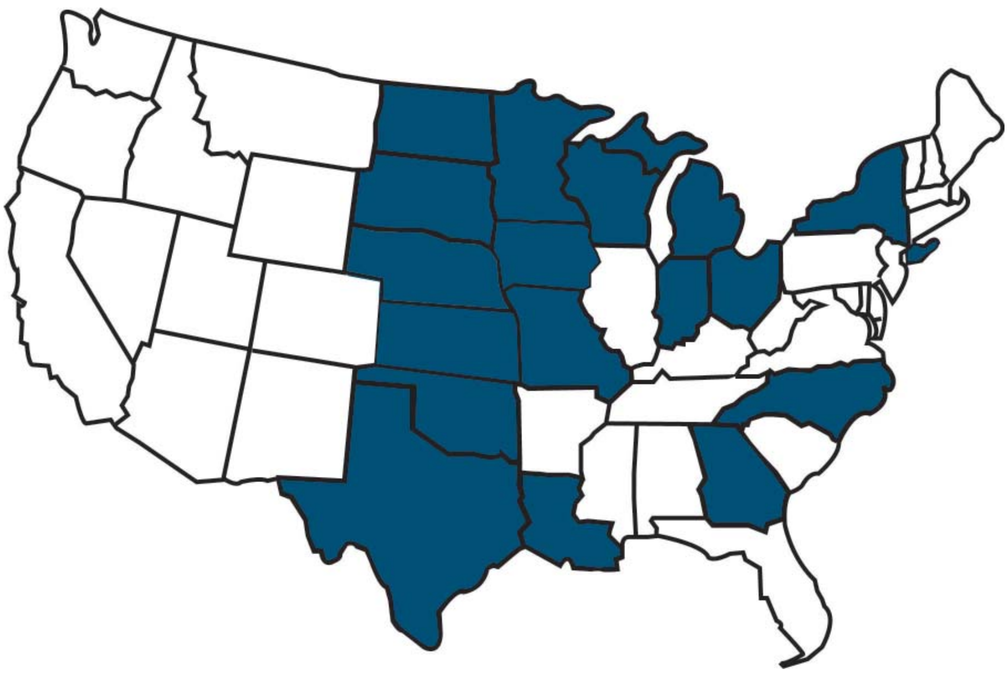
Testing Guide

for Implementing Concrete Paving Quality Control Procedures

March 2008



National Concrete Pavement Technology Center

Tech Center

Center for Transportation Research and Education

Iowa State University

This testing guide is a product of an FHWA 17-state pooled fund: **Material and Construction Optimization for Prevention of Premature Pavement Distress in PCC Pavements, TPF-5(066)**

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16. Abstract

Construction of portland cement concrete pavements is a complex process. A small fraction of the concrete pavements constructed in the United States over the last few decades have either failed prematurely or exhibited moderate to severe distress. In an effort to prevent future premature failures, 17 state transportation agencies pooled their resources, and a pooled fund research project, Material and Construction Optimization for Prevention of Premature Pavement Distress in PCC Pavements, was undertaken in 2003. Its purpose was to evaluate existing quality control tests, and then select and advance the state-of-the-practice of those tests most useful for optimizing concrete pavements during mix design, mix verification, and construction. This testing guide is one product of that project. The guide provides three recommended testing schemes (Levels A, B, and C, depending on a pavement's design life and traffic volumes, etc.) that balance the costs of testing with the risk of failure for various project types. The recommended tests are all part of a comprehensive suite of tests described in detail in this guide.

Testing Guide for Implementing Concrete Paving Quality Control Procedures

March 2008

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This publication is intended solely for use by professional personnel who are competent to evaluate the significance and limitations of the information provided herein and who will accept total responsibility for the application of this information.

Acknowledgments

The project team is grateful to many members of the national concrete pavement community who contributed in various ways to the multi-year pooled fund, Material and Construction Optimization for Prevention of Premature Pavement Distress in PCC Pavements, TPF-5(066) (the MCO project), through which this guide was developed.

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Finally, our sincere thanks to Chair John Staton, manager of materials section, Michigan Department of Transportation, and the entire technical advisory committee, which enthusiastically guided the work of the MCO project team. The list below attempts to capture the names of everyone who served the committee as a member or substitute. Many other individuals attended meetings and/or provided advice, and we appreciate their dedicated effort as well.

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Executive Summary

Construction of portland cement concrete pavements is a complex process. A small fraction of the concrete pavements constructed in the United States over the last few decades has either failed prematurely or exhibited moderate to severe distress. In an effort to prevent future premature failures, 17 state transportation agencies pooled their resources. Their goal: Stop simply duplicating acceptance tests that fail to provide feedback that can be effectively utilized to prevent premature failures. Instead, move quality control of portland cement concrete pavements to a new level of effectiveness.

A pooled fund research project entitled Material and Construction Optimization for Prevention of Premature Pavement Distress in PCC Pavements was undertaken in 2003. Some key features of the research project include the following:

- Identification and characterization of five focal properties of portland cement concrete used for pavements: workability, strength development, air entrainment, permeability, and shrinkage.
- Developing a comprehensive approach to evaluating material properties and construction processes. Test procedures should be performed during all stages of a project. Material properties are tested and compared across all three project stages: mixture design, mixture verification, and quality control.
- Establishing a suite of tests, that was then evaluated for effectiveness and practicality during 16 on-site project demonstrations utilizing a mobile concrete laboratory.
- Evaluation of new concrete testing procedures, modified procedures, and standard test procedures.
- Development of three suites of tests and an accompanying guide for implementing quality control procedures that will reduce the likelihood of premature failures.

The most common criteria used for acceptance of portland cement concrete pavements include thickness, air content, strength, and smoothness. However, these widely used acceptance criteria do not adequately address the potential for premature failures, most notably permeability and shrinkage. Unfortunately, reliable and repeatable test procedures do not exist for all of the focal properties which are of interest. Therefore, it is necessary to implement multiple quality control tests in conjunction with statistical process control procedures which will help identify when a material and/or process has changed.

Recognizing that concrete pavement projects come in a wide range of sizes and scopes, three suites of tests have been developed (Levels A, B, and C). Each suite is applicable to a certain type of project to balance the risks of failures with the costs of testing. It is not necessary to have the same level of mixture design testing and quality control on a low-volume road as one would have on an urban interstate route.

This guide provides the basic information necessary to implement a comprehensive suite of tests and has been designed around the following three-step strategy:

1. Fully characterize the mixture properties during the mixture design stage.
2. Verify that the materials delivered to the project site will yield concrete properties comparable to those that were observed during the mixture design stage.
3. Monitor material properties and construction processes for changes by utilizing statistical control charts.

Chapter 1: Background

The construction of durable concrete pavements is an increasingly challenging task for civil engineers and contractors. Extreme demands are placed on portland cement concrete (PCC) pavements from numerous factors, including the increasing number and variety of ingredients in the concrete, severe environmental conditions, the routine use of deicing chemicals, and increasing traffic volumes (*1*).

This document is a product of the research conducted under transportation pooled fund project Material and Construction Optimization for Prevention of Premature Pavement Distress in PCC Pavements (TPF-5[066]). This was a five-year study, begun in 2003 with the purpose of investigating the tests and quality control procedures that are necessary in order for PCC pavements to perform as designed without experiencing premature distress.

The study investigated the entire PCC paving process, focusing on the PCC materials and the tests needed to characterize them and control their quality (*1*). Larson (*2*) identified two objectives of the research project:

1. Evaluate conventional and new technologies and procedures for testing concrete and concrete materials to prevent materials and construction problems that could lead to premature pavement distress.
2. Develop and implement a suite of tests that relate performance to both design and field control of PCC mixtures and enable industry to satisfy specific performance requirements.

This study was initiated by the Midwest Concrete Consortium, an organization of departments of transportation (DOTs), universities, and industry in ten upper Midwestern states, and Federal Highway Administration (FHWA). It was a collaborative effort of state agencies, industry partners through the American Concrete Pavement Association (ACPA) and the local Chapters, FHWA, and the National Concrete Pavement Technology Center (CP Tech Center) at Iowa State University. All partners contributed time in an advisory role, effort to help organize and accomplish the field demonstrations in each of the 16 states, and financial support for the research effort. It was this active involvement of all the partners that made this project unique from most research efforts and was a significant factor in the successful outcome of this work.

Iowa was the lead state for the pooled fund and the CP Tech Center managed the research (*1*). The research was divided into three major phases:

- Phase I: Data collection, test development, pilot projects, and technology transfer.
- Phase II: Continued development of testing procedures and field demonstration projects.
- Phase III: Technology transfer and implementation assistance.

The 17 states that participated in the pooled fund field demonstration projects are shown on the map in figure 1.1 along with the year that the field demonstration occurred. Nebraska was originally part of the pooled fund, but dropped out of the

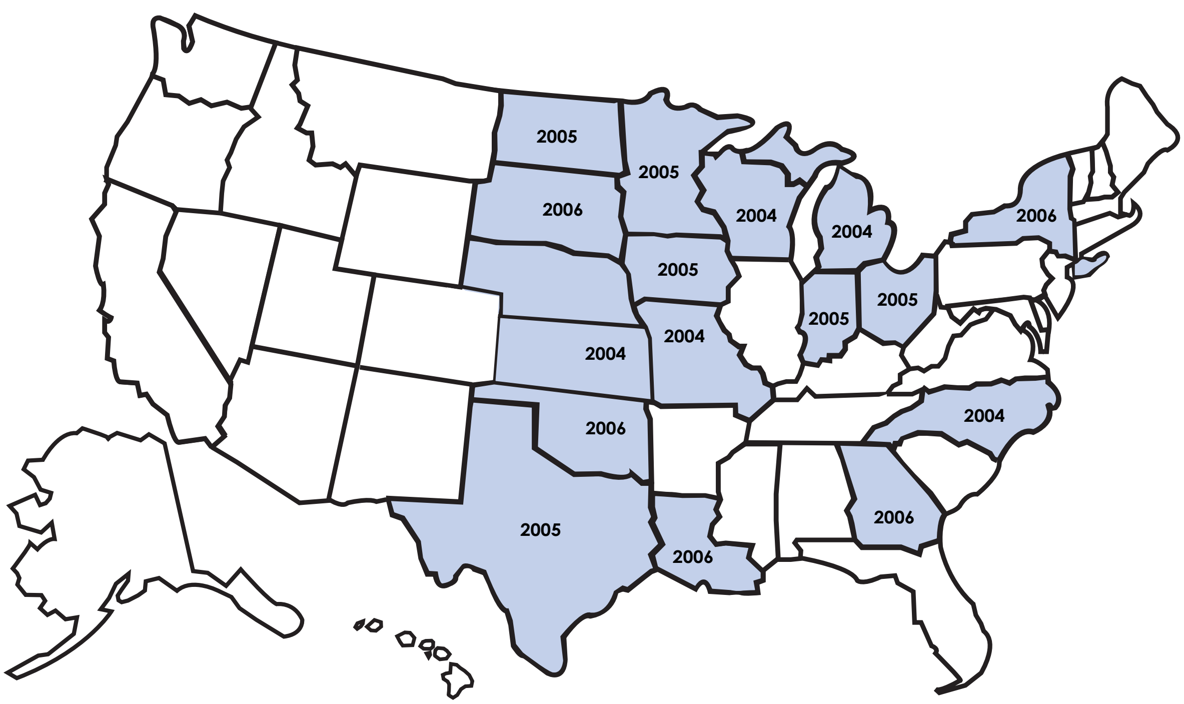

Figure 1.1 Seventeen pooled fund project states

pooled fund at the conclusion of 2004. Oklahoma joined the pooled fund at the beginning of 2005 and participated in the field demonstration phase of the study. The distribution of states participating in the field demonstration projects categorized by Long-Term Pavement Performance (LTPP) program climatic regions is shown in table 1.1. Kansas was included in the total for wet-freeze zone projects because the field demonstration project was located on I-35 on the Kansas-Missouri border. The field demonstration project in Texas was located on I-20 in Palo Pinto County, which is located in the dry-nonfreeze environmental zone.

Industry funding was provided to purchase a mobile concrete laboratory trailer (figure 1.2). This trailer was an integral part of performing the field demonstration projects and will be utilized by the CP Tech Center on future projects.

This project collaborated with ongoing related research and incorporated findings when possible. The research included FHWA Task 64, Software to Identify Rapid Optimization of Available Inputs, and FHWA Task 4, Tests or Standards to Identify Compatible Combinations of Individually Acceptable Concrete Materials.

A number of research efforts were initiated based on the needs identified in this project:

- Integrated Materials and Construction Practices Manual—CP Tech Center.
- Developing a Simple and Rapid Test for Monitoring the Heat Evolution of Concrete Mixtures for Both Laboratory and Field Applications—CP Tech Center.
- Improving Variability and Precision of Air-Void Analyzer (AVA) Test Results and Developing Rational Specification Limits—CP Tech Center.
- Durability-Based Field Testing Pilot Projects—Michigan DOT.
- Air System Emphasis—Ohio DOT.
- Set Time Testing—Missouri DOT.
- Boil Test/Rapid Chloride—Kansas DOT.
- Optimized Gradation Pilot Project—Texas DOT.
- Use of Pea Gravel as an Intermediate Aggregate—South Dakota DOT.
- James Cementometer Evaluation—Minnesota DOT.

This extensive list demonstrates the interest in testing and quality control that is shared by many agencies and researchers. The research not only gave assistance in this area but became a catalyst for many others to pursue specific research and development in this area.

Table1.1 Distribution of Field Demonstration Projects by LTPP Environmental Zone

LTPP environmental zones (*3*)	No. of states
Wet-freeze	9
Wet-nonfreeze	4
Dry-freeze	2
Dry-nonfreeze	1
Total	16

Figure 1.2 Mobile concrete lab

Chapter 2: Research Approach

A three-phase approach was used for the development of a standard suite of tests that can be used to evaluate the performance requirements of portland cement concrete for pavement. A brief outline of the activities associated with the suite of tests during each phase is provided.

Phase I

Phase I of the study established a preliminary suite of tests. Five focal properties of portland cement concrete for pavement were identified. A list of potential test procedures was compiled for each of the focal properties. In addition, the need to address materials testing at three different project stages was identified (figure 2.1). Table 2.1 shows the framework of the initial suite of tests matrix.

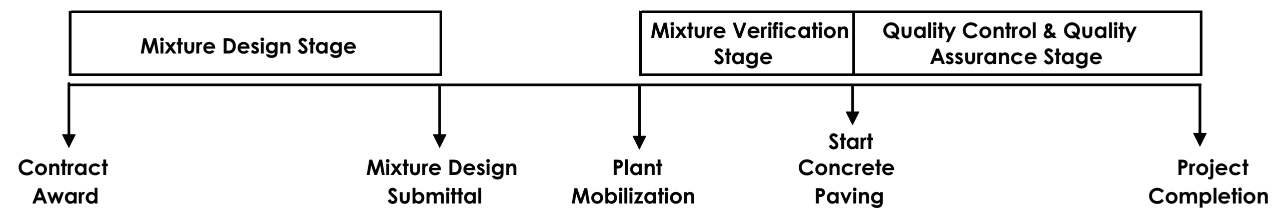

Figure 2.1 Project stage timeline (not to scale)

Table 2.1 Phase I Initial Suite of Tests Matrix

Focal property	Mixture design stage	Mixture verification stage	Quality control stage
Workability	Differential scanning calorimetry	Differential scanning calorimetry	Differential scanning calorimetry -portable
	X-Ray diffraction	X-Ray diffraction	
	X-Ray fluorescence	X-Ray fluorescence	
	Blaine fineness		
	Combined gradation	Combined gradation	Combined gradation
	Time of setting	Time of setting	
	Premature stiffening	Premature stiffening	
	Slump	Slump	Slump
	Concrete temperature	Concrete temperature	Concrete temperature
	Heat signature	Heat signature	
Strength development	Std. Strength tests	Maturity – strength curve	Maturity – slab temp.
Air entrainment	Pressure meter	Pressure meter	Pressure meter
	Unit weight	Unit weight	Unit weight
	AVA	AVA	AVA
	Linear traverse		
Permeability	Rapid chloride		
Shrinkage	CTE Free shrinkage test	HIPERPAV	HIPERPAV

Phase II

The initial suite of tests was then further refined into a field test plan during Phase II. This test plan was utilized as a guideline for the execution of the demonstration projects. The testing frequency and sampling locations were identified. It was also determined that the testing for the mixture design stage would be performed at the PCC Pavement and Materials Research Laboratory (PCC Lab) at the CP Tech Center. The field test plan is shown in table 2.2.

Table 2.2 Phase II Field Test Plan

Focal property	Test name	Frequency	Sample location	Test location
Workability				
	Differential scanning calorimetry	1/day	cement storage at plant	PCC Lab
	X-Ray fluorescence	1/day	cement storage at plant	PCC Lab
	X-Ray diffraction	1/day	cement storage at plant	PCC Lab
	Blaine fineness	1/job	cement storage at plant	PCC Lab
	Shilstone coarseness and workability factors	use available contractor/DOT data		mobile lab
	Combined percent retained	use available contractor/DOT data		mobile lab
	0.45 Power chart	use available contractor/DOT data		mobile lab
	Set time	1/day	plant	mobile lab
	False set	1/day	plant	mobile lab
	Cementitious heat generation	1/day	cement storage at plant	mobile lab
	Mortar flow	1/day	plant	mobile lab
	Slump	1/day	grade	mobile lab
	Concrete temperature	1/day	grade	mobile lab
Strength development				
	Concrete strength - 7 day	1/job	grade	mobile lab
	Microwave water content	1/day	grade	mobile lab
	Heat signature	1/week	plant	mobile lab
	Maturity-strength relationship	1/job	plant	mobile lab
	In-place maturity	1/day	grade a.m. and p.m.	grade
Air entrainment				
	Air content	1/day	grade	grade
	Unit weight	1/day	grade	grade
	Air-void analyzer	1/day	grade	mobile lab
	Hardened air-void properties	2/job	cores matching AVA locations	PCC Lab
	Foam index test	1/job	plant	mobile lab
Permeability				
	Rapid chloride penetration	1/job	cores matching AVA locations	PCC Lab
Shrinkage				
	CTE	1/job	cores matching AVA locations	PCC Lab
	HIPERPAV	1/day	mobile lab	mobile lab
	Subbase temperature	1/day	grade	grade
	Weather data	1/day	mobile lab	mobile lab

Over the course of the first three demonstration projects in 2004, field sampling worksheets were developed and test groups were introduced to facilitate simplified scheduling of the demonstration project sampling and testing. Examples of these field sampling worksheets are provided in appendix A.

Modifications were made to the field test plan throughout Phase II. These modifications occurred for various reasons. Foam index was the only test that was dropped from the field demonstration projects. After numerous repetitions of this procedure, the research team concluded that this procedure did not provide quantitative feedback that could be used during production to modify the concrete batching process. However, foam index and foam drainage tests are referenced in the final suite of tests as a component of material incompatibility testing during the mixture design stage.

Additional test procedures were evaluated during Phase II as well. The pooled fund Technical Advisory Committee (TAC) provided guidance and feedback throughout the project. Based on the guidance from the TAC, the following adjustments were made to the field test plan:

- Additional sampling in front of the paver for the Air-Void Analyzer (AVA) was initiated in 2006. These test results were then compared to the test results from sampling locations behind the paver in the finished slab. No statistically significant difference (spacing factor and specific surface) was observed for AVA samples obtained in front of the paver, behind the paver on a vibrator path, and behind the paver between vibrator paths. This conclusion may not apply under all circumstances, and some mixtures may react differently under excessive vibration.
- Permeable voids test (ASTM C 642) was added in 2006 and compared to rapid chloride penetration (RCP) test (ASTM C 1202). As a member of the pooled fund, the Kansas Department of Transportation further evaluated the correlation of early-age permeable voids test results with standard RCP test results. Based on the preliminary results of these comparisons, the permeable voids test was added to the final suite of tests.
- Freeze-thaw durability test (ASTM C 666) of cores taken from AVA sampling locations was also added as a follow-up to previous work done by the Missouri Department of Transportation. A correlation between durability factor and spacing factor as measured by the AVA could not be established due to the limited number of freeze-thaw specimens that were tested.
- Standard pressure air content tests (ASTM C 231) were performed on samples of hand-vibrated concrete in 2006. These tests were an attempt to potentially determine the stability of the entrained air bubbles for a given mixture. Of the two mixtures that were evaluated with this method, differences in air content before vibrating and after vibrating could not be distinguished.

Project staff also evaluated the Chase Air Indicator as an alternative test method in the field. This device is not intended to serve as a replacement for either the pressure or volumetric method for measuring air content. The Chase Air Indicator was used less than 10 times. When used, the results were comparable to the pressure air method (±1.5%). However, no benefit was observed for continuing its use.

The Material and Construction Optimization for Prevention of Premature Pavement Distress in PCC Pavements (MCO) project cooperated with an on-going heat evolution research project at the CP Tech Center on two demonstration projects. The New York and South Dakota MCO demonstration projects both included additional calorimetry and set time testing (ASTM C 403) to evaluate the use of calorimetry testing as an estimate of initial and final set times. The results of the calorimetry predictions of initial set and final set correlated very well with the ASTM C 403 test results.

Phase II testing spanned 2 years and 2 months, from August 2004 through September 2006. The last thirteen demonstration projects were conducted with similar schedules following the test group organization. Depending on weather and the contractor's schedule, approximately eight to ten concrete batches were sampled during a normal two-week demonstration project. A typical demonstration project schedule is shown in table 2.3.

Table 2.3 Typical Demonstration Project Schedule

	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
Week #1	Travel	Setup Group B	Group A Group A(m)	Group A Group C Group A(s)	Group A(m) Group A Group C	Group A Group C	Test maturity specimens if necessary
Week #2	Test maturity specimens if necessary	Group A Group C	Group A Group C Group A	Group A Group A Group C	Group A(b) Cores	Cores Stow & pack equipment	Travel

Group A tests include the following sampled at the paver:

- Environmental conditions, base temperature, and soil temperature.
- Concrete temperature.
- Slump.
- Unit weight sampled ahead of the paver.
- Air content sampled ahead of the paver.
- Mortar flow.
- Microwave water content.
- AVA—three samples obtained behind the paver.

Group A(m) adds the placement of a maturity sensor.

Group A(s) adds the preparation of three cylinders to be tested for compressive strength at seven days.

Group A(b) adds unit weight and air content testing of samples obtained from behind the paver.

Group B tests include the following sampled at the plant/mobile lab trailer:

- Environmental conditions.
- Concrete temperature.
- Slump.
- Unit weight.
- Air content.
- Mortar flow.
- Microwave water content.
- Set time.
- Compressive strength maturity specimens—13.
- Flexural strength maturity specimens—13.
- Calorimetry heat signature specimen.

Group C tests include the following sampled at the plant:

- Temperature of cementitious materials at the time of sampling.
- Cementitious heat generation (coffee cup).
- Early stiffening (false set).
- Combined gradation.
- HIPERPAV.

At the conclusion of Phase II, the data from the sixteen demonstration projects were compiled, analyzed, and a final suite of tests was drafted.

The goal of this research was to identify the properties that could lead to premature distress and select the tests that would quantify those properties. None of the 16 projects visited exhibited such properties, with the possible exception of the North Dakota project. There, the pavement that was placed during the demonstration effort has performed well; however, cracking occurred in pavement placed after the lab had left.

This is not surprising. Projects that experience serious mixture or construction problems are rare. To only perform testing on one project in each state would mean that the probability of picking one with problems would be very small. Therefore, the data collected are limited with respect to testing potentially nondurable concrete. The data did allow evaluation of the tests and the authors feel they did accomplish the goals of the research.

Phase III

Final modifications to the suite of tests in Phase III have been debated extensively by the research team and the TAC. The material incompatibility protocol developed under separate research by Taylor (*4*) is referenced in the mixture design stage of testing. Even though the MCO project did not include aggregate testing, aggregate durability and alkali-silica reactivity test procedures are referenced as well.

A primary concern of the TAC was that "one size does not fit all"— performing the entire suite of tests on smaller and/or non-critical projects would not be cost-effective. Thus, a project design level hierarchical scenario was adopted. The final suite of tests can now be considered as a three-dimensional matrix. Project design levels mirror the hierarchy established in the Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures (M-E PDG) (*5,6*). Addition of the project level criteria provides flexibility for the suite of tests to fit all projects.

Chapter 3: Focal Properties

Five focal properties of portland cement concrete for pavement serve as the foundation for the suite of tests. These focal properties were identified during the initial stages of the research as a way to potentially characterize the performance characteristics of the concrete. A brief description of the focal properties is given here to explain the researchers' approach to identifying potential performance issues related to premature distress in concrete pavements.

Workability

In 1932, Powers described workability in the following way: "Analogous to the soil in its initial condition, an unworkable concrete mixture is one in which the solid particles are locked together forming a more or less rigid structure. A workable mixture on the other hand is one in which the solids are suspended by a completely enveloping, continuous body of water. (Thus, the common nickname "mud" for concrete is not at all inapt provided the mixture referred to is workable.)"(*7*). Workability of a mixture is a function of the materials: aggregate gradation, water-cementitious materials (w/cm) ratio, air content, admixtures, and cementitious chemistry all influence the workability. Project factors such as material temperature, ambient temperature, subbase temperature, and haul time also impact workability.

For a given placement method, there is an ideal workability range. When concrete is outside this ideal workability range, other focal properties can be adversely affected. Modern paving equipment is capable of placing very stiff mixtures. However, excessive vibration of these stiff mixtures can lead to segregation and loss of entrained air (*8*). Premature pavement failures are not directly diagnosed as a failure to meet workability criteria. They are, however, attributed to the other focal properties, which can all be adversely impacted by workability issues. Segregation can reduce permeability, reduce strength, and increase shrinkage. Loss of air entrainment can reduce freeze-thaw durability. For this study, workability is considered as a focal property because of its potentially adverse impacts on the other focal properties.

Strength Development

During the course of this study, a wide variety of material combinations were observed. Figure 3.1 shows the distribution of seven-day compressive strengths from the demonstration

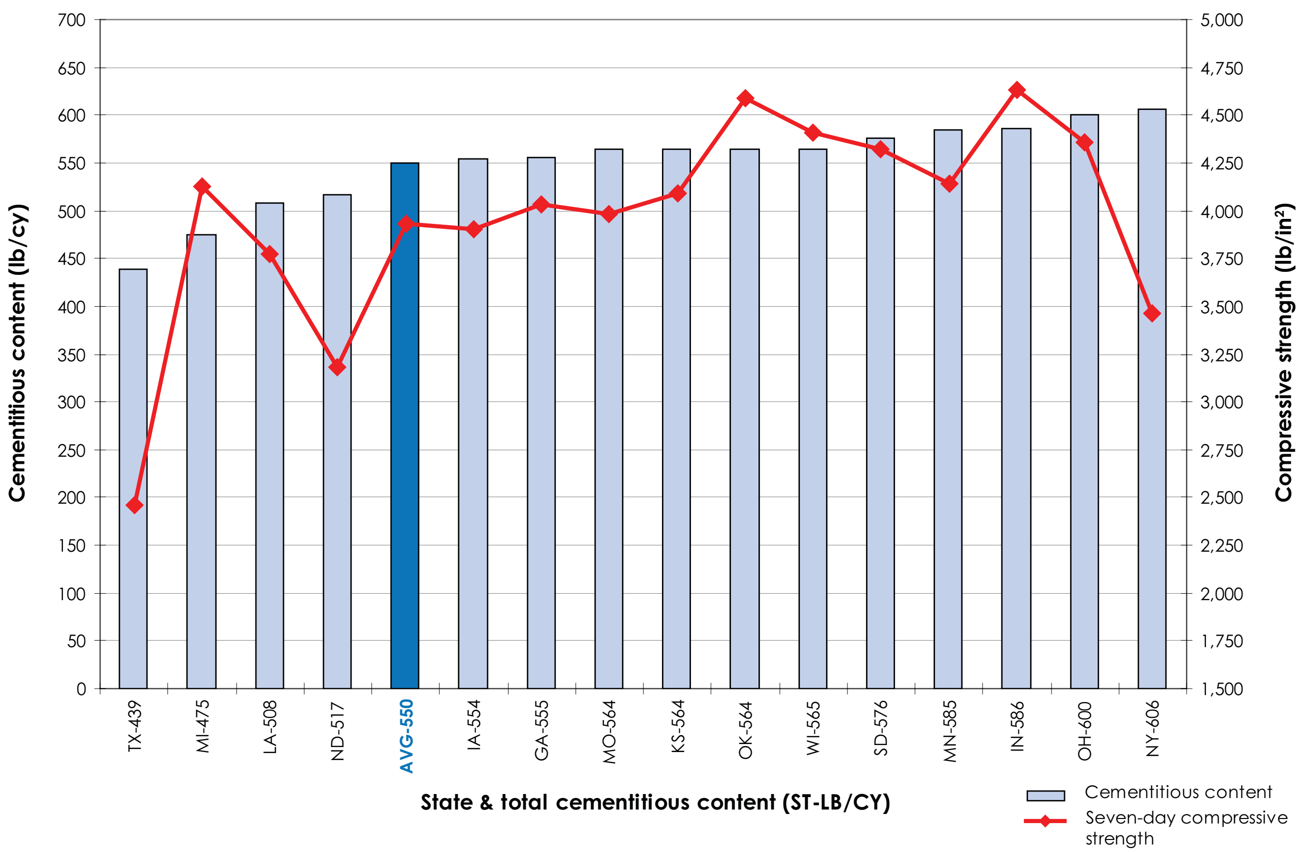

Figure 3.1 Demonstration project seven-day compressive strengths

projects. The data values are sorted from lowest to highest along the x-axis by total cementitious content per cubic yard. It is apparent from this distribution that concrete can be designed to meet a given strength using a variety of aggregate types (limestone, gneiss, gravel, etc.) at a multitude of w/cm values. What cannot be discerned from this chart is the rate of strength gain during the first 72 hours after placement (strength development). Characterizing the strength development of a mixture may be more important than focusing on ultimate strength. The consensus of the research team and the TAC is that premature pavement failures due to strength development issues occur more frequently than premature failures caused by low strengths.

The rate of strength development of a concrete mixture is a primary factor associated with uncontrolled cracking of a newly constructed pavement. Figure 3.2 illustrates how this rate of strength gain can differ for two mixtures that have similar seven-day compressive strengths. While both the ND-517 and NY-606 mixtures had comparable seven-day compressive strengths (3,180 and 3,460), as shown in figure 3.1, the rate of strength development was slower for the ND-517 mixture. In figure 3.2, it can be seen that ND-517 reached an estimated 275 psi in 18.7 hours, while NY-606 reached the same value in 12.7 hours. These estimated flexural strengths are based on the strength-maturity relationships for each mixture and the actual pavement temperatures from the time of placement through three days. This difference in strength development had real-world consequences. The pavement constructed with mixture ND-517 experienced early-age random cracking that required full-depth repairs. Even though the repairs were made with great care, the homogeneity of the pavement has been affected, and the potential for premature failure is higher than if the cracks had not occurred. These data support the fact that it is important to monitor strength development.

Air Entrainment

Premature pavement distresses caused by freeze-thaw damage are often directly attributable to an inferior air-void system in the concrete. Most construction specifications specify minimum air content. However, this is not always adequate to assure the freeze-thaw durability of a pavement. Air-void systems are characterized by spacing factor and specific surface. These properties can be measured on a sample of hardened concrete in accordance with ASTM C 457, or the Air-Void Analyzer (AVA) can be used on a fresh mortar sample.

Spacing factor characterizes the fraction of paste within some distance of an air void (*9*). Specific surface is the air-void

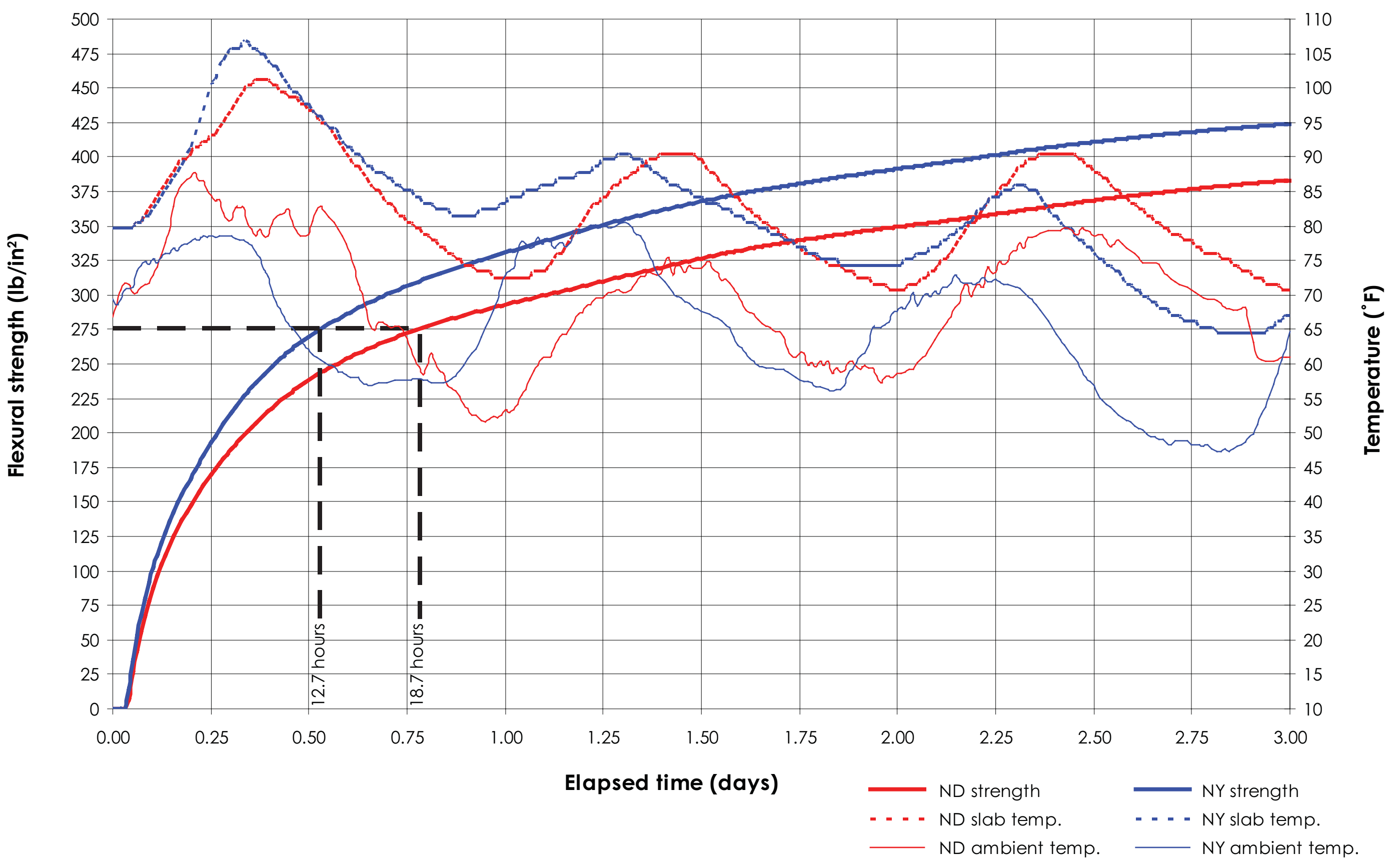

Figure 3.2 Early-age estimated in-place flexural strength (ND & NY)

volume of a sample, reported as the surface area of measured air voids per unit of air-void volume.

The most commonly used air content test (ASTM C 231) measures the total percent of air in a concrete mixture. This is both entrapped and entrained air. Entrapped air does not protect the pavement from freeze-thaw damage. Likewise, the total air content provides no information regarding the air-void properties. Under certain circumstances, a mixture with adequate total air content may not be freeze-thaw resistant. If the entrained air bubbles are not properly distributed, the pavement may experience premature failure from freeze-thaw damage. Figure 3.3 is a photograph illustrating deterioration from freezing and thawing of a pavement with an inadequate air-void system. The damage normally starts at the joints where water is trapped. Air entrainment was included as a focal property for this research based on previous research results documenting the relationship between air entrainment and freeze-thaw resistance, as well as field experience with numerous pavements that failed prematurely due to poor air-void systems.

Permeability

The permeability of a portland cement concrete pavement is a measure of how resistant it is to the penetration of fluids. Lower permeability means a higher resistance to moisture infiltration. A concrete mixture's paste system is the primary factor that impacts permeability. If the paste system has a large number of connected pores, it will be permeable (*10*). Low-permeability mixtures are associated with low w/cm, addition of supplementary cementitious materials (SCMs), and excellent curing practices that promote higher levels of cement hydration.

Figure 3.3 Deficient air-void system resulting in freeze-thaw damage

Moisture is a key factor associated with alkali-silica reactivity (ASR) and freeze-thaw damage to pavements. Thus, a pavement with low permeability will be more resistant to ASR and freeze-thaw distresses. As the use of deicing solutions applied to pavements increases, low-permeability mixtures become even more important. Reducing the permeability of a pavement is one way to combat the potential for ASR.

Shrinkage

The risk of uncontrolled cracking in a concrete pavement increases as shrinkage increases. With respect to portland cement concrete, shrinkage refers to a change in volume of the concrete. The total shrinkage in concrete is comprised of five additive factors (*10,11*):

- Autogenous shrinkage—the volume change of cement paste ingredients as they hydrate.
- Plastic shrinkage—loss of moisture before the concrete sets.
- Drying shrinkage—loss of moisture after the concrete sets.
- Thermal shrinkage—contraction as a result of reducing temperature, primarily a function of the coarse aggregate's coefficient of thermal expansion (CTE).
- Settlement—aggregates sinking in the fluid suspension, forcing water to rise to the surface (bleeding), which then evaporates out of the concrete.

The total amount of shrinkage for a given concrete mixture is primarily a function of the volume of paste (water content). The risk of uncontrolled cracking can be mitigated by reducing the total volume of paste in the mixture and by preventing early evaporation through the timely application of a complete coverage of curing compound.

Other Properties

Material Incompatibilities

As cementitious paste systems have become more complex through the introduction of supplementary cementitious materials and multiple admixture combinations, unexpected interactions between acceptable ingredients have become more common. These incompatibilities can impact multiple focal properties. Examples of effects include early stiffening, excess retardation, early-age random cracking, unacceptable air voids, and unstable air systems (*4*). Ideally, the potentially deleterious effects of incompatibilities should be evaluated during the mixture design stage. However, the incompatibility protocol should be repeated during the mixture verification stage and as a troubleshooting aid whenever difficulties are observed or when quality control results indicate a material incompatibility may occur.

A protocol for identifying these potential incompatibilities was developed under separate research by Taylor et al. (*4*). Similar to ASTM or AASHTO procedures, this protocol is summarized in this report. The full protocol is available from the FHWA at http://www.fhwa.dot.gov/pavement/pub_details.cfm?id=439.

Alkali-Silica Reactivity (ASR)

ASR deterioration will occur when aggregates with reactive silica are combined with cementitious materials containing sufficient quantities of alkali and then exposed to sufficient moisture (*12*). ASR was not directly studied in this research. However, it cannot be ignored as a potential factor contributing to the premature failure of portland cement concrete pavements. Under normal circumstances, it is assumed that the specifying agency has screened aggregate sources for ASR potential. If the aggregate has not been pre-approved by an agency, ASR testing should be performed. Protocols are available from the Portland Cement Association (PCA), the American Association of State Highway and Transportation Officials (AASHTO), the Canadian Standards Association (CSA), and a draft is being reviewed by FHWA.

Aggregate Durability

D-cracking is a concrete materials related distress that is related to the porosity of the coarse aggregate. The aggregate particles absorb water, which expands when it freezes. D-cracking generally begins in the lower levels of pavements where moisture levels are higher. Stresses generated during freezing and thawing cycles eventually exceed the tensile strengths of the saturated aggregate and surrounding mortar, resulting in premature failure of the pavement (*13*). Like ASR, aggregates are normally screened by specifying agencies and pre-approved for use. Whenever the aggregates that are proposed to be used have not been pre-approved, freeze-thaw durability testing should be performed.

Chapter 4: Implementing the Suite of Tests

Acceptance Criteria or Quality Control?

Over the past four years, the MCO project has evaluated many new and existing test procedures in both a laboratory and a field environment. One clear conclusion from this extensive effort is that no magic black box exists that will tell us everything we want to know about the quality of a pavement. In fact, many of the procedures included in the final suite of tests do not currently have the precision that would allow acceptance criteria to be defined for them. This prompts the question of whether we should just wait until new technologies are developed that give us the answers we desire? Or, should we take the best of what is currently available and move forward with quality control techniques that will help us prevent premature failures? Even though premature failures are rare, the consequences are too severe to ignore.

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

Long-term durability is related to a combination of concrete properties. To make matters more confusing, the combination of concrete properties that yield durable concrete in one climatic region is different from what is required in another region. For example, air entrainment is critical in a wet-freeze environment, while it is unnecessary in a nonfreeze region. Based on current practice and historical experience, state highway agencies can specify a combination of concrete properties that they deem will result in a durable pavement. Commonly, acceptance criteria are based on combinations of strength, thickness, air content, and combined gradation. However, there are other properties that can be evaluated in a laboratory during the mixture design stage: permeability, time of set, air-void structure, and heat signature. Rather than establishing acceptance criteria for all of these properties, verification and process control testing can be performed on the project to identify when the materials and/or construction processes change in a manner that may negatively impact the long-term durability of the pavement. Monitoring change through the use of additional test procedures and Statistical Process Control (SPC) techniques is the basis for implementing the suite of tests.

Implementation Paths

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

Regardless of the motivation (specification or limiting liability) for using the suite of tests as a quality control (QC) tool, implementing SPC is integral to moving forward with the suite of tests for the prevention of premature failures. In general, the current state of QC procedures is better described as duplicative acceptance testing rather than true process control. Coupling SPC with the suite of tests will provide feedback that will enable the identification of changes in the materials or construction processes that may contribute to premature failures. Chapter 5, Implementing Quality Control Elements, serves as a guide for establishing SPC techniques that should be used with the suite of tests.

Defining the Project Level

Concrete paving projects come in a variety of sizes and shapes, and none are identical. Because of this variation, one size does not fit all. To avoid wasting resources on unnecessary testing, it is imperative that the risk of premature failure is balanced against the cost of additional process control testing. Three project levels (A, B, and C) are provided to permit flexibility in addressing projects of differing scope and size. Correctly assigning the project level cannot be overemphasized. It is not necessary to perform the same level of testing on a low-volume road as on an urban interstate. Although the M-E PDG hierarchical approach was the inspiration for providing project levels as a way to address projects of varying scope and size, the project level assignments for this work may not be the same as those selected for the pavement design process. The suites of tests have been intentionally labeled as Levels A, B, and C in contrast to the M-E PDG's Levels 1, 2, and 3. While there may be circumstances where a Level 2 pavement design is used, this does not mean that the Level B suite of tests should automatically be applied to the project. It may be that a state transportation agency (STA) has developed Level 2 inputs as they implemented the M-E PDG; however, the decision regarding what suite of tests level to assign should be based on other factors.

The suite of tests project levels are defined as shown in table 4.1.

The definitions of each level are general in nature. No specific criterion is given regarding project size, project cost, or annual average daily traffic (AADT). Sound engineering judgment should be used when assigning a project level (choosing which suite of tests to use). If concrete pavements have historically performed well in a certain area, there is no need to arbitrarily require additional process control testing when the risk of premature failure is very small—Level C or a modified Level B would be appropriate. A combination of project size and AADT is probably the best way to evaluate which project level is appropriate for a given project. The risk of premature failure is directly related to initial cost and user delay costs associated with maintenance and/or replacement of the prematurely failed pavement. Even when AADT is extremely high, if the project size is small (can be repaired or replaced in a short time frame), it would not warrant a Level A assignment.

Table 4.1 Typical Project Characteristics by Project Level

Project level	Project characteristics
A	Urban freeways with the highest AADT (minimum 100,000 and 95th percentile when compared to all other routes in the same population center) --and-- Limited or no alternative routes exist Primary freight routes that would have significant economic impact if disrupted for prolonged periods Complex projects that would require an extended duration for maintenance or replacement
B	Interstate and primary U.S. or state highway routes that carry significant volumes of freight Major urban intersections Alternative routes resulting in extensive delays (economic impact) Primary routes to special event centers that carry very high peak traffic loads
C	City streets Low-volume roads

When considering AADT as a relative indicator of potential user delay costs, it is important to recognize that user delay costs are an estimate of economic impact associated with highway construction. Thus, commuter trips are treated differently than trips that are associated with actual performance of work (through freight, deliveries, sales calls, etc.). AADT values that have large components of commuter trips and other trips which do not have an economic impact should be adjusted downward when assigning the project level.

In the case of a local entity (city or county) that is making the determination of project level, AADT and project scope should be compared across the entire population center. For example, an intersection project may have the highest AADT within a particular suburb's city limits; however, when compared to traffic conditions within the metropolitan area, the AADT for that intersection is below the median value of other routes and intersections. Assignment of the project level should be limited strictly to a "common sense" assessment of the risk associated with premature pavement failure. This "common sense" engineering judgment approach also applies to keeping the project cost in perspective. Even if a particular intersection project makes up the majority of a local entity's public works budget for a year, it does not automatically mean that it should be designated as a Level A project.

When assigning the project level, the following questions should be reflected upon:

- Have premature concrete pavement failures occurred more than in isolated situations in this region in the past?
- If this pavement fails prematurely, how significant will the user delay costs be as compared to other routes in the metropolitan area? Is the AADT high for my agency or is it high compared to all other routes in the area?
- Is the increased cost of process control testing justified by reduced maintenance costs or prolonged pavement life?

Human nature leads us to sometimes skew our priorities because our reputations are connected to the success or failure of a project. Every project cannot be a Level A project. Engineering judgment has to enter into the assignment of the project level to avoid wasting resources. Figure 4.1 illustrates what the distribution of project levels might look like for a state highway agency: 75% of the projects are Level B, 20% are Level C, and 5% are Level A.

Estimated Testing Effort by Project Stage and Project Level

Current quality control practices vary from state to state. Contractors in some markets are accustomed to extensive internal QC programs, while some agencies still perform the majority of material testing on paving projects (QC and acceptance). In most cases, implementing the suite of tests for any project level will require additional testing during the mixture design and mixture verification stages. Process control testing for Level C projects does not entail any testing procedures that are not already widely accepted.

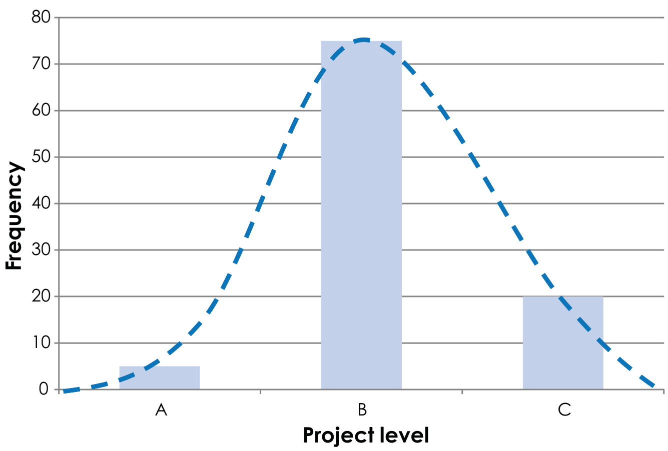

Figure 4.1 Hypothetical distribution of project levels for a state highway agency

An estimate of testing effort by man hours has been developed for each project level (table 4.2). These estimates are based on experience gained through the MCO research project. Contractors may use these estimates as a starting point for assessing the level of testing effort.

The proposed suites of tests are shown as figures 4.2, 4.3, and 4.4. When reviewing these figures, the following points should be considered:

- Three suites are provided to permit the flexibility of addressing projects of differing scope. Correctly assigning the project level cannot be overemphasized. It is not necessary to perform the same level of testing on a low-volume road as on an urban interstate.
- Testing during the mixture design stage is necessary to fully characterize the performance characteristics of the mixture. Comparing test results between the mixture design stage and the mixture verification stages will identify major changes in the materials that may impact the performance characteristics observed in the lab during the mixture design stage.
- Testing during the quality control stage must be coupled with SPC to identify changes in the materials and/or construction processes. Again, this point cannot be overemphasized. Each of the test procedures evaluated has a degree of variability and/or imprecision that makes them impractical for use as an acceptance criteria. However, when properly administered in a comprehensive SPC quality control plan, they can identify changes in the process that will help to prevent premature failures.

A suggested list of testing equipment for implementation of each suite of tests is provided in appendix C.

Table 4.2 Estimated Testing Effort by Project Level and Project Stage

	Project stage						
	Mixture design		Mixture verification		Quality control		
Project level	Total duration (days)	Man hours	Total duration (days)	Man hours	Total duration (working days)	Man hours	No. of technicians
A	7*	150	7**	80	5	200	4 & QC manager
B	7*	70	7**	75	5	135	3
C	7*	60	3	30	5	85	2

* Permeable voids testing may take longer than 7 days, depending on the length of time required to fully dry and saturate the specimens.

**It is not necessary to wait the full 7 days (or longer) for results of the permeable voids testing to proceed with paving if all other tests indicate that the field mixture has properties similar to the baseline values established by the mixture design.

Level A Suite of Tests (recommended)

Urban freeways with the highest AADT (minimum 100,000). Limited or no alternative routes. Primary freight routes that would have significant economic impact if disrupted for prolonged periods. Complex projects that would require an extended time for maintenance or replacement.

Mixture Property			Project Stage		
Test Name	**Test Procedure(s)**	**Proposed Testing Frequency (minimum 1 per day)**	**Mixture Design/ Proportioning**	**Pre-Construction Mixture Verification**	**Quality Control**
Workability					
Combined Grading: Coarseness and Workability Factors, 0.45 Power Curve, and Percent Retained on Individual Sieves	ASTM C 136 / AASHTO T 27	every 1,500 yd^3	✓	✓	✓
Aggregate Moisture Content	ASTM C 566 / AASHTO T 255	every 1,000 yd^3	✓	✓	✓
Slump and Loss of Workability	ASTM C 143 / AASHTO T 119	every 500 yd^3	✓	✓	✓
Mortar Flow	ASTM C 1437	each project stage noted	✓	✓	
Vibrator Monitoring	manufacturer's recommendations	continuous automated monitoring			✓
Cementitious Heat Generation (coffee cup)	*MCO Testing Guide* pages 59–61	every 1,500 yd^3	✓	✓	✓
False Set	ASTM C 359 / AASHTO T 136	only when early stiffening is detrimental			✓
Strength Development					
Microwave Water Content	AASHTO T 318	every 500 yd^3	✓	✓	(optional) AASHTO T 318 or strength testing
Heat Signature (calorimetry)	*MCO Testing Guide* pages 67–69	1 per day	✓	✓	✓
Set Time	ASTM C 403	each project stage noted	✓	✓	
Concrete Strength (3 and 7 day)	ASTM C 39 / AASHTO T 22 ASTM C 78 / AASHTO T 97 ASTM C 293 / AASHTO T 177	every 500 yd^3	✓	✓	(optional) AASHTO T 318 or strength testing
Air Entrainment					
Unit Weight	ASTM C 138 / AASHTO T 121	every 500 yd^3	✓	✓	✓

Figure 4.2 Level A suite of tests

Level A Suite of Tests (recommended), continued

Mixture Property			Project Stage		
Test Name	**Test Procedure(s)**	**Proposed Testing Frequency (minimum 1 per day)**	**Mixture Design/ Proportioning**	**Pre-Construction Mixture Verification**	**Quality Control**
Air Content	ASTM C 231 / AASHTO T 152 ASTM C 173 / AASHTO T 196	every 500 yd^3	✓	✓	✓
Air-Void Analyzer	*MCO Illustrated Test Procedure Hyperdocument*	every 1,500 yd^3	✓	✓	✓
Hardened Air Properties	ASTM C 457 or equivalent image analysis procedure	only when AVA results indicate potential durability issues	✓	✓	✓
Permeability					
Rapid Chloride Penetration	ASTM C 1202 / AASHTO T 277	each project stage noted	✓		
Permeable Voids (boil test)	ASTM C 642	each project stage noted	✓	✓	
Shrinkage					
Coefficient of Thermal Expansion	AASHTO TP 60	each project stage noted	✓		
HIPERPAV	*MCO Testing Guide* page 93	two stress–strength analyses per day (a.m. & p.m.)	✓	✓	✓
Other Properties					
Strength–Maturity Relationship for Early Opening to Traffic (optional)	ASTM C 1074 / AASHTO T 325	(optional) place two sensors every day (a.m. & p.m.)		✓ (optional) develop strength–maturity relationship	✓ (optional)
Material Incompatibilities	*Identifying Incompatible Combinations of Concrete Materials: Volume II-Test Protocol*	each project stage noted	✓	✓	whenever air-void property or early stiffening issues arise
Alkali-Silica Reactivity	agency material prequalification ASTM C 1260 ASTM C 1293 ASTM C 1567 / AASHTO T 303	n/a			
Aggregate Durability	agency material prequalification ASTM C 666 / AASHTO T 161	n/a			

Figure 4.2 Level A suite of tests, continued

Level B Suite of Tests (recommended)

Interstate and primary U.S. or state highway routes that carry significant volumes of freight. Major urban intersections. Alternative routes that result in extensive delays (economic impact). Primary routes to special event centers that carry very high peak traffic loads.

Mixture Property			Project Stage		
Test Name	**Test Procedure(s)**	**Proposed Testing Frequency (minimum 1 per day)**	**Mixture Design/ Proportioning**	**Pre-Construction Mixture Verification**	**Quality Control**
Workability					
Combined Grading: Coarseness and Workability Factors, 0.45 Power Curve, and Percent Retained on Individual Sieves	ASTM C 136 / AASHTO T 27	every 1,500 yd^3	✓	✓	✓
Aggregate Moisture Content	ASTM C 566 / AASHTO T 255	every 1,000 yd^3	✓	✓	✓
Slump and Loss of Workability	ASTM C 143 / AASHTO T 119	every 500 yd^3	✓	✓	✓
Vibrator Monitoring	manufacturer's recommendations	continuous automated monitoring			✓
Strength Development					
Microwave Water Content	AASHTO T 318	every 500 yd^3	✓	✓	(optional) AASHTO T 318 or strength testing
Heat Signature (calorimetry)	*MCO Testing Guide* pages 67–69	at each project stage noted	✓	✓	
Set Time	ASTM C 403	at each project stage noted	✓	✓	
Concrete Strength (3 and 7 day)	ASTM C 39 / AASHTO T 22 ASTM C 78 / AASHTO T 97 ASTM C 293 / AASHTO T 177	every 500 yd^3	✓	✓	(optional) AASHTO T 318 or strength testing
Air Entrainment					
Unit Weight	ASTM C 138 / AASHTO T 121	every 500 yd^3	✓	✓	✓
Air Content	ASTM C 231 / AASHTO T 152 ASTM C 173 / AASHTO T 196	every 500 yd^3	✓	✓	✓
Hardened Air Properties	ASTM C 457 or equivalent image analysis procedure	at each project stage noted	✓		

Figure 4.3 Level B suite of tests

Level B Suite of Tests (recommended), continued

Mixture Property			Project Stage		
Test Name	**Test Procedure(s)**	**Proposed Testing Frequency (minimum 1 per day)**	**Mixture Design/ Proportioning**	**Pre-Construction Mixture Verification**	**Quality Control**
Permeability					
Permeable Voids (boil test)	ASTM C 642	at each project stage noted	✓	✓	
Shrinkage					
HIPERPAV	*MCO Testing Guide* page 93	two stress-strength analyses per day (a.m. & p.m.)	✓	✓	✓
Other Properties					
Optional for all Project Levels: Strength-Maturity Relationship for Early Opening to Traffic	ASTM C 1074 / AASHTO T 325	(optional) place two sensors every day (a.m. & p.m.)		✓ (optional) develop strength-maturity relationship	✓ (optional)
Material Incompatibilities	*Identifying Incompatible Combinations of Concrete Materials: Volume II-Test Protocol*	at each project stage noted	✓	✓	perform whenever air void property or early stiffening issues arise
Alkali-Silica Reactivity	agency material prequalification ASTM C 1260 ASTM C 1293 ASTM C 1567 / AASHTO T 303	n/a			
Aggregate Durability	agency material prequalification ASTM C 666 / AASHTO T 161	n/a			

Figure 4.3 Level B suite of tests, continued

Level C Suite of Tests (recommended)

City streets and low-volume roads.

Mixture Property			Project Stage		
Test Name	**Test Procedure(s)**	**Proposed Testing Frequency (minimum 1 per day)**	**Mixture Design/ Proportioning**	**Pre-Construction Mixture Verification**	**Quality Control**
Workability					
Combined Grading: Coarseness and Workability Factors, 0.45 Power Curve, and Percent Retained on Individual Sieves	ASTM C 136 / AASHTO T 27	every 1,500 yd^3	✓	✓	✓
Aggregate Moisture Content	ASTM C 566 / AASHTO T 255	every 1,000 yd^3	✓	✓	✓
Slump and Loss of Workability	ASTM C 143 / AASHTO T 119	every 500 yd^3	✓	✓	✓
Strength Development					
Concrete Strength (3 and 7 day)	ASTM C 39 / AASHTO T 22 ASTM C 78 / AASHTO T 97 ASTM C 293 / AASHTO T 177	at each project stage noted	✓	✓	
Air Entrainment					
Unit Weight	ASTM C 138 / AASHTO T 121	every 500 yd^3	✓	✓	✓
Air Content	ASTM C 231 / AASHTO T 152 ASTM C 173 / AASHTO T 196	every 500 yd^3	✓	✓	✓
Permeability					
Permeable Voids (boil test)	ASTM C 642	at each project stage noted	✓		
Other Properties					
Optional for all Project Levels: Strength-Maturity Relationship for Early Opening to Traffic	ASTM C 1074 / AASHTO T 325	(optional) place two sensors every day (a.m. & p.m.)		✓ (optional) develop strength-maturity relationship	✓ (optional)
Alkali-Silica Reactivity	agency material prequalification ASTM C 1260 ASTM C 1293 ASTM C 1567 / AASHTO T 303	n/a			
Aggregate Durability	agency material prequalification ASTM C 666 / AASHTO T 161	n/a			

Figure 4.4 Level C suite of tests

Chapter 5: Implementing Quality Control Elements

Every process has some variation. A world class marksman can hit the bull's-eye with every shot, but there will still be some "spread" to his shots. This predictable "spread" is called common cause variability. An amateur marksman has more common cause variability than the professional does (figure 5.1). Unusual changes that arise in a process are called special cause variability. In the case of a professional marksman, if someone were to bump his arm during a shot, the bullet would miss the bull's-eye by a wide margin due to a special cause (figure 5.1).

Process control testing in conjunction with control charts will help us identify and remove special cause variability, resulting in a stable process. After a stable process is established, process improvements can be implemented to reduce common cause variability (*14*).

Justification for Statistical Process Control

If our objective is to prevent premature pavement failures, and assuming that we start a project with materials and construction processes that will yield a durable pavement, then it would be useful to know when something in our materials and/or processes changes. **The primary purpose of using Statistical Process Control (SPC), specifically control charts, is to identify change. Their function is not to indicate whether a test result passes or fails acceptance criteria, but rather to indicate if a test result was unusual** (*15*). Three conditions must be consistently met to achieve high levels of quality (*16*):

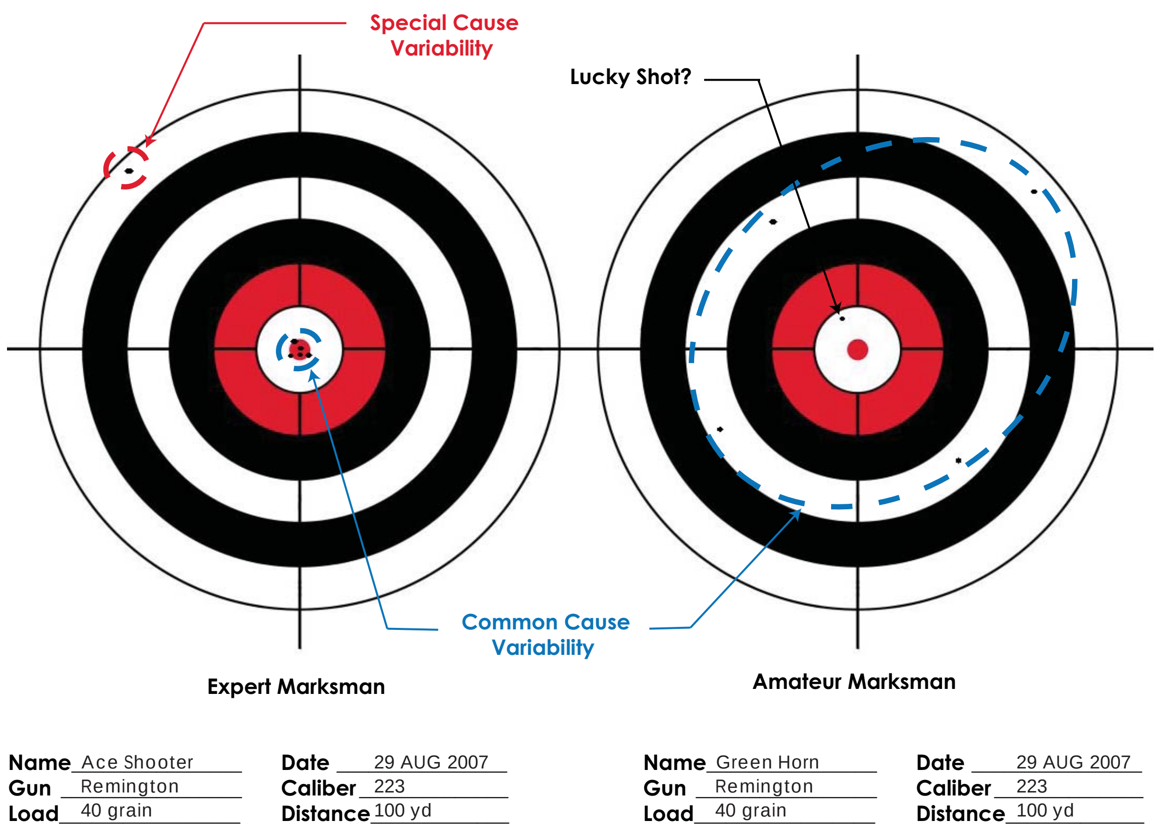

Figure 5.1 Common cause and special cause variability

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

Finally, the *Implementation Manual for Quality Assurance* (*17*) published by the American Association of State Highway and Transportation Officials states, "The need for contractors to use statistical control charts cannot be overemphasized. A control chart provides a visual indication of whether a process is in control."

Quality control (QC) in whatever form is a process that is used to facilitate producing a product that meets specifications. Thus, QC efforts may involve tests and/or observations of factors that are not necessarily specification requirements, but need to be monitored to assure specification compliance. Many of the acceptance criteria used for concrete pavements cannot be measured for days or even weeks after the pavement is in place. Measuring alternative material characteristics and properties during the construction process is the only way that we currently have to identify material deficiencies and/or construction processes that may contribute to the premature failure of a pavement.

Control Chart Basics

What makes up a control chart and what does it look like?

A control chart consists of the following components (*14*) (figure 5.2):

- The average of test results plotted as the centerline.
- Upper and lower limits, usually plotted at 3 times the standard deviation (3s) of the test data; these limits define the boundaries of common cause variability.
- Test data plotted over time.

How do I calculate the control limits?

The upper and lower control limits should be based on data that are representative of the process while it is stable, meaning that no special causes have affected any of the data points used. This is important because the purpose of the control limits is to reflect the voice of the process (reflect common cause variability) (*18*). Control limits are drawn at three standard deviations (3s or three-sigma) above and below the average centerline. Three-sigma limits strike a good balance between filtering out noise (common cause variability) and identifying important signals of process changes (special cause variability) (*14, 18*). Table 5.1 provides an example of calculating control limits.

Temporary control limits can be established with as few as 10 data points collected while the process is stable. They should be revised again when 15, 20, and 25 test results are available. After the control limits are established based on 25 test results, it is not necessary to revise them unless the process has changed. For example, if the batching sequence was changed so that water-reducing admixture is introduced later in the mixing sequence, this may reduce the amount of temper water needed to reach the desired workability. Such a change would likely be reflected in the test data by reduced variability in unit weight (improved consistency). This is a positive change because common cause variability has been reduced and the process has been improved. Before revising the control limits, the following questions should be asked (*18*):

- Do the limits need to be revised to accurately reflect the voice of the process?
- Do the data represent a distinctly different behavior from that previously observed?
- Is the reason for the change in test results known?

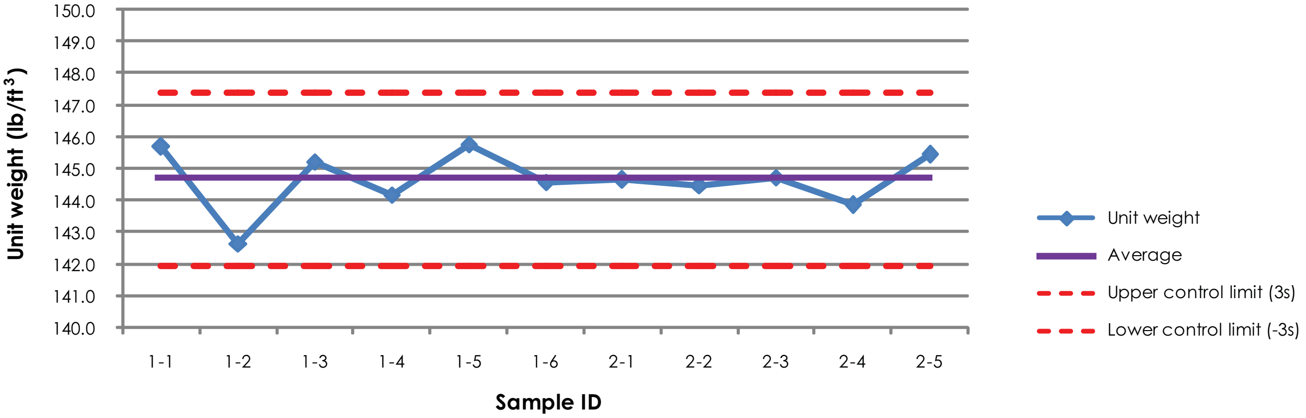

Figure 5.2 Example control chart

Table 5.1 Example Calculations of Average and Control Limits

Sample ID	Unit weight (lb/ft³)
1-1	145.7
1-2	142.6
1-3	145.2
1-4	144.2
1-5	145.8
1-6	144.6
2-1	144.6
2-2	144.5
2-3	144.7
2-4	143.8
2-5	145.4
Average	144.65
Sample standard deviation	0.91
Upper control limit (3s)	147.38 144.65 + (3 • 0.91)
Lower control limit (-3s)	141.92 144.65 - (3 • 0.91)

- Is the revised process behavior desirable (has the process actually been improved)?
- Will the new process remain stable (has the common cause variability been reduced permanently)?

If the answer to any of these questions is yes, then the control limits should be revised based on data from the improved process. It is important to remember that the 3s control limits represent the true common cause variability. If they are too tight, resources will be wasted chasing after phantom special cause variability. If they are too loose, special cause variability will go unnoticed.

What can I compare my 3s control limits with to see if they are in the ballpark?

A multi-step analysis of the MCO test results from the 16 demonstration projects was performed to look at what typical control limits may be appropriate for portland cement concrete paving projects. An example of the MCO 3s data analysis for air content is provided for reference.

1. Calculate the average, standard deviation, and coefficient of variation (standard deviation ÷ average) for each state demonstration project and sort the data (smallest to largest) by coefficient of variation (table 5.2).

Table 5.2 MCO Average Air Content and Variability by State

State	No. of samples	Average air content (%)	Std. Dev.	Coeff. of variation
GA	11	5.6	0.3	0.046
MN	11	7.1	0.6	0.081
NC	5	4.8	0.4	0.090
WI	8	6.0	0.6	0.097
IA	14	8.0	0.8	0.101
LA	6	5.2	0.6	0.116
SD	10	6.3	0.7	0.117
NY	9	6.1	0.8	0.128
KS	5	5.9	0.8	0.132
IN	9	6.3	1.0	0.162
OH	6	5.9	1.0	0.165
OK	8	5.9	1.0	0.173
ND	11	8.1	1.5	0.185
MI	5	5.7	1.1	0.186
MO	5	7.5	1.5	0.201
TX		test apparatus failure		

minimum (all projects) 4.3
maximum (all projects) 11.3

The coefficient of variation is used in this analysis so that a fair comparison of variability can be made between data sets with different average values. Comparing variability based on standard deviation would lead to an incorrect conclusion by skewing the analysis towards data sets that have lower average air contents. For instance, referring to table 5.2, even though the standard deviation for IA is greater than the standard deviation for LA (0.8% vs. 0.6%), because the average air content in IA is 54% greater than in LA (8.0% vs. 5.2%), the relative variability of the IA data set is less than it is for LA. Many of the test procedures evaluated in the MCO project require similar treatment (comparisons using the coefficient of variation) because the concrete properties vary from mixture to mixture. This variation between mixtures in the MCO data set is similar to what an individual contractor may experience between projects when the materials and mixture proportions are different. Variability comparisons between mixtures with different average values for test results can be made using the coefficient of variation.

Figure 5.3 is a graph of the average air content test data from table 5.2. However, it is sorted by average air content and includes upper and lower quartiles. These quartiles give an indication of the variability of data within each data set (states). By definition, 50% of the test values fall between the upper and lower quartiles, while 25% of the test results are greater than the upper quartile and 25% are less than the lower quartile.

Note that the MO data set has a limited set of values—one test result has skewed the average beyond the range of the upper and lower quartile values (table 5.3).

2. Calculate the average coefficient of variation for the top half (least variability) of state demonstration project data sets (table 5.4).

3. Repeat this process for each test procedure data set (table 5.5).

Table 5.3 MO Demonstration Project Tabular Air Content Data

Sample No.	Air content
1	6.0
2	7.0
3	7.0
4	7.3
5	10.0
Average	7.5
Lower quartile limit	7.0
Upper quartile limit	7.3

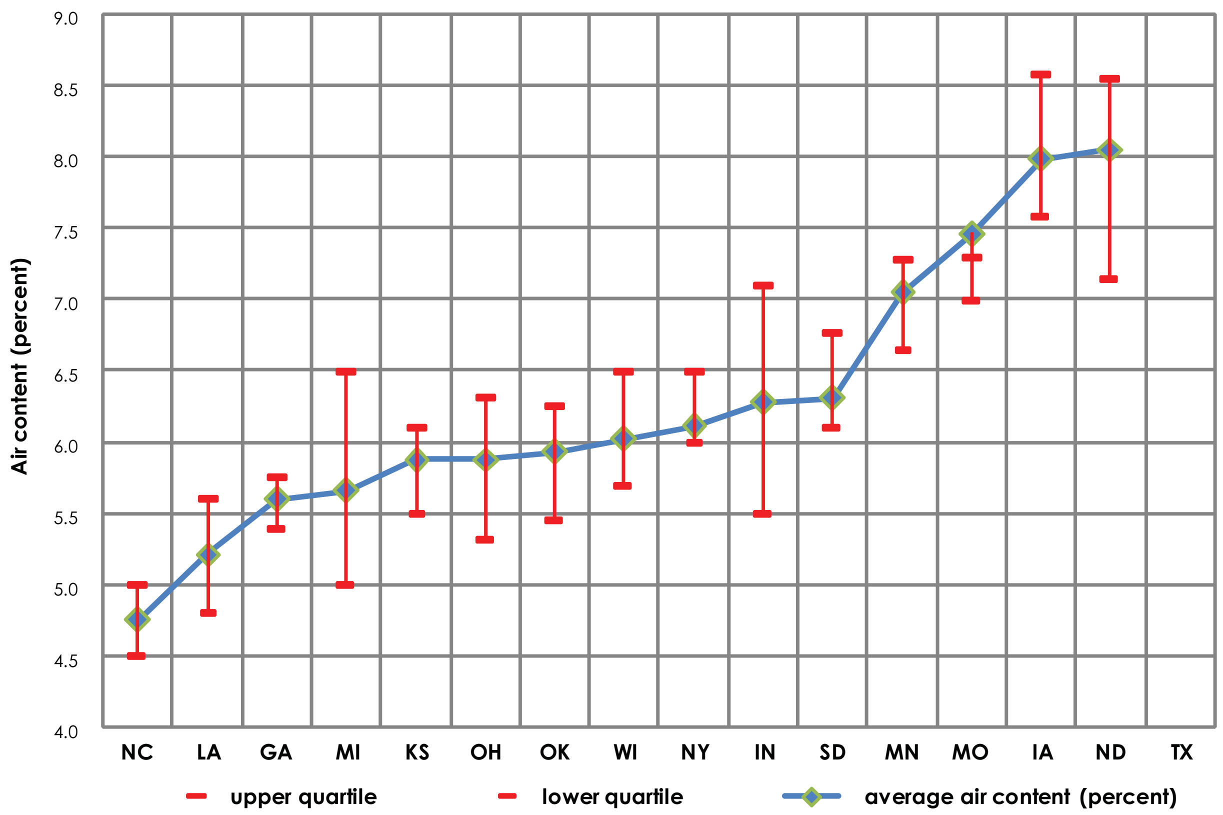

Figure 5.3 MCO average air content by state with upper and lower quartiles

Table 5.4 Average Coefficient of Variation for Top Half of MCO State Data Sets (Air Content)

State	No. of samples	Average air content (%)	Std. Dev.	Coeff. of variation
GA	11	5.6	0.3	0.046
MN	11	7.1	0.6	0.081
NC	5	4.8	0.4	0.090
WI	8	6.0	0.6	0.097
IA	14	8.0	0.8	0.101
LA	6	5.2	0.6	0.116
SD	10	6.3	0.7	0.117
NY	9	6.1	0.8	0.128
			average	0.097

Table 5.5 Rule of Thumb 3s Control Limits based on MCO Data Sets

Test procedure	Average coefficient of variation for the top ½ of 16 MCO data sets	Average standard deviation for the top ½ of 16 MCO data sets	Rule of thumb -3s lower control limit from MCO data sets	Rule of thumb 3s upper control limit from MCO data sets	Example -3s & 3s control limits based on typical values
Coarseness factor	0.052*	n/a	Target - (3[0.052•Target])	Target + (3[0.052•Target])	Target = 60.0 -3s = 50.6 3s = 69.4
Workability factor	0.020*	n/a	Target - (3[0.020•Target])	Target + (3[0.020•Target])	Target = 36.0 -3s = 33.8 3s = 38.2
Combined % retained on individual sieves (3/8# and larger)(%)	0.147*	n/a	Target - (3[0.147•Target])	Target + (3[0.147•Target])	Target = 13 -3s = 7 3s = 19
Combined % retained on individual sieves (#4 and #8)(%)	0.112*	n/a	Target - (3[0.112•Target])	Target + (3[0.112•Target])	Target = 11 -3s = 7 3s = 15
Combined % retained on individual sieves (#16, #30, #50, and #100)(%)	0.061*	n/a	Target - (3[0.061•Target])	Target + (3[0.061•Target])	Target = 8 -3s = 6 3s = 10
Combined % retained on individual sieves (#200)(%)	0.170*	n/a	Target - (3[0.170•Target])	Target + (3[0.170•Target])	Target = 2.0 -3s = 1.0 3s = 3.0
Slump (in.)	0.231	n/a	Target - (3[0.231•Target])	Target + (3[0.231•Target])	Target = 2.0 -3s = 0.6 3s = 3.4
Mortar flow (%)	0.077	n/a	Target - (3[0.077•Target])	Target + (3[0.077•Target])	Target = 85 -3s = 65 3s = 105
Microwave water content (w/cm)	0.043	n/a	Target - (3[0.043•Target])	Target + (3[0.043•Target])	Target = 0.42 -3s = 0.37 3s = 0.47
Unit weight (lb/ft^3)	0.007	n/a	Target - (3[0.007•Target])	Target + (3[0.007•Target])	Target = 148.0 -3s = 144.9 3s = 151.1

continued on next page

Table 5.5 Rule of Thumb 3s Control Limits based on MCO Data Sets, continued

Test procedure	Average coefficient of variation for the top ½ of 16 MCO data sets	Average standard deviation for the top ½ of 16 MCO data sets	Rule of thumb -3s lower control limit from MCO data sets	Rule of thumb 3s upper control limit from MCO data sets	Example -3s & 3s control limits based on typical values
Air content (%)	0.097	n/a	Target - (3[0.097•Target])	Target + (3[0.097•Target])	Target = 6.0 -3s = 4.3 3s = 7.7
Spacing factor (in.)	n/a	0.0017**	Target - 0.0051	Target +0.0051	Target = 0.0060 -3s = 0.0009 3s = 0.0111
Specific surface ($in.^{-1}$)	n/a	124.8**	Target - 374.4	Target +374.4	Target = 1,000 -3s = 626 3s = 1,374

*Coefficient of variation values for gradation are based on the average of MCO data sets that contained at least 6 samples (IA, IN, MN, ND, NY, OK, and SD).

**Standard deviation values for AVA are based on the top half of data sets that had a minimum specific surface of 600 in^{-1} (IA, MN, ND, NY, and SD) or a maximum spacing factor less than 0.0100 in. (IA, IN, MI, MN, SD, and WI).

The standard deviations and coefficients of variation listed in table 5.5 can be used as a starting point for establishing upper and lower control limits (3s and -3s) by using a target value (average) that is appropriate for the project mixture proportions and placement conditions. However, the control limits should be revised as soon as 10 data points can be collected during construction while the process is stable. Control limits on subsequent projects can be based on previous project data by using the coefficient of variation to compare test values that have different average values (targets).

How do I recognize special cause variability?

Simple tests exist to help spot special cause variability. Assuming that the 3s limits have been properly set, the control charts can be evaluated by the following criteria (*10*):

A. One test result is outside of the 3s limits.

B. Six consecutive test results are all increasing or decreasing.

C. Nine consecutive test results are on the same side of the average value.

D. Fourteen consecutive test results are alternating up and down.

These four tests as shown in figure 5.4 are the primary indicators used to identify process changes due to special causes.

Four other secondary tests can be used to analyze the control charts for process changes (*10*):

- Two of three consecutive test results are more than 2s from the average (and on the same side of the average).
- Four of five consecutive test results are more than 1s from the average (and on the same side of the average).
- Fifteen consecutive test results are within 1s of the average.
- Eight consecutive test results are all more than 1s from the average (on either side of the average).

When test results trigger a positive answer to any of these criteria, it is unstable or out of control.

What should I do if the test results indicate that a process is out of control?

Tracing the root cause of unstable conditions relies heavily on knowledge of the process inputs and feedback from people involved. Often, someone involved in the process can point to the source of what caused a test result to be different from the previous test results (*19*). Short-term fixes should be implemented while permanent solutions that will adequately address the special cause variability are investigated. Avoid changing the process to accommodate the special cause variability—this usually increases costs (*19*).

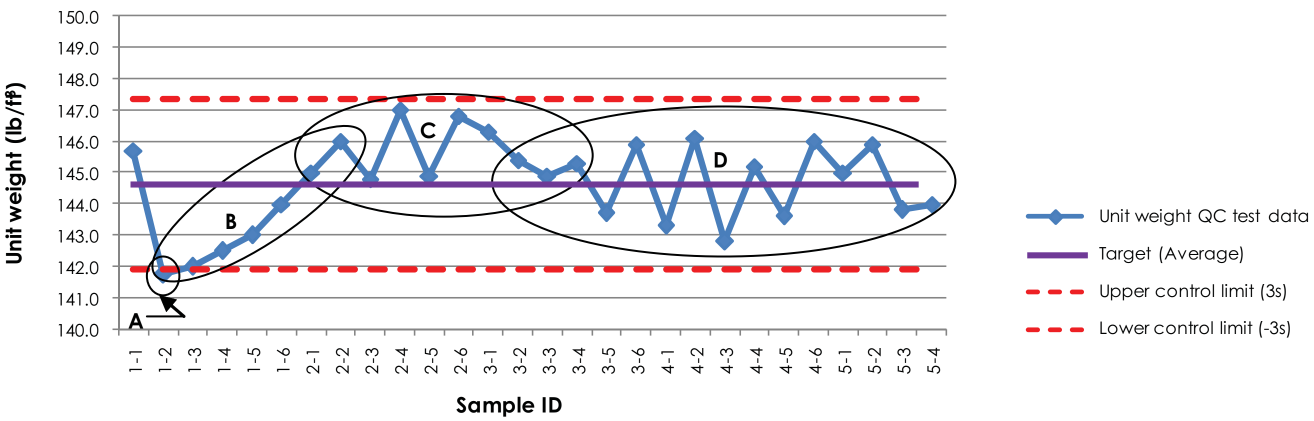

Figure 5.4 Control chart showing out-of-control test conditions

Chapter 6: Example Level B Project

The following outline provides a step-by-step example of implementing the suite of tests and SPC control charts on a hypothetical Level B project.

I. Example Project Information

A. Location—I-35 in Payne Co., Oklahoma.

B. Length—5 miles.

C. AADT = 25,000 (25% trucks).

D. Bid opening date—December 5, 2007.

E. Contract award date—December 17, 2007.

F. Notice to proceed—March 1, 2008.

G. Northbound paving scheduled for June 1, 2008 through June 30, 2008 (anticipated mixture temperature ≈ 80°F).

H. Southbound paving scheduled for September 1, 2008 through September 30, 2008 (anticipated mixture temperature ≈ 85°F).

I. Typical section—10-in. dowel jointed whitetopping.

J. Target slump at point of delivery (approximately 15 min. after mixing) = 2 in.

K. Portland cement concrete specification requirements.

1. Minimum compressive strength = 4,000 lb/in^2.
2. Minimum flexural strength for opening to construction traffic = 450 lb/in^2.
3. Air content—4.5% to 7.5%.
4. Minimum cementitious content = 564 lb/yd^3.
    a. Maximum fly ash replacement = 20% by mass = 113 lb/yd^3.
    b. Portland cement = 451 lb/yd^3.
5. Maximum water-cementitious materials ratio (w/cm) = 0.48.
6. Maximum mixture temperature = 90°F.
7. Aggregate durability and alkali-silica reactivity—use agency pre-approved aggregates.
8. Combined gradation.
    a. Target coarseness factor between 45% and 75%.
    b. Target workability factor between 33% and 40%.
    c. Project tolerance of ±5% percentage points from target coarseness and workability factors established by the approved mixture proportions.
9. Maximum permeable pore space (mixture design and verification—14 days) = 12%.

II. Mixture Design Stage

Establish baseline values that will be used for comparison during the mixture verification and quality control stages.

A. January 3, 2008: Contractor develops mixture proportions based on specification requirements and lowest cost locally available materials.

1. Given each aggregate producer's typical sieve analysis results, an iterative process of changing the individual aggregate proportions is used to arrive at a combined gradation that is cost-effective, meets specification, and allows for normal project variability (table 6.1 and figures 6.1, 6.2, and 6.3).
2. Based on past experience, the mixture proportions are calculated using the absolute volume method (table 6.2).
    a. Target slump = 2 in.
    b. Target air content = 6%.
    c. Target w/cm = 0.40.

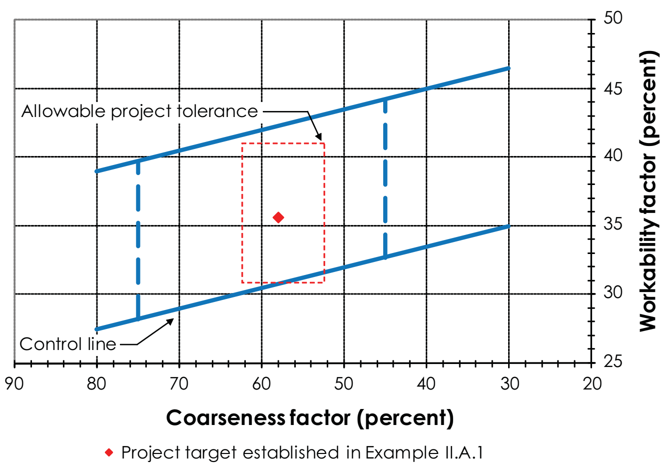

Figure 6.1 Example project target coarseness and workability factors and allowable project tolerance

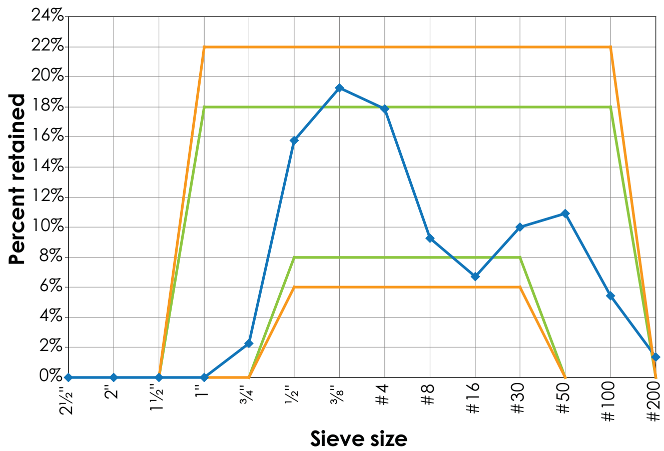

Figure 6.2 Example project combined percent retained with "8–18" & "6–22" limits

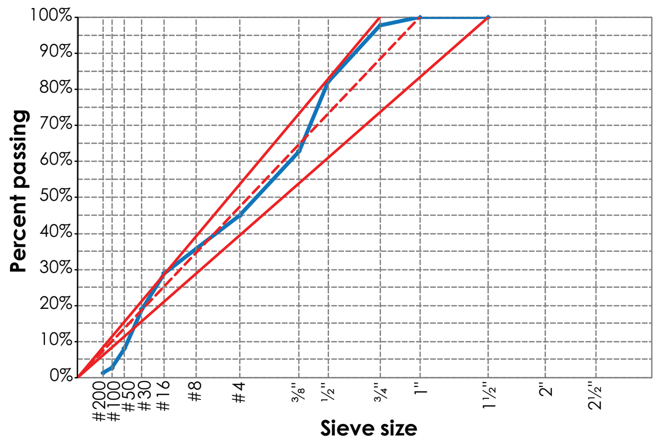

Figure 6.3 Example project 0.45 power curve

Table 6.1 Example Level B Project Target Aggregate Gradations

Project: Example MCO Testing Guide Project
Mixture ID: PCC for paving
Sample comments: Establish target mixture proportions
Test date: Project target

Total cementitious material: 564 lb/yd³
Agg. ratios: 45.00% (coarse) 20.00% (intermediate) 35.00% (fine) = 100.00%

Percent passing						
Sieve	**45% coarse**	**20% intermediate**	**35% fine #1**	**Combined % retained**	**Combined % retained on each sieve**	**Combined % passing**
2½ in.	100%	100%	100%	0%	0%	100%
2 in.	100%	100%	100%	0%	0%	100%
1½ in.	100%	100%	100%	0%	0%	100%
1 in.	100%	100%	100%	0%	0%	100%
¾ in.	95%	100%	100%	2%	2%	98%
½ in.	60%	100%	100%	18%	16%	82%
⅜ in.	35%	60%	100%	37%	19%	63%
#4	5%	40%	99%	55%	18%	45%
#8	2%	25%	85%	64%	9%	36%
#16	1%	20%	70%	71%	7%	29%
#30	1%	5%	50%	81%	10%	19%
#50	1%	3%	20%	92%	11%	8%
#100	1%	2%	5%	97%	5%	3%
#200	0.9%	1.5%	1.5%	98.8%	1.4%	1.2%

Workability factor 35.7
Coarseness factor 57.9

Table 6.2 Example Project Absolute Volume Method Mixture Proportioning Worksheet

Mixture proportions - Absolute volume method

General information					
Project:	Example MCO Testing Guide project				
Contractor:	Contracting company name				
Mixture description:	PCC for paving				
Mixture ID:	1 CG				
Anticipated date(s) of placement:	June 2008 and September 2008				
Cementitious materials	Source	Type	Spec. Gravity	lb/yd³	% Replacement by mass
Portland cement:	Cement supplier	I	3.150	451	
GGBFS:					
Fly ash:	Fly ash supplier	C	2.650	113	20.04%
Silica fume:					
Other pozzolan:					
				564	lb/yd³
				6.0	sacks/yd³
Aggregate information	Source	Type	Spec. gravity SSD	Absorption (%)	% Passing #4
Coarse aggregate:	Rock supplier	Crushed limestone	2.680	0.6%	5%
Intermediate aggregate:	Pea gravel supplier - 4x8	Natural	2.630	4.0%	40%
Fine aggregate #1:	Sand supplier - classified sand	Natural	2.630	4.0%	99%
Fine aggregate #2:					
Coarse aggregate %:	45.0%				
Intermediate aggregate %:	20.0%				
Fine aggregate #1 % of total fine agg.:	100.0%				
Fine aggregate #2 % of total fine agg.:					
Fine aggregate #1 %:	35.0%				
Fine aggregate #2 %:					
Admixture information	Source / Description		oz/yd³		oz/cwt
Air entraining admix.:	Admix. Company / AEA 2X		6.00		1.06
Admix. #1:	Admix. Company / WRA		22.55		4.00
Admix. #2:					
Admix. #3:					
Mix proportion calculations					
Water/cementitious materials ratio:	0.400				
Air content:	6.00%				
	Volume (ft³)	Batch weights SSD (lb/yd³)	Spec. gravity	Absolute volume (%)	
Portland cement:	2.294	451	3.150	8.498%	
GGBFS:					
Fly ash:	0.683	113	2.650	2.531%	
Silica fume:					
Other pozzolan:					
Coarse aggregate:	8.454	1,414	2.680	31.311%	
Intermediate aggregate:	3.757	617	2.630	13.916%	
Fine aggregate #1:	6.575	1,079	2.630	24.353%	
Fine aggregate #2:					
Water:	3.615	226	1.000	13.390%	
Air:	1.620			6.000%	
	27.000	3899		100.000%	
	Unit weight (lb/ft³)	144.4	Paste	30.419%	
			Mortar	61.661%	

B. January 7, 2008: An estimate of materials required to make three individual 2-ft³ lab batches is prepared. The required material quantities, plus additional 25%, are collected from each supplier and delivered to the laboratory for mixture design testing.

    1. A sample is obtained from an alternate fly ash source too. From previous experience, the contractor anticipates that there may be supply constraints and mixture performance issues with the lowest cost fly ash.

C. January 8, 2008: Aggregates are saturated to homogeneous moisture content.

D. January 8, 2008: Material incompatibility testing is performed. Refer to FHWA-HRT-06-080, *Identifying Incompatible Combinations of Concrete Materials: Volume II – Test Protocol*, for test procedures and discussion of interpreting test results.

    1. Combined materials chemical composition analysis is performed based on supplier provided data (table 6.3).

    2. Foam drainage—test four samples (figures 6.4 and 6.5).

        a. Cement + fly ash #1 + air entraining admixture #1 (AEA 1) + water reducing admixture (WRA) prepared at 75ºF.

        b. Cement + fly ash #1 + air entraining admixture #2 (AEA 2) + WRA prepared at 75ºF.

        c. Cement + fly ash #2 + air entraining admixture #1 (AEA 1) + water reducing admixture (WRA) prepared at 75ºF.

        d. Cement + fly ash #2 + air entraining admixture #2 (AEA 2) + WRA prepared at 75ºF.

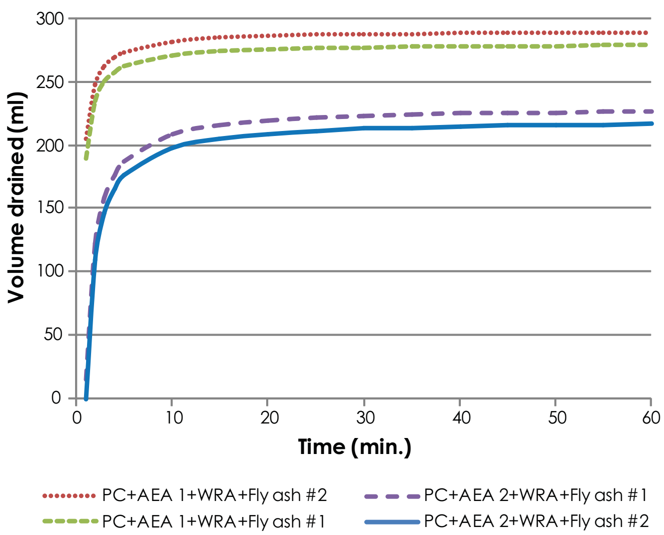

Figure 6.4 Example foam drainage test results

    3. Stiffening (modified ASTM C 359)—test six mortar samples (three fly ash #1 and three fly ash #2) prepared at 75ºF, 85ºF, and 90ºF (figure 6.6).

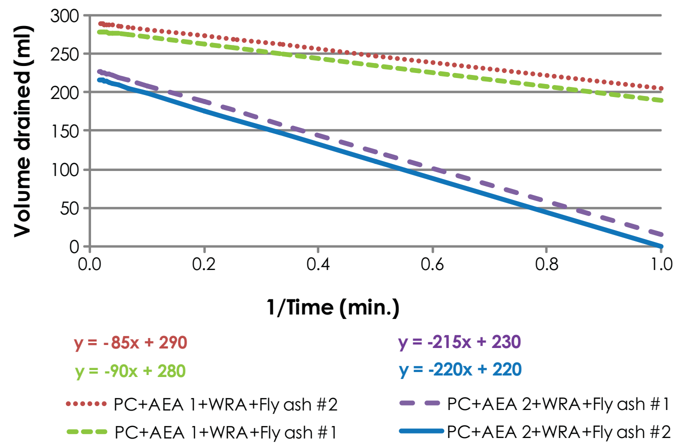

Figure 6.5 Example foam drainage slope and intercept analysis

Note: Based on the criteria from FHWA-HRT-06-080, *Identifying Incompatible Combinations of Concrete Materials: Volume II – Test Protocol*, foam drainage test results for AEA 1 indicate that air entrainment may be an issue (slope of -90). Therefore, the contractor proceeds with mixture design stage testing using AEA 2.

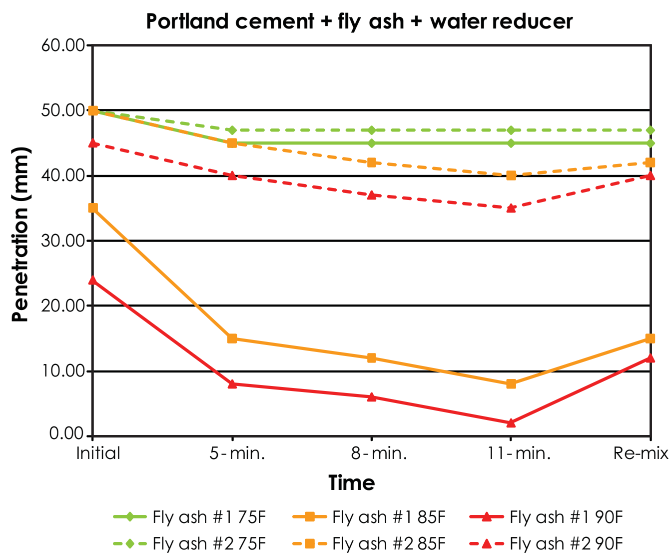

Figure 6.6 Example stiffening tests (ASTM C 359) for mixture design incompatibility testing

Note: Comparing between the C 359 stiffening test results for fly ash #1 and fly ash #2, it is evident that the penetration values for fly ash #1 are noticeably lower (indicating a stiffer paste) at temperatures greater than 75ºF. If fly ash #1 is utilized during construction, efforts should be made to keep the concrete temperature below 80ºF to avoid early stiffening issues.

Table 6.3 Example Level B Cementitious Materials Chemical Analysis for Incompatibility Testing Protocol

Mixture design stage: Preliminary chemical analysis					
Item	**Portland cement (%)**	**SCM fly ash #1 (alternate fly ash #2 shown in blue) (%)**	**Combined (80%/20%)**	**Recommended guidelines (*4*)**	**Action**
CaO	64.4	25.3 (17.6)	56.6	If SCM CaO is greater than 10%, test the SCM to determine C_3A content.	Based on 25.3% CaO content of the SCM, assume that the SCM will contribute C_3A to the system. Monitor the effects of the SCM with stiffening tests (ASTM C 359) and temperature development curves or perform x-ray diffraction (XRD) testing to quantify the SCM's C_3A content.
C_3A	7	not reported	unknown	Cement C_3A content greater than 8% is more likely to exhibit aluminate/sulfate imbalances. Any C_3A in the fly ash may result in early stiffening due to a C_3A/sulfate imbalance. Always evaluate SCM(s) with the intended cement	C_3A in the cement is o.k., effects of additional C_3A contributed by the fly ash will be identified by stiffening tests (ASTM C 359) and temperature development curves.
SO_3	2.7	1.35 (1.75)	2.4	Total sulfate content less than 3% is more likely to be problematic	Effects of low sulfate content will be identified by temperature development curves.
Fineness (kg/m^2)	338	------	------	Information only - finer particle size will accelerate cementitious reactions	
Fineness (% passing #325)	------	88.8 (82.2)	------	Information only - finer particle size will accelerate cementitious reactions	
Sulfate Form					
Gypsum - $CaSO_4 \cdot 2H_2O$	not reported	------	------	Approximately 50% of the sulfate should be in the form of gypsum	Information unavailable—rely on temperature development curves to identify potential issues or perform differential scanning calorimetry (DSC) testing to quantify the form of sulfate.
Plaster - $CaSO_4 \cdot ½H_2O$	not reported	------	------	Plaster content greater than 50% is likely to be problematic	Information unavailable—rely on temperature development curves to identify potential issues or perform differential scanning calorimetry (DSC) testing to quantify the form of sulfate.

4. Temperature development—test six mortar samples (three fly ash #1 and three fly ash #2) prepared at 75ºF, 85ºF, and 90ºF (figure 6.7).

E. January 9, 2008: Aggregates are sampled for sieve analysis testing and the coarseness factor and workability factor are calculated from the test results (figure 6.8).

F. January 10, 2008, 6:00 a.m.: Aggregates are sampled for moisture content testing (table 6.4).

G. January 10, 2008, 8:00 a.m.: Lab batch proportions are adjusted for aggregate moisture contents (table 6.5).

H. January 10, 2008, 8:30 a.m.: Correct mass of raw materials is weighed up for two 2-ft³ lab batches.

I. January 10, 2008, 10:00 a.m.: Lab batch #1 is mixed, and the following tests are performed or samples prepared (table 6.6):

1. Slump at 5, 10, 15, and 20 min.
2. Unit weight.
3. Air content.
4. Heat signature samples are prepared and placed in a calorimeter for monitoring (10:30 a.m.)(figure 6.9).
5. Mortar sample for set time is sieved from the concrete and prepared in accordance with ASTM C 403 (10:30 a.m.)(figure 6.10).

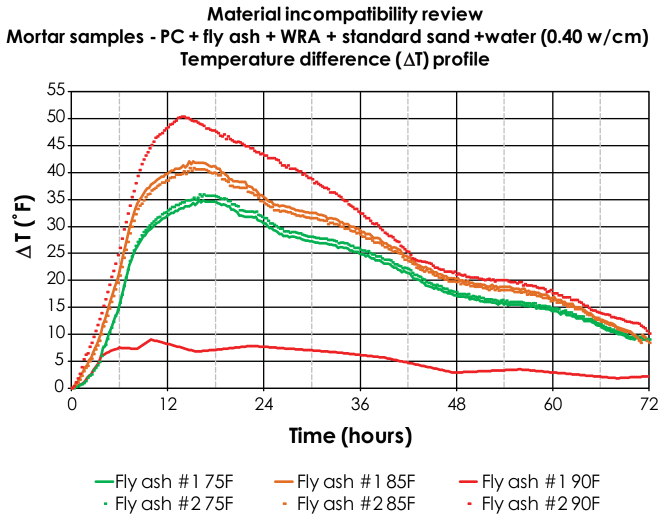

Figure 6.7 Example temperature development curves for incompatibility testing

Note: The temperature development curve for the fly ash #1 mixture at 90ºF is typical of a system where the calcium has been consumed early in the hydration process. For further explanation of this type of system incompatibility, refer to *Identifying Incompatible Combinations of Concrete Materials: Volume I – Final Report*, page 111 (*20*). Since the mixture with fly ash #2 did not exhibit the same temperature development characteristics at 90ºF, the contractor proceeds with mixture design testing utilizing fly ash #2.

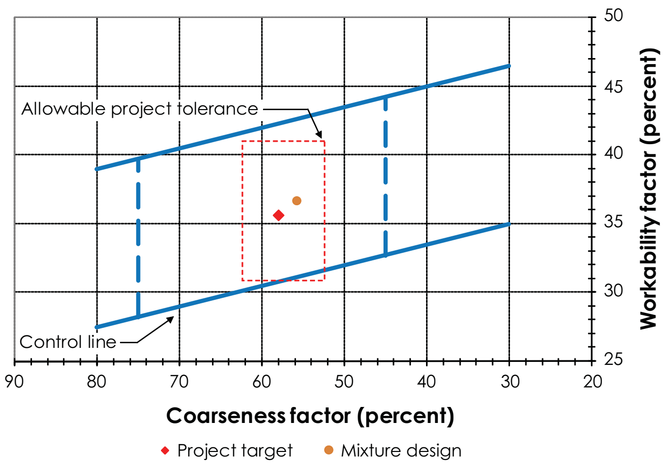

Figure 6.8 Example mixture design coarseness factor and workability factor

Table 6.4 Mixture Design Aggregate Moisture Contents

Supplier/material	Original mass (g)	Dried mass (g)	Moisture content (%)	Absorption* (%)	Free moisture (%)
Rock supplier / Crushed limestone	4,200.0	4,150.0	1.2	0.6	0.6
Pea gravel supplier / 4x8	2,200.0	2,080.0	5.8	4.0	1.8
Sand supplier / Classified sand	1,520.0	1,435.0	5.9	4.0	1.9

*Absorption values taken from agency material prequalification records

Table 6.5 Example Adjusted Lab Batch Weights

Adjusted lab batch weights						
Mixture proportion calculations	Volume (ft³)	Batch weights SSD (lb/yd³)	2ft³ SSD Lab batch weights (lb)	Free moisture (%)	Free moisture (lb)	Adjusted 2ft³ batch weights (lb)
Portland cement:	2.294	451	33.4			33.4
GGBFS:						
Fly ash:	0.683	113	4.2			4.2
Silica fume:						
Other pozzolan:						
Coarse aggregate:	8.454	1,414	52.4	0.6	0.3	52.7
Intermediate aggregate:	3.757	617	22.8	1.8	0.4	23.2
Fine aggregate #1:	6.575	1,079	40.0	1.9	0.8	40.7
Fine aggregate #2:						
Water:	3.615	226	8.4			6.9
Air:	1.620					

Admixture information	Source / Description	oz/yd³	oz/cwt	Admixture dosage (oz)	Admixture dosage (cc)
Air entraining admix.:	Admix. company / AEA 2X	6.00	1.06	0.44	13.14
Admix. #1:	Admix. company / WRA	22.55	4.00	1.67	49.40
Admix. #2:					
Admix. #3:					

Table 6.6 Example Lab Batch #1 Worksheet

Lab batch worksheet		
Project:	I-35 Payne Co.	
Lab batch description:	Lab batch #1	
Date:	10-Jan-08	
Batching start time:	10:07 AM	
Mixing end time:	10:10 AM	
Concrete temp. (°F):	74.2	
Slump:		
5 min.	10:15 AM	2.75
10 min.	10:20 AM	2.25
15 min.	10:25 AM	2.00
20 min	10:20 AM	1.75
Air content:	5.5%	
Unit weight:	145.1	
Heat signature data collector started:	10:20 AM	
Set time mortar sample obtained:	10:30 AM	

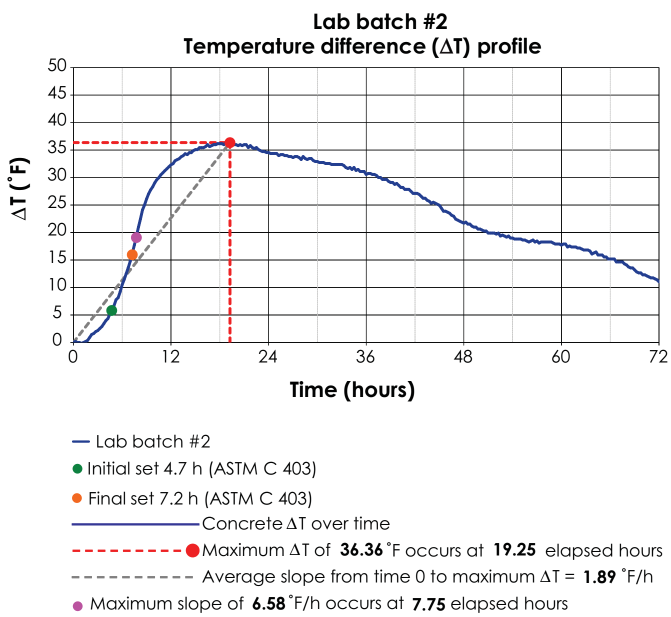

Figure 6.9 Example mixture design heat signature curve

Note: No current criteria or suggested values exist for concrete heat signature. However, this example mixture design heat signature curve will serve as a baseline for comparison to identify changes during the mixture verification and quality control stages.

Penetration Resistance ASTM C 403

Project:	I-35 Payne Co.
Test description:	Mixture design evaluation
Date:	10-Jan-08
Time:	10:10 AM
Operator:	BZ

Time	Temperature (°F)	Elapsed time	Needle #	Reading (lb)	Penetration resistance (lb/in²)	Log (PR)	Log (f)
1:40 PM	75.1	**210**	**1**	**117**	**117**	2.07	2.32
2:40 PM	76.2	**270**	**2**	**180**	**360**	2.56	2.43
3:10 PM	77.0	**300**	**4**	**200**	**800**	2.90	2.48
3:40 PM	78.9	**330**	**10**	**120**	**1,200**	3.08	2.52
4:25 PM	80.7	**375**	**20**	**62**	**1,600**	3.20	2.57
4:40 PM	81.6	**390**	**40**	**60**	**2,400**	3.38	2.59
4:55 PM	82.3	**405**	**40**	**78**	**3,120**	3.49	2.61
5:10 PM	83.4	**420**	**40**	**114**	**4,560**	3.66	2.62
Initial set (at 500 lb/in²)		estimated times based on test data	**282** min		**4.71** h		
Final set (at 4,000 lb/in²)			**434** min		**7.24** h		

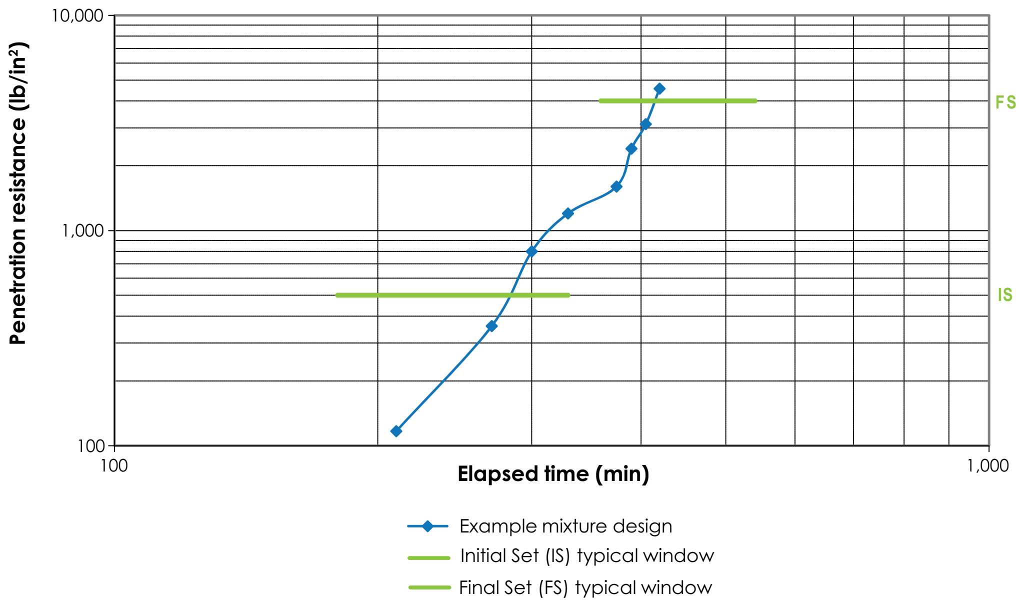

Figure 6.10 Example setting time test result

J. January 10, 2008, 1:00 p.m.: Lab batch #2 is mixed, and the following tests are performed or samples prepared (tables 6.7 and 6.8):

1. Slump at 5 and 15 min.
2. Unit weight.
3. Air content.
4. Microwave water content.
5. Compressive strength specimens are prepared: twelve 4 x 8 in. cylinders.
6. Permeable voids specimens are prepared: three 4 x 8 in. cylinders.
7. Hardened air specimens are prepared: two 4 x 8 in. cylinders.

K. January 11, 2008, 1:00 p.m.: All cylinder specimens are de-molded and placed in a proper curing environment.

L. January 13, 2008, 1:30 p.m.: Three-day compressive strength specimens are tested (table 6.9).

Table 6.7 Example Lab Batch #2 Worksheet

Lab batch worksheet		
Project:	I-35 Payne Co.	
Lab batch description:	Lab batch #2	
Date:	10-Jan-08	
Batching start time:	1:08 PM	
Mixing end time:	1:11 PM	
Concrete temp. (°F):	74.2	
Slump:		
5 min.	1:16 PM	3.00
15 min.	1:26 PM	2.25
Air content:	6.2%	
Unit weight:	144.2	
Microwave water content:	0.41	
Seventeen 4 x 8 in. cylinder specimens finished and capped	1:40 PM	

Table 6.8 Example Mixture Design Test Results

	Concrete temperature (°F)	Slump (in.)				Air content (%)	Unit weight (lb/ft³)	Microwave w/cm ratio
		5 min.	10 min.	15 min.	20 min.			
Batch #1	74.2	2.75	2.25	2.00	1.75	5.5	145.1	
Batch #2	74.2	3.00		2.25		6.2	144.2	0.41

Table 6.9 Example Mixture Design Compressive Strength Results

Compressive strength testing

Project: I-35 Payne Co.

Date cast: 10-Jan-08

Time cast: 1:40 PM

		1					2					3					
Date tested	Operator	Time of test	Load (lb)	Diameter (in)	Load rate (lb/sec)	f'_c (lb/in²)	Time of test	Load (lb)	Diameter (in)	Load rate (lb/sec)	f'_c (lb/in²)	Time of test	Load (lb)	Diameter (in)	Load rate (lb/sec)	f'_c (lb/in²)	Average
13-Jan-08	BZ	1:30 PM	44,350	4.00	350	3,530	1:40 PM	45,350	4.00	360	3,610	1:50 PM	46,460	4.00	380	3,700	**3,610**
17-Jan-08	BZ	1:00 PM	57,190	4.00	370	4,550	1:10 PM	58,860	4.00	340	4,680	1:20 PM	59,120	4.00	390	4,700	**4,640**
7-Feb-08	BZ	1:00 PM	62,120	4.00	350	4,940	1:10 PM	64,440	4.00	360	5,130	1:20 PM	63,500	4.00	380	5,050	**5,040**

f'_c = load/ $(\pi \times r^2)$

M. January 14, 2008, 10:30 a.m.: Heat signature test data downloaded from the calorimeter and plotted on a standard time versus temperature graph (figure 6.9).

N. January 14, 2008: Hardened air specimens are cut, polished, and prepared for testing in accordance with ASTM C 457 or an equivalent image analysis method.

O. January 15, 2008: Hardened air testing (figure 6.11).

P. January 17, 2008, 1:00 p.m.: Seven-day compressive strength specimens are tested (table 6.9).

Q. January 24, 2007, 9:00 a.m.: Permeable void testing complete (table 6.10).

R. February 7, 2008: 28-day compressive strength specimens are tested (table 6.9).

Project: I-35 Payne Co.
Test description: Hardened air - image analysis (ASTM C 457 Equivalent)
Sample description: Average results of 4 specimens

Air-void parameter	Chords < 0.5 mm	Chords < 1.0 mm	All chords	Suggested criteria
Air content (%)	5.11	6.35	6.96	>4.50
Specific surface (mm^{-1})	40.42	33.69	30.90	>24
Specific surface (in^{-1})	1027	856	785	>600
Spacing factor (mm)	0.124	0.134	0.140	<0.20
Spacing factor (in.)	0.0049	0.0053	0.0055	<0.008

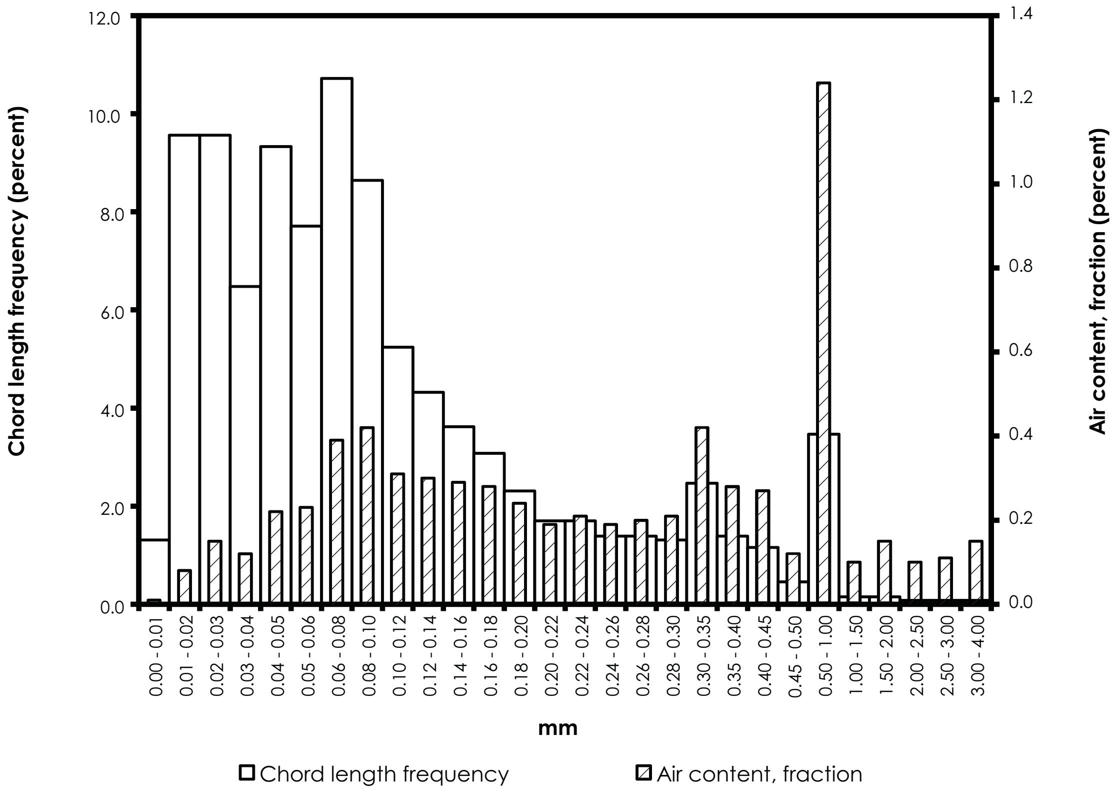

Figure 6.11 Example hardened air test results

Table 6.10 Example Permeable Voids Procedure Notes, Test Data, and Results

Mixture design stage: Permebale voids testing (ASTM C 642)			
Date	**Time**	**Description of test activity**	**Test data (average of 9 specimens) (g)**
10-Jan-08	1:40 PM	Permeable void cylinder specimens cast and capped	n/a
16-Jan-08	1:30 PM	Prepare three 2-in. tall sections from each cylinder, make the first sawcut ½ in. from the top of the cylinder and make additional sawcuts in two-inch increments	n/a
16-Jan-08	3:00 PM	Determine the mass of each 2-in. cylinder section	952.2
16-Jan-08	3:30 PM	Place the specimens in a 210ºF to 230ºF oven for 24 hours	n/a
17-Jan-08	3:30 PM	Remove the specimens from the oven and allow them to cool in dry air to a temperature of 68ºF to 77ºF	n/a
18-Jan-08	7:00 AM	Determine the mass of each 2-in. cylinder section	926.8
18-Jan-08	8:00 AM	Place the specimens in a 210ºF to 230ºF oven for 24 hours	n/a
19-Jan-08	8:00 AM	Remove the specimens from the oven and allow them to cool in dry air to a temperature of 68ºF to 77ºF	n/a
19-Jan-08	3:00 PM	Determine the mass of each 2-in. cylinder section (A-mass of oven dried sample in air)	924.7
19-Jan-08	4:00 PM	Place the specimens in a 70ºF water bath for 48 hours	n/a
21-Jan-08	4:00 PM	Determine the mass of each 2-in. cylinder section	958.7
21-Jan-08	5:00 PM	Place the specimens in a 70ºF water bath for 24 hours	n/a
22-Jan-08	5:00 PM	Remove the specimens from the water bath, towel off surface moisture, and determine the mass of each specimen	963.8
22-Jan-08	6:00 PM	Place the specimens in a 70ºF water bath for 24 hours	n/a
23-Jan-08	7:00 AM	Remove the specimens from the water bath, towel off surface moisture and determine the mass of each specimen; if the change in mass from the previous determination is less than 0.5%, record this mass as B (B-mass of surface dry sample in air after immersion)	964.4
23-Jan-08	8:00 AM	Boil the specimens for 5 hours	n/a
23-Jan-08	1:00 PM	Remove the specimens from the boiling vessel and allow to cool for at least 14 hours until they are between 68ºF and 77ºF	n/a
24-Jan-08	7:00 AM	Towel off surface moisture and determine the mass of each specimen (C-mass of surface dry sample in air after immersion and boiling)	966.8
24-Jan-08	8:00 AM	Suspend the specimen by a wire and determine the apparent mass in water (D-apparent mass of sample in water after immersion and boiling)	546.6
			Mixture Design
		Bulk density, dry (Mg/m^3)	2.20
		Apparent density (Mg/m^3)	2.45
		Volume of permeable pore space (voids)	10.0%

Note: Permeable pore space (voids) is an indicator of permeability just as ASTM C 1202 rapid chloride penetration is. However, ASTM C 642 does not require specialized testing equipment. Preliminary testing performed by Kansas DOT and others indicates that a permeable pore space less than 12% will result in durable concrete with respect to permeability.

S. February 8, 2008: HIPERPAV analyses are performed using mixture design information and average weather inputs for Phase I paving. Results indicate that for these assumptions, stress does not exceed strength when contraction joints are sawed within 12 hours of placement (figures 6.12 and 6.13).

T. Mixture design stage testing summary.

1. AEA 1 was rejected during incompatibility testing due to foam drainage test results, -1/k (slope) less than 100.

2. Fly ash #1 was rejected during incompatibility testing due to a heat development curve for 90°F mixture temperature that indicated a material incompatibility.

3. Temperature development and stiffening tests performed on the fly ash #2 mixture at 90°F mixture temperature indicate that workability properties will be adequate even at the maximum specification limit for mixture temperature.

4. Slump loss testing indicates that the target slump of 2 in. should be achievable at the point of delivery.

5. Hardened air testing indicates an adequate air-void system—spacing factor = 0.0055 in. and specific surface = 785 in^{-1}.

6. Set time testing shows typical results—initial set at 4.7 h and final set at 7.2 h.

7. Concrete heat signature curve shows typical results.

8. All specification requirements were met.

   a. 28-day compressive strength = 5,040 lb/in^2 (4,000 required).

   b. Lab batch air content meets 4.5% to 7.5% criteria.

   c. Lab batch w/cm is less than maximum 0.48.

   d. Combined gradation of lab batch materials meets specification.

   e. Volume of permeable voids is 10% (12% maximum specified).

U. February 11, 2008: Mixture design is submitted for approval.

V. March 19, 2008: Mixture design approval.

III.Mixture Verification Stage

Compare field-tested materials and processes to the baseline values obtained in the mixture design stage. Strict criteria for acceptable differences between the mixture verification and mixture design stages do not exist for many of the test parameters. At a minimum, meeting specification criteria should always be the first priority. However, meeting specification criteria may not be an adequate indicator of whether the mixture will perform in the field similar to the way it performed in the lab. Experience and common sense must prevail when comparing the mixture verification test results to the mixture design results and making the ultimate decision to proceed with pavement construction with or without adjustments to the materials, mixture proportions, and/or processes.

A. May 19, 2008: Aggregate delivery and stockpiling operations begin.

B. May 20, 2008: Aggregate quality control testing begins; random sampling for sieve analysis is performed for every

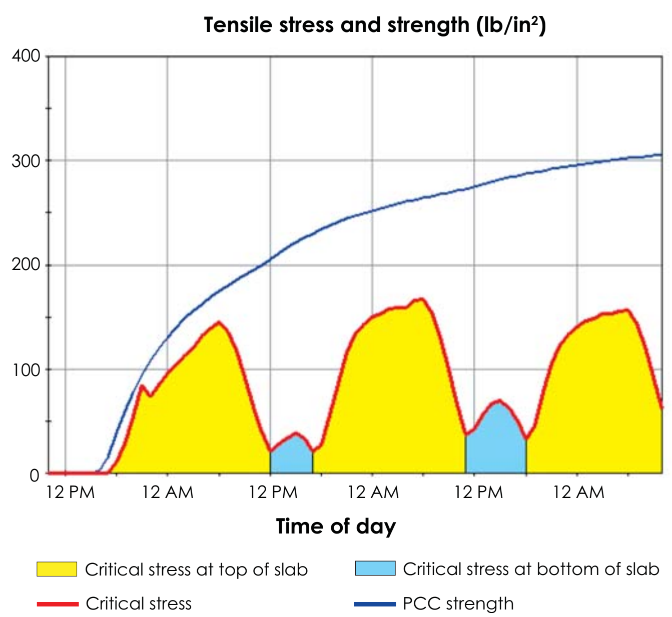

Figure 6.12 HIPERPAV analysis—10:00 a.m. placement

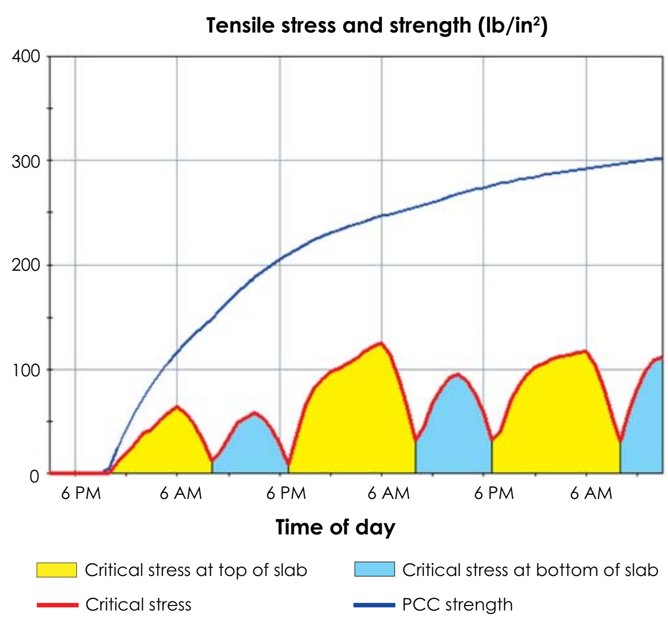

Figure 6.13 HIPERPAV analysis—3:00 p.m. placement

1,000 ton of coarse aggregate, 500 ton of intermediate aggregate, and 800 ton of fine aggregate.

C. May 22, 2008: Erection and setup of the central mix batch plant is completed.

D. May 23, 2008: Batch plant scales are calibrated and certified; bulk admixtures are delivered to the project.

E. May 26, 2008: Portland cement and fly ash deliveries commence.

F. May 27, 2008: Incompatibility testing is performed on project materials.

1. Chemical analysis based on updated mill certification test values (table 6.11).

2. Foam drainage (figures 6.14 and 6.15).

Table 6.11 Mixture Verification Chemical Analysis

Item	Portland cement (%)	SCM fly ash #2 (%)	Combined (80%/20%)	Action
CaO	64.1 64.4	17.9 17.6	55 55	Negligible change - no action is necessary
MgO	2.4	5.5	3.0	
C_3A	7 7	not reported	unknown	Negligible change - no action is necessary
SO_3	2.6 2.7	1.77 1.75	2.4 2.5	Negligible change - no action is necessary
Fineness (kg/m^2)	345 338	------	------	
Fineness (% passing #325)	------	84.1 82.2	------	
Sulfate Form				
Gypsum - $CaSO_4 \cdot 2H_2O$	not reported	------	------	Information unavailable—rely on temperature development curves to identify potential issues or perform differential scanning calorimetry (DSC) testing to quantify the form of sulfate.
Plaster - $CaSO_4 \cdot ½H_2O$	not reported	------	------	Information unavailable—rely on temperature development curves to identify potential issues or perform differential scanning calorimetry (DSC) testing to quantify the form of sulfate.

Mixture design values shown in black   Mixture verification values shown in blue

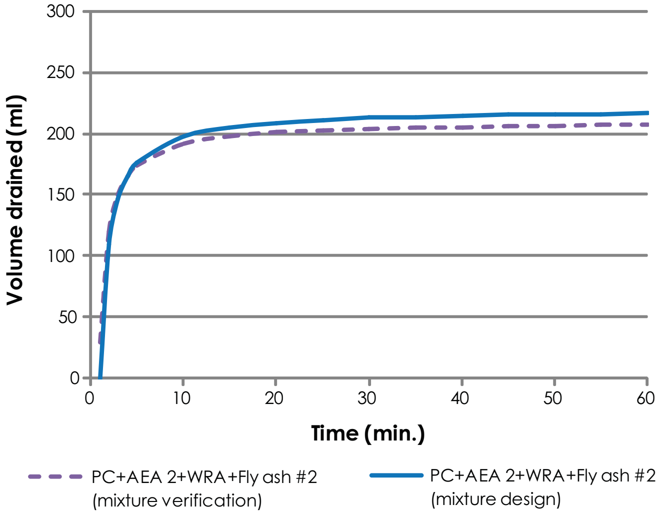

Figure 6.14 Mixture verification foam drainage results

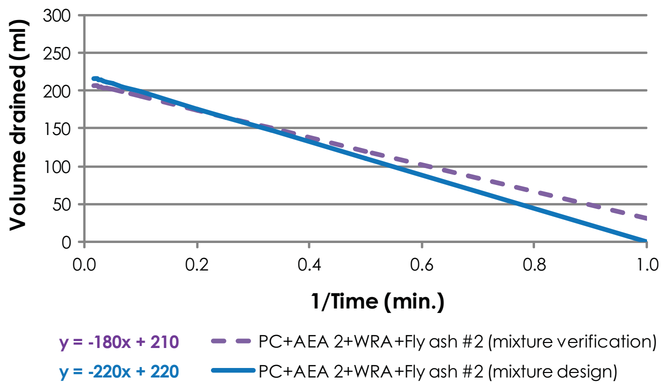

Figure 6.15 Mixture verification foam drainage slope and intercept analysis

3. Stiffening (modified ASTM C 359)—three mortar samples prepared at 75°F, 85°F, and 90°F (figure 6.16).

G. May 28, 2008: Aggregate quality control test results are evaluated for specification compliance and compared to mixture design stage test results (figure 6.17).

H. May 29, 2008, 8:00 a.m.: A 6-yd³ trial batch of the approved mixture design is mixed and tested.

1. Concrete temperature = 77.4°F.
2. Slump (5 min.) = 3.5 in.
3. Unit Weight = 140.3 lb/ft³.
4. Air content = 8.5%.

Note: The air content test result exceeds the maximum specification; therefore, this batch is rejected for further testing, and the dosage of AEA is adjusted.

I. May 29, 2008, 9:00 a.m.: A second 6-yd³ trial batch of the adjusted approved mixture design is mixed and tested.

1. Concrete temperature = 78.1°F.
2. Slump (5 min.) = 2.75 in.
3. Unit Weight = 144.1 lb/ft³.
4. Air content = 6.2%.

J. May 29, 2008, 9:10 a.m.: The following tests are performed or samples prepared on the second batch.

1. Microwave water content.
2. Slump at 10, 15, and 20 min.
3. Heat signature samples are prepared and placed in a calorimeter for monitoring (9:30 a.m.).
4. Mortar sample for set time is sieved from the concrete and prepared in accordance with ASTM C 403 (9:30 a.m.).
5. Compressive strength specimens are prepared: six 4 x 8 in. cylinders.
6. Permeable voids specimens are prepared: three 4 x 8 in. cylinders.
7. Flexural strength specimens for establishing a maturity–strength relationship curve are prepared: thirteen 6 x 6 x 21 in. beams.

K. May 30, 2008: Fresh concrete test results are compiled and compared with mixture design test results (table 6.12).

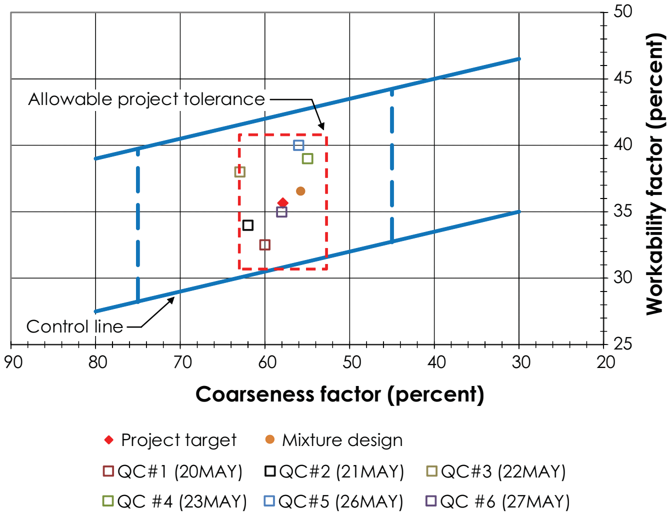

Figure 6.17 Mixture verification combined gradation analysis

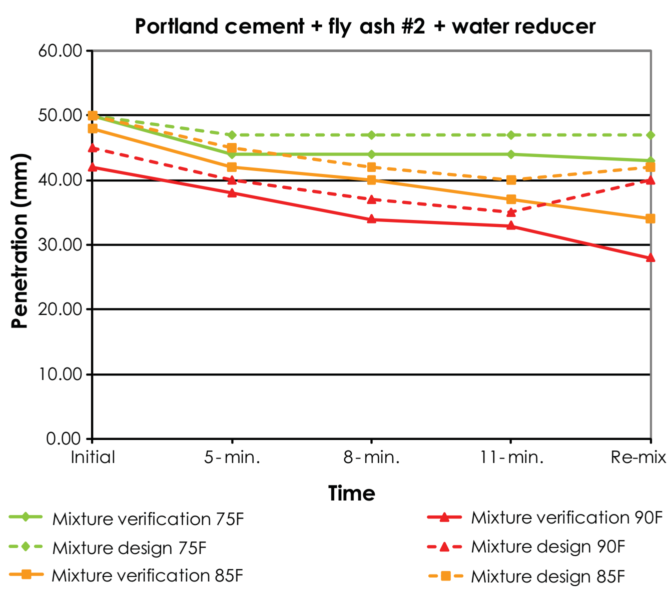

Figure 6.16 Mixture verification stiffening tests (Modified ASTM C 359)

Table 6.12 Comparison of Mixture Design and Mixture Verification Fresh Concrete Properties

	Lab batch #1	Lab batch #2	Mixture verification
Concrete temperature (°F)	74.2	74.2	78.1
Slump (5 min.) (in.)	2.75	3.00	2.75
Slump (10 min.) (in.)	2.25		2.50
Slump (15 min.) (in.)	2.00	2.25	2.25
Slump (20 min.) (in.)	1.75		2.00
Unit weight (lb/ft³)	145.1	145.1	144.1
Air content (%)	5.5	6.2	6.2
Microwave w/cm ratio		0.41	0.43
Initial set (h)	4.71		4.95
Final set (h)	7.24		7.60

L. HIPERPAV analysis is delayed until the day before paving begins (see quality control stage figures 6.12 and 6.13).

M. June 1, 2008: Three-day compressive strength test results are compared to the mixture design (table 6.13).

N. June 1, 2008: Heat signature data are downloaded from the calorimeter sensor(s), plotted, and compared to the mixture design data (figure 6.18).

O. June 3, 2008: Maturity testing is completed and initial strength–maturity relationship curve is developed (figure 6.19).

Table 6.13 Mixture Verification Comparison of Three-Day Compressive Strength

	Mixture design	Mixture verification	Difference (%)
3-day compressive strength	3,610	3.530	-2
7-day compressive strength			
28-day compressive strength			

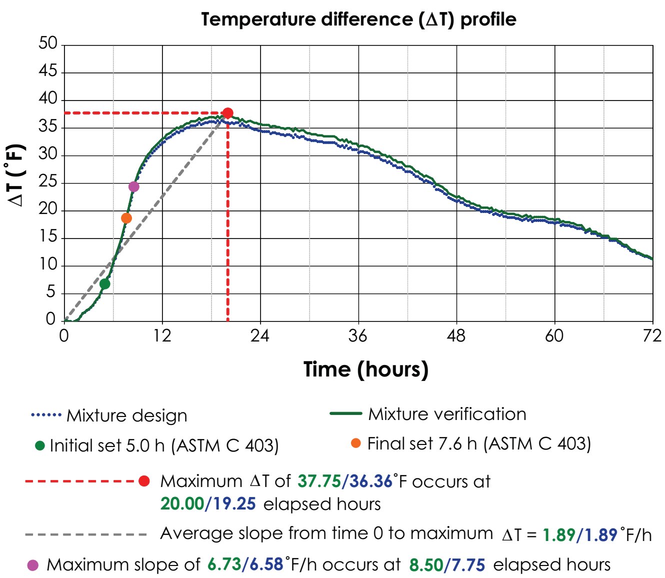

Figure 6.18 Mixture verification heat signature

Note: Comparisons between mixture design and mixture verification test results for fresh concrete properties, three-day compressive strengths, and heat signature show that the mixture characteristics have not changed significantly. Concrete paving may commence as scheduled with no changes to the mixture proportions or material sources.

P. June 5, 2008: Seven-day compressive strength test results are compared to the mixture design (table 6.14).

Q. June 7, 2008: Boil test is completed and results are compared to the mixture design values (table 6.15).

R. June 7, 2008: Seven-day compressive strength and permeable pore space (boil test) mixture verification tests confirm that the mixture characteristics are comparable to the mixture design. Process control testing should identify any changes that occur during construction.

IV. Quality Control (QC) Stage

Establish that the mixture is comparable to the mixture design during the mixture verification stage. Quality control efforts are focused on identifying changes to the materials and/or construction processes through the use of control chart techniques.

A. May 20, 2008: Aggregate quality control testing begins; random sampling for sieve analysis is performed at a frequency of every 1,500 yd³ for each aggregate as determined by the mixture proportions: 1,000 ton of coarse aggregate, 500 ton of intermediate aggregate, and 800 ton of fine aggregate (see mixture verification stage figure 6.16 for results). Performing quality control testing as the aggregate is delivered eliminates the need for obtaining belt samples during concrete paving operations. Provided that stockpiling operations do not cause segregation and/or

Table 6.14 Mixture Verification Comparison of Three- and Seven-Day Compressive Strengths

	Mixture design	Mixture verification	Difference (%)
3-day compressive strength	3,610	3.530	-2
7-day compressive strength	4,640	4,710	2

Table 6.15 Mixture Verification Comparison of Boil Test Results

	Mixture design	Mixture verification	Difference (%)
Bulk density, dry (Mg/m^3)	2.20	2.25	
Apparent density (Mg/m^3)	2.45	2.49	
Volume of permeable pore space (voids)	10.0 %	9.7 %	-0.3

Flexural strength maturity curve

State:	OK
Sensor type:	I-button
Date cast:	29-May-08
Time cast:	9:30 AM
Air temp.:	26.1˚C
Concrete temp.:	25.6˚C

Specimen #	Date broken	Time broken	Age at break (h)	TTF at time of break (˚C-h)	Specimen temp. at time of break (˚C)	Flexural strength (lb/in^2)	Mixture information	
1	30-May-08	4:00 PM	30.50	820	29.0	315	**Air:**	6.2 %
2	30-May-08	4:10 PM	30.67	826	29.0	330	**Slump:**	2.75 in.
3	30-May-08	4:20 PM	30.83	832	29.0	300	**Unit weight:**	144.1 lb/ft^3
4	31-May-08	4:00 PM	54.50	980	26.3	390	**Fly ash source:**	GHI #2
5	31-May-08	4:10 PM	54.67	984	26.3	395	**GGBFS source:**	n/a
6	31-May-08	4:20 PM	54.83	987	26.3	380	**Cement source:**	Cement supplier
7	2-Jun-08	7:30 AM	94.00	1,820	25.2	505	**Coarse agg. source:**	Rock supplier
8	2-Jun-08	7:40 AM	94.17	1,823	25.2	510	**Intermediate agg. source:**	Pea gravel supplier
9	2-Jun-08	7:50 AM	94.33	1,826	25.2	520	**Fine aggregate source:**	Sand supplier
10	3-Jun-08	8:45 AM	119.25	2,229	23.4	580	**Water reducer brand:**	Admix company
11	3-Jun-08	8:55 AM	119.42	2,233	23.4	585	**Add. rate:**	22.55 oz/yd^3
12	3-Jun-08	9:00 AM	119.50	2,236	23.4	575	**Air admixture brand:**	Admix company
							Add. rate:	6.00 oz/yd^3
							Desired flexural strength:	450 lb/in^2
							Required TTF:	1355

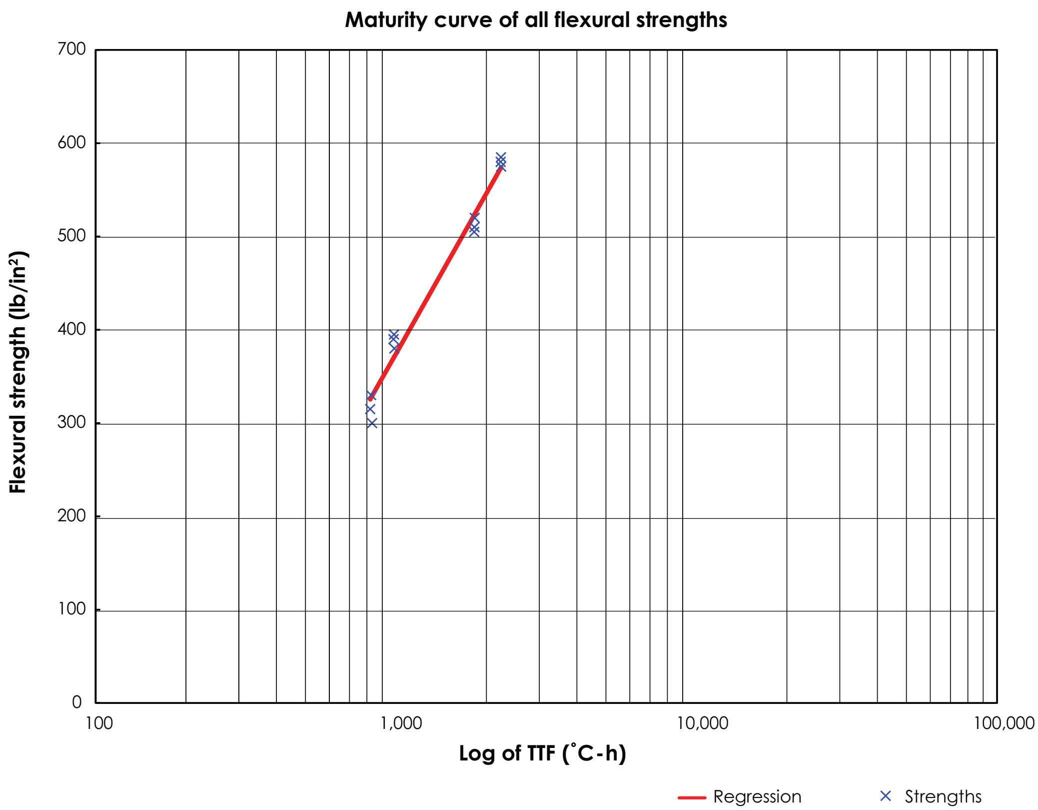

Figure 6.19 Initial strength-maturity relationship developed during mixture verification stage

degradation of the aggregates, the quality control tests performed during delivery will assure that out-of-specification materials are rejected and that the aggregates used meet specification. The success of this approach to QC of aggregate gradation is dependent on proper stockpile management techniques (CAUTION, LOADER OPERATORS) and sampling procedures.

B. Other process control test procedures (fresh and hardened concrete testing) will be utilized to identify changes in the materials and construction processes.

C. May 30, 2008: Random sampling times/locations are determined for upcoming quality control testing (approximate paving days 1 through 3) (table 6.16).

Table 6.16 QC Stage Random Sampling Worksheet

Slump and loss of workability (5, 10, 15, & 20 min.)
Microwave water content
Unit weight
Air content

***3-day and 7-day compressive strengths (every 4th sample)
Sampling frequency: 500 yd^3
Sample from the batch containing **random sample cumulative yd^3** as shown in the table

Sample #	Random #	Sample range cumulative yd^3		Random sample cumulative yd^3
1	0.6207	1	500	311
2	0.0287	501	1000	515
3	0.0510	1001	1500	1026
4***	0.3292	1501	2000	1665
5	0.0622	2001	2500	2032
6	0.0618	2501	3000	2532
7	0.5579	3001	3500	3279
8***	0.1677	3501	4000	3585
9	0.1286	4001	4500	4065
10	0.9259	4501	5000	4963
11	0.3388	5001	5500	5170
12***	0.0558	5501	6000	5529
13	0.3706	6001	6500	6186
14	0.3178	6501	7000	6660
15	0.6004	7001	7500	7301
16***	0.6170	7501	8000	7809
17	0.9064	8001	8500	8453
18	0.8620	8501	9000	8931
19	0.8871	9001	9500	9444
20***	0.2507	9501	10000	9626

D. June 1, 2008: HIPERPAV analyses are performed for the next day's paving using actual forecast weather data and other inputs from the mixture verification testing results (see appendix B for detailed instructions on obtaining hourly forecast data).

E. June 2, 2008: Paving commences; even though mixture verification permeability and seven-day compressive strength results are not completed yet, all other mixture verification test results compared favorably with the mixture design test values.

1. Typical daily QC activities during construction.

   a. 5:00 a.m.: Sample aggregates from stockpile locations that are representative of today's morning concrete production; perform aggregate moisture testing and adjust mixture proportions as necessary for actual aggregate moisture contents; sample aggregates from materials delivered and stockpiled the previous day and perform sieve analysis tests.

   b. 7:05 a.m.: Air content testing—begin with the first three batches, adjust as necessary, and continue with every batch until three consecutive batches are within specification tolerance.

   c. Sample #1: Time and location are determined by random sampling worksheet; slump (5, 10, and 15 min.), microwave water content, unit weight, and air content tests are performed.

   d. 9:00 a.m.: Sample aggregates from stockpile locations that are representative of today's mid-day concrete production; perform aggregate moisture testing and adjust mixture proportions as necessary for actual aggregate moisture contents.

   e. Sample #2: Time and location are determined by random sampling worksheet; slump (5, 10, and 15 min.), microwave water content, unit weight, and air content tests are performed and maturity sensor is placed in fresh pavement.

   f. 1:00 p.m.: Sample aggregates from stockpile locations that are representative of today's afternoon concrete production; perform aggregate moisture testing and adjust mixture proportions as necessary for actual aggregate moisture contents; sample aggregates from materials delivered and stockpiled today and perform sieve analysis tests.

   g. Sample #3: Time and location are determined by random sampling worksheet; slump (5, 10, and 15 min.), microwave water content, unit weight, and air content tests are performed.

h. Sample #4: Time and location are determined by random sampling worksheet; slump (5, 10, and 15 min.), microwave water content, unit weight, and air content tests are performed and compressive strength specimens are prepared.

i. Sample #5: Time and location are determined by random sampling worksheet; slump (5, 10, and 15 min.), microwave water content, unit weight, and air content tests are performed and maturity sensor is placed in fresh pavement.

j. Sample #6: Time and location are determined by random sampling worksheet; slump (5, 10, and 15 min.), microwave water content, unit weight, and air content tests are performed.

k. Test compressive strength specimens whenever specimens reach three-day and/or seven-day ages.

2. Typical QC management activities.

   a. Enter all test data into a QC database.

   b. Print all test reports and file with original work-sheets attached.

   c. Print control charts and evaluate for special cause variability.

   d. Obtain updated hourly forecast data and perform HIPERPAV analyses for the next morning's and afternoon's paving.

   e. Download vibrator monitor data. Review the data files for changes in vibrator frequency that may indicate potential workability issues that have not been identified by other testing. Also, verify that all vibrators are functioning properly.

   f. Generate random sampling locations for the next day as necessary.

F. June 3, 2008 through June 27, 2008:

1. Typical QC activities are repeated each day. Aggregate gradation sampling is adjusted for actual aggregate quantities received.

2. June 3, 2008, 4:30 p.m.: Update the following days' and subsequent HIPERPAV analyses for actual project strength–maturity relationship test results.

3. June 6, 2008, 5:00 p.m.: Evaluate the first five days' QC data and determine if the process has been stable for any 15 to 25 consecutive sample locations. If the process has been stable, calculate the 3s control limits based on the QC data represented by the stable period. Revise the control limits as necessary (see Chapter 5, page 24 for guidance). Repeat this evaluation of control limits weekly and whenever the process changes.

G. June 11, 2008: Northbound mainline paving is completed.

H. June 12, 2008: Northbound tied shoulder paving commences.

I. June 16, 2008, 2:30 p.m.: The microwave water content control chart indicates that a special cause variability condition exists (figure 6.20).

1. Sample 11-2 is outside of the 3s upper control limit.

2. The QC manager discusses the situation with the paving superintendent and discovers that the mixture had become unworkable early in the day. As a result of the loss of workability, the superintendent instructed the plant to increase the water by 2½ gallons per cubic yard (this shows up in sample 11-1). An additional 1½ gallon per cubic yard was added at approximately 2:00 p.m. (this appears in sample 11-2).

3. 3:15 p.m.: Paving is temporarily suspended.

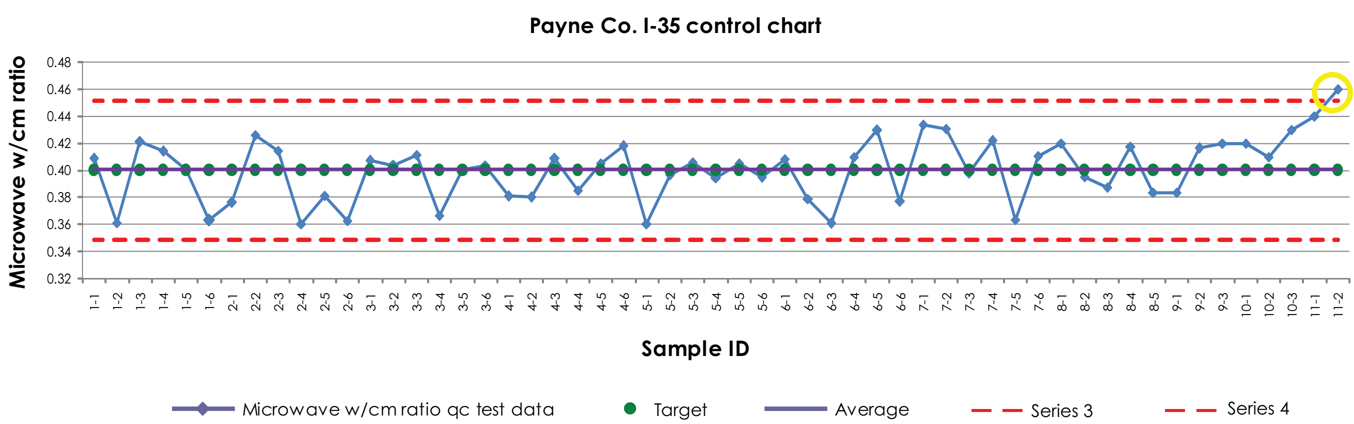

Figure 6.20 Example w/cm QC test data

4. 3:30 p.m.: After consulting the troubleshooting guide in the *Integrated Materials and Construction Practices for Concrete Pavement: A State-of-the-Practice Manual* (12), it appears that an incompatibility related to the sulfate/aluminate reaction is occurring. A 6-yd³ batch is mixed in which the fly ash in the mixture is reduced from 113 lb/yd³ to 56 lb/yd³, the portland cement is increased by 57 lb/yd³, and the additional water is also removed from the mixture.

5. 3:45 p.m.: Fresh concrete properties are tested on the adjusted 6-yd³ batch: slump, loss of workability, air content, and microwave water content tests are all acceptable.

6. 4:00 p.m.: The contractor and owner's representative meet and compare the fresh properties of the revised concrete mixture with the fresh properties of the original mixture design and project QC records to date. After a thorough review, each party agrees that there is limited risk in proceeding with the revised mixture. Paving resumes at 5:00 p.m., with the agreement that QC testing frequency will be doubled for the next 6,000 yd³ of production.

7. 6:00 p.m.: After reviewing QC data, it is concluded that the loss of workability is a function of two inter-related issues. First, the fly ash—workability has been temporarily restored by reducing the amount of fly ash in the mixture. Second, concrete temperatures began to increase after sample 10-2 (figure 6.21).

8. 6:30 p.m.: Water chillers are mobilized at the central batch plant site.

J. June 17, 2008, 7:00 a.m.: Paving is continued with the original mixture proportions as long as the concrete temperature is kept below 85°F. As a safeguard, a decision is made to switch to the adjusted mixture proportions at 11:00 a.m.

K. June 17, 2008, 6:00 p.m.: Water chillers are operational and 5,000 gallons of chilled water will be available for use whenever the concrete temperature exceeds 85°F.

L. June 18, 2008, 12:30 p.m.: Chilled water is added to each batch of concrete to maintain the concrete temperature below 85°F.

M. June 27, 2008, 3:00 p.m.: Northbound paving is completed.

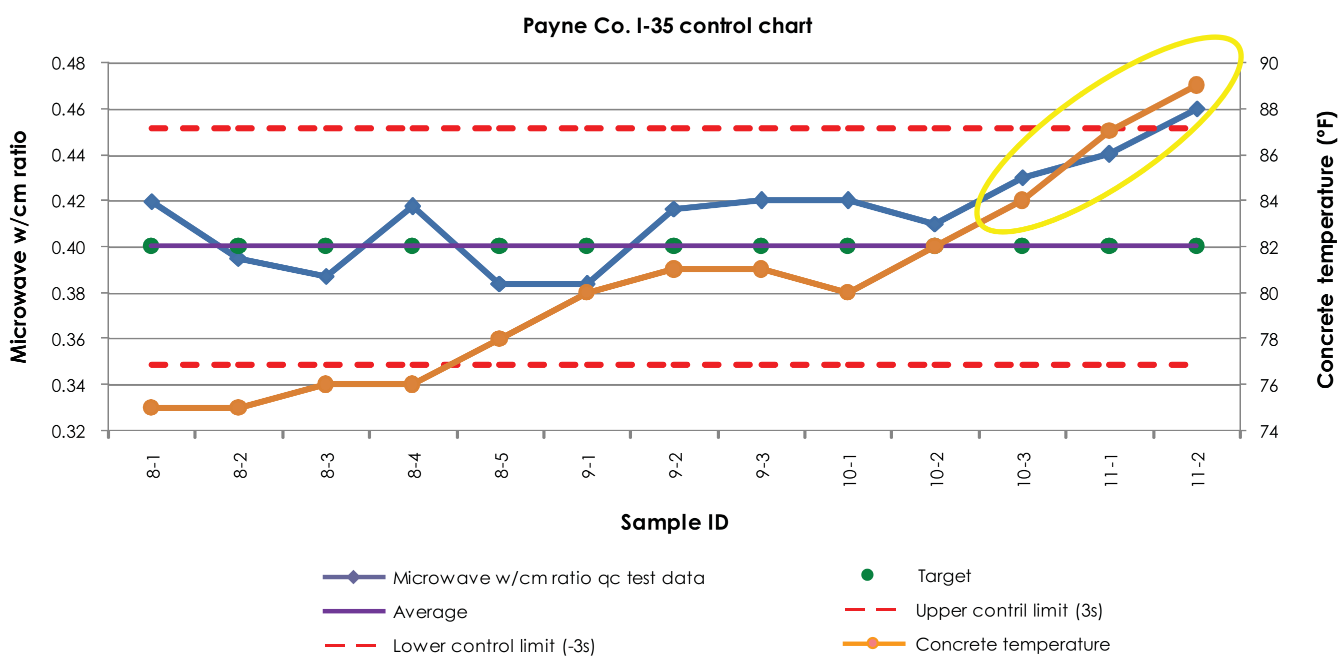

Figure 6.21 Example w/cm QC test data with corresponding concrete temperatures

Note: While loss of workability testing did reveal some change in the rate of slump loss from 5 to 15 min., it was not enough to identify the special cause variability. Without microwave water content testing and control charts, the impact of additional water would not have been identified for at least three days by compressive strength testing, if it was discovered at all. Identifying a change in the water content allowed the contractor to go beyond diagnosing the symptom (addition of water) to addressing the root causes of the workability issue (increased concrete temperature and fly ash reaction).

V. Phase II—Southbound Paving

A. August 18, 2008: Aggregate delivery and stockpiling operations begin.

B. August 19, 2008: Aggregate quality control testing begins.

C. August 21, 2008: Erection and setup of the central mix batch plant is completed.

D. August 22, 2008: Batch plant scales are calibrated and certified; bulk admixtures are delivered to the project.

E. August 26, 2008: Portland cement and fly ash deliveries commence.

F. August 27, 2008: Incompatibility testing is performed on project materials.

G. August 28, 2008: Aggregate quality control test results are evaluated for specification compliance and compared to mixture design stage test results.

H. August 29, 2008, 8:00 a.m.: Complete mixture verification process is repeated to assure that mixture properties are comparable to the mixture design and northbound QC test results.

I. August 31, 2008: Random sampling times/locations are determined for upcoming quality control testing (approximate paving days 1 through 3).

J. September 1, 2008: HIPERPAV analyses are performed for the next day's paving using actual forecast weather data and other inputs from the mixture verification testing results.

K. September 2, 2008, 7:00 a.m.: Southbound paving and typical QC operations begin.

L. October 3, 2008, 2:00 p.m.: Southbound paving is completed.

Chapter 7: Test Procedures

A summary of each of the test procedures included in the suite of tests is provided for reference. These summaries do not replace published standards. They are intended to offer additional information regarding the test procedures, equipment required, and the way test data should be interpreted.

Each test procedure summary is presented in the same format to assist the reader in understanding the purpose for each test and how to interpret test results:

- Purpose—Why Do This Test?
- Principle—What is the Theory?
- Test Procedure—How is the Test Run?
- Test Apparatus
- Test Method
- Output—How Do I Interpret the Results?
- Construction Issues—What Should I Look For?

Combined Grading

Purpose – Why Do This Test?

Aggregate grading may influence the water requirement, workability, and paste content of a mixture. These in turn may impact the risk of segregation, bleeding, and increased shrinkage of concrete paving mixtures.

It is desirable to cost-effectively blend different aggregate sizes to obtain a smooth grading curve for the combined aggregates system.

Principle – What is the Theory?

The sieve analysis (amount of material retained or passing a series of sieves with different-sized openings) is compared to optimized systems using a number of numerical and graphical models. The closer the batch grading is to the optimum, the lower the risk of grading-related problems in the mixture.

Test Procedure – How is the Test Run?

Sieve analyses are conducted in accordance with ASTM C 136 for the coarse and fine fractions, and the data are applied to the following models.

The coarseness/workability chart plots a single point on a graph, with the coarseness factor on the horizontal axis and the workability factor on the vertical axis, where

Coarseness factor = ([percent retained on $\frac{3}{8}$-in. sieve] / [percent retained on #8 sieve]) • 100

Workability factor = percent passing #8 sieve • 100

The 0.45 power chart plots the combined grading on a chart with sieve size on the horizontal axis (scale = sieve size $[\mu m]^{0.45}$) and percent passing on the vertical axis.

The combined percent retained chart plots the material retained on each sieve with sieve size on the horizontal axis and percent passing on the vertical axis.

Test Apparatus (figure 7.1)

- Scale.
- Sieves.
- Oven.
- Mechanical sieve shaker (optional).

Test Method – Refer to ASTM C 136 for Comprehensive Guidance

1. Obtain a representative sample of the aggregates.
2. Dry the sample to a constant mass.
3. Sieve the sample.
4. Determine the mass of material retained on each individual sieve and calculate the percentage retained.

Output – How Do I Interpret the Results?

Points on the coarseness/workability chart (figure 7.2) represent the coarseness factor and the workability factor for a mixture based on the grading test results of each individual aggregate. For an optimized grading mixture, the points should plot above the control line (28<workability factor<44) and inside the zone labeled well graded (45<coarseness factor<75).

continued on next page

Figure 7.1 Sieve analysis test equipment

Combined Grading, continued

When the sample combined grading plot on the 0.45 power chart (Figure 7.3) crosses back and forth across the maximum density line, it indicates gap grading.

A general rule of thumb for optimized grading is to have between 8 and 18 percent retained on each individual sieve on the combined percent retained chart (Figure 7.4). Note that the combined gradation shown in Figure 7.4 has two sieves that fall outside the "8–18" band, but this does not necessarily indicate that the mixture is unacceptable. All three charts should be used in conjunction before determining that a mixture's combined gradation is unacceptable. Two or more points in a valley on the combined percent retained chart indicates a more severe gap grading condition that should be addressed.

Each of the charts (figures 7.2 through 7.4) provides a different perspective of gradation. When used together, the information in these three charts can provide the contractor and the agency with a basis for evaluating the combined grading of a concrete mixture.

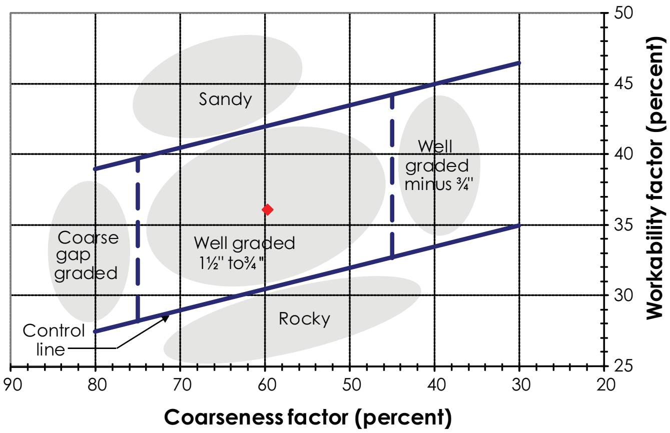

Figure 7.2 Coarseness factor chart

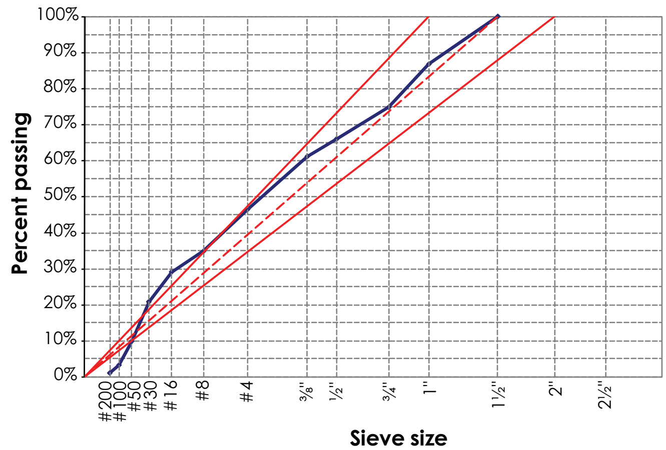

Figure 7.3 0.45 Power curve

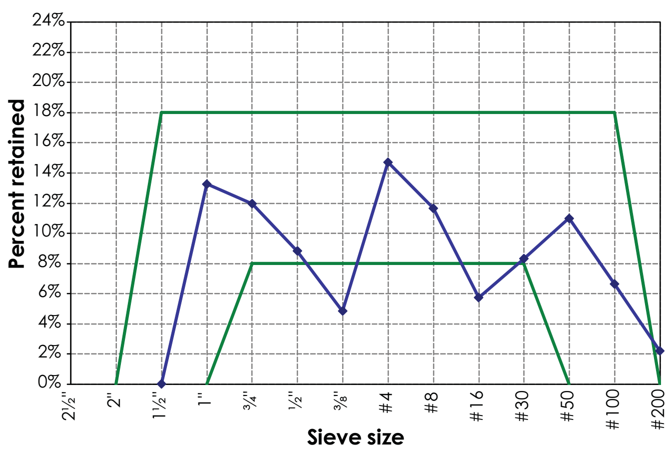

Figure 7.4 Combined percent retained chart with "8–18" limits

Construction Issues – What Should I Look For?

Modest variations in grading are to be expected from batch to batch and generally do not have a significant impact on performance. Extreme variations in grading and workability should be addressed as they occur.

Workability concerns attributable to aggregate grading can be identified by observing the following conditions:

- Stockpile segregation and/or inconsistent stockpiling methods.
- Inconsistent slump (mixture water is static while grading changes).
- Excessive bleeding.
- Variation in vibrator frequencies.
- Edge slump.
- Poor consolidation observed in cores.
- Segregation observed in cores.

Aggregate Moisture Content

Purpose – Why Do This Test?

Mixture proportions must be adjusted for the moisture found in the aggregate stockpiles. Batching concrete based on inaccurate aggregate moisture contents can impact workability, strength development, air entrainment, permeability, and shrinkage of the concrete mixture. Adjusting mixture proportions based on the actual aggregate moisture content is critical to producing uniform concrete.

Principle – What is the Theory?

Mixture proportions are based on the total water content for a given mixture design. Water is introduced into a concrete mixture from two sources: the water added during batching and any free water on the aggregate particles. Aggregates can be found in four moisture conditions:

- Oven dry—aggregate particles are completely dry and able to absorb water from the mixture.
- Air dry—aggregates are partially dry and able to absorb water from the mixture.
- Saturated surface dry (SSD)—aggregates have absorbed all of the water that they potentially can and are dry on the surface. Water is neither absorbed from nor contributed to the mixture.
- Damp or wet—aggregates fully absorbed the water and have excess moisture on the surface (free water).

Aggregates are most commonly found in the air dry or damp/wet states. Air dry aggregates will absorb paste (water + cementitious material + air) from the mixture. Damp or wet aggregates will add water to a mixture increasing the w/cm. Both conditions will adversely affect concrete properties.

Test Procedure – How is the Test Run?

ASTM C 566, the Standard Test Method for Total Evaporable Moisture Content of Aggregate by Drying, determines the moisture content of an aggregate sample by drying the aggregate and determining the mass of water present in the aggregate sample.

Test Apparatus (figure 7.5)

- Scale for measuring the mass of wet and dried aggregate samples.
- Oven, microwave oven, or hot plate for heating the aggregate samples.
- Heat-resistant sample container.

Test Method – Refer to ASTM C 566 for Comprehensive Guidance

1. Sample a sufficient mass of aggregate in accordance with ASTM D 75 from the stockpile in a location that is representative of the aggregate that will be batched subsequent to this moisture content test. Protect the sample from moisture loss until the original mass is determined.
2. Weigh the sample and determine its mass.

continued on next page

Figure 7.5 Sieve analysis test equipment

Aggregate Moisture Content, continued

3. Dry the sample thoroughly until further heating yields an additional loss of mass less than 0.1%.
4. Calculate the moisture content by subtracting the dry mass from the original mass and dividing by the dry mass.

   Moisture content (%) = ([original mass – dry mass] ÷ dry mass) • 100

   Note: Failure to completely dry the sample and/or any loss of aggregate particles during the test will yield incorrect results.

Output – How Do I Interpret the Results?

Test results should be provided to the batch plant as soon as possible so that mixture proportions can be adjusted to match the actual moisture condition of the aggregates being batched (table 7.1).

Repeat aggregate moisture testing whenever unit weight and/or microwave water content testing indicate an out-of-control condition in the total water content of a mixture (figure 7.6).

Construction Issues – What Should I Look For?

Failing to adjust mixture proportions for the correct aggregate moisture content may be identified through unit weight testing and microwave water content testing (figure 7.6). Concrete batched with the incorrect volume of water will primarily affect workability, strength development, permeability, and shrinkage properties. Aggregate stockpiles that have variable moisture contents will result in non-uniform concrete, adversely affecting the workability. Strive for consistent moisture content throughout the aggregate stockpile. If possible, allow recently delivered aggregates 24 to 36 hours to drain before incorporating into the project.

Table 7.1 Aggregate Moisture Content Test Results

Aggregate moisture content	
Project	I-35 Payne Co.
Aggregate	1 ½ in. limestone coarse aggregate
Aggregate absorption from previous testing	0.71%
Minimum sample mass required (kg)	6.0
Date & time sampled	2-Jun-08 1:30 PM
Location(s) sampled	East ¼ of stockpile, 50 ft. north of working face
Approximate date and time aggregate represented by this sample will be batched	3-Jun-08 7:00 AM
Original mass (W)(g)	6228.0
Dried mass (D)(g)	5994.0
Moisture content	3.9%

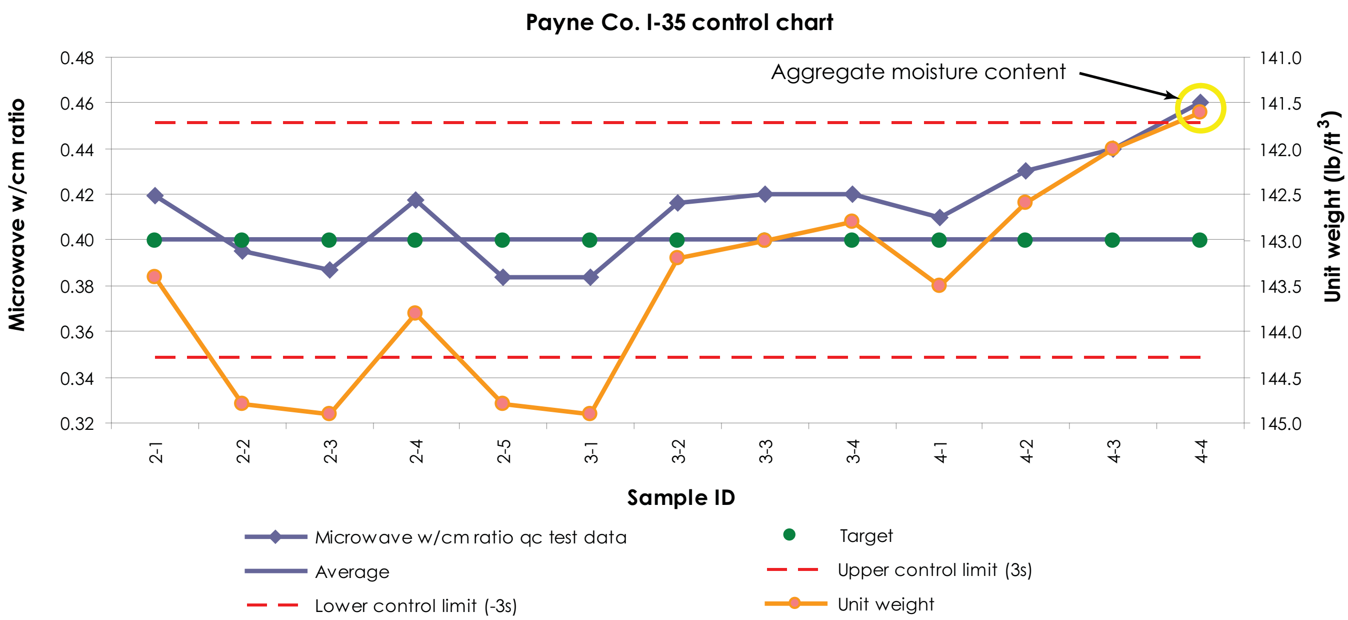

Figure 7.6 Microwave w/cm and unit weight test results indicate potential aggregate moisture error

Concrete Slump

Purpose – Why Do This Test?

The standard slump test should be considered as a pseudo-measure of workability. It does not necessarily reflect workability properties that correlate to the ability to place concrete with a slipform paver. However, slump can be used as an indicator of between-batch variability (uniformity). Changes in slump indicate variability in the materials and/or the batching process. Thus, slump is a process control test procedure and should not be considered as an acceptance criteria. Slump can also be used as an indicator of early stiffening. Performing slump tests at 5 minutes and 20 minutes after batching is a practice that is encouraged. Monitoring the slump loss over time can identify early stiffening issues associated with material changes, incompatibilities, or changes in the concrete temperature.

Principle – What is the Theory?

Water content, combined gradation, cementitious chemistry, mixing time, air content, and concrete temperature all interact to affect slump. A slump test cannot identify which of these factors is changing—it simply measures the slump. Uniformity of the concrete slump and slump loss is of primary concern. Concrete uniformity and early stiffening can be monitored by performing slump tests randomly 5 minutes after batching and again 20 minutes after batching (at the point of delivery).

Test Procedure – How is the Test Run?

ASTM C 143, the Standard Test Method for Slump of Hydraulic-Cement Concrete, determines how much a concrete sample settles (slumps) when it is unconfined. Concrete is consolidated inside of a 12-in. tall cone-shaped form. When the form is removed, the concrete is unconfined and it "slumps." The difference between its original 12-in. height and its height immediately after the form is removed is the slump.

Test Apparatus (figure 7.7)

- Slump mold.
- Tamping rod.
- Flat and nonabsorbent base.

Test Method – Refer to ASTM C 143 for Comprehensive Guidance

The following steps summarize the sampling and testing procedures for concrete produced at a central mix plant and transported in nonagitating trucks:

1. Sample concrete at the central mix plant.
2. Perform the first slump test 5 minutes after the concrete batch is discharged from the mixing drum.
3. Sample concrete at the placement location and test. Perform the second slump test 20 minutes after the concrete batch is discharged from the mixing drum.
4. Measure and record the following for each test:
   a. Concrete temperature.
   b. Ambient temperature.
   c. Time.
   d. Slump.
5. Graph the test results.

Figure 7.7 Slump testing equipment

Concrete Slump, continued

Output – How Do I Interpret the Results?

Graphing the slump test data as shown in Figure 7.8 will be helpful in monitoring material and process uniformity. Slump loss results can also be graphed similar to Figure 7.9 as a means to identify a change in the early stiffening characteristics of a mixture.

Construction Issues – What Should I Look For?

Test results that vary by more than 2 in. from sample to sample may indicate material and/or process control deficiencies. Contributing factors that should be investigated as a cause of the slump variability include the following:

- Aggregate moisture(s).
- Stockpile segregation.
- Mixing time.
- Air content.
- Concrete temperature.
- Material incompatibilities.
- Batching proportions and/or scale tolerances.

Changes in the slump loss after 15 minutes that affect the early stiffening characteristics may be addressed by lowering the initial concrete temperature.

Note: A common—but generally inappropriate—field response is to add water, increasing the initial slump to compensate for early stiffening. But adding water above the approved mixture design content to overcome early stiffening is detrimental to shrinkage, permeability, and strength; thus, it should be avoided whenever possible.

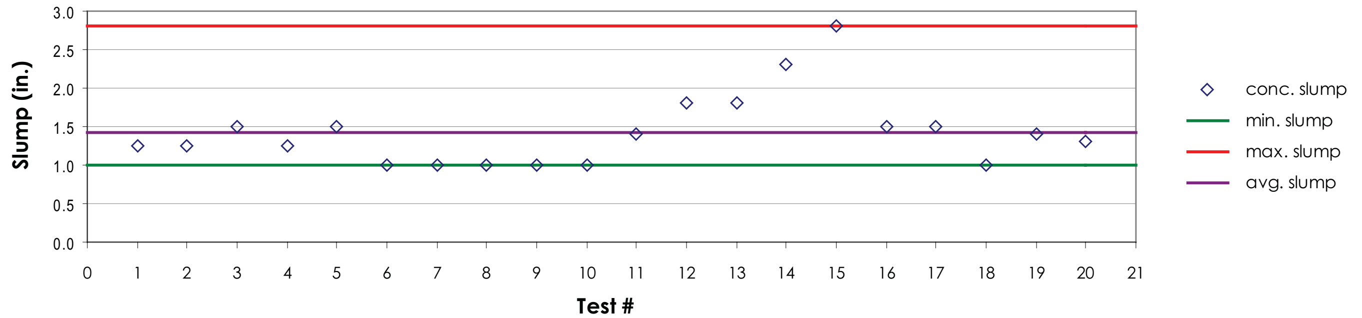

Figure 7.8 Slump test chart measured at placement

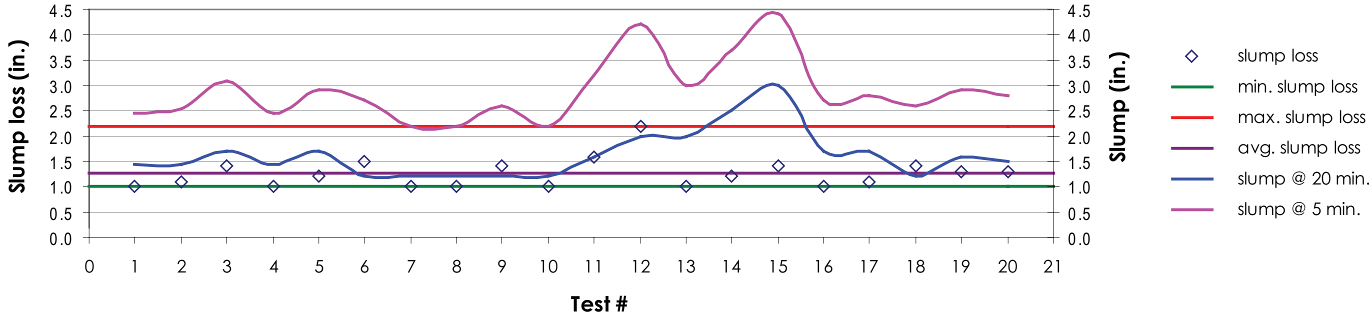

Figure 7.9 Slump loss chart measured at plant

Mortar Flow

Purpose – Why Do This Test?

Similar to slump, mortar flow is a relative measure of workability. Changes in flow indicate variability in the materials and/or the batching process that may not be observed from slump testing alone. Mortar flow is most sensitive to water content and air content. It is also more sensitive than the slump test for stiff concrete mixtures. Mortar flow is a process control test procedure and should not be considered as an acceptance criteria.

Principle – What is the Theory?

Water content, fine aggregate gradation, cementitious chemistry, mixing time, air content, and concrete temperature all interact to affect mortar flow. A flow test cannot identify which of these factors is changing—it simply measures the flow of a given mortar. Uniformity of the mortar flow is the primary concern.

Test Procedure – How is the Test Run?

ASTM C 1437, the Standard Test Method for Flow of Hydraulic-Cement Mortar, determines how much a mortar sample flows when it is unconfined and consolidated. Mortar is placed inside 2-in. tall conical brass mold. When the mold is removed, the mortar is vibrated at 1.67 Hz as the flow table rises and drops ½ in., 25 times in 15 seconds. The mortar changes from a conical shape with a 4-in. base to a "pancake." Mortar flow is reported as a percentage based on the change in diameter from 4 in. to the final diameter of the mortar "pancake."

Test Apparatus (figure 7.10)

- Flow table.
- Flow mold.
- Caliper.
- Tamper, trowel, and straight edge.
- Vibratory mortar sampler (required for field sampling).

Figure 7.10 Mortar flow testing equipment

Mortar Flow, continued

Test Method – Refer to ASTM C 1437 for Comprehensive Guidance

1. Obtain a representative mortar sample.
   a. Field samples should be obtained by vibrating a sample of concrete across a #4 sieve. Figure 7.10 shows an example of a sampling apparatus that fits on the end of a vibrator.
   b. Lab samples may be mixed or sieved.
2. Fill the mold with mortar in two 1-in. lifts, tamp each lift 20 times.
3. Strike the mortar off flush with the top of the mold.
4. Remove the mold.
5. Drop the table 25 times in 15 seconds.
6. Measure the diameter of the mortar.
7. Calculate and report the mortar flow as a percentage of the original base diameter.

Output – How Do I Interpret the Results?

Typical process control charts will be helpful in monitoring material and process uniformity.

Construction Issues – What Should I Look For?

Mortar flow testing may indicate changes in the mixture that are not discernable from slump testing alone. Variability in the mortar flow test results may indicate changes in the following:

- Total water content of the mixture.
- Aggregate moisture(s).
- Mixing time.
- Air content.
- Concrete temperature.
- Material incompatibilities.
- Batching proportions and/or scale tolerances.

Vibrator Monitoring

Purpose – Why Do This Test?

Proper vibration is essential to providing long-term durability for a portland cement concrete pavement. Excessive vibration can adversely affect the entrained air properties of the concrete, resulting in premature failure due to freeze-thaw deterioration. Segregation is also an unwanted by-product of excessive vibration. A pavement that is segregated has an excess of paste in the upper portion and a highly permeable matrix of coarse aggregate in the lower portion; strength is reduced, and the pavement is left susceptible to the intrusion of unwanted fluids. A pavement that is undervibrated will have excessive voids, resulting in reduced strength and durability.

Principle – What is the Theory?

Automatic vibrator monitors provide real-time feedback to the paver operator, as well as the capability to download vibrator frequency data for further analysis. Each mixture will react differently to vibration. In general, gap-graded mixtures will segregate more easily than dense-graded mixtures. Pavement thickness and paver velocity are also factors that should be considered when determining a maximum vibrator frequency. Some state departments of transportation (DOTs) specify a maximum vibrator frequency in the range of 7,000 to 9,000 vpm.

Test Procedure – How is the Test Run?

Vibrator monitoring is not a test. Rather, it is a continuous process check. The hardware provides alarms to warn the operator when pre-programmed specification limits are exceeded. Because a paver operator has many duties besides watching the vibrator monitor, it is important to download and review the data daily.

Test Apparatus

- Vibrator monitor.
- Portable computer for daily analysis.

Test Method – Refer to Manufacturer's Recommendations

Output – How Do I Interpret the Results?

Graphing the daily vibrator monitor data as shown in figure 7.11 provides a quick check of whether vibrators are malfunctioning or set at too high of a frequency.

Construction Issues – What Should I Look For?

Vibration issues are difficult to identify from simply observing the freshly placed pavement. Segregation may be recognized in cores taken from the hardened pavement. However, underconsolidation due to a "dead" vibrator is more difficult to identify unless a core is coincidentally taken in the path of the "dead" vibrator. In short, vibrator monitors provide the best and quickest feedback about potential consolidation issues in the pavement.

Vibrator Monitoring, continued

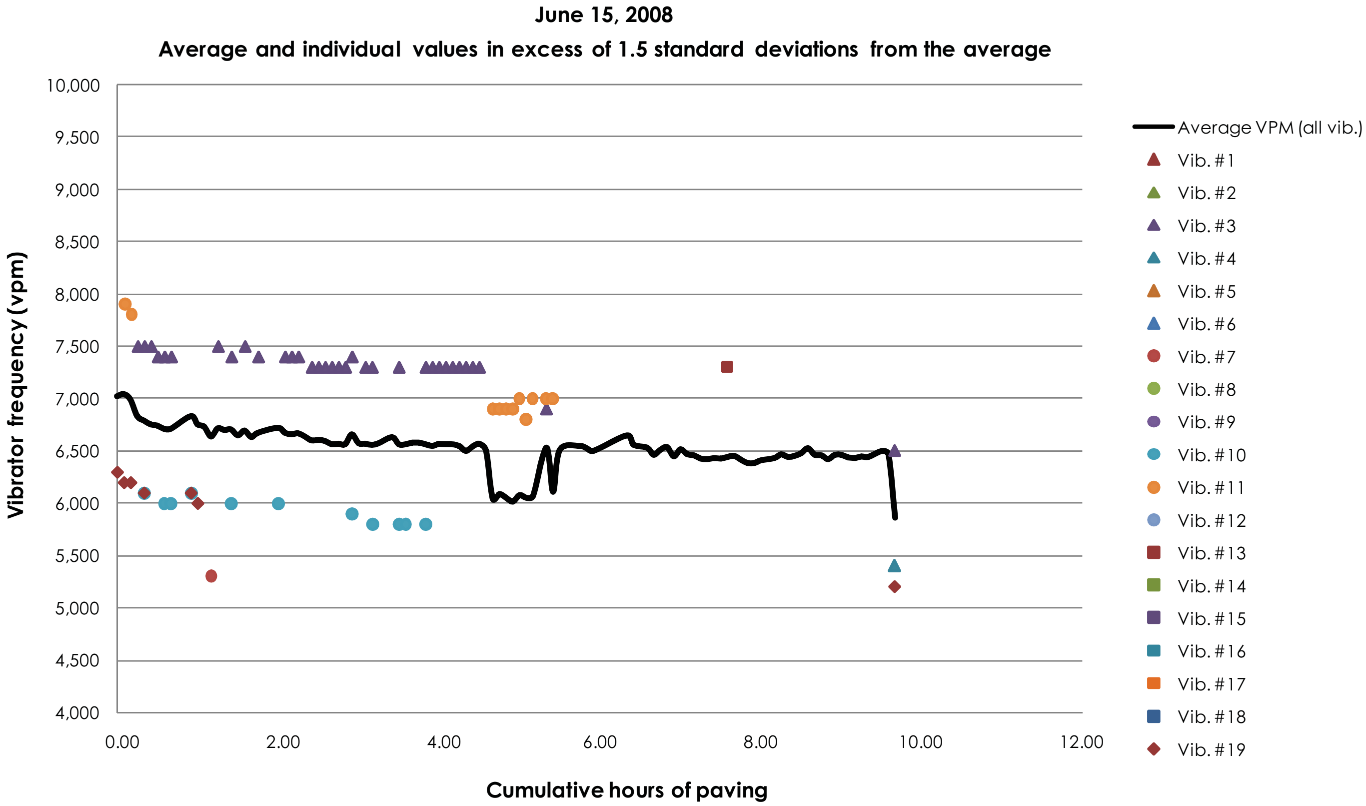

Figure 7.11 Vibrator frequency (data points at 5 min. intervals)

Cementitious Heat Generation - Coffee Cup

Purpose – Why Do This Test?

The coffee cup test procedure can be used to monitor the uniformity of cementitious materials that are supplied on a paving project. To effectively monitor the uniformity of the cementitious materials, it is necessary to perform this test at least once each day that portland cement and/or supplementary cementitious materials (SCMs) are delivered to the project. This test should not be used to accept or reject materials that are supplied. However, it should serve as a process control and troubleshooting aid. If the workability of the mixture changes significantly during construction, the coffee cup test results can be reviewed to identify whether a change in the cementitious materials is contributing to the workability issue. Conversely, the coffee cup test results may indicate that the cementitious materials have been consistent, suggesting that the workability issue is caused by another factor.

Principle – What is the Theory?

Cementitious paste mixtures generate heat as they hydrate. Although this test is not capable of identifying specific chemical changes in the cementitious materials, monitoring the heat generated by paste mixtures prepared from project materials can identify whether changes in the cementitious materials have occurred.

Test Procedure – How is the Test Run?

Paste mixtures are prepared in the same proportions as the project mixture design, and the temperature of these mixtures is recorded over time.

Test Apparatus (figure 7.12)

- Slotted tube sampler as described by ASTM C 183 is preferred.
- Airtight sample containers for portland cement and SCMs capable of holding 10 lb of material.
- Clean plastic gallon jug for mixing water sample.
- Five one-liter plastic beakers.
- Plastic tub for cooling or warming test materials in ice water or warm water.
- Digital scale that measures mass to the nearest 0.1 g.
- Sealable plastic mixing bottle.
- Test container with Styrofoam cork and insulated enclosure.
- Thermometer capable of measuring to the nearest 0.1°F (temperature sensors that measure and record the temperature of the sample over time may also be used).

Test Method – As Developed by the CP Tech Center, Iowa State University

1. Obtain representative samples of portland cement, any SCMs, and mixture water. Cementitious samples should be obtained in accordance with ASTM C 183 whenever possible. If project conditions do not allow this, care should be taken to assure that the material samples are representative of the materials being delivered to the project site.
    a. A minimum 10 lb grab sample should be obtained from bulk storage and bulk shipping containers.
    b. Measure and record the temperature of the cementitious materials immediately after sampling.
2. Calculate the mass of materials required for the test.
    a. If no SCMs are utilized in the mixture, the standard test requires 500 g of portland cement and 200 g of water (test #1).
    b. When SCMs are used in the mixture, replace the portland cement with a portion of SCMs equivalent to the mixture proportions (test #2).

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Figure 7.12 Cementitious heat generation test equipment and materials

Cementitious Heat Generation - Coffee Cup, continued

i. Example—the project mixture design calls for 423 lb of portland cement and 141 lb of fly ash.
Total cementitious materials = 564 lb
Portland cement = 423 lb (75%)
Fly ash = 141 lb (25%)

ii. Materials required for the test

1. Test #1: portland cement + water
Portland cement = 500 g
Water = 200 g

2. Test #2: portland cement + SCMs + water
Portland cement = 375 g (500 g • 75%)
Fly ash = 125 g (500 g • 25%)
Water = 200g

3. Total materials required for test #1 and test #2
Portland cement = 875 g
Fly ash = 125 g
Water = 400 g

c. Label and store the remaining portland cement and fly ash in airtight containers. This material can be used for further testing if necessary.

3. Cool or warm the cementitious materials and water to 70ºF ± 3ºF.

a. Transfer the required total mass of portland cement + 100 g to a plastic beaker.

b. Transfer the required total mass of SCMs + 50 g to a plastic beaker.

i. Cool portland cement and SCMs by bathing the beakers in ice water; stir occasionally to thoroughly cool the entire sample.

ii. Warm portland cement and SCMs by bathing the beakers in warm water; stir occasionally to thoroughly warm the sample.

c. Transfer the required total mass of water + 100 g to a plastic beaker.

i. Water may be cooled by adding ice or chilling in a refrigerator; stir occasionally to thoroughly cool the entire sample.

ii. Water may be warmed in a microwave oven or by bathing the beaker in warm water; stir occasionally to thoroughly warm the sample.

4. Test #1: portland cement + water.

a. Weigh 500 g of portland cement that has been cooled or warmed to 70ºF ± 3ºF and transfer to a sealable mixing bottle.

b. Weigh 200 g of mixing water that has been cooled or warmed to 70ºF ± 3ºF and transfer to the mixing bottle containing the portland cement.

c. Seal the mixing bottle.

d. Start a timer.

e. Vigorously shake the mixing bottle containing the portland cement and water until the timer reaches 1 minute.

f. Transfer the paste mixture from the mixing bottle to an insulated container and insert a thermometer.

g. Record the temperature of the paste when the timer reaches 2 minutes and continue to record the temperature at one-minute intervals until the timer reaches 11 minutes (10 temperature readings).

h. Discard the paste mixture; clean and dry all test equipment.

5. Test #2: portland cement + SCMs + water (when SCMs are used).

a. Weigh the required amount of portland cement that has been cooled or warmed to 70ºF ± 3ºF and transfer to a sealable mixing bottle.

b. Weigh the required amount of SCMs that has been cooled or warmed to 70ºF ± 3ºF and transfer to a sealable mixing bottle.

c. Seal the mixing bottle and agitate the portland cement and SCMs to obtain a homogeneous mixture.

d. Remove the lid from the mixing bottle.

e. Weigh 200 g of mixing water that has been cooled or warmed to 70ºF ± 3ºF and transfer to the mixing bottle containing the portland cement and SCMs.

f. Seal the mixing bottle.

g. Start a timer.

h. Vigorously shake the mixing bottle containing the portland cement, SCMs, and water until the timer reaches 1 minute.

Cementitious Heat Generation - Coffee Cup, continued

i. Transfer the paste mixture from the mixing bottle to an insulated container and insert a thermometer.

j. Record the temperature of the paste when the timer reaches 2 minutes and continue to record the temperature at one-minute intervals until the timer reaches 11 minutes (10 temperature readings).

k. Discard the paste mixture; clean and dry the test equipment.

Output – How Do I Interpret the Results?

Plot the test results on a graph as shown in figure 7.13. Significant differences in the peak temperature and/or the time required to reach peak temperature may indicate changes in the cementitious materials.

Tests #1A and #1B were performed on material from the same sample. The shape of the temperature profiles for #1A and #1B is essentially the same and the difference between temperature readings is less than 1ºF. Tests #2 and #3 were performed on samples obtained one day after tests #1A and #1B. The shape of the temperature profiles for tests #2 and #3 is obviously different than for tests #1A and #1B. Maximum temperature for test #2 is 2.3ºF greater than the average peak temperature of tests #1A and #1B, while the difference in peak temperature for test #3 and the average maximum temperature of tests #1A and #1B is 2.7ºF.

The change in shape of the temperature profile and the difference between maximum temperatures observed for tests #2 and #3 as compared to tests #1A and #1B indicate that the portland cement changed from one day to the next. If the workability properties of the mixture had been adversely affected, the coffee cup test results could have been reviewed to identify that the change in cement contributed to the change in workability. Comparing the test result of actual mixture proportion of cement and SCMs with that of the cement only can help identify which material may be contributing to the problem.

Construction Issues – What Should I Look For?

Changes in workability, water demand, and early stiffening may be caused by changes in the cementitious materials. Cementitious heat generation test results may be used as a troubleshooting aid when these issues occur by either identifying that the cementitious materials did change, or confirming that they were unchanged and did not contribute to the problem observed in the concrete mixture.

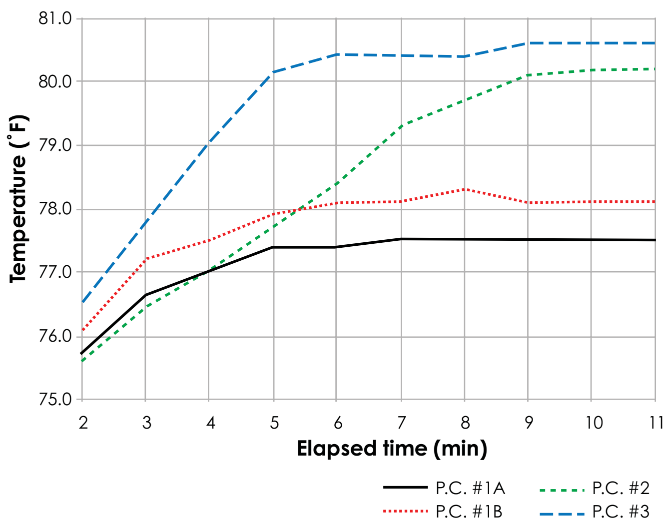


Figure 7.13 Cementitious heat generation (coffee cup) test results

Early Stiffening and False Set

Purpose – Why Do This Test?

Some portland cements and combinations of cement and pozzolans may be prone to false set. False set reduces the workability of the concrete mixture. Workability can be restored by remixing without the addition of water.

Since remixing is not normally possible when a central mix plant and dump trucks are used for delivery, the false set condition is usually offset by adding more mixing water, which increases the water-cementitious materials (w/cm) ratio. This is poor practice.

Performing the penetration resistance test on the cementitious materials and admixtures during the mixture design stage will indicate whether the mixture is prone to false set due to material incompatibilities.

Principle – What is the Theory?

As concrete mortar stiffens (sets), the resistance required for a 10-mm diameter rod to penetrate into the mortar will increase. The depth of penetration of the 10-mm rod into a mortar sample is measured and recorded at various times. If, after remixing, the 10-mm rod penetrates the mortar sample to a depth greater than was measured before remixing, then a false set condition is occurring.

Test Procedure – How is the Test Run?

ASTM C 359, the *Standard Test Method for Early Stiffening of Portland Cement (Mortar Method)* (false set), tests a laboratory-mixed mortar. The test method uses a Vicat apparatus to measure the depth of penetration of a 10-mm diameter plunger 10 seconds after it is released into the mortar at fixed time intervals.

Test Apparatus (figure 7.14)

- Vicat: A frame holding the 10-mm rod and an indicator to measure the depth of penetration in mm.
- Mortar mold: A box 51-mm wide x 51-mm high x 152-mm long (2- x 2- x 6-in.) used for containing the mortar sample.
- Mixer: A laboratory mixer used for remixing the mortar sample.

Test Method – Refer to ASTM C 359 for Comprehensive Guidance

1. Mix a mortar sample using materials from the project.
2. Place the mortar sample in the mold, consolidate it, and strike it off.
3. Using the Vicat, hold the 10-mm rod in contact with the top surface of the mortar by a set screw.
4. Release the rod from the set screw and allow it to penetrate into the mortar. Record the depth of penetration 10 seconds after the rod is released.
5. Take penetration readings 3 minutes, 5 minutes, 8 minutes, and 11 minutes after batching.
6. After the 11-minute reading, remix the mortar sample for 1 minute.
7. Replace the mortar sample in the mold, consolidate it, and strike it off.
8. Measure the penetration 45 seconds after completion of remixing.
9. Record the depths of penetration for each of the five repetitions.

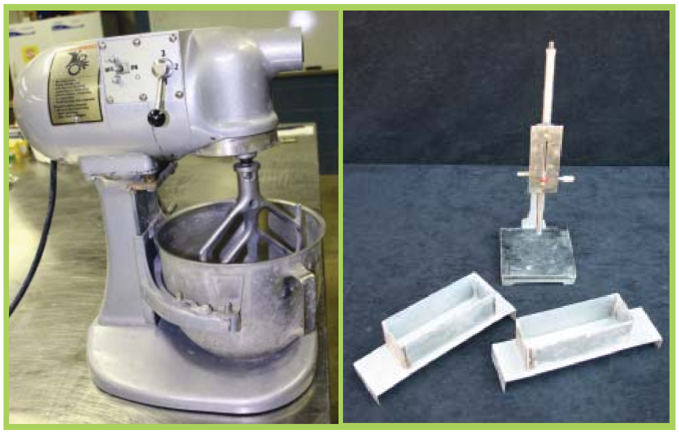


Figure 7.14 False set testing equipment

Early Stiffening and False Set, continued

Output – How Do I Interpret the Results?

The depths of penetration are reported in tabular and graphical format, as in this example (figure 7.15):

Initial penetration	50 mm
5-minute penetration	40 mm
8-minute penetration	25 mm
11-minute penetration	10 mm
Remix penetration	25 mm

If, as shown in the example, the penetration after remixing is greater than the 11-minute penetration, false set is occurring. Also, if the penetration depth decreases from 50 mm to approximately 10 mm before re-mixing, flash set or severe early stiffening of the mixture is likely.

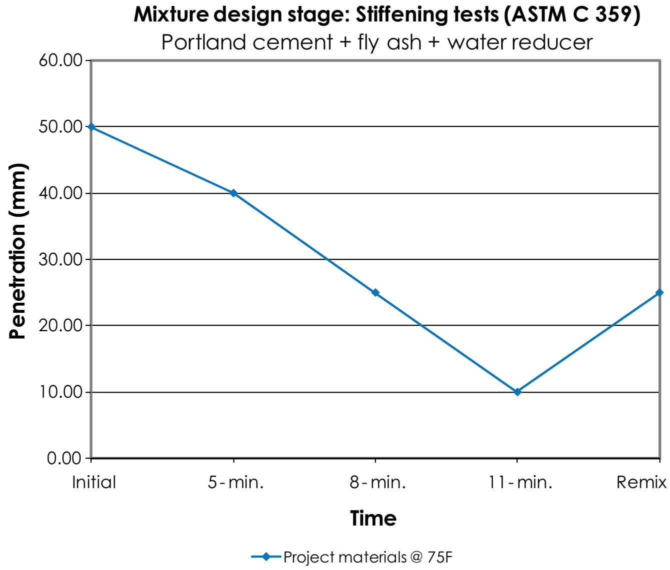


Figure 7.15 Example false set test results

Construction Issues – What Should I Look For?

Situations that may indicate the occurrence of false set include the following:

- Excessive vibration that essentially remixes the concrete.
- Loss of workability during moderate temperatures.
- Workability changes that occur when pozzolans and/or admixtures are removed or added.

Water-Cementitious Materials Ratio (Microwave)

Purpose – Why Do This Test?

The water-cementitious materials (w/cm) ratio has a significant effect on the strength and permeability of a pavement. Acceptance strength tests on hardened concrete are normally performed at least seven days after placement of the concrete. The microwave method can be used to obtain w/cm ratio results within hours, instead of waiting days for strength results. Monitoring the test results may provide an early flag of potentially low-strength concrete, allowing the contractor to adjust operations sooner than conventional strength testing might indicate.

Concrete strength varies inversely with the amount of water in the mixture. In simplest terms, for a given cementitious content, less water leads to higher strength. Other factors, such as consolidation, curing, aggregate quality, air content, and aggregate shape, affect strength as well. For a given mixture with a constant amount of cement, the w/cm ratio has the greatest impact on strength.

Principle – What is the Theory?

The total water in a concrete mixture comes from the following sources:

- Moisture absorbed in the aggregate.
- Free water on the aggregate.
- Water added in the batching process.

The mass of water removed from a fresh mixture by drying in a microwave can be used to calculate the w/cm ratio of the mixture.

Test Procedure – How is the Test Run?

The test is described in AASHTO T 318. A sample of fresh concrete from the project is weighed and then dried in a microwave oven. It is then reweighed to determine the mass of water that was contained in the mixture. The water absorbed in the aggregate is subtracted from the total, and the remainder is used to calculate the w/cm ratio using the batched cementitious materials content.

Test Apparatus (figure 7.16)

- Microwave oven for drying the concrete sample.
- Glass pan and fiberglass cloth (a container for the concrete sample).
- Scale to obtain the mass of the sample.
- Porcelain pestle for grinding the sample as it is dried.

Test Method – Refer to AASHTO T 318 for Comprehensive Guidance

1. Weigh the glass pan and fiberglass cloth (tare).
2. Place the concrete sample in the glass pan on top of the fiberglass cloth.
3. Weigh the glass pan, fiberglass cloth, and concrete sample.
4. Heat the concrete sample in the microwave oven for five minutes.
5. Remove the sample from the microwave, weigh, and break up the sample using the pestle.
6. Reheat the sample for five minutes.

continued on next page

Figure 7.16 Microwave water content test equipment

Water-Cementitious Materials Ratio (Microwave), continued

7. Repeat the weighing, breaking, and heating cycle at two-minute intervals until the sample loses less than 1 g of mass between reheating cycles.

8. Record the mass of the wet concrete sample, the mass of the dry concrete sample, and the difference between the two masses (mass of total water content).

Output – How Do I Interpret the Results?

The total water content of the concrete sample can be expressed as a percentage:

Total water content % (W_t) = (wet sample mass – dry sample mass) / wet sample mass

This W_t can be monitored and used as a relative indicator of potential variability in pavement strength.

It should be noted that the value of W_t will not provide the true w/cm ratio because the microwave test drives out all of the water in the concrete, including the water that is absorbed in the aggregate. As such, the value of W_t will be greater than the true w/cm ratio of the mixture. By compensating for the measured absorption of the aggregate, the result from this test can be used to monitor variability in the concrete from batch to batch.

Test results should be plotted on control charts.

Construction Issues – What Should I Look For?

When variations in W_t are noted, aggregate moisture contents and plant operations should be reviewed to ensure that materials are being batched in the proper proportions.

Heat Signature (Adiabatic Calorimetry Test)

Purpose – Why Do This Test?

Heat signature is a representation of the heat of hydration generated by a specific concrete mixture over time. Variations in the chemistry and dosage of portland cement and supplementary cementitious materials (SCMs), along with interactions between them and chemical admixtures, may be flagged by the heat signature. Changes in the heat signature of a concrete mixture can impact construction issues related to strength development and proper saw timing.

Principle – What is the Theory?

Chemical reactions that occur as concrete hardens emit heat (heat of hydration). By insulating a standard cylinder of concrete from the influence of outside temperatures and using sensors to record the heat generated by the concrete, it is possible to measure the heat signature of a concrete mixture. A chart that plots time on the x-axis and temperature change on the y-axis is produced from this data.

Graphing the temperature difference is preferable to graphing the actual concrete temperature. Even though the heat signature curve for the same mixture will be different depending upon the beginning temperature of the mixture, it is easier to compare the curves when the results are normalized by using the temperature difference (ΔT) as the value for the y-axis.

$\Delta T = T_n - T_0$

T_n = Temperature of the concrete sample at time n (after the initial temperature reading)

T_0 = Initial concrete temperature at the beginning of the test

Test Procedure – How is the Test Run?

A concrete cylinder(s) is placed inside an insulated container that is equipped with temperature sensors that record the temperature of the concrete sample(s) at 15-minute intervals. The temperature and time data are transmitted to a personal computer, where data are stored and analyzed.

Test Apparatus

- Calorimeter: insulated container equipped with temperature sensors (figure 7.17).
- Standard concrete cylinder(s).
- Personal computer.

Test Method

1. Prepare the test apparatus for use—program the temperature sensor(s) to measure and record temperature at a regular time interval (3 to 15 min.).
2. Sample the mixed concrete and cast the concrete cylinder(s).
3. Insert the temperature sensor into the cylinder(s) and record the time when it is inserted into the fresh concrete.

continued on next page

Figure 7.17 Calorimeter

Heat Signature (Adiabatic Calorimetry Test), continued

4. Place the concrete cylinder(s) in the insulated container and close the container.
5. Maintain the temperature of the environment where the insulated container is located at 73˚F ± 3˚F.
6. Open the container at the conclusion of the test and download the temperature data from the sensor.
7. Graph the temperature data with time on the x-axis and ΔT on the y-axis.
8. Record and note the following values on the heat signature graph:
   a. Maximum temperature (T_{max}).
   b. Minimum elapsed time at which T_{max} occurs.
   c. Maximum slope between two individual temperature measurements (S_{max}, ˚/h).
   d. Minimum elapsed time at which S_{max} occurs.
   e. Average slope from the minimum temperature to the maximum temperature (S_{avg}, ˚/h).

Output – How Do I Interpret the Results?

The current practice for interpreting heat signature results is empirical—the curves should be visually compared to each other and differences in the maximum temperature, average slope, and maximum slope should be noted as compared to heat signature curves that have been characterized qualitatively. As a history or library of heat signature curves is developed, the mixtures and corresponding heat signature curves should be characterized by field observations and field test results. Some suggested general guidelines for characterizing the performance of the mixture that relate to heat signature curves are as follows:

- Random cracks occurred with this mixture due to slow strength development.
- Random cracks occurred with this mixture due to rapid strength development.
- Workability issues due to early stiffening.
- Workability issues related to hot weather or elevated concrete temperature (>85˚F).
- If the field performance of a mixture was good, note the range of concrete temperatures that the mixture was placed at (e.g., 66˚F to 88˚F).

A heat signature curve can be compared to the curves of other mixtures during the mixture design stage to identify whether the mixture will perform well in the field (figure 7.18). The example shown in figure 7.18 illustrates the heat signature curves developed during the mixture design stage for various projects. Qualitative comments regarding the field performance of each mixture are necessary to assist in identifying potential problems that may occur with the mixture that is being tested in the lab.

Significant changes in the heat signature may also indicate that the source materials have changed or that there was a problem with batching.

During the mixture verification stage, the heat signature curve of the project batched mixture is compared to the curve from the mixture design stage to evaluate whether the materials have changed significantly (figure 7.19).

Construction Issues – What Should I Look For?

Heat signature of portland cement concrete should be utilized as a tool for evaluating the early-age properties of a concrete mixture during all three project stages. Issues, such as random cracking of the pavement due to the rate of strength development (too slow or too fast), hot/cold weather placement issues, and the variability or change in raw material properties during construction, can be identified using heat signature testing.

Changes in heat signature may impact the following concrete properties:

- Workability and consolidation.
- Rate of strength gain.
- Ultimate concrete strength.
- Initial window for sawcutting contraction joints.

Heat Signature (Adiabatic Calorimetry Test), continued

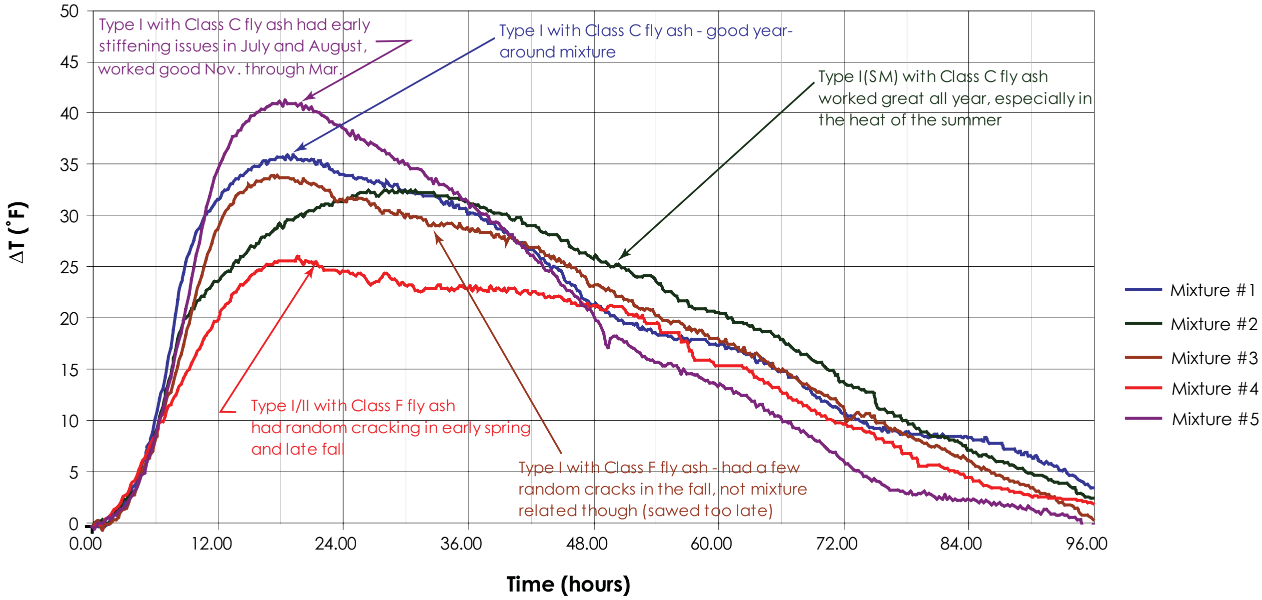
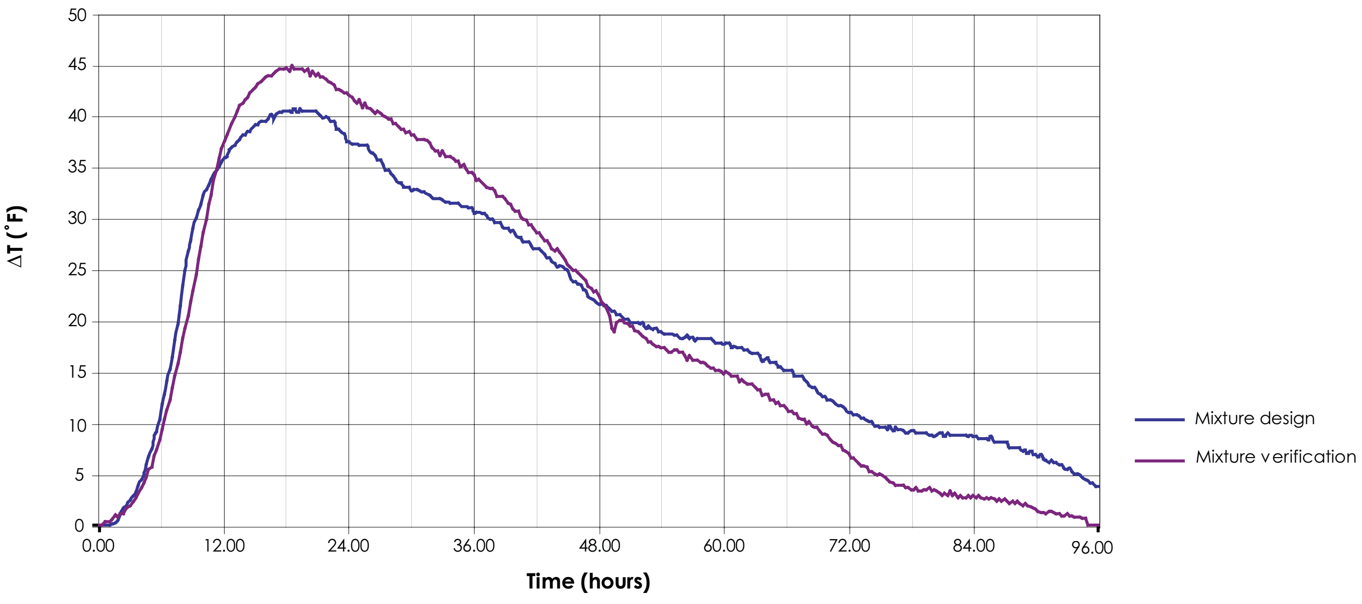


Figure 7.18 Qualitative comparison of heat signature curves during the mixture design stage



	Maximum ΔT ˚F	Elapsed hours to max. ΔT ˚F	Average slope from time 0 to max. ΔT ˚F/h	Maximum slope ˚F/h	Elapsed hours to max. slope ˚F
Mixture design	40.70	18.75	2.17	7.29	7.75
Mixture verification	44.91	18.50	2.43	6.22	9.25
Difference	4.20	-0.25	0.26	-1.07	1.50

Figure 7.19 Comparison between mixture verification and mixture design heat signatures

Set Time

Purpose – Why Do This Test?

Determining the set time of a concrete mixture during the mixture design and mixture verification phases enables comparison of the mixture's early strength development characteristics. Such a comparison may reveal changes in the mixture's behavior and properties as compared to what was observed during the mixture design stage. Early identification of strength development trends may be helpful in preventing uncontrolled cracking in the pavement.

Principle – What is the Theory?

The hydration process for a given concrete mixture is complex and dependent on the interaction of many factors (materials and processes). Set time testing identifies two points on the hydration curve: initial set and final set. Initial set occurs at 500 lb/in^2 (penetration resistance) and final set is defined to occur at 4,000 lb/in^2 (penetration resistance). Even though the initial and final set values are arbitrary and may not have any connection to field behavior of the pavement, these test values provide an objective measure of the concrete mixture's early strength development characteristics.

Test Procedure – How is the Test Run?

ASTM C 403, the *Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resisitance*, determines the penetration resistance (expressed in lb/in^2) of a mortar sample over time. Penetration resistance is a function of the force required for a needle of known bearing area to penetrate a curing mortar sample to a depth of 1 in. A penetrometer with varying size needles is used to determine the penetration resistance.

Test Apparatus (figure 7.20)

- Container for mortar specimen(s).
- Penetration needles with the following bearing areas (in^2):1.00, 0.50, 0.25, 0.05, 0.025.
- Penetrometer.
- Tamping rod.
- Pipet.
- Thermometer.
- Vibratory mortar sampler (suggested for field sampling).

Test Method

1. Prepare a lab mortar sample or obtain a mortar sample from a field-mixed batch.
2. Record the time at which cementitious materials first come into contact with water.

continued on next page

Figure 7.20 Set time testing equipment

Set Time, continued

3. Record the temperature of the fresh mortar sample, place in a container, consolidate, and level the top surface of the mortar.
4. Maintain the ambient test conditions at 68°F to 77°F (lab and field tests).
5. Begin penetration testing approximately 3 to 4 hours after initial contact between the cement and water. Continue penetration testing at 30 to 60 minute intervals, decreasing the needle bearing area as necessary, until final set of 4,000 lb/in^2 occurs.
6. For each penetration, record the ambient temperature, mortar temperature, force, and bearing area.
7. Calculate the penetration resistance by dividing the force by the penetration area.
8. Plot the results.

Output – How Do I Interpret the Results?

Plot the set time for mixture design and mixture verification tests together (figure 7.21). Compare the results and note whether the field-mixed concrete has significantly different set time characteristics than the mixture design.

Construction Issues – What Should I Look For?

Delays in normal setting may lead to uncontrolled cracking as stresses build up in the pavement before it has time to gain enough strength for sawcutting operations. This is especially critical in hot and/or dry weather conditions. Accelerated set will require earlier sawcutting operations.

Set Time, continued

Penetration Resistance ASTM C 403

Project:	I-35 Payne Co.
Test description:	Mixture verification
Date:	29-May-08
Time:	9:10 AM
Operator:	BZ

Time	Air/mortar temperature (°F)	Elapsed time	Needle #	Reading (lb)	Penetration resistance (lb/in²)	Log (PR)	Log (f)
12:50 PM	69.0/73.2	**220**	**1**	**112**	**112**	2.05	2.34
1:50 PM	69.4/74.3	**280**	**2**	**175**	**350**	2.54	2.45
2:20 PM	69.5/74.8	**310**	**4**	**198**	**792**	2.90	2.49
2:50 PM	70.3/76.7	**340**	**10**	**120**	**1,200**	3.08	2.53
3:20 PM	71.1/78.8	**370**	**20**	**75**	**1,500**	3.18	2.57
3:40 PM	71.6/79.9	**390**	**40**	**55**	**2,200**	3.34	2.59
4:10 PM	72.3/80.2	**420**	**40**	**80**	**3,200**	3.51	2.62
4:40 PM	72.1/81.6	**450**	**40**	**115**	**4,600**	3.66	2.65
Initial set (at 500 lb/in²)		estimated times based on test data	**290** min		**4.84** h		
Final set (at 4,000 lb/in²)			**452** min		**7.53** h		

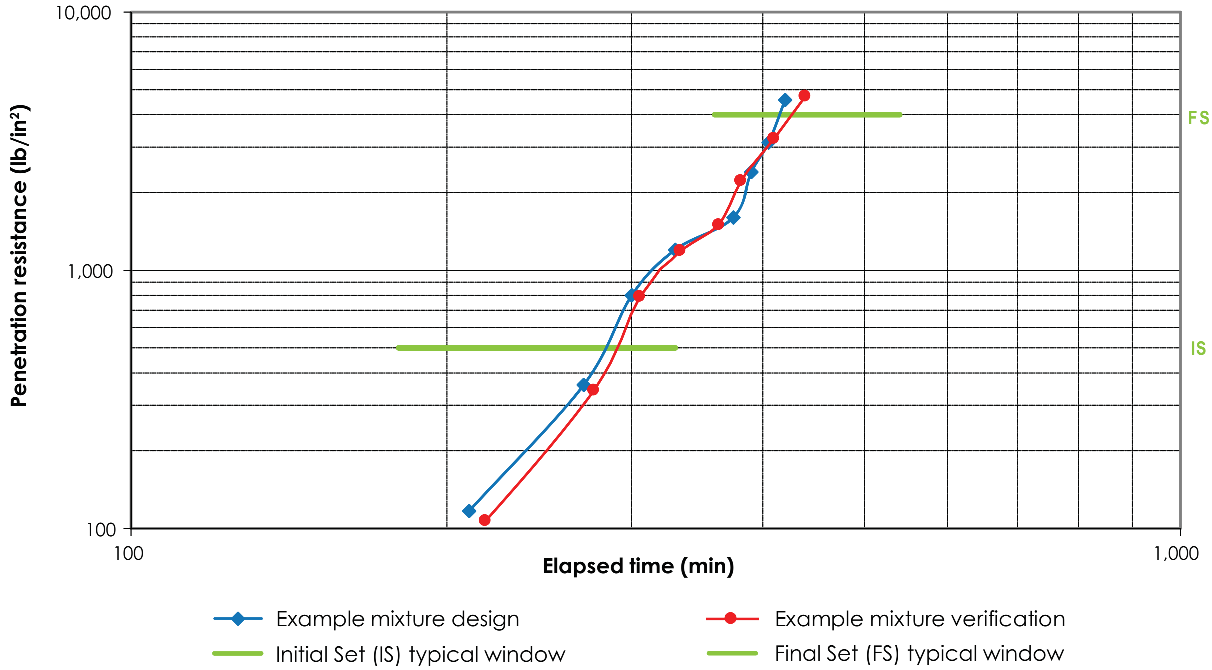


Figure 7.21 Plotting set time for mixture design and mixture verification

Flexural Strength and Compressive Strength (Three and Seven Day)

Purpose – Why Do This Test?

Concrete strength is critical because it reflects concrete's ability to carry intended loads. Flexural and compressive strength testing are currently the standard methods of evaluating and assessing pay factors for pavement concrete. The tests are required for calibrating maturity-based monitoring systems.

Principle – What is the Theory?

A measured force is applied to concrete samples of consistent cross-sectional area (beams and cylinders) until the samples fail. The force required to break the sample is used to calculate the strength based on the cross-sectional area of the sample.

Test Procedure – How is the Test Run?

Samples of fresh concrete from the project are cast in cylinder and/or beam molds. These test specimens are cured in laboratory conditions until they are broken in accordance with ASTM C 39 (compression) or ASTM C 78 (flexure). A consistent and continuously increasing force is applied to the test specimens by a hydraulic testing machine. The maximum force required to break the sample and the actual dimensions of each sample are recorded.

Test Apparatus

- Cylinder and beam molds for casting strength specimens (6-in. diameter x 12-in. height or 4-in. diameter x 8-in. height for cylinders and 6-in. width x 6-in. height x 24-in. length for beams).
- Curing tanks to provide consistent curing conditions for the specimens.
- Hydraulic testing frame for applying the force (figure 7.22).
- Cutoff saw, neoprene cap, and miscellaneous tools for preparing the specimens.

Test Method

1. Sample and cast cylinder and beam specimens in accordance with standard procedures.
2. Cover and protect specimens from evaporation and damage for 24 hours.
3. Remove specimens from the molds and transfer to the curing tanks.
4. Cure the specimens in a controlled environment until they are broken.
5. Remove the specimens from the curing tanks.
6. Place the specimens in the hydraulic testing frame and apply a force until the specimen breaks.
7. Record the maximum force applied and the dimensions of the specimen.

Figure 7.22 Hydraulic compression tester

Flexural Strength and Compressive Strength (Three and Seven Day), continued

Output – How Do I Interpret the Results?

Strength results are reported in a tabular format in units of pounds per square inch (lb/in^2). Other data in the report should include specimen identification, specimen dimensions, span length (beams), and maximum force applied.

Formulas for concrete strength calculations are as follows:

Flexural strength = ([force x span] / [width x depth^2])

Compressive strength = force / (π x radius^2)

Construction Issues – What Should I Look For?

Laboratory-cured strength tests are a representation of the concrete mixture's strength properties. The strength of the pavement will differ from laboratory-molded and laboratory-cured specimens due to differences in consolidation and differences in the curing environment. Core specimens taken from the slab can be used to verify pavement strengths.

Conditions that may prevent the strength tests from being representative of the actual concrete strength include the following:

- The load rate does not conform to standard procedures; faster load leads to higher strength test results.
- Beam specimens are allowed to dry before testing, resulting in lower strength test results.
- Specimen dimensions are not uniform, or equipment surfaces are not straight and flat, resulting in lower strength test results.
- Specimens are not adequately consolidated, resulting in lower strength test results.
- Quality control and acceptance specimens should be cured in a lab environment (70°F to 76°F), which leads to a difference between the temperature history of the specimens and the pavement. Thus, the strength of the specimens is not equivalent to the strength of the pavement.

The strength of the concrete pavement structure is influenced by the following factors:

- Water-cementitious materials ratio.
- Air content.
- Consolidation.
- Curing conditions.
- Aggregate grading, quality, and shape.

Concrete strength has long been an acceptance criterion for concrete pavements. From a long-term performance standpoint, characteristics other than strength have a significant impact on pavement durability. Adequate strength is a good indicator of concrete quality, but it does not guarantee performance. Focusing on strength alone may ignore important properties, such as air entrainment, permeability, and workability.

Unit Weight

Purpose – Why Do This Test?

The unit weight of fresh concrete is a general indicator that the concrete has been batched in the correct proportions. It is a good indicator of batch-to-batch uniformity.

Principle – What is the Theory?

A concrete mixture design is composed of several ingredients: portland cement, supplementary cementitious materials (SCMs), fine aggregate, coarse aggregate, admixtures, air, and water. All of these materials have different specific gravities. A variation in the unit weight of a mixture will indicate a change in proportioning of the mixture, often in the water or air content.

Test Procedure – How is the Test Run?

A sample of mixed concrete is consolidated in a container of known volume and weighed to determine the unit weight of the mixed concrete (ASTM C 138).

Test Apparatus (figure 7.23)

- Measure: cylindrical container, usually a standard pressure air pot.
- Scale for weighing the sample.
- Tamping rod, vibrator, mallet, and strike-off plate for consolidating the sample in the air pot.

Test Method – Refer to ASTM C 138 for Comprehensive Guidance

1. Determine the level-full volume of the air pot.
2. Weigh the empty air pot.
3. Consolidate a sample of fresh concrete in the air pot using the tamping rod or vibrator and mallet until it is approximately $1/8$ in. above the top rim of the air pot.
4. Using the strike-off plate, finish the concrete so that it is level-full with the top rim of the air pot.
5. Clean off all excess concrete from the exterior of the air pot.
6. Weigh the air pot full of concrete.
7. Record the empty mass, full mass, and volume of the air pot.

Output – How Do I Interpret the Results?

The unit weight of the concrete mixture is reported in pounds per cubic foot (lb/ft^3):

Unit weight = (full mass – empty mass) / volume

The unit weight of the mixture should be compared with the unit weight of the mixture design to identify potential problems in the batching process or changes in raw materials. Typical 3s control charts should also be used to identify changes in the materials and/or processes indicated by unit weight test results.

A variability of more than 3 lb/ft^3 may be considered significant.

Construction Issues – What Should I Look For?

When variations in unit weight measurements are observed, the following potential causes should be reviewed:

- Sample consolidation. (Was the sample fully consolidated in the air pot?)
- Air content of the concrete.
- Water content of the concrete.
- Batch proportions of each material.
- Changes in raw material densities (specific gravities).

Figure 7.23 Unit weight test equipment

Air Content (Plastic Concrete, Pressure Method)

Purpose – Why Do This Test?

Entrained air is essential to the long-term durability of concrete pavements that are subject to freezing and thawing. Air content is a commonly specified parameter in paving specifications. It is usually measured at the point of placement using a pressure meter (normally a type B meter). Although this test does not provide air system parameters, it is quick, easy to run, and has worked very well for years as a quality control tool.

Principle – What is the Theory?

The fresh concrete is fully consolidated in an airtight container. Pressure from a fixed-volume cell is applied to the sample in the container. Air in the sample is compressed, and the reduction in pressure in the cell is directly related to the volume of air in the sample. The air content of the sample is thus read directly from the gauge of a properly calibrated meter.

Test Procedure – How is the Test Run?

The test is described in ASTM C 231. A sample of fresh concrete is fully consolidated in the air meter and struck off level-full. A known volume of air at a known pressure is applied to the sample in an airtight container. The air content of the concrete is read from the gauge on the pressure meter apparatus.

Test Apparatus (figure 7.24)

- Measuring bowl and airtight cover (type B meter) for holding the sample and measuring the air content.
- Tamping rod/vibrator and mallet for consolidating the sample.

Test Method – Refer to ASTM C 231 for Comprehensive Guidance

1. Consolidate the concrete in the measuring bowl using a tamping rod or vibrator and mallet.
2. Strike off the concrete in the measuring bowl so that it is level with the top rim.
3. Clean the edge and rim of the measuring bowl and clamp the cover on to form an airtight seal.
4. Pump air into the air chamber until the gauge needle is stabilized on the initial pressure line.
5. Open the valve between the air chamber and the measuring bowl.
6. Tap the measuring bowl with the mallet to ensure that pressure is equalized.
7. Tap the gauge lightly if necessary to stabilize the needle indicator.
8. Record the percentage of air content indicated on the gauge.

Output – How Do I Interpret the Results?

Air content of the fresh concrete mixture is read directly from the gauge of a calibrated type B pressure meter.

This is a measure of the percentage of total air content in a concrete mixture. Both entrained air and entrapped air are measured.

continued on next page

Figure 7.24 Air content test equipment (pressure meter)

Air Content (Plastic Concrete, Pressure Method), continued

The results are compared to the specified limits and should be plotted on control charts for ease of identifying significant changes in air content (figure 7.25).

Construction Issues – What Should I Look For?

Air content should be monitored regularly during paving (minimum one test every 500 yd^3). Additionally, samples should be taken behind the paver for air content testing at least once per day.

Generally, air contents greater than 4.5 percent in the in-place concrete (depending on exposure and aggregate size) provide adequate protection from freeze-thaw conditions. However, the use of an AVA is recommended for quality control purposes for Level A projects to be sure that proper bubble spacing and bubble size are present.

High air contents are less worrisome than low air contents, unless the strength is reduced to critical levels due to the high air content.

Air content can be affected by many factors, ranging from cement and admixture chemistry to mixing time and aggregate grading.

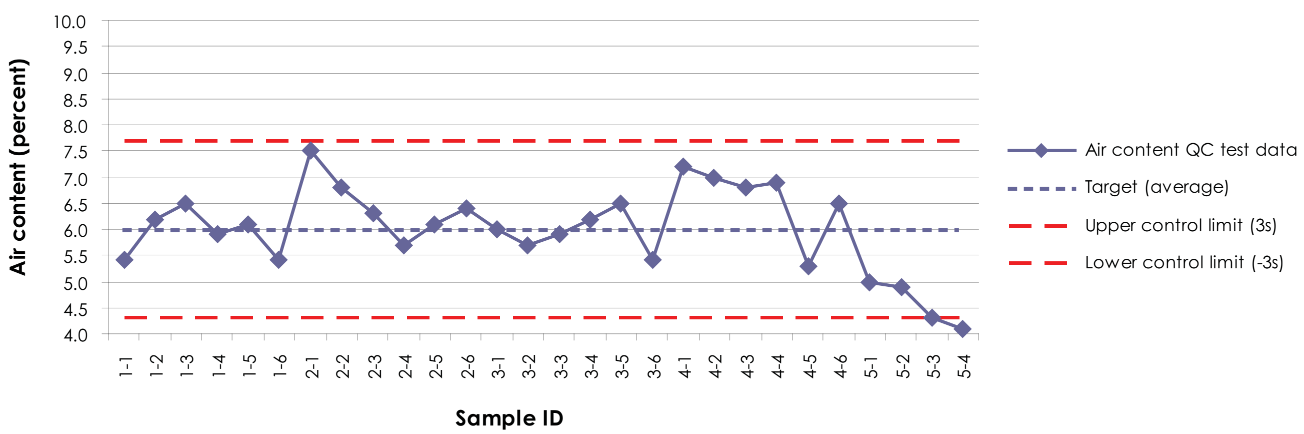


Figure 7.25 Air content control chart

Air-Void Analyzer (AVA)

Purpose – Why Do This Test?

Freeze-thaw resistance of concrete is primarily controlled by an air-void system with closely spaced small bubbles. The air-void analyzer provides a method of measuring the spacing factor in fresh concrete, rather than waiting for microscopical analysis of hardened concrete. A sample of mortar is taken from the concrete after it has been through the paver and tested immediately, with a result obtained in about 30 minutes. The AVA test should be used for quality control, not acceptance.

Principle – What is the Theory?

Gently stirring a sample of fresh concrete mortar releases the air bubbles through a viscous fluid and then through a column of water. The air bubbles are captured under a submerged bowl that is connected to a scale. As the air bubbles collect, the buoyancy (mass) of the bowl is recorded over time. The measurement of the buoyancy of different-sized bubbles (over time) is a function of Stoke's Law (larger bubbles rise faster than smaller bubbles).

Test Procedure – How is the Test Run?

A sample of fresh concrete mortar is taken from the slab behind the paver using a vibrating cage attached to a hand drill. A 20-cc portion of the mortar sample is injected into the instrument, which then gently stirs it to release the air bubbles into the fluid.

The measurement continues for 25 minutes or until the weight of the bowl remains unchanged for 3 minutes.

Software then processes the scale readings that were taken over time and, using an algorithm, calculates the air-void spacing factor and bubble size.

An AASHTO standard is currently being developed for the AVA.

Test Apparatus (figure 7.26)

- Portable drill with vibrating cage for obtaining mortar sample.
- Air-void analyzer (AVA) with all supplies, cables, etc.
- Personal computer with AVA software.

Figure 7.26 AVA setup in a portable lab and AVA sampling equipment

Air-Void Analyzer (AVA), continued

Test Method – Refer to Applicable AASTHO/ ASTM Standards and CP Tech Center's AVA Hyperdocument for Comprehensive Guidance

1. Obtain a sample of fresh mortar behind the paver.
2. Using a syringe, extract 20 cc of mortar from the sample.
3. Eject the 20-cc sample from the syringe and gently agitate it for 30 seconds.
4. The bubbles are released from the mortar sample and, over time, rise through the separation liquid and through a column of water.
5. As the bubbles rise, they are collected underneath a submerged bowl.
6. The buoyancy (mass) of the submerged bowl is measured over time as the bubbles are collected.
7. The test is concluded when the mass of the submerged bowl remains constant for 3 minutes or at the end of 25 minutes, whichever occurs first.
8. The computer and software collect and analyze the data from the scale, which is part of the AVA.

Output – How Do I Interpret the Results?

Software provided with the AVA produces tabular and graphical reports. Values are reported for the following:

- Spacing factor: Values less than 0.01 in. are desirable, although values less than 0.15 in. are commonly considered acceptable.
- Specific surface (bubble size): Values greater than 600 in^{-1} are desirable.
- Air-void content of paste.
- Air-void content of concrete.

Test results should be plotted graphically (figures 7.27 and 7.28) and monitored to assure air-void properties are within suggested limits.

Construction Issues – What Should I Look For?

AVA testing should be implemented as a quality control tool for Level A projects of a critical nature that are located in wet-freeze climates. Even though correlations between conventional air-void testing (ASTM C 457) and image analysis techniques are not reliable, the AVA provides the only way to obtain feedback regarding the air-void properties of a fresh concrete sample. Field results can be obtained within one hour of concrete placement.

Comparisons between the AVA and ASTM C 457 test results on the same concrete reveal that the AVA test results are conservative. Thus, a marginal spacing factor measured with the AVA may be adequate in certain cases. Because of this undefined bias, the AVA should not currently be used as a test method for acceptance. Future research and improvements may make this possible. Best practice for AVA use as a quality control tool include monitoring the specific surface and spacing factor test results for trends and changes during production. Materials and construction processes should be monitored closely whenever AVA spacing factor test results exceed 0.0150 in.

Air-Void Analyzer (AVA), continued

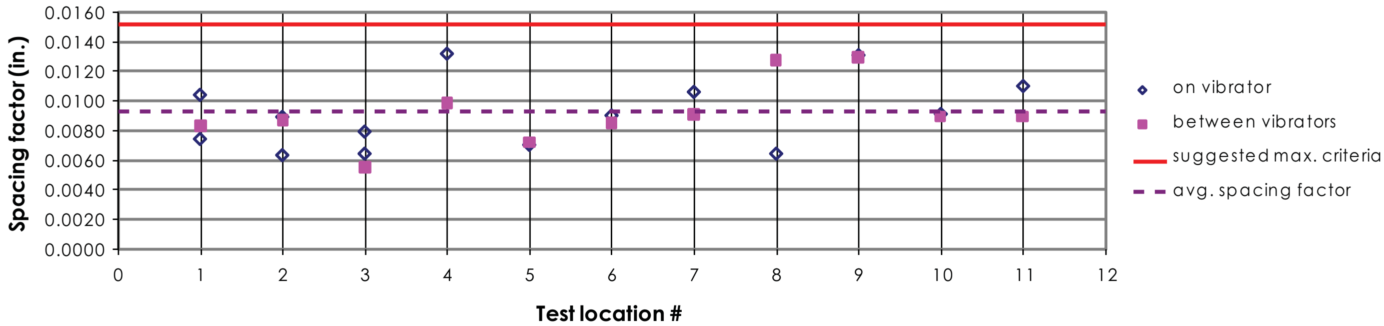


Figure 7.27 Spacing factor results (IA MCO demonstration project)

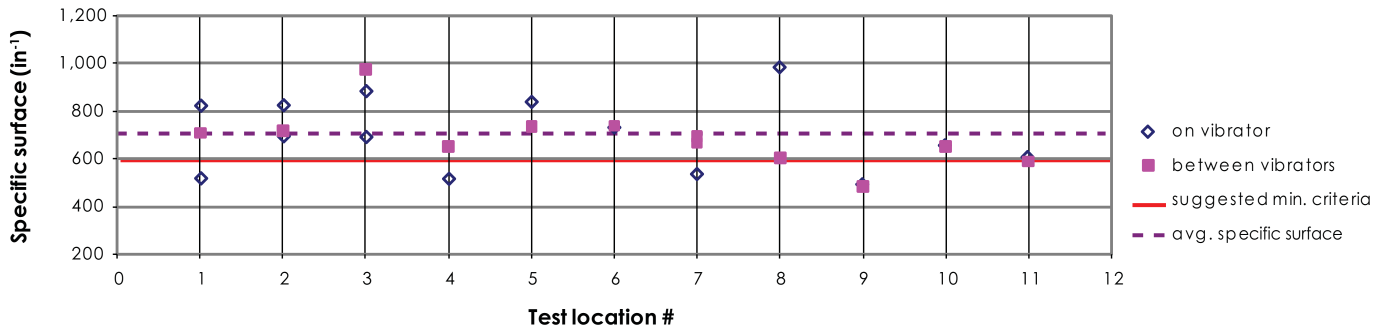


Figure 7.28 Specific surface results (IA MCO demonstration project)

Air Content (Hardened Concrete)

Purpose – Why Do This Test?

Another method of determining the quality of an air-void system in concrete is microscopical analysis of hardened concrete. This method provides information on the total air content, as well as the spacing factor and other parameters.

Principle – What is the Theory?

The air-void structure of concrete can be measured and characterized by examining a section of a core with a microscope. The linear traverse method consists of measuring the air voids as a polished concrete sample travels under a microscope in regularly spaced lines. The length of travel across air voids is compared to the length of travel across paste and aggregate, and the data are used to calculate the air content, spacing factor, and specific surface of the air voids in the concrete sample.

Test Procedure – How is the Test Run?

The manual method is described in ASTM C 457. A core from the slab is sectioned and polished. The apparatus is used to move a core sample under a microscope (or vice versa) in straight lines. The total length traversed and the length traversed across air voids are recorded.

Alternate automated methods use computer hardware and software to analyze an image of a polished concrete sample. These image analysis methods produce similar results for entrained air properties of concrete.

Test Apparatus (figure 7.29)

- Saw for cutting a section of a core.
- Polishing tools for grinding, lapping, and preparing the core section.
- Hardware and software for measuring air voids in the core section.

Generic Automated Test Method – Refer to ASTM C 457 for Comprehensive Guidance or Manufacturer's Recommendations for Specific Image Analysis Techniques

1. Obtain a core from the pavement.
2. Cut a section of the core.
3. Grind, lap, and polish the core section until it is smooth and flat.
4. Cover the polished face of the core section with black ink from a stamp pad.
5. Heat the core to 54°C (130°F) and coat the ink-covered core section with a zinc paste.
6. Allow the core section to cool, and scrape the zinc paste off the surface. The melted zinc paste will remain in the

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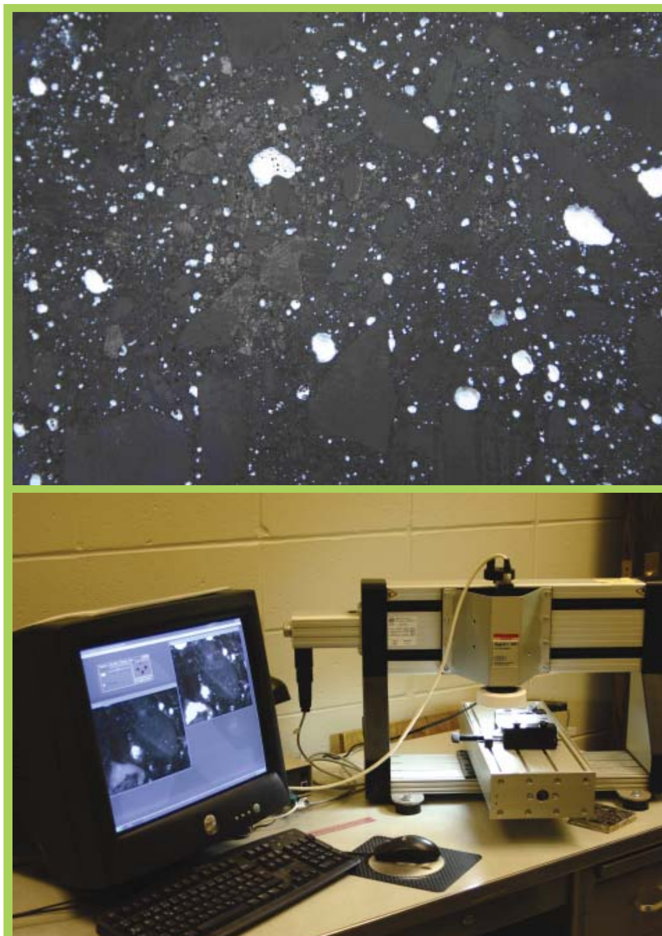


Figure 7.29 Close-up of a concrete core section prepared for testing and rapid-air test equipment

Air Content (Hardened Concrete), continued

air voids of the surface, providing a white contrast to the black ink surface of the core section.

7. Mount the prepared core section in the image analysis apparatus.
8. Start the image analysis apparatus.
9. The image analysis hardware and software automatically traverse the section and record the data.

Output – How Do I Interpret the Results?

The software produces a tabular report showing air content, spacing factor, and specific surface area of the air voids (table 7.2). A digital image of the core section can also be viewed or printed.

The air content is expressed as a percent of volume of the concrete sample.

Spacing factor is the average distance from any point to the nearest air void, or the maximum length measured from the cement paste to the edge of an air void.

Specific surface area is the surface area of the air voids divided by the air voids' volume.

Construction Issues – What Should I Look For?

Spacing factors should be less than 0.2 mm (0.008 in.).

Air-void spacing can be impacted by many factors, ranging from cement and admixture chemistry to mixing time to aggregate grading.

Table 7.2 Example Hardened Air Test Results

Air-void parameter	Chords < 0.0197 inch	Chords < 0.0394 inch	All chords
Number of voids	2683	2752	2770
Percent of total number of voids	96.9	99.4	100
Length of air traversed (in.)	11.01	12.85	14.00
Percent of total length of air traversed	78.7	91.8	100
Air content (%)	11.59	13.52	14.73
Average chord length (in.)	0.0041	0.0047	0.0051
Paste to air ratio	2.07	1.77	1.63
Specific surface (in^{-1})	974.8	856.8	791.6
Void frequency (in^{-1})	28.24	28.97	29.16
Spacing factor (in.)	0.0021	0.0021	0.0021

Rapid Chloride Ion Penetration

Purpose – Why Do This Test?

The ability of concrete to resist the transportation of chlorides is an important factor in its potential durability. If chlorides can be prevented from reaching any steel in the concrete, then the risk of corrosion is reduced.

The test method also provides an indirect measure of the permeability of the concrete, a critical parameter in all durability-related distress mechanisms. The lower the permeability, the longer the concrete will survive chemical and environmental attack.

Principle – What is the Theory?

The permeability of concrete can be indirectly assessed by measuring the electrical conductance of a sample of concrete.

Test Procedure – How is the Test Run?

The test is described in ASTM C 1202. A 2-in. thick section is obtained from a 4-in. diameter pavement core or lab molded cylinder. The core section is completely saturated with water in a vacuum apparatus. Electrical current is passed from one side of the core section to the other side while it is contained within a cell that has a sodium chloride solution on one side of the core and a sodium hydroxide solution on the other side. The electric current is applied and measured for six hours.

Test Apparatus (figure 7.30)

- Vacuum saturation apparatus: Completely saturates the sample.
- Sodium chloride solution.
- Sodium hydroxide solution.
- Sealed cell: Holds the core specimen with each liquid solution on opposite sides of the core section and has electrical leads for connecting a DC electrical source.
- DC power supply: Provides constant DC power to the test specimen.
- Voltmeter: Measures and records volts and amps on both sides of the core specimen.

Test Method – Refer to ASTM C 1202 for Comprehensive Guidance

1. Completely saturate the core section with water.
2. Place the saturated core section in the sealed cell containing the two different sodium solutions on either side of the core section.
3. Connect the power supply and voltmeter.
4. Apply a 60-volt DC current across the cell for six hours.
5. Convert the ampere-seconds curve recorded from the test to coulombs.

Output – How Do I Interpret the Results?

The electrical current is conducted through the concrete by chloride ions that migrate from one side of the core section to the other side. Higher permeability will result in a higher current being carried through the core section.

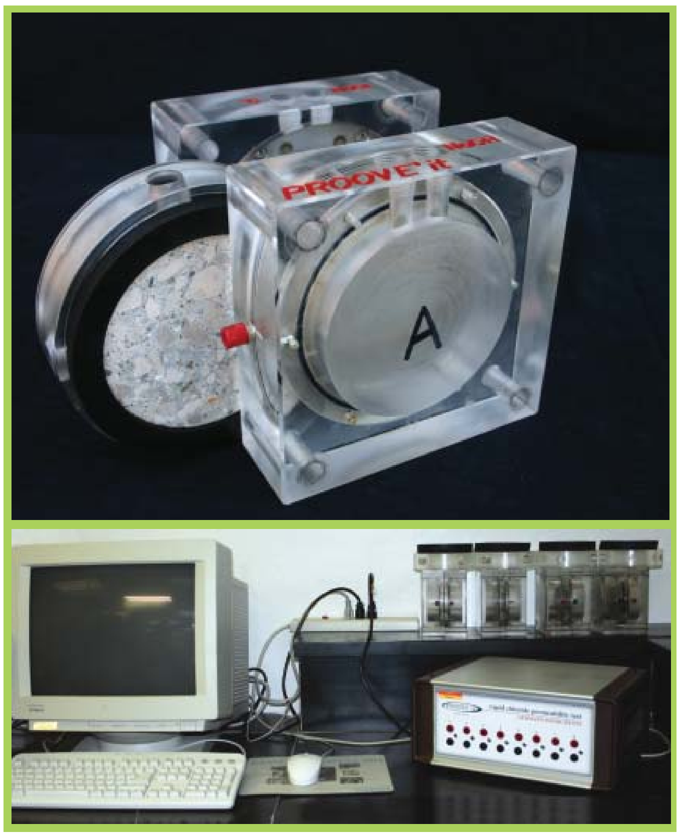


Figure 7.30 RCP test equipment

Rapid Chloride Ion Penetration, continued

The test results are expressed in coulombs, and the permeability of the concrete is classified according to table 7.3. Note that differences within the range of 1,300 to 1,800 coulombs are not significant.

Table 7.3 Relationship Between Coulombs and Permeability

Coulombs	Permeability
Greater than 4,000	High
2,000 to 4,000	Moderate
1,000 to 2,000	Low
100 to 1,000	Very low
Less than 100	Negligible

Construction Issues – What Should I Look For?

Mixture design issues that can influence permeability include the following:

- Lower water-cementitious materials ratio will lead to lower conductivity.
- Use of fly ash; ground, granulated blast-furnace slag; and silica fume will generally reduce conductivity.

Paving process inputs that influence permeability include the following:

- Improved consolidation will reduce conductivity.
- Premature final finishing when excessive bleed water is present will increase surface permeability.
- Proper curing will reduce conductivity.

Permeable Voids (Boil Test)

Purpose – Why Do This Test?

Permeability of the concrete in a portland cement concrete pavement is a major factor for long-term durability. Pavements with low permeability resist penetration of moisture into the concrete matrix, leading to improved freeze-thaw resistance and improved resistance to damage from ASR. Compared to other test methods for permeability, the boil test is simple to perform and does not require any specialized equipment. Although limited, studies by the Kansas Department of Transportation show a strong correlation between boil test results and the rapid chloride penetration test method (ASTM C 1202).

Principle – What is the Theory?

Permeability is defined as the ease with which fluids can penetrate concrete (*12*). Permeability can be lowered by reducing the number of connected pores within the paste system of a mixture. This can be accomplished through a lower w/cm, improved curing, and the use of SCMs. The boil test measures the volume of permeable pore space in a concrete mixture.

Test Procedure – How is the Test Run?

ASTM C 642, the *Standard Test Method for Density, Absorption, and Voids in Hardened Concrete*, estimates the volume of permeable pore space in a hardened concrete specimen by determining the hardened concrete's density in different states (oven dry, saturated, saturated-boiled).

Test Apparatus (figure 7.31)

- Scale accurate to 0.025% of the mass of the specimen.
- Container for immersing the samples.
- Wire for suspending the sample in water.
- Hot plate.

Test Method – Refer to ASTM C 642 for Comprehensive Guidance

1. Section cores or cylinders in accordance with the specimen volume required by C 642.
2. Determine the mass of the concrete samples.
3. Oven dry the samples and determine their mass.
4. Saturate the samples and determine their mass.
5. Boil the samples for 5 hours.
6. Remove the samples from the boiling container and cool the samples for at least 14 hours.
7. Dry the surface of the samples and determine their mass after immersion and boiling.
8. Suspend the sample in water by a wire and determine the

continued on next page

Figure 7.31 Boil test equipment

Permeable Voids (Boil Test), continued

apparent mass of the sample in water after immersion and boiling.

9. Calculate the volume of permeable pore space.

Output – How Do I Interpret the Results?

For portland cement concrete pavements, a volume of permeable pores less than or equal to 12% is desirable for long-term durability. The worksheet below summarizes example test results for tests performed on a 4-in. lab molded cylinder.

Construction Issues – What Should I Look For?

Permeability of a pavement, or its resistance to the infiltration of harmful fluids, can be adversely affected by segregation of the mixture during paving operations. Both inadequate consolidation and over-vibration can leave a concrete pavement vulnerable.

The following mixture design issues can influence permeability:

- Lower water-cementitious materials ratio will lead to a reduction in permeable voids.
- Use of fly ash; ground, granulated blast-furnace slag; and silica fume will generally reduce permeable voids.

The following paving process inputs influence permeability:

- Improved consolidation will reduce permeable pores.
- Premature final finishing when excessive bleed water is present will increase surface permeability.
- Proper curing will reduce permeable pores.

Table 7.4 Example Permeable Voids Lab Worksheet

	Description of test activity	Test data (average of 9 specimens) (g)
	Determine the mass of each 2-in. cylinder section	952.2
	Place the specimens in a 210ºF to 230ºF oven for 24 hours	n/a
	Remove the specimens from the oven and allow them to cool in dry air to a temperature of 68ºF to 77ºF	n/a
	Determine the mass of each 2-in. cylinder section	926.8
	Place the specimens in a 210ºF to 230ºF oven for 24 hours	n/a
	Remove the specimens from the oven and allow them to cool in dry air to a temperature of 68ºF to 77ºF	n/a
A	Determine the mass of each 2-in. cylinder section (A-mass of oven dried sample in air)	924.7
	Place the specimens in a 70ºF water bath for 48 hours	n/a
	Determine the mass of each 2-in. cylinder section	958.7
	Place the specimens in a 70ºF water bath for 24 hours	n/a
	Remove the specimens from the water bath, towel off surface moisture, and determine the mass of each specimen	963.8
	Place the specimens in a 70ºF water bath for 24 hours	n/a
B	Remove the specimens from the water bath, towel off surface moisture, and determine the mass of each specimen; if the change in mass from the previous determination is less than 0.5%, record this mass as B (B-mass of surface dry sample in air after immersion)	964.4
	Boil the specimens for 5 hours	n/a
	Remove the specimens from the boiling vessel and allow to cool for at least 14 hours until they are between 68ºF and 77ºF	n/a
C	Towel off surface moisture and determine the mass of each specimen (C-mass of surface dry sample in air after immersion and boiling)	966.8
D	Suspend the specimen by a wire and determine the apparent mass in water (D-apparent mass of sample in water after immersion and boiling)	546.6
	Bulk density, dry (Mg/m^3)	2.20
	Apparent density (Mg/m^3)	2.45
	Volume of permeable pore space (voids)	10.0%

Coefficient of Thermal Expansion

Purpose – Why Do This Test?

The expansion and contraction of concrete due to temperature changes can impact the durability of joints and the risk of cracking in concrete pavements.

Principle – What is the Theory?

Concrete expands and contracts as its temperature changes. When a saturated cylinder of concrete is exposed to changing temperature conditions, its change in length can be measured by a linear variable differential transformer (LVDT).

Test Procedure – How is the Test Run?

A saturated concrete cylinder or core is subjected to temperature changes from 10°C to 50°C (50°F to 120°F). The change in length of the cylinder is measured and recorded at different temperatures (AASHTO TP 60).

Test Apparatus (figure 7.32)

- Caliper to measure the initial length of the core specimen.
- Water tank: Maintains saturation of the sample and varies the temperature of the water from 10°C to 50°C (50°F to 120°F).
- Support frame: Holds the core specimen and the LVDT.
- Thermometer: Measures the water temperature.
- LVDT: Measures the length change of the specimen (resolution = 0.00025 mm [0.00001 in.]).

Test Method – Refer to AASHTO TP 60 for Comprehensive Guidance

1. Soak a 4-in. diameter core in water for a minimum of 48 hours.
2. Measure the length of the saturated core using calipers.
3. Place the core in the support frame that is submerged in the water tank.
4. Adjust the temperature of the water tank to 10°C (50°F).
5. Maintain the temperature until three consecutive LVDT readings taken every 10 minutes change by less than 0.00025 mm (0.00001 in.). Record the initial LVDT and temperature values.
6. Set the temperature of the water tank to 50°C (120°F).
7. Maintain the temperature until three consecutive LVDT readings taken every 10 minutes change by less than 0.00025 mm (0.00001 in.). Record the second LVDT and temperature values.
8. Adjust the temperature of the water tank to 10°C (50°F).
9. Maintain the temperature until three consecutive LVDT readings taken every 10 minutes change by less than 0.00025 mm (0.00001 in.). Record the final LVDT and temperature values.

Output – How Do I Interpret the Results?

The coefficient of thermal expansion (CTE) is a function of length change due to a change in temperature.

CTE = (measured length change / specimen length) / measured temperature change

The CTE reported is the average of two test values.

The CTE is reported in microstrain/°F. Typical values for concrete can range from $4(10^{-6})$°F to $7(10^{-6})$°F. CTE is most affected by aggregate type. Concrete produced with siliceous aggregates has a higher CTE than concrete produced with limestone aggregates.

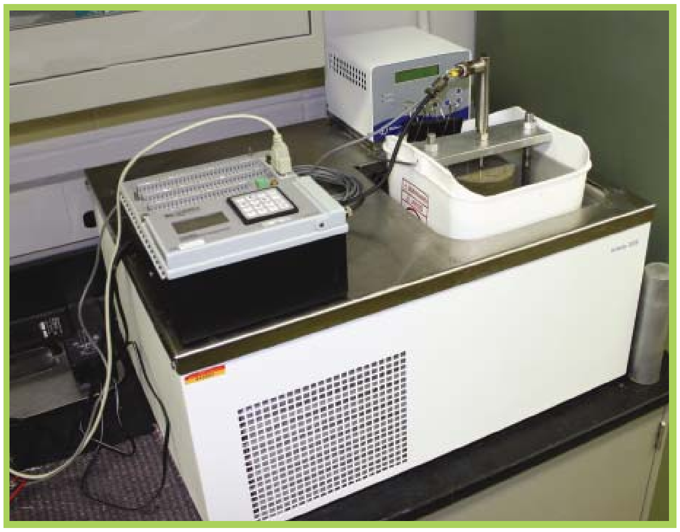


Figure 7.32 CTE testing equipment

Coefficient of Thermal Expansion, continued

Construction Issues – What Should I Look For?

Thermal expansion/contraction is a factor that should be considered in the design phase. During construction, the following items should be monitored for conformity with the plans to avoid the possible adverse effects of thermal expansion and contraction:

- Joint layout and spacing.
- Joint width.

HIPERPAV

Purpose – Why Do This Test?

HIPERPAV is a software tool that predicts the strength of concrete pavement as well as the internal stresses that a concrete pavement may experience in the first 72 hours of its life. When stresses exceed the strength, cracks will occur. HIPERPAV does not prevent cracks, but it provides the user with information about the likely risk of early cracking in the pavement, allowing preventative actions to be taken. Using HIPERPAV is analogous to driving at night with headlights. We are able to see potential dangers sooner than if we were driving by the light of the night sky.

Principle – What is the Theory?

HIPERPAV simulates the strength gain and internal stresses of a concrete pavement through a computer model that considers the following factors:

- Materials.
- Mixture proportions.
- Subbase and subgrade support.
- Subbase friction.
- Subbase temperature.
- Concrete temperature.
- Curing procedures.
- Sawcutting procedures.
- Weather conditions (temperature, humidity, wind, and cloud cover).
- Slab design (thickness, width, length, steel, etc.).
- Time.

Test Procedure – How is the Test Run?

Project-specific inputs are entered into the software.

Test Apparatus

- Personal computer.
- HIPERPAV software.

Test Method – Refer to HIPERPAV help files for user documentation

Output – How Do I Interpret the Results?

The graphical output of HIPERPAV is very easy to understand. When stress approaches or exceeds strength, the probability of early cracking is increased (figure 7.33).

Construction Issues – What Should I Look For?

Many factors can contribute to early cracking. From a construction perspective, placement temperatures, sawcutting, and curing are the processes that can be most easily adjusted to counteract cracking potential. Working in the cooler part of the day, and/or controlling materials temperatures will help reduce stresses. Early and thorough curing will reduce the stresses within the pavement as well as benefit permeability properties. Sawcutting should be performed as soon as is practical (avoid excess raveling) to relieve stresses within the pavement.

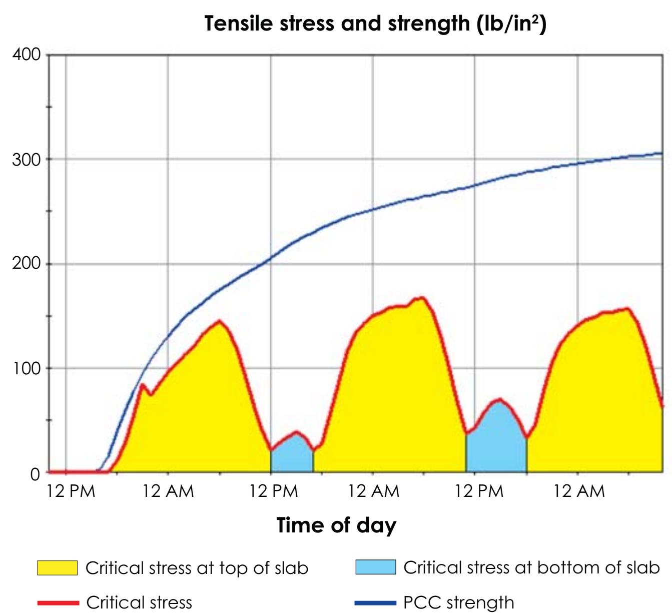


Figure 7.33 Example HIPERPAV output

Concrete Maturity

Purpose – Why Do This Test?

Measuring the maturity of concrete pavements is a nondestructive test method for estimating in-place concrete strength. It is quickly becoming standard practice. Maturity may be used as a criterion for opening a pavement to traffic and for quality control purposes.

Principle – What is the Theory?

The degree of hydration (leading to strength) of a given mixture design is a function of time and temperature. Correlation curves can be developed for a mixture design that estimate concrete strength based on its maturity. The in-place strength of a pavement can be estimated by monitoring the temperature of the slab over time and using the correlation curve that was developed for that mixture.

A maturity curve (strength estimate based on maturity) is only applicable to a specific mixture design.

Test Procedure – How is the Test Run?

The maturity curve is developed by casting, curing, and testing standard strength specimens while measuring and recording the temperature of those specimens over time (ASTM C 1074).

Maturity testing is performed by inserting a temperature sensor in the slab and then downloading the temperature data to a computer that compares the slab temperature data to the maturity curve.

Test Apparatus (figure 7.34)

- Beams, cylinders, and hydraulic loading frame for strength testing to develop the maturity curve.
- Sensors to measure the temperature of the test specimens and of the pavement.
- Computer software to analyze strength, temperature, and time data for developing the maturity curve and estimating the pavement strength.

Test Method – Refer to ASTM C 1074 for Comprehensive Guidance

- Maturity Curve:
    - Cast 13 strength specimens from materials that are mixed at the project site.
    - Completely embed a temperature sensor in one of the specimens. This specimen is used only for recording the temperature over time and will not be broken.
    - Cure all the strength specimens in the same location.
    - Test the strength of the specimens at one, three, five, and seven days, or at four intervals that span the pavement opening strength. Break and average three specimens at each age.
    - Download and record the time/temperature factor (TTF) for each set of strength specimens when they are broken.
    - Plot the strength and TTF data for the strength specimens on a graph, with log TTF on the x-axis and concrete strength on the y-axis.
    - Fit a smooth curve through the plotted points.
- In-Place Maturity (estimated strength):
    - Completely embed a temperature sensor in the pavement.
    - Download the TTF from the sensor at any time.
    - Estimate the strength of the concrete pavement using computer software and the appropriate maturity curve.

Figure 7.34 Measuring in-place maturity

Concrete Maturity, continued

Output – How Do I Interpret the Results?

Commercially available maturity systems normally include software that provides the estimated concrete strength based on the maturity of the concrete (TTF). A sample maturity curve is shown in figure 7.35 and a sample in-place maturity graph is shown in figure 7.36.

Specimen #	Date broken	Time broken	Age at break (h)	TTF at time of break (˚C-h)	Specimen temp. at time of break (˚C)	Flexural strength (lb/in²)
1	30-May-08	4:00 PM	30.50	820	29.0	315
2	30-May-08	4:10 PM	30.67	826	29.0	330
3	30-May-08	4:20 PM	30.83	832	29.0	300
4	31-May-08	4:00 PM	54.50	980	26.3	390
5	31-May-08	4:10 PM	54.67	984	26.3	395
6	31-May-08	4:20 PM	54.83	987	26.3	380
7	2-Jun-08	7:30 AM	94.00	1,820	25.2	505
8	2-Jun-08	7:40 AM	94.17	1,823	25.2	510
9	2-Jun-08	7:50 AM	94.33	1,826	25.2	520
10	3-Jun-08	8:45 AM	119.25	2,229	23.4	580
11	3-Jun-08	8:55 AM	119.42	2,233	23.4	585
12	3-Jun-08	9:00 AM	119.50	2,236	23.4	575

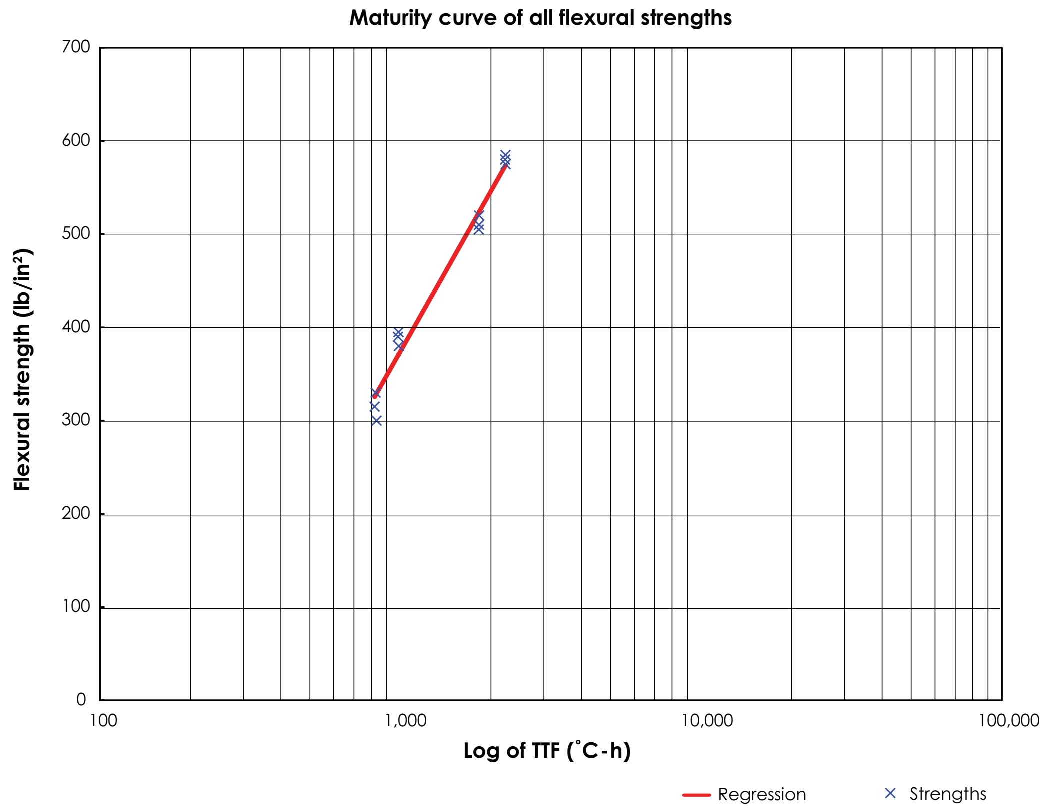


Figure 7.35 Maturity curve

Concrete Maturity, continued

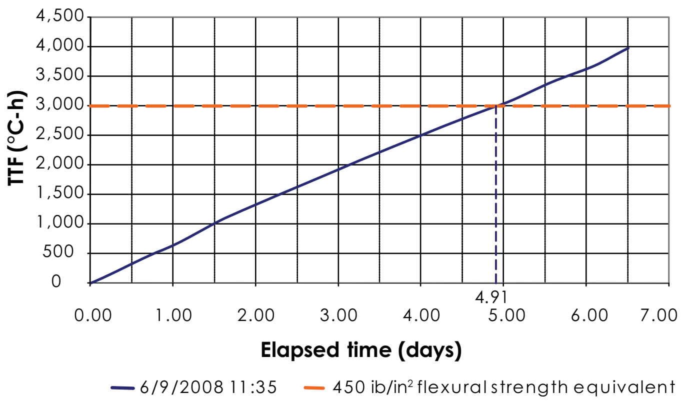


Figure 7.36 In-place pavement maturity

Construction Issues – What Should I Look For?

Maturity testing is a way of nondestructively estimating the early-age strength of a concrete pavement.

It cannot be overemphasized that the maturity vs. strength relationship is mixture-specific. Maturity estimates of in-place strength are valid only if the pavement being tested is constructed using the same mixture proportions that were used to develop the maturity curve.

Changes in the water-cementitious materials ratio, air content, grading, aggregate proportions, admixtures, etc., may introduce some inaccuracy in the estimate of the strength of the pavement.

Material Incompatibilities

Purpose – Why Do This Test?

Portland cement concrete mixtures for paving are complex systems. There have been many examples of premature pavement distresses caused by a material incompatibility issue (*20*). If no effort is made to identify potential material incompatibilities in a laboratory environment, then field problems may lead to project delays and/or modified construction methods that only temporarily mask the problem.

Laboratory analysis of mixtures for potential incompatibilities consists of a testing protocol that involves preparing paste, mortar, and/or concrete containing different combinations of materials and considers the effect of temperature on potential incompatibilities.

Principle – What is the Theory?

Research conducted by the CTL Group for the FHWA provides the background for utilizing an incompatibility testing protocol. *Identifying Incompatible Combinations of Concrete Materials: Volume I – Final Report* states the following:

"Lack of compatibility among various cementitious materials and admixtures can lead to early stiffening, which could account for many other problems. The tendency to early stiffening may be attributed not only to the individual cementitious materials, but also to interactions among the various cementitious materials and the chemical admixtures. Early stiffening may be caused by excessive calcium sulfate in the form of hemihydrate (plaster) in the cement (false set) or the uncontrolled early hydration reactions of the tricalcium aluminate (C_3A) (flash set). False set may be overcome by continued mixing of the concrete. Early stiffening is not reversible and leads to loss of workability. When concrete is hard to place, it is likely water will be added, which reduces both strength and durability and increases the potential for shrinkage and cracking. The addition of some admixtures improves workability without these negative effects, but the admixtures also add considerably to the cost of the concrete, and they may retard setting.

Early stiffening depends on several factors, including C_3A content and reactivity; alkali content; and the form, content, and distribution of sulfates in the cement. C_3A hydrating in the presence of sulfate ions forms ettringite on its surface. The ettringite acts as a barrier, further limiting reactivity. If supplementary cementing materials, particularly Class C fly ash, contain aluminate phases, and the sulfate is not well distributed in the cement paste, the concrete may experience early stiffening. A balance among the ions in plastic concrete is necessary to prevent early stiffening. Some chemical admixtures, particularly Type A water reducers, may disturb this balance.

Early stiffening can be deleterious to pavement performance. If the concrete cannot be thoroughly consolidated, loss of strength and durability can result, as well as early development of cracking and pavement failures.(2) If extraordinary consolidation efforts are used to achieve the required concrete density, the entrained air-void system may be altered, leading to decreased freeze-thaw durability.(3,4)

Cracking in concrete can also be caused by a host of factors. Shrinkage can occur in fresh or hardened concrete. The major cause of plastic shrinkage cracking is thought to be the tensile stress developed as water evaporates from the surface of the concrete, leaving the capillaries partially filled and creating a disjoining pressure caused by surface tension effects. The risk of cracking may be higher in concretes that exhibit early stiffening because the mix does not remain fluid long enough to allow a layer of bleed water to remain on the surface. While bleeding is generally thought of as detrimental to concrete, bleeding may also have some benefit with relation to the potential for plastic cracking: drying of the surface cannot occur if it is covered with bleed water. Precautions to prevent plastic shrinkage cracking include (1) strict adherence to specifications regarding evaporation rates and cessation of concrete placement if relative humidity is low and temperatures and wind speeds are high, (2) use of fog sprays, and (3) use of evaporation retarding admixtures during and immediately after finishing.

Cracking can also occur because of autogenous shrinkage, drying shrinkage, thermal effects, and external loads. Cracking occurs when and where the maximum principal tensile stress exceeds the tensile strength of the concrete.

A number of paving projects have experienced problems related to use of synthetic air-entraining agents resulting in accumulations (coalescence) of air voids around the aggregate particles. In addition to this problem, the quality of the air-void system in the hardened concrete continues to be a matter of concern. The spacing factor and specific surface are the main parameters of the concrete air-void system that

Material Incompatibilities, continued

indicate the ability of the concrete to resist the damaging effects of frost. In recent years, it has been observed that marginal air-void systems may result from incompatibility between certain water reducers and air-entraining agents." (*20*)

Note: A complete incompatibility testing protocol can be found in *Identifying Incompatible Combinations of Concrete Materials: Volume II – Test Protocol*. Please refer to this publication for test procedures/methods, test apparatus, and guidance on interpreting test data.

Construction Issues – What Should I Look For?

The following construction issues may be caused by material incompatibilities:

- Early stiffening.
- Flash set.
- False set.
- Retarded strength gain.
- Unstable air entrainment.
- Low strength due to coalescence of air voids around aggregate particles.

The most common adaptations to counteract these material incompatibilities are as follows:

- Reduce the dosage of supplementary cementitious materials (SCMs).
- Adjust the temperature of the concrete mixture.
- Delay the introduction of water-reducing admixtures in the batching sequence.

References

1. National Concrete Pavement Technology Center. Material and Construction Optimization for Prevention of Premature Pavement Distress in Portland Cement Concrete Pavements. http://www.cptechcenter.org/mco/ (accessed January 16, 2007).
2. Larson, S. 2006. Goals and Accomplishments. Presentation at the October 24, 2006 MCO Technical Advisory Committee Meeting, Chicago, IL.
3. Hadley, W.O. 1994. *SHRP-LTPP General Pavement Studies: Five-Year Report.* Strategic Highway Research Program National Research Council: 8.
4. Taylor, P.C., V.C. Johansen, L.A. Graf, R.L. Kozikowski, J.Z. Zemajtis and C.F. Ferraris. 2006. *Identifying Incompatible Combinations of Concrete Materials: Volume II – Test Protocol.* Report HRT-06-080. Washington, D.C.: Federal Highway Administration, U.S. Department of Transportation.
5. Hallin, J.P., et al. 2004. *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures.* Washington, D.C.: National Cooperative Highway Research Program.
6. Khanum, T., H. Mustaque, S.A. Romanoschi, and R. Barezinsky. 2005. Concrete Pavement Design in Kansas Following the Mechanistic-Empirical Pavement Design Guide. *Proceedings of the 2005 Mid-Continent Transportation Research Symposium.* Ames, Iowa: Iowa State University.
7. Powers, T. C. 1932. Studies of Workability of Concrete. *Journal of the American Concrete Institute* 28: 419.
8. Steffes, R. and S. Tymkowicz. 2002. Vibrator Monitors: Concrete Paving Technology Generates Buzz. *Transportation Research Board TR News* 223: 19.
9. Snyder, K.A. 1998. A Numerical Test of Air Void Spacing Equations. Advanced Cement Based Materials 8: 28-44. http://ciks.cbt.nist.gov/garboczi/spacing/node10.html (accessed February 13, 2007).
10. Taylor, P.C., S. Kosmatka, G. Voigt, et al. 2006. *Integrated Materials and Construction Practices for Concrete Pavement: A State-of-the-Practice Manual.* Report FHWA HIF-07-004. Washington, D.C.: Federal Highway Administration, U.S. Department of Transportation.
11. Mokarem, D.W., R. Meyerson and R. Weyers. 2003. *Development of Concrete Shrinkage Performance Specifications.* Final Contract Report. Charlotesville, VA: Virginia Transportation Research Council.
12. Folliard, K.J., M. Thomas, B. Fournier, K. Kurtis and J. Ideker. 2006. *Interim Recommendations for the Use of Lithium to Mitigate or Prevent Alkali-Silica Reaction (ASR).* Report FHWA-HRT-06-073. Washington, D.C.: Federal Highway Administration, U.S. Department of Transportation.
13. Stark, D.C. 1976. *Living with Marginal Aggregates.* STP 597. West Conchohoken, PA: American Society for Testing Materials.
14. Skymark Corporation. Control Charts. http://www.skymark.com/resources/tools/control_charts.asp (accessed August 23, 2007).
15. Day, K.W. 1999. *Concrete Mix Design, Quality Control and Specification.* 2nd ed. New York, NY: Routledge.
16. Trost, S.M. 2003. *Evaluation of Percent-Within-Limits-Specifications.* Final Report. Oklahoma City, OK: Oklahoma Department of Transportation.
17. AASHTO. 1996. *Implementation Manual for Quality Assurance.* Washington, DC: American Association of State Highway and Transportation Officials.
18. Wheeler, D. 1996. SPC Toolkit: When Do I Recalculate My Limits? *Quality Digest.* http://www.qualitydigest.com/may/spctool.html (accessed August 23, 2007).
19. Skymark Corporation. Responding to Variation. http://www.skymark.com/resources/responding_to_variation.asp (accessed August 29, 2007).
20. Taylor, P.C., V.C. Johansen, L.A. Graf, R.L. Kozikowski, J.Z. Zemajtis and C.F. Ferraris. 2006. *Identifying Incompatible Combinations of Concrete Materials: Volume I – Final Report.* Report HRT-06-079. Washington, D.C.: Federal Highway Administration, U.S. Department of Transportation.

Appendices

Appendix A: Example Field Sampling Worksheets

Material and Construction Optimization for the Prevention of Premature Pavement Distress in Portland Cement Concrete Pavements – TPF-5(066)

Sample Information: **Test Group A Field Test Sheet**

Project: OKDOT Demo. Project I-35, Love Co.

Date: 4-Apr-06 Time: 3:00 PM

Type of Paving: mainline / shoulder / ramp or handwork Direction of Paving: northbound / southbound eastbound or westbound

Sta: 85+60 Latitude: 33 43.6944 Longitude: 97 09.5217

Mix ID: Class A - M/L #2 Truck ID: #34

Comments: Center lane - samples taken from east edge

Environmental Conditions:

Dew Point: 61.0 Relative Humidity: 53%

Wind Speed: 7.0 Ambient Temp.: 80.0

Concrete Properties:

Concrete Temp. (probe): 78.8 Base Temp. (surface): 109.8

Base/Soil Temp. (internal): 71.4 Slump (in.): 1.75

Air Content (ahd.): 5.7% 0.25 ft^3 Concrete Mass (ahd.): 36.2

Unit Weight (lb/ft^3): 144.7

Flow Table Caliper Readings (25 drops in 15 sec.)

#1 22.00 #3 22.00

#2 23.00 #4 22.00

Total: 89.0%

AVA Sample Time: 3:24 PM

#1	on or between	24	inches from edge
#2	on or between	15	inches from edge
#3	on or between	15	inches from edge

☑ slump

☑ flow

☑ unit weight ahead of paver

☑ pressure air ahead of paver

☑ ava #1, #2 & #3

☑ microwave w/c ratio sample obtained for testing at lab trailer

Material and Construction Optimization for the Prevention of Premature Pavement Distress in Portland Cement Concrete Pavements – TPF-5(066)

Sample Information:

Test Group B Field Test Sheet

Project: OKDOT Demo. Project I-35, Love Co.

Date: 5-Apr-06

Time: 8:15 AM

Type of Paving: mainline / shoulder / ramp or handwork

Direction of Paving: northbound / southbound eastbound or westbound

Sta: 78+40

Latitude: 33 43.2400

Longitude: 97 09.4914

Mix ID: Class A - M/L #2

Truck ID: n/a

Comments: Concrete delivered from the middle of batch #25 via front end loader

Environmental Conditions:

Dew Point: 74.0

Relative Humidity: 62%

Wind Speed: 3.0

Ambient Temp.: 64.0

Concrete Properties:

Concrete Temp. (probe): 70.4

Air Content (ahd.): 6.4%

Slump (in.): 2.25

Flow Table Caliper Readings (25 drops in 15 sec.)

#1	22.00	#3	22.00
#2	23.00	#4	22.00
		Total:	89.0%

0.25 ft^3 Concrete Mass (ahd.): 35.8

Unit Weight (lb/ft^3): 143.2

Data Logger Start Times:

Flex. Maturity Logger: 9:00 AM

IQ Drum (6" x 12"): 8:20 AM

Comp. Maturity Logger: 8:45 AM

IQ Drum (mortar): 8:30 AM

First Penetration for Set Time (sample time + 3 hours): 11:30 AM

☑ slump

☑ pressure air

☑ iq drums (mix & mortar)

☑ flow

☑ set time (penetration resistance)

☑ maturity (compressive and fexural)

☑ unit weight

☑ microwave water content

Material and Construction Optimization for the Prevention of Premature Pavement Distress in Portland Cement Concrete Pavements – TPF-5(066)

Sample Information: **Test Group C Field Test Sheet**

Project: OKDOT Demo. Project I-35, Love Co.

Date: 5-Apr-06 Time: 1:30 PM

Portland Cement Sample Temp.: 114.4 Fly Ash Sample Temp.: 82.8

GGBFS Sample Temp.: n/a

Comments: Sampled cement from truck (ticket #9904551)

Sampled fly ash from bulk storage - all fly ash in the pig was delivered on 04APR2006

Mix Time Observations:

Batch #1 (sec.) 145

Batch #2 (sec.) 133 Average Mix Time (sec.)(avg. cycle time - 35 sec.): 104

Batch #3 (sec.) 138

☑ cement sample temp. ☑ mix time observations (3) and average

☑ fly ash sample temp. ☑ cementitious heat generation (coffee cup) ☐ false set (when necessary)

☑ ggbfs sample temp. ☑ combined gradation ☑ HIPERPAV

Appendix B: Sample HIPERPAV Forecast Data

Even though HIPERPAV includes geographical climatic data for use as default values, actual weather forecast data are available and should be used whenever possible. Used correctly, HIPERPAV is a tool that can help quantify the risk of early-age cracking in portland cement concrete pavements. HIPERPAV requires four environmental inputs: ambient temperature, wind speed, humidity, and cloud cover. Early-age concrete behavior is highly influenced by these environmental factors.

To demonstrate how environmental factors affect the potential for early-age cracking, consider the following example:

- A contractor is paving on a project near Edmond, Oklahoma, on a late summer day. A summary of the typical section, mixture proportions, and concrete properties is shown in table B.1.
- Figures B.1 and B.2 show both the HIPERPAV default environmental inputs and forecast weather data obtained from the National Oceanic and Atmospheric Administration (NOAA) website for the Edmond, Oklahoma area. Note that even though both data sets have similar temperature profiles, the forecast data are distinctly different for cloud cover, humidity, and wind velocity—especially over the first 30 hours.
- How much will the HIPERPAV predictions be affected by the two different sets of environmental data? Figure B.3 shows the strength and stress profiles predicted by HIPERPAV for both data sets when the no-sawing option is enabled. HIPERPAV predicts that the stress will exceed the strength three hours earlier for the analysis that is based on the forecast environmental conditions. This three-hour difference could be critical, depending on when sawcutting operations actually begin and how quickly they progress. Using forecast data will help quantify the risk of early-age cracking more accurately than HIPERPAV default environmental inputs.

Table B.1 Typical HIPERPAV Inputs for Example Paving Project

Item	Value
Pavement thickness	12 in.
Slab width	14 ft
Transverse joint spacing	15 ft
Dowel bar diameter	1.50 in.
Subgrade k-value	200 lb/in²/in.
Cement stabilized subbase thickness	4 in.
Cement stabilized subbase modulus	100,000 lb/in²
Type I portland cement	451 lb/yd³
Class C fly ash	113 lb/yd³
Limestone coarse aggregate	1824 lb/yd³
Natural fine aggregate	1255 lb/yd³
Water-cementitious material ratio	0.43
Average 28-day splitting tensile strength	470 lb/in²
Maturity relationship	Tensile strength =0.098(x°F•hr)+80.57

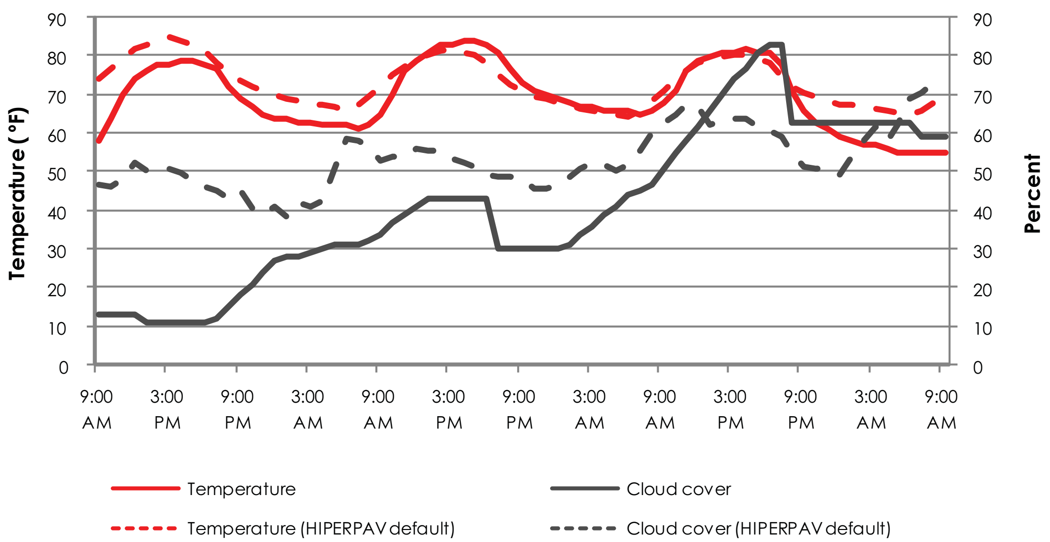


Figure B.1 Temperature and cloud cover (HIPERPAV default and forecast)

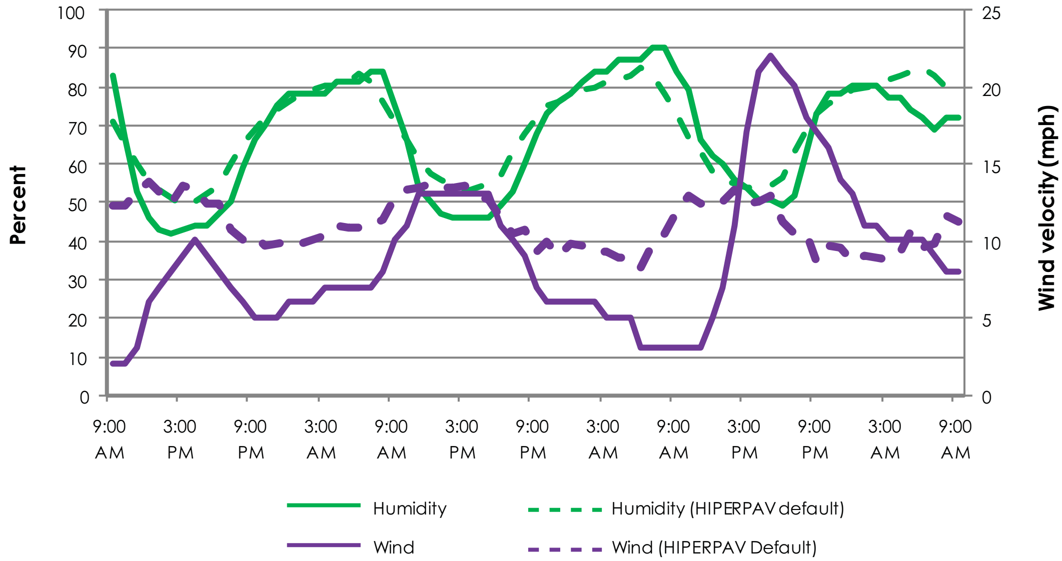


Figure B.2 Humidity and wind (HIPERPAV default and forecast)

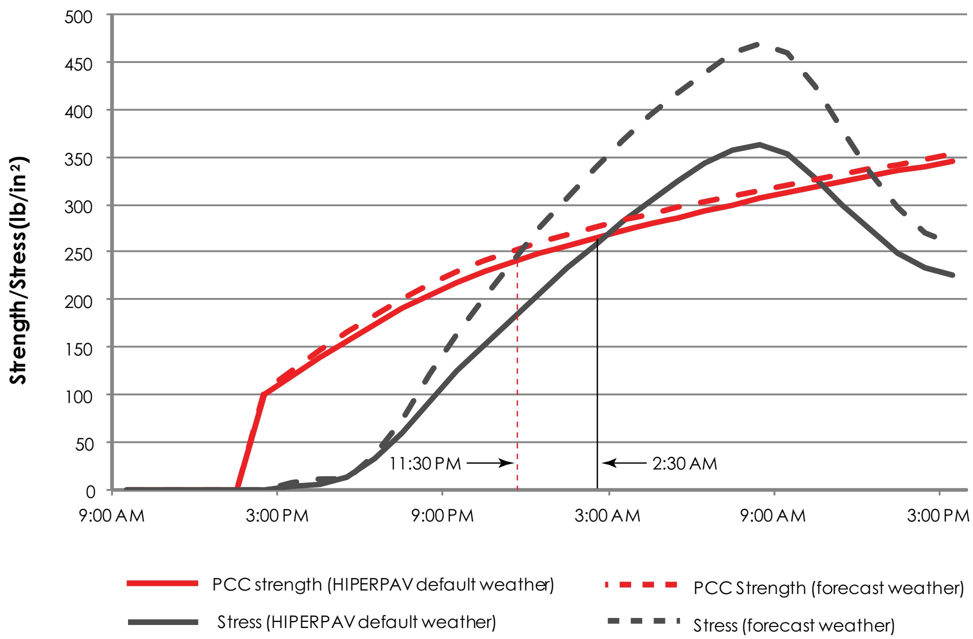
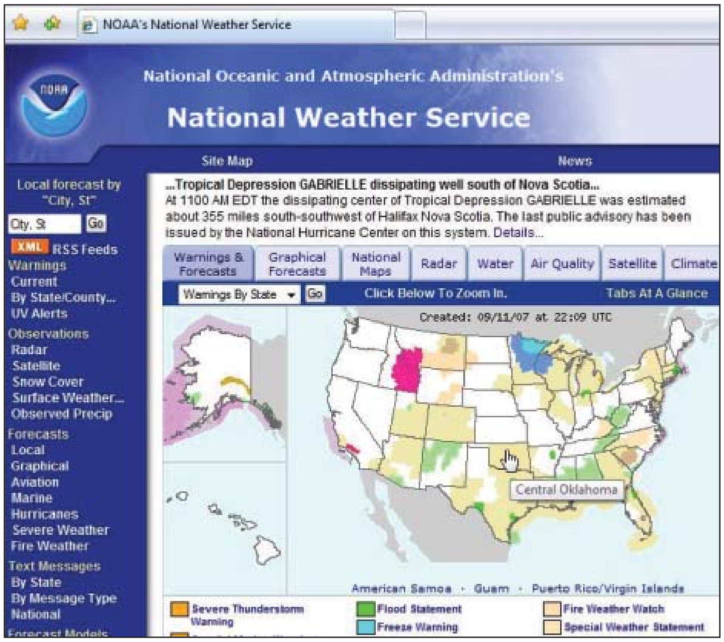


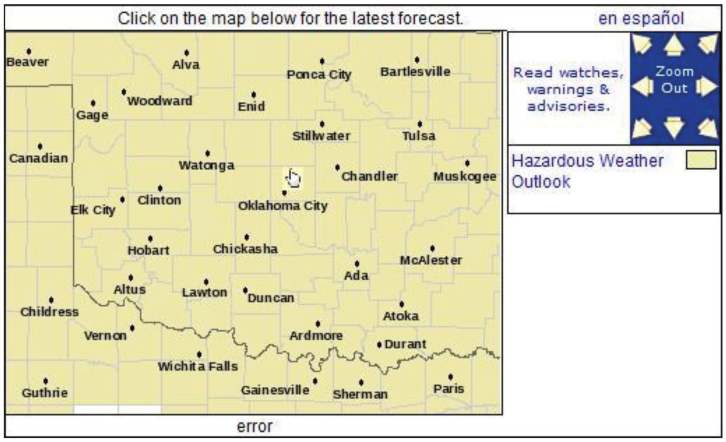
Figure B.3 HIPERPAV stress and strength profile predictions (default and forecast weather)

Fortunately, NOAA provides hourly weather forecast data that can be used for the HIPERPAV environmental inputs. The following outline provides a step-by-step procedure for accessing the NOAA data and copying these data into the HIPERPAV software.

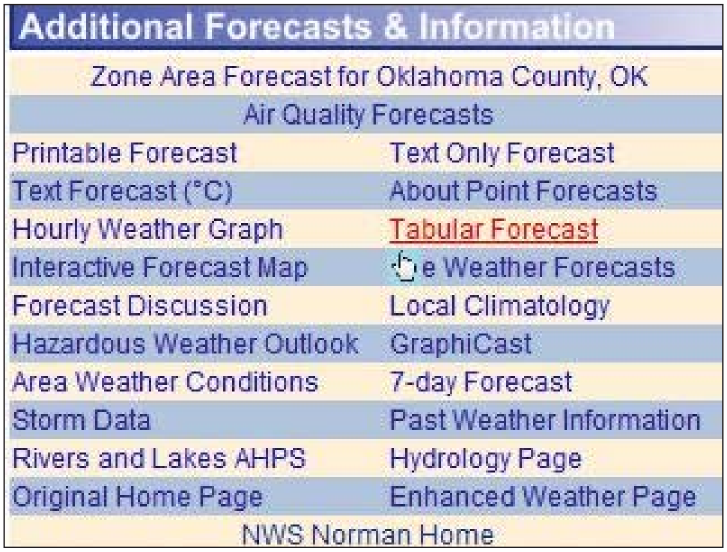
1. Go to http://www.weather.gov and click on the map in the area of the project that you are working on (example is central Oklahoma) or enter the zip code, click "go," and proceed to Step #3.



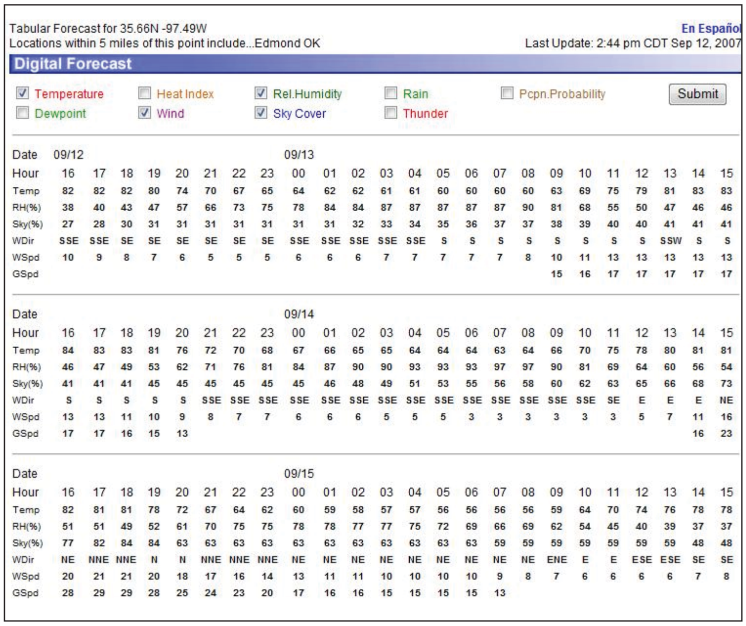
2. From the next screen, you can click on a smaller-scale map to better define the area for which you want to obtain forecast data.



3. At the bottom right of the next page, click on "Tabular Forecast."



4. On the next page, deselect all of the forecast options except for temperature, relative humidity, wind, and sky cover. Then click on submit and the page will reload with the next 72 hours of forecast data for temperature, relative humidity, wind and sky cover.



Tabular Forecast for 35.66N -97.49W
Locations within 5 miles of this point include...Edmond OK

En Español
Last Update: 2:44 pm CDT Sep 12, 2007

Digital Forecast

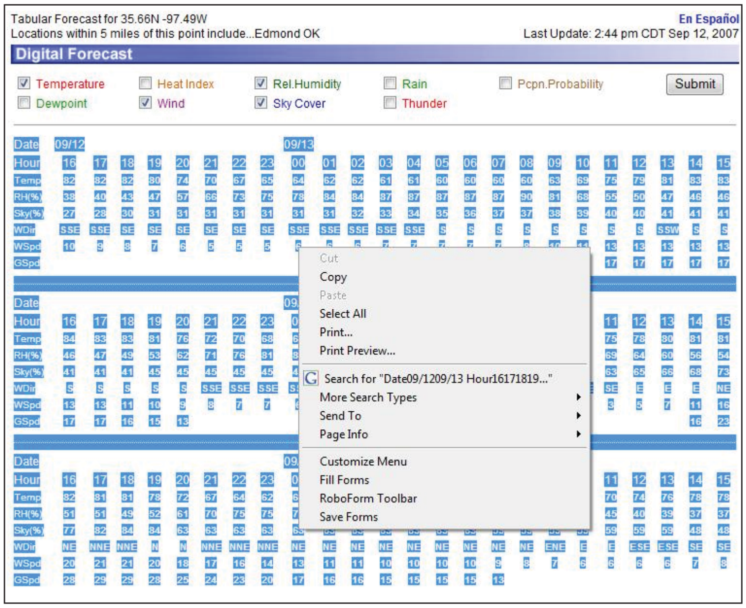
☑ Temperature ☐ Heat Index ☑ Rel.Humidity ☐ Rain ☐ Pcpn.Probability Submit
☐ Dewpoint ☑ Wind ☑ Sky Cover ☐ Thunder

Date	09/12								09/13															
Hour	16	17	18	19	20	21	22	23	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15
Temp	82	82	82	80	74	70	67	65	64	62	62	61	61	60	60	60	60	63	69	75	79	81	83	83
RH(%)	38	40	43	47	57	66	73	75	78	84	84	87	87	87	87	87	90	81	68	55	50	47	46	46
Sky(%)	27	28	30	31	31	31	31	31	31	31	32	33	34	35	36	37	37	38	39	40	40	41	41	41
WDir	SSE	SSE	SE	SE	SE	SE	SE	SE	SSE	SSE	SSE	SSE	SSE	S	S	S	S	S	S	S	S	SSW	S	S
WSpd	10	9	8	7	6	5	5	5	6	6	6	7	7	7	7	7	8	10	11	13	13	13	13	13
GSpd																		15	16	17	17	17	17	17

Date									09/14															
Hour	16	17	18	19	20	21	22	23	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15
Temp	84	83	83	81	76	72	70	68	67	66	65	65	64	64	64	63	64	66	70	75	78	80	81	81
RH(%)	46	47	49	53	62	71	76	81	84	87	90	90	93	93	93	97	97	90	81	69	64	60	56	54
Sky(%)	41	41	41	45	45	45	45	45	45	46	48	49	51	53	55	56	58	60	62	63	65	66	68	73
WDir	S	S	S	S	S	SSE	SSE	SSE	SSE	SSE	SSE	SSE	SSE	SSE	SSE	SSE	SSE	SSE	SSE	SE	E	E	E	NE
WSpd	13	13	11	10	9	8	7	7	6	6	6	5	5	5	3	3	3	3	3	3	5	7	11	16
GSpd	17	17	16	15	13																		16	23

Date									09/15															
Hour	16	17	18	19	20	21	22	23	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15
Temp	82	81	81	78	72	67	64	62	60	59	58	57	57	56	56	56	56	59	64	70	74	76	78	78
RH(%)	51	51	49	52	61	70	75	75	78	78	77	77	75	72	69	66	69	62	54	45	40	39	37	37
Sky(%)	77	82	84	84	63	63	63	63	63	63	63	63	63	63	63	59	59	59	59	59	59	59	48	48
WDir	NE	NNE	NNE	N	N	NNE	NNE	NNE	NE	NE	NE	NE	NE	NE	NE	NE	NE	ENE	E	E	ESE	ESE	SE	SE
WSpd	20	21	21	20	18	17	16	14	13	11	11	10	10	10	10	9	8	7	6	6	6	6	7	8
GSpd	28	29	29	28	25	24	23	20	17	16	16	15	15	15	15	13								

5. Using a mouse, highlight the forecast data, right click, and copy the forecast data.



6. The data can be pasted directly into a spreadsheet application. Horizontal lookup formulas can be used to reformat the data into columns that can be directly copied into HIPERPAV. An example of the spreadsheet used for copying NOAA weather data into HIPERPAV for the MCO project is shown at the right.

7. Manually add one data point (#73) to the end of the NOAA forecast data. This is necessary because HIPERPAV uses 73 hourly weather inputs. Using the same value as data point #72 is acceptable. Select a column of forecast data to copy into HIPERPAV (example spreadsheet shows temperature highlighted in blue).

Date	12-Sep															13-Sep								
Hour	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	0	1	2	3	4	5	6	7	8
Temp	58	64	70	74	76	78	78	79	79	78	77	72	69	67	65	64	64	63	63	62	62	62	61	62
RH(%)	83	67	53	46	43	42	43	44	44	47	50	59	66	70	75	78	78	78	78	81	81	81	84	84
Sky(%)	13	13	13	13	11	11	11	11	11	11	12	15	18	21	24	27	28	28	29	30	31	31	31	32
WDir	SSW	SSW	S	S	SSE	SSE	SSE	SSE	SSE	SE	SE	SE	SE	SE	SE	SSE	SSE	SSE	SSE	SSE	S	S	S	S
WSpd	2	2	3	6	7	8	9	10	9	8	7	6	5	5	5	6	6	6	7	7	7	7	7	8
GSpd																								

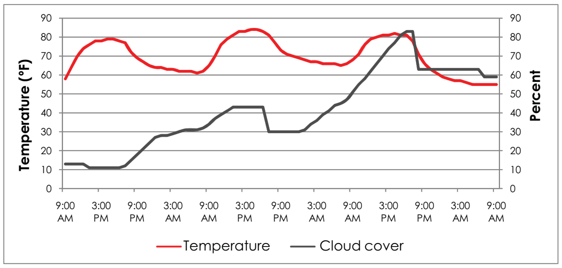
Date																14-Sep								
Hour	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	0	1	2	3	4	5	6	7	8
Temp	65	70	76	79	81	83	83	84	84	83	81	77	73	71	70	69	68	67	67	66	66	66	65	66
RH(%)	75	66	54	50	47	46	46	46	46	49	53	60	68	73	76	78	81	84	84	87	87	87	90	90
Sky(%)	34	37	39	41	43	43	43	43	43	43	30	30	30	30	30	30	31	34	36	39	41	44	45	47
WDir	S	S	S	S	SSW	S	S	S	S	S	S	SSE	SSE	SSE	SSE	SSE	SSE	SSE	SSE	SSE	SSE	SSE	SSE	SSE
WSpd	10	11	13	13	13	13	13	13	13	11	10	9	7	6	6	6	6	6	5	5	5	3	3	3
GSpd																								

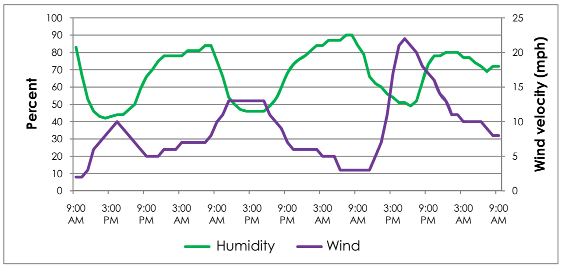
Date																15-Sep								
Hour	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	0	1	2	3	4	5	6	7	8
Temp	68	71	76	79	80	81	81	82	81	81	78	71	66	63	61	59	58	57	57	56	55	55	55	55
RH(%)	84	79	66	62	60	56	54	51	51	49	52	63	73	78	78	80	80	80	77	77	74	72	69	72
Sky(%)	51	55	58	62	66	70	74	77	81	83	83	63	63	63	63	63	63	63	63	63	63	63	59	59
WDir	SSE	SSE	SE	E	E	ENE	NE	NE	NNE	NNE	N	NNE	NNE	NNE	NNE	NE	NE	NE	NE	NE	NE	NE	NE	NE
WSpd	3	3	3	5	7	11	17	21	22	21	20	18	17	16	14	13	11	11	10	10	10	10	9	8
GSpd							24	29	31	29	28	25	24											

Paste NOAA tabular forecast into cell B1

date	hour	data point	temp	humidity	sky	wind
9/12/2007	9	1	58	83	13	2
9/12/2007	10	2	64	67	13	2
9/12/2007	11	3	70	53	13	3
9/12/2007	12	4	74	46	13	6
9/12/2007	13	5	76	43	11	7
9/12/2007	14	6	78	42	11	8
9/12/2007	15	7	78	43	11	9
9/12/2007	16	8	79	44	11	10
9/12/2007	17	9	79	44	11	9
9/12/2007	18	10	78	47	11	8
9/12/2007	19	11	77	50	12	7
9/12/2007	20	12	72	59	15	6
9/12/2007	21	13	69	66	18	5
9/12/2007	22	14	67	70	21	5
9/12/2007	23	15	65	75	24	5
9/13/2007	0	16	64	78	27	6
9/13/2007	1	17	64	78	28	6
9/13/2007	2	18	63	78	28	6
9/13/2007	3	19	63	78	29	7
9/13/2007	4	20	62	81	30	7
9/13/2007	5	21	62	81	31	7
9/13/2007	6	22	62	81	31	7
9/13/2007	7	23	61	84	31	7
9/13/2007	8	24	62	84	32	8
9/13/2007	9	25	65	75	34	10
9/13/2007	10	26	70	66	37	11
9/13/2007	11	27	76	54	39	13
9/13/2007	12	28	79	50	41	13
9/13/2007	13	29	81	47	43	13
9/13/2007	14	30	83	46	43	13
9/13/2007	15	31	83	46	43	13
9/13/2007	16	32	84	46	43	13
9/13/2007	17	33	84	46	43	13
9/13/2007	18	34	83	49	43	11

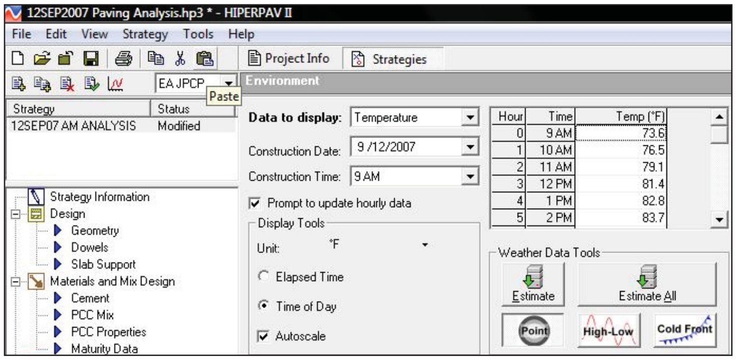
Forecast weather data:
9/12/07 9:00 AM to 9/15/07 9:00 AM





8. Paste the forecast data from the spreadsheet into HIPERPAV.

9. Repeat the copy-and-paste routine for the remaining environmental inputs.



Appendix C: Suggested Testing Equipment by Suite Level

This equipment list is provided as a guideline only. It should not be considered as comprehensive, nor should it be considered as a required shopping list. Under many circumstances, it may be most cost-effective to utilize a combination of outsourced testing services and contractor quality control efforts.

Common laboratory equipment	Specialized testing equipment (significant capital investment required [>$1,000])
Level C testing equipment list	
Balances	Sieve shaker
Sieves	Strength testing machine
Oven/hot plate/microwave	
Heat resistant container for moisture content testing	
Slump cone and base	
Tamping rods (slump, unit weight, & strength)	
Compressive strength molds	
Flexural strength molds	
Vibrator for strength specimens	
Rubber mallet (1.25 lb ±0.50 lb)	
Shovels	
Hand floats	
Scoops	
Vibrating reed tachometer	
Wheelbarrow(s)	
Concrete thermometer	
Unit weight cylinder (usually a pressure air pot)	
Acrylic strike-off plate (unit weight and pressure air content)	
Air meter(s)	
Container for immersing boil test specimens	
Wire for suspending boil test specimens in water	
Additional equipment required for Level B	
Microwave oven	Automatic vibrator monitors installed on slipform pavers
Pyrex dish	Calorimeter
Fiberglass cloth	Personal computer
Vibratory mortar sampler (see figure C.1)	Linear traverse device, point count device, or image analysis hardware and software (commercially available)
Mortar specimen containers	
Penetration needles	
Penetrometer	
Pipet(s)	
HIPERPAV software (available for free download from FHWA)	
Kitchen blender	
Graduated cylinders (10, 100, 500 and 1,000 mL)	
Stop watch/timer	

Common laboratory equipment	Specialized testing equipment (significant capital investment required [>$1,000])
Additional equipment required for Level A	
Mortar flow table	Air-void analyzer (commercially available)
Mortar flow calipers	Rapid chloride penetration equipment (commercially available)
Flow mold	Coefficient of thermal expansion test equipment (commercially available)
Tamper, trowel and straightedge for mortar flow testing	Freezing and thawing apparatus (commercially available)
Plastic container for cementitious heat generation testing (see figure C.2)	Dynamic testing apparatus
Foam block for cementitious heat generation testing (see figure C.2)	
Containers for early stiffening testing	
Vicat apparatus	
Mixer, bowl, paddle, and scraper	
Prism molds	
Length comparator	
Tempering tank	

Figure C.1 Vibratory mortar sampler

Figure C.2 Plastic container and foam block for cementitious heat generation testing

Notes

Notes

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