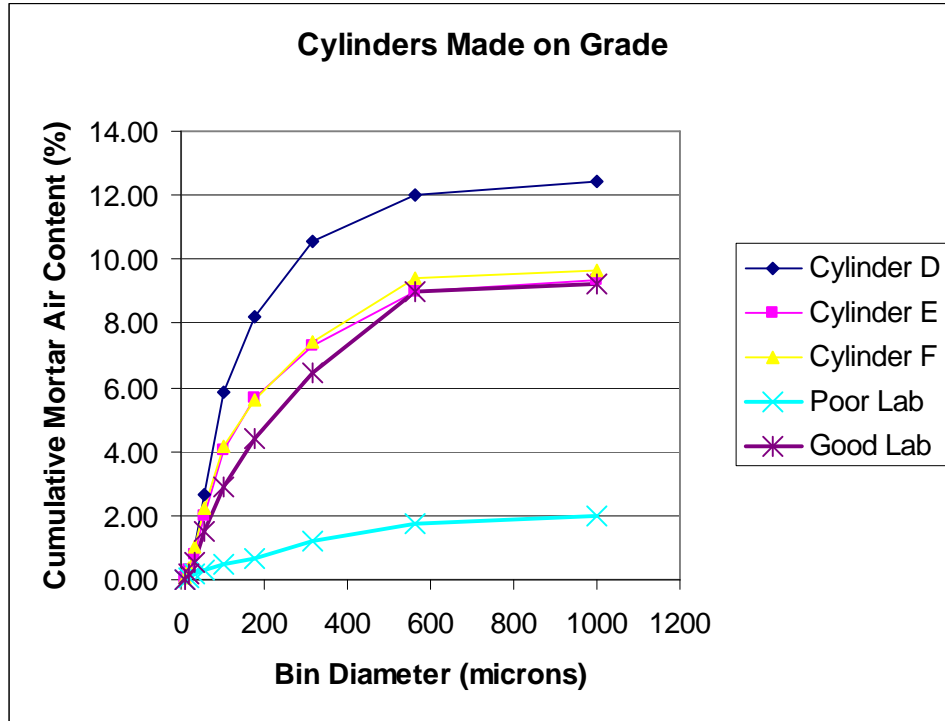


Figure 9. Hardened air content of cylinders from Site 5

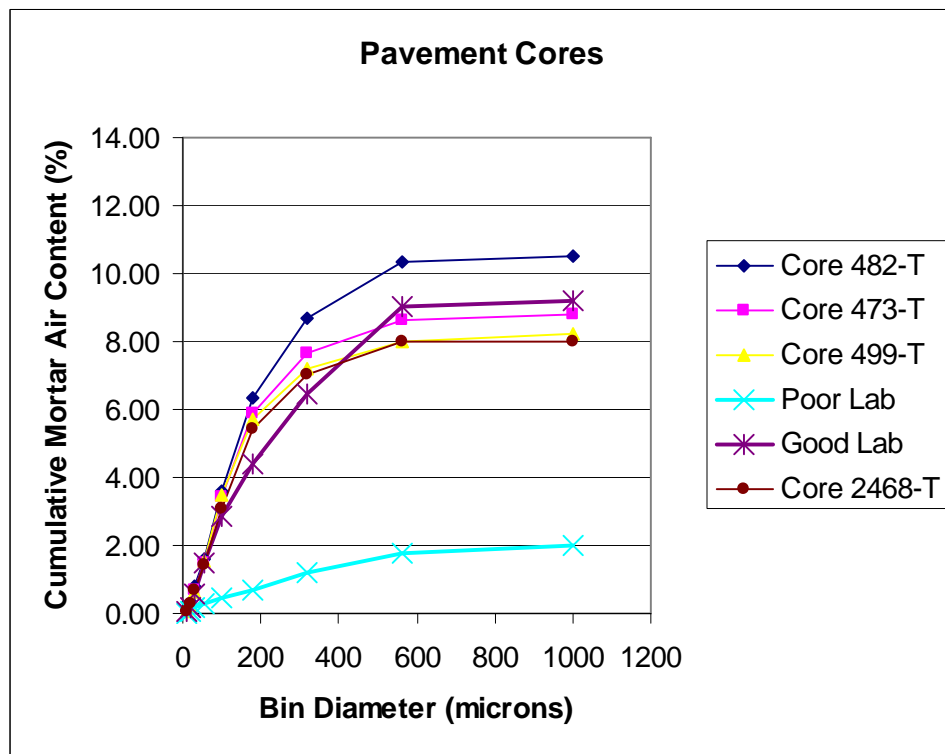


Figure 10. Hardened air content of cores extracted from Site 5 (T = top)

### *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 the Acme 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  $\pm 7.5\%$  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 <sub>2</sub>	20.80	20.52	19.32	20.60
Al <sub>2</sub> O <sub>3</sub>	5.55	5.38	5.28	4.13
Fe <sub>2</sub> O <sub>3</sub>	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 <sub>3</sub>	2.96	2.82	2.70	2.88
Na <sub>2</sub> O	0.19	0.16	0.16	0.06
K <sub>2</sub> O	0.50	0.61	0.49	0.67
TiO <sub>2</sub>	0.26	0.24	0.22	0.40
P <sub>2</sub> O <sub>5</sub>	0.48	0.26	0.40	0.10
SrO	0.05	0.05	0.05	0.05
Mn <sub>2</sub> O <sub>3</sub>	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 <sub>2</sub>	34.96	35.54	37.25
Al <sub>2</sub> O <sub>3</sub>	19.86	18.55	9.20
Fe <sub>2</sub> O <sub>3</sub>	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 <sub>3</sub>	Not reported	2.21	Not measured
Na <sub>2</sub> O	3.20	2.33	0.32
K <sub>2</sub> O	0.53	0.38	0.43
TiO <sub>2</sub>	Not reported	1.55	0.45
P <sub>2</sub> O <sub>5</sub>	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	
<b>Total</b>	<b>1.000</b>	

**Coarse Aggregate Grading**

<i>Sieve Opening</i>	<i>% Retained</i>
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 %  $\text{Na}_2\text{O}$ ) 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	Na <sub>2</sub> O (%)	K <sub>2</sub> O (%)	SO <sub>3</sub> (%)	total alkali as %Na <sub>2</sub> O
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
<b>Statistic mean</b>	0.185	0.592	3.403	0.575
<b>std dev (s<sub>e</sub>)</b>	0.002	0.002	0.011	0.003
<b>CV, %</b>	1.04	0.37	0.32	0.56
<b>d2s</b>	0.005	0.006	0.031	0.009
<b>d2s%</b>	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
	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
	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
	std dev	0.09	0.20
	CV%	2.78	14.67
	Standard Deviation		
Pooled	(estimate for s <sub>e</sub> )	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<sub>e</sub>) 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 <sub>2</sub> O	K <sub>2</sub> O	SO <sub>3</sub>	total alkali	Gypsum	Bassanite	Ratio
		(%)	(%)	(%)	as %Na <sub>2</sub> O	(%)	(%)	(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 <sub>c</sub>	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 <sub>c</sub>	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 <sub>c</sub>	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 <sub>c</sub>	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 <sub>c</sub>	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 <sub>c</sub>	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). Cementitious 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







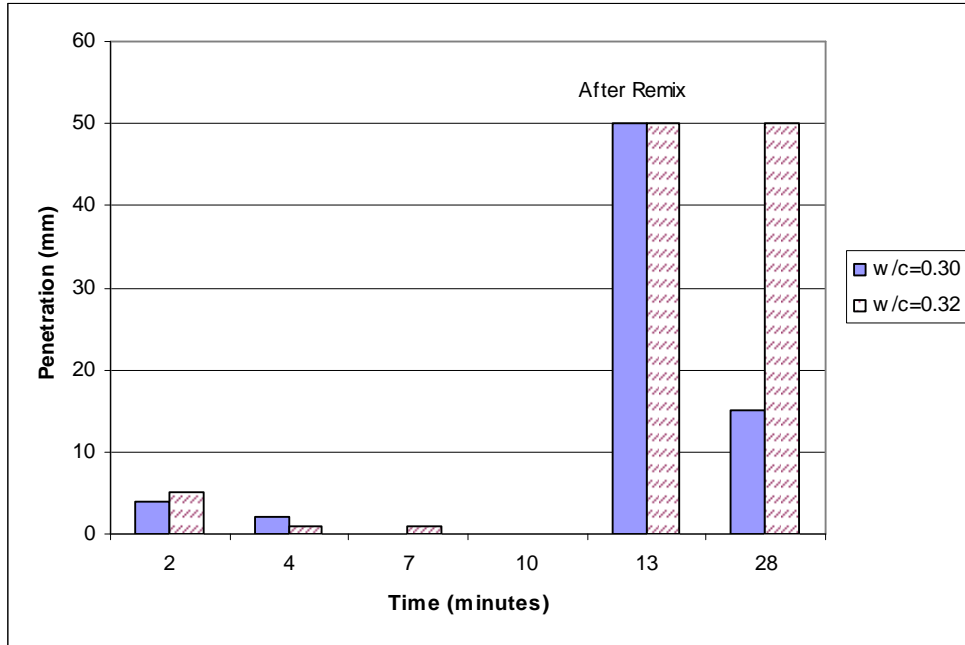




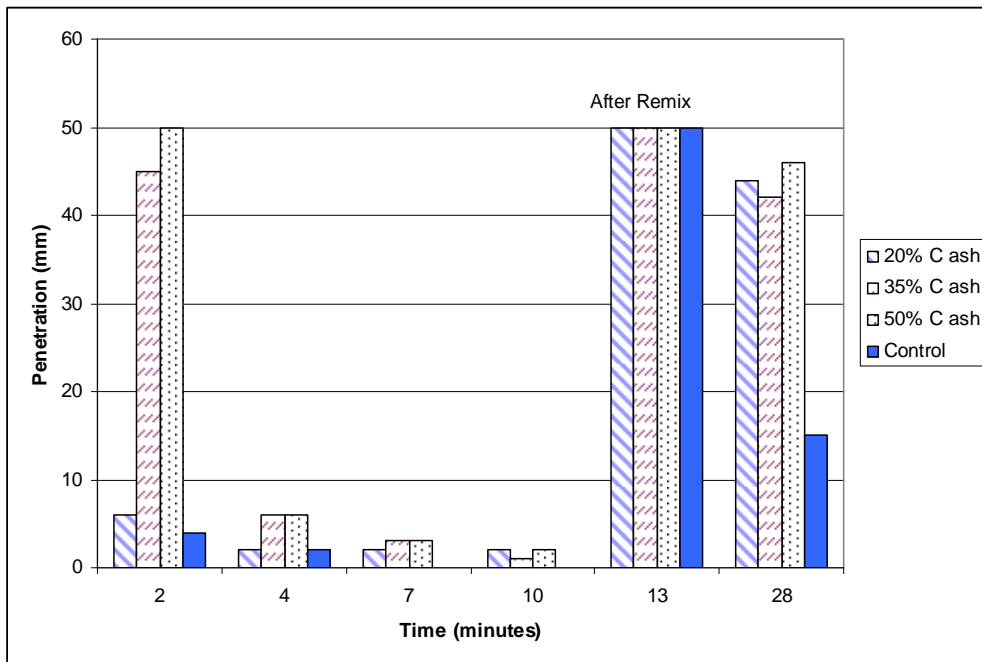




influence of increasing fly ash replacement on the false set behavior of the cement. This particular fly ash behaves like a low-range water reducer and allows all of the mixtures to perform better at the “normal” water–cement ratio of 0.30.



**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**

























































## **APPENDIX A: CLARIFICATION OF PROJECT DETAILS**













**APPENDIX B: VIBRATING SLOPE APPARATUS (VSA) OPERATING DETAILS**













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

























**APPENDIX D: RAW DATA FROM LAB STUDY**

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

<b>Sample</b>	<b>Na<sub>2</sub>O (%)</b>	<b>K<sub>2</sub>O (%)</b>	<b>SO<sub>3</sub> (%)</b>	<b>total alkali as %Na<sub>2</sub>O</b>	<b>Gypsum (% G)</b>	<b>Bassanite (% B)</b>	<b>Ratio (G/B)</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
<b>average</b>	0.111	0.568	2.584	0.485	0.560	0.902	0.648
<b>std dev</b>	0.008	0.009	0.032	0.013	0.131	0.181	0.218
<b>CV, %</b>	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
<b>average</b>	0.143	0.498	2.580	0.471	2.044	1.796	1.179
<b>std dev</b>	0.009	0.008	0.045	0.004	0.191	0.300	0.309
<b>CV, %</b>	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
<b>average</b>	0.158	0.452	2.884	0.456	0.427	3.439	0.116
<b>std dev</b>	0.017	0.036	0.176	0.019	0.540	0.494	0.132
<b>CV, %</b>	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
<b>average</b>	0.085	0.087	2.807	0.142	2.987	1.617	2.122
<b>std dev</b>	0.014	0.029	0.081	0.029	1.088	0.572	1.298
<b>CV, %</b>	17.08	33.01	2.89	20.30	36.44	35.37	61.19

**Table D.1. (continued)**

<b>Sample</b>	<b>Na2O (%)</b>	<b>K2O (%)</b>	<b>SO3 (%)</b>	<b>total alkali as %Na2O</b>	<b>Gypsum (% G)</b>	<b>Bassanite (% B)</b>	<b>Ratio (G/B)</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
<b>average</b>	0.092	0.593	2.895	0.483	1.166	1.670	0.842
<b>std dev</b>	0.019	0.039	0.061	0.034	0.310	0.567	0.518
<b>CV, %</b>	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			
<b>average</b>	0.137	0.448	2.724	0.432	0.380	2.988	0.142
<b>std dev</b>	0.026	0.049	0.051	0.039	0.327	0.471	0.141
<b>CV, %</b>	18.94	11.03	1.87	8.91	85.98	15.78	99.29













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

Mix#	Mix (pc-ash-slag)	Slump (in.)		Slump loss	AEA (ml/100lb)	Unit wt. (pcf)	Air%	Strength (psi)			w/cm
		0min	30min					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
	<b>average</b>	<b>1.92</b>	<b>1.33</b>	<b>0.58</b>	<b>26.67</b>	<b>141.53</b>	<b>6.67</b>	<b>5513.50</b>	<b>6600.00</b>	<b>6931.17</b>	<b>0.42</b>
	<b>std dev</b>	<b>0.14</b>	<b>0.14</b>	<b>0.14</b>	<b>2.89</b>	<b>0.99</b>	<b>0.58</b>	<b>312.65</b>	<b>510.88</b>	<b>418.89</b>	<b>0.00</b>
	<b>CV, %</b>	<b>7.5</b>	<b>10.8</b>	<b>24.7</b>	<b>10.8</b>	<b>0.7</b>	<b>8.7</b>	<b>5.7</b>	<b>7.7</b>	<b>6.0</b>	<b>0.7</b>
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
	<b>average</b>	<b>2.17</b>	<b>1.50</b>	<b>0.67</b>	<b>25.00</b>	<b>142.13</b>	<b>6.00</b>	<b>6259.17</b>	<b>7672.56</b>	<b>7975.11</b>	<b>0.38</b>
	<b>std dev</b>	<b>0.29</b>	<b>0.00</b>	<b>0.29</b>	<b>0.00</b>	<b>0.31</b>	<b>0.17</b>	<b>478.21</b>	<b>430.34</b>	<b>340.87</b>	<b>0.00</b>
	<b>CV, %</b>	<b>13.3</b>	<b>0.0</b>	<b>43.3</b>	<b>0.0</b>	<b>0.2</b>	<b>2.9</b>	<b>7.6</b>	<b>5.6</b>	<b>4.3</b>	<b>0.0</b>
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
	<b>average</b>	<b>1.92</b>	<b>1.33</b>	<b>0.58</b>	<b>24.00</b>	<b>142.93</b>	<b>5.73</b>	<b>5596.83</b>	<b>7710.61</b>	<b>8478.50</b>	<b>0.39</b>
	<b>std dev</b>	<b>0.14</b>	<b>0.38</b>	<b>0.29</b>	<b>0.00</b>	<b>0.81</b>	<b>0.40</b>	<b>388.16</b>	<b>231.42</b>	<b>109.84</b>	<b>0.00</b>
	<b>CV, %</b>	<b>7.5</b>	<b>28.6</b>	<b>49.5</b>	<b>0.0</b>	<b>0.6</b>	<b>7.0</b>	<b>6.9</b>	<b>3.0</b>	<b>1.3</b>	<b>0.0</b>
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
	<b>average</b>	<b>2.00</b>	<b>1.42</b>	<b>0.58</b>	<b>27.50</b>	<b>142.33</b>	<b>5.83</b>	<b>5109.67</b>	<b>7646.78</b>	<b>8338.50</b>	<b>0.41</b>
	<b>std dev</b>	<b>0.50</b>	<b>0.38</b>	<b>0.14</b>	<b>0.00</b>	<b>1.10</b>	<b>0.55</b>	<b>120.74</b>	<b>368.88</b>	<b>260.67</b>	<b>0.00</b>
	<b>CV, %</b>	<b>25.0</b>	<b>27.0</b>	<b>24.7</b>	<b>0.0</b>	<b>0.8</b>	<b>9.4</b>	<b>2.4</b>	<b>4.8</b>	<b>3.1</b>	<b>0.0</b>
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
	<b>average</b>	<b>1.50</b>	<b>1.08</b>	<b>0.42</b>	<b>38.33</b>	<b>142.53</b>	<b>5.43</b>	<b>4951.33</b>	<b>7639.22</b>	<b>8082.67</b>	<b>0.42</b>
	<b>std dev</b>	<b>0.25</b>	<b>0.14</b>	<b>0.14</b>	<b>7.64</b>	<b>0.61</b>	<b>0.40</b>	<b>373.06</b>	<b>206.91</b>	<b>243.23</b>	<b>0.00</b>
	<b>CV, %</b>	<b>16.7</b>	<b>13.3</b>	<b>34.6</b>	<b>19.9</b>	<b>0.4</b>	<b>7.4</b>	<b>7.5</b>	<b>2.7</b>	<b>3.0</b>	<b>0.0</b>
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
	<b>average</b>	<b>1.42</b>	<b>0.92</b>	<b>0.50</b>	<b>40.00</b>	<b>142.87</b>	<b>5.63</b>	<b>3387.50</b>	<b>6700.00</b>	<b>7963.50</b>	<b>0.37</b>
	<b>std dev</b>	<b>0.29</b>	<b>0.29</b>	<b>0.00</b>	<b>0.00</b>	<b>0.12</b>	<b>0.49</b>	<b>110.75</b>	<b>221.17</b>	<b>181.99</b>	<b>0.00</b>
	<b>CV, %</b>	<b>20.4</b>	<b>31.5</b>	<b>0.0</b>	<b>0.0</b>	<b>0.1</b>	<b>8.8</b>	<b>3.3</b>	<b>3.3</b>	<b>2.3</b>	<b>0.0</b>