Development of Performance Properties of Ternary Mixtures:

Field Demonstrations and Project Summary

National Concrete Pavement Technology Center

Final Report
July 2012

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16. Abstract

Supplementary cementitious materials (SCM) have become common parts of modern concrete practice. The blending of two or three cementitious materials to optimize durability, strength, or economics provides owners, engineers, materials suppliers, and contractors with substantial advantages over mixtures containing only portland cement. However, these advances in concrete technology and engineering have not always been adequately captured in specifications for concrete.

Users need specific guidance to assist them in defining the performance requirements for a concrete application and the selection of optimal proportions of the cementitious materials needed to produce the required durable concrete. The fact that blended cements are currently available in many regions increases options for mixtures and thus can complicate the selection process. Both portland and blended cements have already been optimized by the manufacturer to provide specific properties (such as setting time, shrinkage, and strength gain). The addition of SCMs (as binary, ternary, or even more complex mixtures) can alter these properties, and therefore has the potential to impact the overall performance and applications of concrete.

This report is the final of a series of publications describing a project aimed at addressing effective use of ternary systems. The work was conducted in several stages and individual reports have been published at the end of each stage.

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DEVELOPMENT OF PERFORMANCE PROPERTIES OF TERNARY MIXTURES: FIELD DEMONSTRATIONS AND PROJECT SUMMARY

Final Report
July 2012

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INTRODUCTION

Supplementary cementitious materials (SCMs), such as fly ash, slag cement, natural pozzolans and silica fume, have become common parts of modern concrete practice (PCA 2002; Transportation Research Board 1990; ACI 2007). The blending of two or three cementitious materials to optimize durability, strength, or economics provides owners, engineers, materials suppliers, and contractors with substantial advantages over mixtures containing only portland cement. However, these advances in concrete technology and engineering have not always been adequately captured in specifications for concrete.

Usage is often limited because of prescriptive limitations or - legacy perceptions about how such materials will perform. In addition, some SCMs can exhibit significant variation in chemical and physical properties within a given source and, more commonly, between sources. Hence, current literature contains contradictory reports concerning the "optimal use" of supplementary cementitious materials.

Users need specific guidance to assist them in defining the performance requirements for a concrete application and the selection of optimal proportions of the cementitious materials needed to produce the required durable concrete. The fact that blended cements are currently available in many regions increases options for mixtures and thus can complicate the selection process. Both portland and blended cements have already been optimized by the manufacturer to provide specific properties (such as setting time, shrinkage, and strength gain). The addition of SCMs (as binary, ternary, or even more complex mixtures) can alter these properties, and therefore has the potential to impact the overall performance and applications of concrete.

This report is the final of a series of publications describing a project aimed at addressing effective use of ternary systems. The work was conducted in several stages and individual reports have been published at the end of each stage.

PROJECT SUMMARY

The goal of this project was to provide the quantitative information needed to make sound engineering judgments pertaining to the selection and use of SCMs in conjunction with portland or blended cement. This information will lead to a more effective utilization of supplementary materials and/or blended cements, enhancing the life-cycle performance and cost effectiveness of transportation pavements and structures.

The efforts of this project were directed at producing test results that support the following specific goals:

- Provide quantitative guidance for ternary mixtures that can be used to enhance the performance of structural and pavement concrete
- Provide a solution to the cold weather issues that are currently restricting the use of blended cements and/or SCMs

- Identify how to best use ternary mixes when rapid strength gain is needed
- Develop performance-based specifications for concrete used in transportation pavements and structures

BACKGROUND

Engineers for state departments of transportation (DOTs) throughout the United States have used fly ash and slag cement as a partial replacement for portland cement in concrete production on a regular basis since the implementation of the Resource Conservation and Recovery Act in 1986. The Texas DOT (TxDOT) was one of the first states to conduct work to optimize the use of fly ash or slag cement to produce concrete mixtures that meet specific performance objectives (Tikalsky et al. 1988).

For many years, most states implemented a strategy that was meant to produce concrete mixtures that exhibit performance similar to mixtures employing only portland cement. With the growing availability of slag cement and silica fume, and the limited supply of fly ash in some markets, the selection of materials for any given job has become more complicated.

SCMs have the potential to dramatically improve the overall performance by increasing the longevity of the transportation infrastructure and decreasing the life-cycle cost of that infrastructure. The introduction of fly ash, silica fume and slag cement in ternary combinations has periodically provided the following benefits to DOT and associated agencies:

- Excellent long-term strength
- Lower clinker and lower environmental emissions associated with concrete
- Mitigation of Alkali Silica Reaction (ASR)
- Mitigation of sulfate attack
- Resistance to corrosion
- Durability for highways and bridges
- Reduction of construction issues related to binary concrete mixtures

However, the following technical issues may be periodically caused by the introduction of fly ash, silica fume, or slag cement:

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

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

OUTLINE OF RESEARCH STAGES

The first stage of this study consisted of laboratory experiments that examined the influence of combinations and proportions of cement, slag cement, silica fume, calcined kaolinite, and fly ash on specific performance properties of paste and mortar specimens (Tikalsky et. al., 2007). The testing program used a wide range of different materials and many different dosage levels.

Test results were evaluated to identify material combinations for potential optima in the various performance responses. Chemical admixtures (water reducers, air-entraining agents, and accelerators) were included in this phase of the study to compare how setting time, water demand, and air content vary in ternary mixtures. Phase I results were used to help develop models for predicting the performance of ternary systems based on the materials in the system.

All of the materials used in the study were subjected to bulk chemical and physical testing in accordance with the appropriate ASTM International (ASTM) or American Association of State Highway and Transportation Officials (AASHTO) methods.

In addition, X-ray diffraction (XRD) was used to determine the minerals present in the bulk samples and selected paste specimens. Glass content of the various SCMs and blended cements was estimated using semi-quantitative XRD analysis.

The second stage used the information obtained from the paste and mortar work to select a range of materials and dosages to investigate the effects different combinations in laboratory concrete mixtures tested under cold, hot, and ambient conditions (Tikalsky et. al., 2011).

The materials used in both stages were identical so that the mortar test results could be directly compared to the test results obtained from concrete test specimens.

The third stage of the project was to assist states in constructing pavements and structures using ternary mixtures. A mobile laboratory was used to collect samples and conduct field tests at the construction sites.

LABORATORY STUDY ON PASTE AND MORTAR SUMMARY

Introduction

The first stage of this work, the "Laboratory Study on Paste and Mortar," focused on determining performance properties of mortar specimens with ternary cementitious mixture designs (Tikalsy et. al., 2007). Cementitious materials used to develop 117 ternary mixture designs included: Type I, Type I/II, Type ISM, Type IP, Type IPM and a high lime portland cement, Class C fly ash, moderate and low calcium Class F fly ashes, grades 100 and 120 slag cement, silica fume, and metakaolin. All cementitious materials were subjected to bulk chemical and physical testing. Mixing and testing were performed at the Pennsylvania State University, University of Utah, and Iowa State University.

In general, no significant technical barriers for pavement and bridge deck construction were found. Ternary combinations with pozzolans comprising between 40 and 50 percent of total cementitious content performed well in cool to hot weather environments. Findings for each property tested are briefly summarized below.

Setting Time and Mortar Flow

In general, the introduction of SCMs increased the time of setting and increased workability. Mixtures containing Class F fly ash had an unexpected decrease in set time, which could be due to the increased fineness of the Class F fly ashes used in the study. The grade 120 slag cement tended to have a decreased flow and time of set compared to the grade 100 slag cement, likely due to the finer grind.

Compatibility

One low-range water reducer showed significant reduction in time to set when used with Class C fly ash. The effect was not observed with other admixtures or fly ashes.

Air Void System

Although most mixtures met the threshold of 0.2 mm (0.008 in.) for air void spacing factor, some mixtures containing Class F fly ash did not meet the minimum criteria of 23 –43 mm^{-1} (600 – 1000 $in.^{-1}$) for specific surface with some WRA.

Mortar Compressive Strength

Most strengths correlated well with the bulk chemistry of the mixture.

The effect of exceeding the recommended dosage of one of the Type A water reducers on mortar early strength was also investigated on a sample of mixture designs. The 3 day compressive strengths were greatly decreased when the recommendations were exceeded. However, by 28 days, the compressive strength of the overdosed mortars was approximately the same as the mixtures with properly-dosed water reducers, which suggested the retardation effect of the water reducer admixture had no long-term effects.

Heat Signature

The heat signature of concrete mixtures describes the hydration process and gives estimates of the time to initial and final set. It was observed that when incorporating SCMs, a reduction in maximum temperature rise and a time delay to maximum heat generation was experienced. With the decrease in heat generated, the general tradeoff is a longer time to initial and final set.

The heat signature of mixtures containing Grade 120 slag cement was significantly higher than mixtures containing grade 100 slag cement. The results also showed that the influence of the silica fume replacement (3 or 5 percent) was negligible when comparing the respective heat signatures. This showed that a 5 percent replacement rate may be used if needed in high-performance concreting applications with no noticeable effect on the heat signature.

Shrinkage

In comparison to a 100 percent Type I portland cement mixture, shrinkage was reduced when the cement was blended with any other constituents. However, when Type I/II Portland cement was blended, shrinkage was observed to be higher than the control. Type IP and Type PM portland cements gave both higher and lower shrinkage results than when blended with an additional constituent. This indicates that cement type can affect shrinkage of ternary combinations.

Sulfate Mortar Bar Testing

Few simple trends could be observed in the sulfate tests. In general, the performances of the mixtures were parallel to the trends expected from the individual materials. Class F fly ash was found to be very good at mitigating sulfate expansion, while mixtures containing Class C fly ash should be tested in the planned combination before being used.

Alkali Silica Reaction (ASR)

The testing found that ternary blends can be designed to mitigate ASR expansion and that increased replacement levels of fly ash decreased ASR expansion. Low dosages of Class C fly ash blended with Class F fly ash did not mitigate ASR expansion. Thirty-five percent or more slag cement was effective in ASR mitigation. Silica fume and metakaolin increased mitigation of ASR when used in ternary blended cements

LABORATORY STUDY ON CONCRETE SUMMARY

Introduction

Based on the laboratory study on paste and mortar, 48 concrete mixtures containing different cementitious combinations were used in the second phase of the work.

- Type I cement with binary combination controls and 26 ternary combinations (31 total combinations with TI cement),
- Type IP with six SCM combinations (seven total),
- Type IPM with four SCM combinations (five total), and
- Type ISM with four SCM combinations (five total).

Each of these combinations is technically and economically advantageous for highway applications. At least 11 of these ternary mixtures have the potential to have sufficient maturity in cold weather concrete operations (compressive strength greater than 3,500 psi at three days at 50°F), and at least 11 of these mixtures have the maturity characteristics suitable for hot weather concrete (less than 2,500 psi at three days at 90°F).

Some general summary comments are provided below. Details should be studied in the full laboratory report.

Fresh Concrete Properties

The majority of mixtures containing fly ash exhibited increased setting time. Mixtures with slag cement had no significant changes on setting time compared to the controls. Metakaolin and silica fume did not appear to have a great effect on setting time. Ternary mixtures followed the trends expected based on their ingredients.

Class C fly ash had a mitigating effect on bleeding up to a point, but when more than 25 percent Class C fly ash was used in the mixture, bleeding increased. Class F fly ash also reduced bleeding, but was not as effective as the C ash and there was no pessimum effect observed with Class F fly ash. Bleeding was slightly increased in the mixtures containing slag cement, but decreased in the mixtures containing metakaolin. The high fineness of silica fume and large specific surface area greatly reduced the bleeding of the mixtures.

Compressive Strength

High replacement levels of SCMs could delay strength gain; therefore, a lower early age strength will likely be obtained for binary and ternary combinations, compared to a 100 percent portland cement mixture. However, many of the ternary mixtures had higher compressive strengths than the pure portland cement control mixture by 28 days.

Freeze-Thaw Resistance

All tested mixtures exhibited sufficient freeze-thaw durability when they contained an entrained air volume greater than 4 percent. Some of the mixtures continued to hydrate during the test and had a durability factor greater than 100 after 300 cycles.

Scaling

Moderate surface scaling was seen in all mixture designs tested. Inclusion of silica fume and metakaolin generally did not reduce the severity of the scaling; however, the addition of fly ash or slag cement did reduce the severity.

Chloride Ion Resistance and Resistivity

An excellent correlation was observed between AASSHTO T277 data and resistivity results obtained using a Wenner four-probe device. The results supported the use of the Wenner device as a quality assurance (QA) tool in concrete field testing. Cylinders cast as QA specimens and placed in wet curing for strength testing could be used for resistivity tests.

Ternary cementitious mixtures had a large effect on reducing diffusion coefficients and increasing of resistivity.

Shrinkage

All mixtures that were tested for shrinkage had strains less than 500 millionths at 28 days, and some had strains less than 500 millionths at 365 days.

Hot and Cold Weather Testing

Compressive strength trended with the temperatures and component reactivities, as expected, and setting times appeared to vary without a clear trend being apparent.

Scaling resistance of the mixtures was varied, predominantly controlled by the type of SCMs in the mixture, while mixing and curing temperatures did not appear to affect performance significantly.

Carbon Dioxide Emissions

Ternary blended cement concrete mixtures were shown to have reduced the carbon dioxide emissions.

FIELD DEMONSTRATION SUMMARY

Introduction

The third phase of the project was intended to demonstrate the use of ternary mixtures in field projects. A mobile laboratory equipped for on-site cement and concrete testing was used to collect data and conduct field observations. Eight construction sites that used ternary mixtures in bridge decks and pavements were assessed. A separate data report was produced for each location and are all attached as Appendices to this report.

Project Information

Table 1 lists the eight projects that were investigated in this study, including three rigid pavement and five bridge deck construction projects.

Table 1. Project introduction

State	Type and Name	Date of field demonstration	Location
UT	Rigid pavement placement	7/28/2009	10400 South
KS	Bridge deck placement	10/28/2009	US 59 northbound bridge
MI	Bridge deck placement	12/18/2009	I-94, Riverside Drive
IA	Rigid pavement improvement	6/7/2010	Southbound of Interstate 29
PA	Bridge deck placement	7/14/2010	State Route 36, section 20, Roaring Spring
NH	Bridge deck placement	8/10/2010	Route 107
NY	Bridge abutment stem	8/16/2011	I-86, Exit 42 Rehabilitation
CA	Rigid pavement improvement	9/28/2011	I-80 Pavement reconstruction

Materials

Cements and Supplementary Cementitious Materials

Table 2 shows chemical and physical compositions of the cementitious materials used for each project. The supplementary cementitious materials all complied with their respective ASTM standards.

Table 2. Chemical compositions and physical properties of cementitious materials

Chemical, %	UT		KS			MI	IA		PA			NH			NY		CA		
	ASTM C1157 cement (E)	F fly ash	Type I/II cement	Silica fume	Slag cement	IT(S25)(P4)	Type IP(25)	C fly ash	Type I/II cement	F fly ash	Slag cement	Type II cement	F fly ash	Slag cement	Type IP(6)	F fly ash	Type II/V cement	F fly ash	Slag cement
Ternary blends composition, % by mass	**67.5 PC + 7.5 limestone**	**25**	**60**	**5**	**35**	**71 PC + 4 SF + 25 Slag cement**	**64 PC+21 F ash**	**15**	**55**	**15**	**30**	**50**	**15**	**35**	**75 PC + 5 SF**	**20**	**67**	**8**	**25**
CaO	-	-	63.22	0.46	42.25	53.30	48.83	26.34	62.40	7.29	41.90	61.30	1.65	41.54	55.50	2.82	65.50	5.23	41.86
SiO_2	-	-	20.97	94.32	38.82	28.70	29.19	35.13	20.10	45.07	34.20	19.40	57.36	35.98	25.00	46.36	21.40	60.26	36.25
Al_2O_3	-	-	4.47	0.28	7.27	5.86	8.62	19.95	4.60	23.83	11.17	4.90	26.57	12.89	5.40	25.17	3.60	24.25	10.69
Fe_2O_3	-	-	2.93	0.31	0.81	1.98	3.80	5.74	2.70	15.02	0.68	3.70	5.40	0.52	3.00	17.72	3.50	4.23	0.78
MgO	-	-	2.30	0.75	9.02	4.68	3.04	4.88	4.00	1.58	6.89	2.30	-	6.11	2.40	-	1.60	1.09	6.15
K_2O	-	-	0.60	0.48	0.50	0.48	0.89	0.42	-	-	0.29	-	-	0.27	-	-	-	1.17	0.62
Na_2O	-	-	0.16	0.08	0.31	0.18	0.39	1.75	-	0.55	0.32	-	0.81	0.29	-	0.70	-	1.31	0.31
SO_3	-	-	2.63	0.05	-	2.52	3.14	1.45	3.40	1.30	-	3.80	0.33	1.09	4.20	0.57	3.40	0.31	2.07
P_2O_5	-	-	0.12	0.09	0.03	0.08	-	-	-	-	0.02	-	-	0.04	-	-	-	0.17	-
TiO_2	-	-	0.31	0.01	0.41	0.27	-	-	-	-	0.44	-	-	0.44	-	-	-	0.89	-
SrO	-	-	0.08	-	0.05	0.05	-	-	-	-	0.07	-	-	-	-	-	-	0.05	-
Mn_2O_3	-	-	0.04	-	0.52	0.18	-	-	-	-	0.38	-	-	0.45	-	-	-	0.02	-
Eq. Alkalies	-	-	0.55	0.40	0.64	0.49	0.97	2.03	0.89	0.67	0.51	0.85	-	0.47	1.00	-	0.27	2.08	0.72
LOI	-	-	2.17	2.58	-	1.60	1.26	0.11	2.10	1.91	-	1.80	1.97	-	1.70	3.48	1.60	0.35	-
Total	-	-	100.55	99.82	100.62	100.37	100.13	97.80	100.19	97.22	96.87	98.05	94.09	100.09	98.20	96.82	100.87	101.41	99.45
Specific gravity	-		3.15	2.25	2.87	-	2.95	2.62	3.15	2.40	2.90	3.15	2.91	2.37	3.15	2.38	3.15	2.06	2.93

Table 3. Fine and coarse aggregate types and properties

ID	Coarse aggregate type	Maximum aggregate size, in.	Specific gravity	Absorption, %	Passing #4 sieve, %	Fine aggregate type	Specific gravity	Absorption, %	Fineness modulus	Methlene blue index
			ASTM C127	ASTM C127			ASTM C 128	ASTM C 128	ASTM C 33	ASTM C 837
KS	granite	1	2.60	0.80	3.0	natural sand	2.61	0.70	2.66	0.75
MI	calcitic limestone	1	2.70	1.73	3.0	natural sand	2.61	1.20	2.80	1.54
	granite	-	2.60	2.33	5.0					
IA	quartzite	1	2.64	0.30	0.7	natural sand	2.65	0.80	3.00	0.63
	p-gravel	-	2.67	1.60	39.0					
PA	dolomitic limestone	1	2.84	0.32	2.0	sandstone	2.61	0.94	2.83	1.08
NH	granite	1	2.67	0.65	3.6	sandstone	2.67	0.78	2.66	1.13
NY	crushed gravel	1.0	2.61	0.50	2.9	generic sand	2.64	2.97	2.90	-
CA	river gravel	1.5	2.76	1.10	1.0	washed concrete sand	2.64	1.90	2.95	-
		1.0	2.75	1.30	3.0					

Aggregate

Table 3 lists the fine and coarse aggregate types and physical properties.

Figure 1 shows the 0.45 power curves of combined aggregate gradation. The coarse aggregate used in the majority field mixtures was a 1 in. maximum size except for California, which used 1.5 inches. The band of upper and lower limits is set up for the 1 in. size. Overall, the combined aggregate gradations are fair.

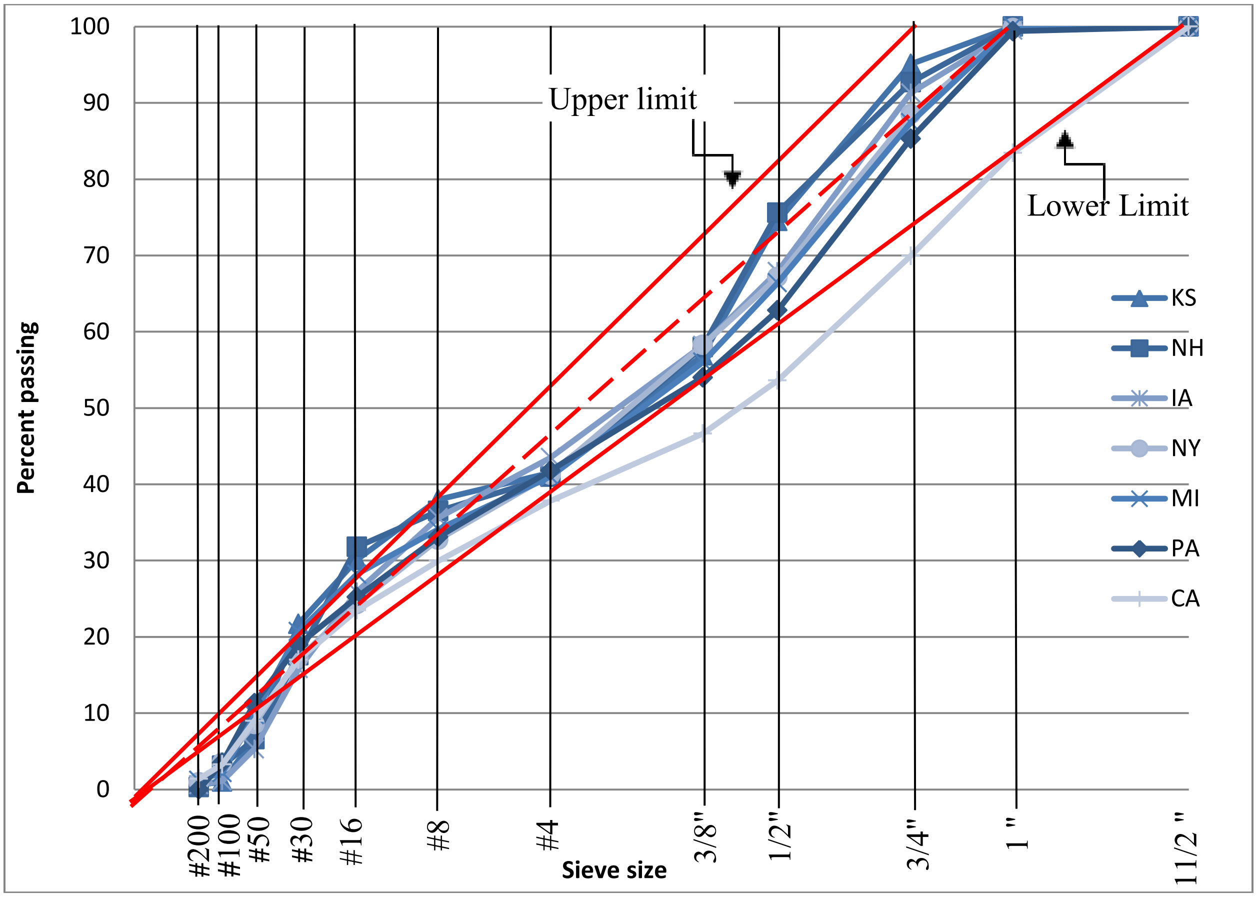

Figure 1. 0.45 Power curve of combined aggregate gradation

Coarseness factor and adjusted workability factor were calculated in accordance with Shilstone's method. The coarseness factor chart (Figure 2) indicates the combined aggregate gradations may be considered well graded for all the field mixtures.

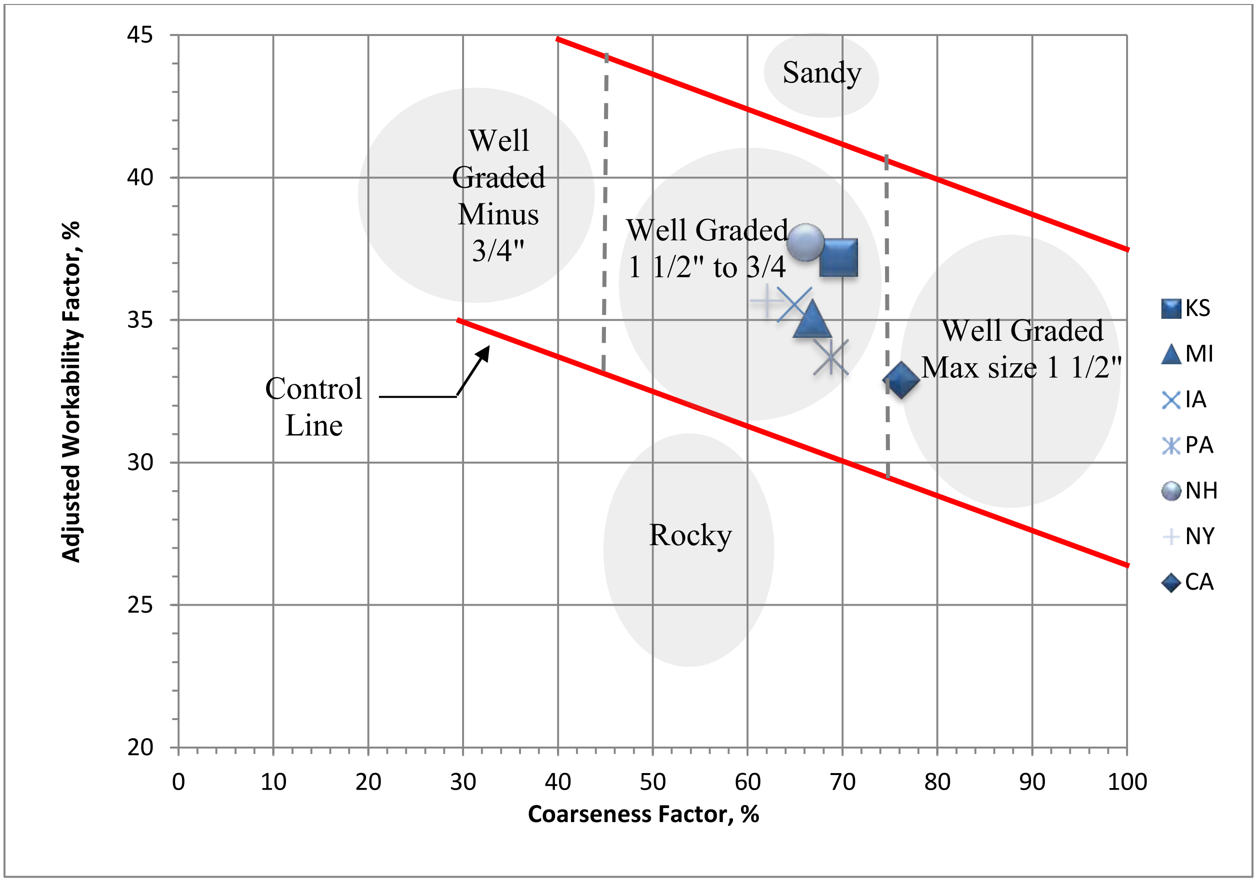

Figure 2. Coarseness factor chart

Mix Proportions

Table 4 shows the mix proportions for each project. Note that the mixture in NH contained polymeric fibers.

Testing Activities Summary

Fresh and hardened concrete properties were tested either in the field or in the laboratory by National CP Tech Center and/or local DOT technicians. Inclement weather prevented the mobile laboratory from reaching the site in Michigan, therefore field data are limited. Materials and samples were shipped to the laboratory for tests on hardened properties. The data are summarized in Table 5. Some tests are not available due to the field and environmental restrictions.

Table 4. Mix proportions for each project

		UT	KS	MI	IA	PA	NH	NY	CA
Cement	lbs/yd^3	493.0	321.0	426.0	478.0	323.0	306.0	540.0	452.0
Fly ash	lbs/yd^3	164.5	-	-	84.0	88.0	92.0	135.0	54.0
Slag cement	lbs/yd^3	-	187.0	150.0	-	176.0	213.0	-	169.0
Silica fume	lbs/yd^3	-	27.0	24.0	-	-	-	-	-
Fine aggregate	lbs/yd^3	1373.0	1217.0	1234.0	1235.0	1210.0	1160.0	1115.0	1130.0
Coarse aggregate 1	lbs/yd^3	1022.0	1371.0	1435.0	1568.0	1928.0	1800.0	1710.0	975.0
Coarse aggregate 2	lbs/yd^3	498.0	463.0	299.0	280.0	-	-	-	926.0
Water	lbs/yd^3	245.0	225.0	228.0	225.0	241.0	269.0	270.0	250.0
Air entraining agent	oz/yd^3	5.9	1.0	11.4	1.5	7.0	3.8	9.2	20.3
Water reducer	oz/yd^3	30.2	4.0	54.0	1.0	35.2	27.5	12.0	33.8
Retarder	oz/yd^3	-	1.0	18.0	4.0	11.7	-	-	-
Accelerator	oz/yd^3	-	1.0	-	-	-	-	-	-
Fiber	lbs/yd^3	-	-	-	-	-	7.0	-	-
Designed Unit weight	lbs/ft^3	-	141.1	140.6	143.3	146.9	142.3	139.6	146.5
Paste content	%	-	30.5	31.8	30.9	32.2	33.5	36.1	33.8
Designed air content	%	-	6.5	6.5	6.0	6.0	5.0	6.5	5.5
Designed w/cm	-	0.37	0.42	0.38	0.40	0.41	0.44	0.40	0.37

Table 5. Summation of tests conducted either in the field or in the laboratory

Tests	Specifications	Project locations							
		UT	KS	MI	IA	PA	NH	NY	CA
Slump	ASTM C143/C360	1 test	9 tests	1 test	1 test	7 tests	5 test	2 tests	2 tests
Unit weight	ASTM C138	n/a	9 tests	1 test	1 test	2 tests	5 test	2 tests	2 tests
Temperature	ASTM C1064	n/a	9 tests	1 test	1 test	7 tests	5 test	2 tests	2 tests
Air content	ASTM C231	1 test	9 tests	1 test	1 test	7 tests	5 test	2 tests	2 tests
Microwave w/c ratio	AASHTO T 318	n/a	2 tests	n/a	1 test	2 tests	1 test	2 tests	2 tests
Setting time	ASTM C403	n/a	1 test	n/a	1 test	1 test	1 test	1 test	1 test
Temperature sensor	-	n/a	n/a	8 sensors	n/a	2 sensors	2 sensors	n/a	n/a
Calorimetry	ASTM C1679	n/a	4 cylinders	n/a	4 cylinders	4 cylinders	4 cylinders	4 cylinders	4 cylinders
Rapid Air Test	ASTM C457	n/a	14 specimens	10 samples	n/a	n/a	n/a	8 specimens	8 specimens
Boil Test	ASTM C642	n/a	4 specimens	n/a	3 specimens	3 specimens	n/a	3 specimens	3 specimens
Rapid chloride permeability	ASTM C1202	4 specimens	4 specimens	3 specimens from	1 specimen	2 specimens	2 specimens	2 specimens	2 specimens
Free drying shrinkage	ASTM C157	4 beams at 1, 3, 14, 28, 56, 91 days	3 beams at 1, 4, 7, 14, 28, 56 days	4 beams at 1, 4, 7, 14, 28, 56 days	3 beams at 1, 4, 7, 14, 28, 56 days	4 beams at 1, 4, 7, 14, 28, 56 days	3 beams at 1, 4, 7, 14, 28, 56 days	3 beams at 1, 4, 7, 14, 28, 56 days	3 beams at 1, 4, 7, 14, 28, 56 days
Restrained shrinkage	ASTM C1581	n/a	4 rings	4 rings	4 rings	4 rings	4 rings	n/a	n/a
Compressive strength	ASTM C39	1, 3, 7, 14, 28, 56 days	1, 3, 7, 28, 56 days	1, 3, 7, 28, 56 days	1, 3, 7, 28, 56 days	1, 3, 7, 28, 56 days	1, 3, 7, 28, 56 days	3, 7, 28, 56 days	3, 7, 28, 56 days
Splitting tensile strength	ASTM C496	n/a	1, 3, 7, 28, 56 days	1, 3, 7, 28, 56 days	1, 3, 7, 28, 56 days	1, 3, 7, 28, 56 days	1, 3, 7, 28, 56 days	3, 7, 28, 56 days	3, 7, 28, 56 days
Static modulus of elasticity	ASTM C469	n/a	1, 3, 7, 28, 56 days	1, 3, 7, 28, 56 days	1, 3, 7, 28, 56 days	1, 3, 7, 28, 56 days	1, 3, 7, 28, 56 days	3, 7, 28, 56 days	3, 7, 28, 56 days
Salt scaling	ASTM C672	4 samples	n/a	n/a	4 samples	3 samples	3 samples	3 samples	3 samples

Table 6. Environmental conditions and fresh concrete property results summary

	UT	KS									IA	PA							NH					NY		CA
Test date	2008/7/28	2009/10/28									2010/6/7	2010/7/14							2010/8/10					2011/8/16		2011/9/28
Recorded time	6:40 AM	8:03 AM	8:20 AM	8:25 AM	8:40 AM	9:20 AM	10:10 AM	10:50 AM	11:04 AM	11:28 AM	1:15 PM	7:20 AM	8:05 AM	8:50 AM	9:27 AM	9:30 AM	10:01 AM	10:38 AM	8:22 AM	9:00 AM	9:15 AM	9:17 AM	9:28 AM	8:05 AM	10:55 AM	9:50 AM
Relative humidity, %	-	65.0	81.0	84.0	81.0	79.0	70.0	60.0	65.0	62.0	65.0	82.0	70.0	75.0	77.0	78.0	79.0	79.0	79.0	75.0	72.0	72.0	72.0	84.0	69.0	40.0
Ambient temperature, °F	60.0	48.0	48.0	49.0	53.0	51.0	57.0	57.0	58.0	62.0	72.0	69.0	77.4	75.4	74.6	72.0	73.9	73.2	71.8	73.1	74.0	74.4	74.4	65.0	72.0	78.0
Wind speed, mph	-	2.4	8.0	4.5	11.2	4.5	6.0	5.0	3.5	3.5	3.0	3.0	-	-	-	7.0	-	-	3.0	1.0	2.0	3.0	1.0	4.0	2.0	2.0
Slump, in.	1.0	7.0	6.5	6.8	6.0	7.5	4.0	3.5	4.5	4.5	2.0	3.5	3.0	6.5	4.5	3.8	3.3	3.3	3.5	3.0	5.5	4.5	4.5	3.8	4.0	0.8
Unit weight, lbs/ft^3	-	137.8	135.6	136.4	138.8	137.8	140.4	139.8	140.8	140.8	135.6	147.3	-	-	-	147.1	-	-	136.0	136.2	141.2	139.6	136.2	138.2	138.0	151.0
Concrete temperature, °F	77.0	55.0	60.0	62.0	62.0	61.0	65.0	62.6	66.0	66.0	74.1	80.4	73.0	74.0	75.0	78.8	79.0	79.0	83.0	80.0	82.2	81.0	81.0	77.2	78.4	76.5
Air content, %	5.4	7.6	9.0	8.3	7.8	7.6	6.6	7.5	5.2	6.4	8.8	6.0	6.8	7.1	5.0	6.0	5.4	5.3	7.5	8.8	6.8	6.6	7.2	6.5	7.3	3.5
Intial setting time, hours	-	-	-	-	-	-	-	3.66	-	-	2.32	3.63	-	-	-	-	-	-	-	-	5.24	-	-	5.76	-	6.37
Final setting time, hours	-	-	-	-	-	-	-	11.66	-	-	8.41	10.96	-	-	-	-	-	-	-	-	8.12	-	-	6.72	-	7.47
Microwave w/cm ratio	-	-	0.44	-	-	-	-	0.45	-	-	0.35	0.50	-	-	-	0.46	-	-	-	-	0.43	-	-	0.46	0.47	0.45

Fresh concrete properties including slump, unit weight, concrete temperature, air content, microwave water-to-cementitious materials ratio (w/cm), setting time, and calorimetry were tested in the field. Concrete samples were cast in the field and transported to the laboratory for further testing, including compressive strength, static modulus of elasticity, splitting tensile strength, free drying shrinkage, restrained drying shrinkage, salt scaling tests, rapid chloride permeability, porosity analysis (boil test), and air void structure (rapid air test).

Results Summary

The fresh concrete properties are summarized in Table 6 along with the environmental conditions measured during field testing.

Fresh Concrete Properties

Slump tests were conducted in accordance with ASTM C143 for most of the projects. The exception was in California where the Kelly-Ball test was run according to ASTM C360. Generally, ternary mixtures used for pavements (UT, IA, and CA) had lower slumps than those used for bridges.

The field tested air contents ranged from 3.5 percent to 9.0 percent. The lowest air content measurement occurred in California field tests.

Figure 3 shows a plot of measured unit weights and air contents for six field mixtures. As expected, unit weights and air contents followed a close trend.

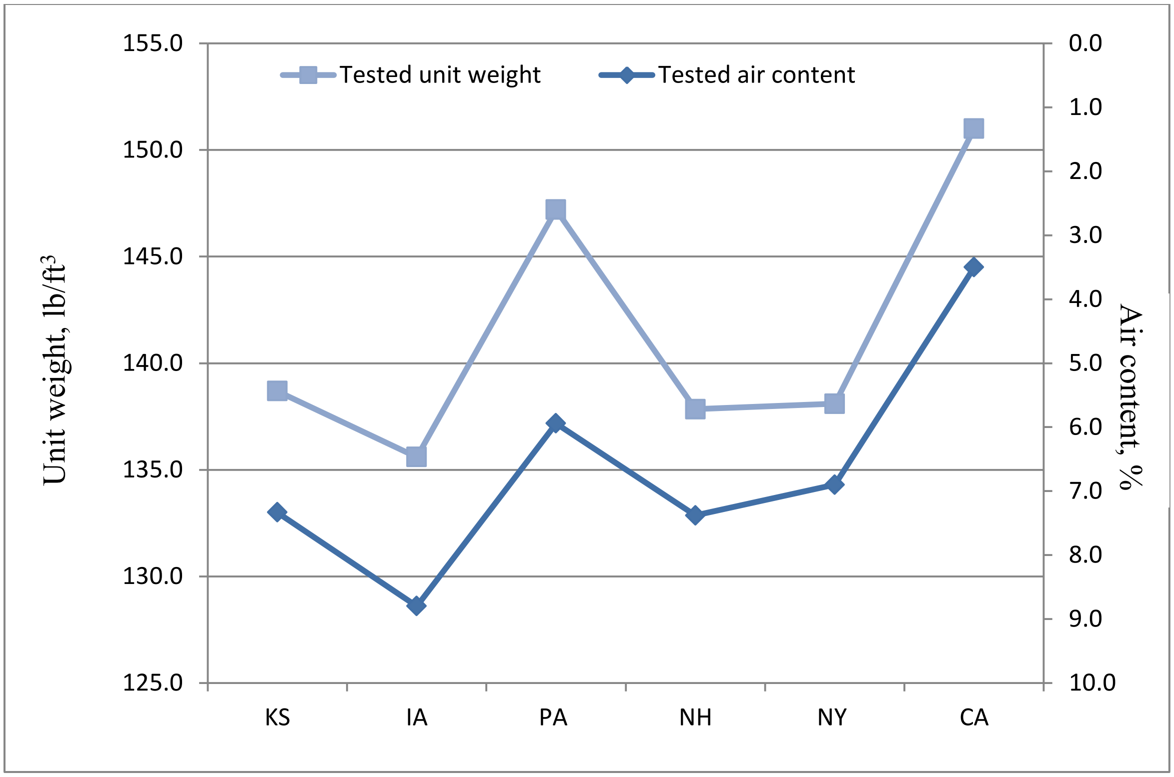

Figure 3. Tested unit weight vs. tested air content

Mortar was manually sieved from concrete samples for setting time measurements. As stated in Phase II final report of this study (Tikalsky et al. 2011), fly ash generally increased the setting time of the mixtures, while slag cement and silica fume did not show a significant impact on setting time. It should be noted that the ambient environment had significant impact on setting time, especially temperature and relative humidity. Overall, no unusual results for setting time were derived from the field mixtures. Measured initial and final setting times are plotted in Figure 4.

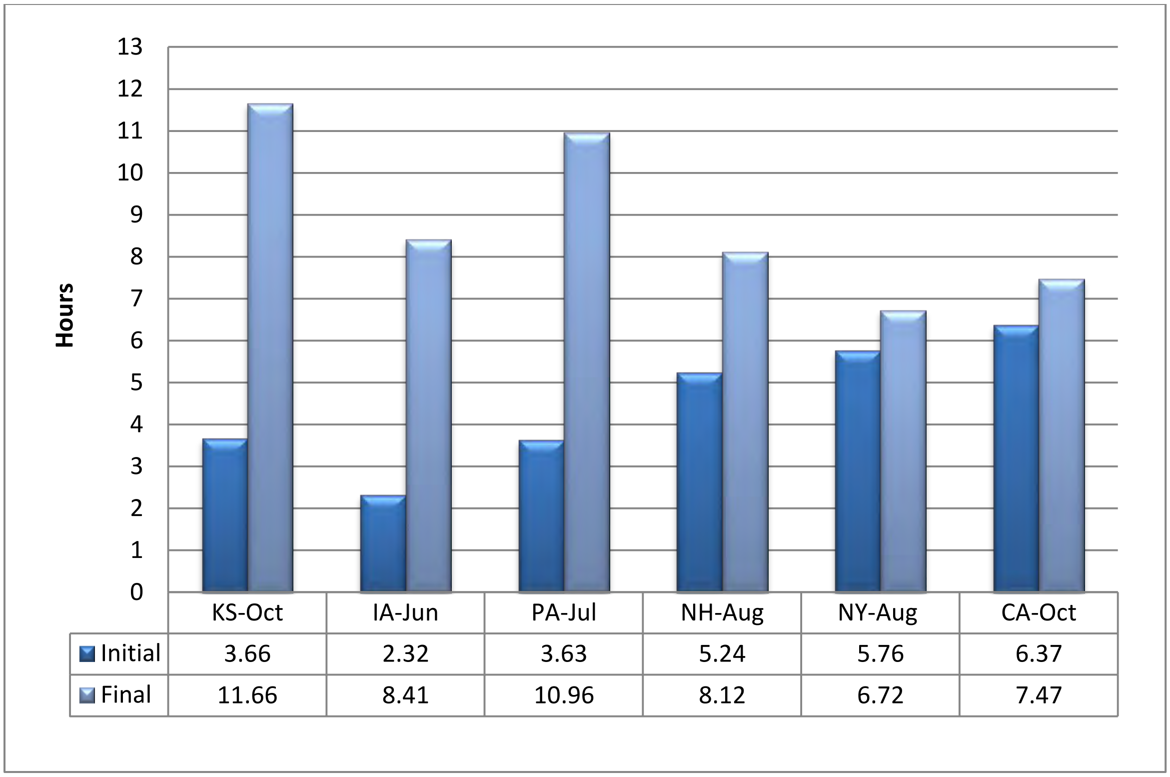

Figure 4. Initial and final setting time

A commercial semi-adiabatic calorimeter was used to measure the temperature rise during early hydration of cementitious materials. Figure 5 shows the heat signature curves. Table 7 summarizes the start, peak, peak to start temperature ratio, and the time to peak temperature for each curve. Temperature peaks seem to be influenced by initial temperature as well the nature of the cementitious system. One-day strength gain is indicated by the area underneath the heat signature curve.

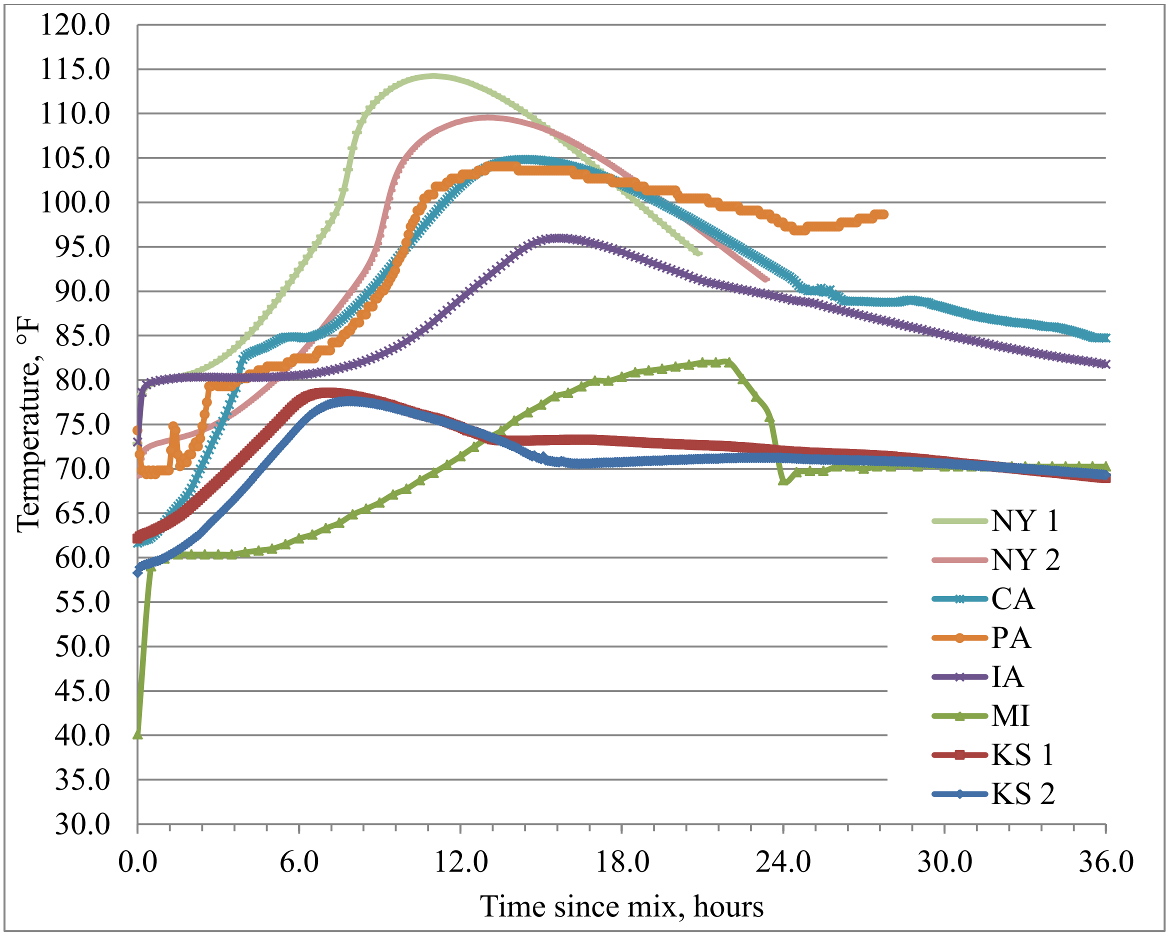

Figure 5. Calorimeter test results

Table 7. Calorimeter parameters

	NY 1	NY 2	CA	PA	IA	MI	KS 1	KS 2
Peak temperature, °F	114.2	109.5	104.8	104.0	95.9	82.0	78.5	77.6
Start temperature, °F	72.8	69.1	61.6	74.3	73.0	40.1	62.1	58.3
Peak to initial temp. ratio	1.57	1.58	1.70	1.40	1.31	2.04	1.26	1.33
Time to peak, hours	11.0	13.5	14.4	13.8	15.8	22.0	6.8	7.9

Notes: the designation 1 and 2 indicate two sets of calorimeter tests.

Hardened Concrete Properties

Mechanical Properties

The rates of development of compressive strength, elastic modulus, and tensile splitting strength can be found in individual field reports. The strength was governed by w/cm ratio regardless of the cementitious content. As would be expected, splitting tensile strength development of the mixtures agreed well with their compressive strength development. High modulus quartzite used in Iowa mixtures led to a higher modulus of elasticity. Most field mixtures had moist-cured 28-day compressive strengths over 4,000 psi and the 28 to 7 days compressive strength ratios shown in Table 8 are greater than 1.23, which indicated a good compressive strength development. The average compressive to splitting tensile strength ratios are listed in Table 8 as well, and the ratios ranging from 9.26 to 13.22 are considered acceptable. The ratio of split tensile to square root of compressive strength range between 6.1 to 7.1. These values are consistently lower than the commonly accepted value of 7.5.

Table 8. 28 to 7 days compressive strength ratio and compressive to splitting tensile strength ratio

	UT	KS	MI	IA	PA	NH	NY	CA
$fc_{-28days}/fc_{-7days}$	1.63	2.00	1.39	1.23	1.11	1.35	1.26	1.27
Ave. fc/fsp	-	9.26	13.22	11.75	10.27	9.38	9.49	9.35
fsp/sqrt(fc)	-	6.8	6.6	6.2	7.1	6.7	6.3	6.1

Free Shrinkage

In this report, the term "free shrinkage" refers to the total shrinkage of unrestrained prism specimens, and may include autogenous and drying shrinkage mechanisms. Figure 6 provides the free shrinkage data.

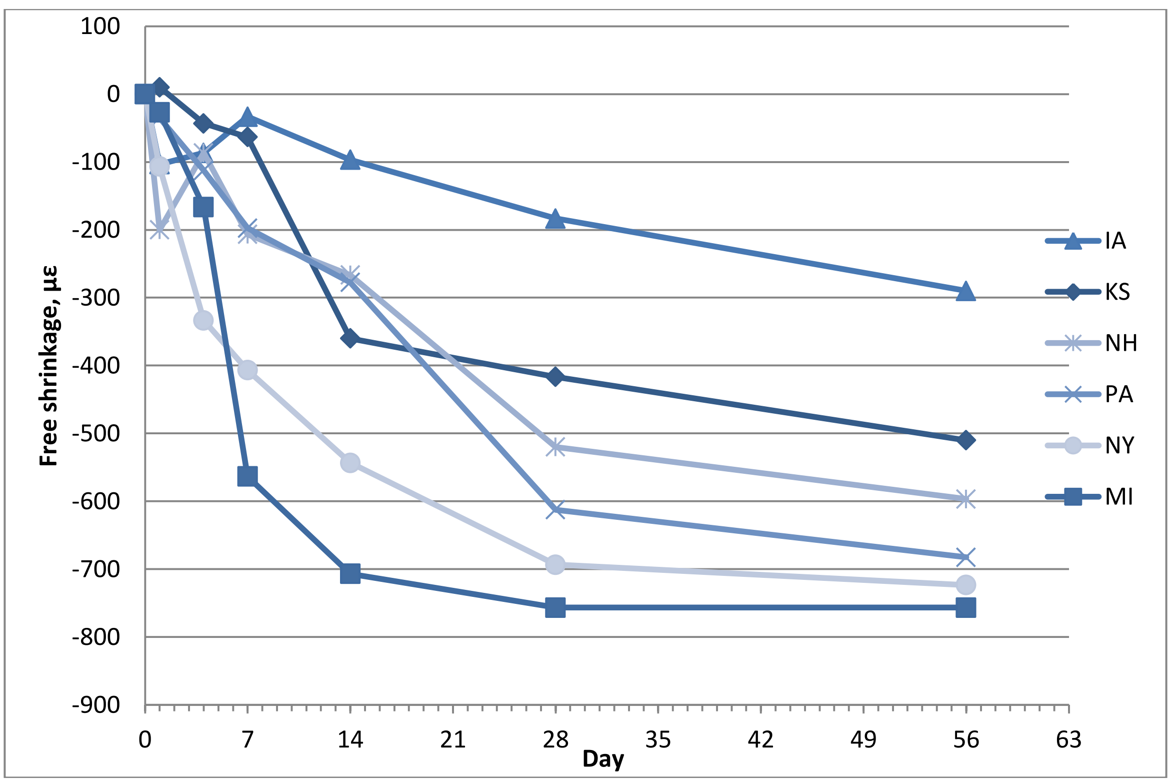

Figure 6. Free shrinkage (after seven days of moist curing) of prisms cast on site with job mixture

Restrained Shrinkage

Five of eight field mixtures, i.e., IA, KS, NH, PA, and MI, were selected for restrained shrinkage tests conforming to modified ASTM C1581. Four concrete rings were cast in the lab using the field mixture proportions in order to assess the potential for shrinkage induced cracking.

Figure 7 gives the strain values in the rings as the concrete shrinks. The Michigan mixture cracked around 7 days. The trends shown in the restrained shrinkage test results are in agreement with the free shrinkage results.

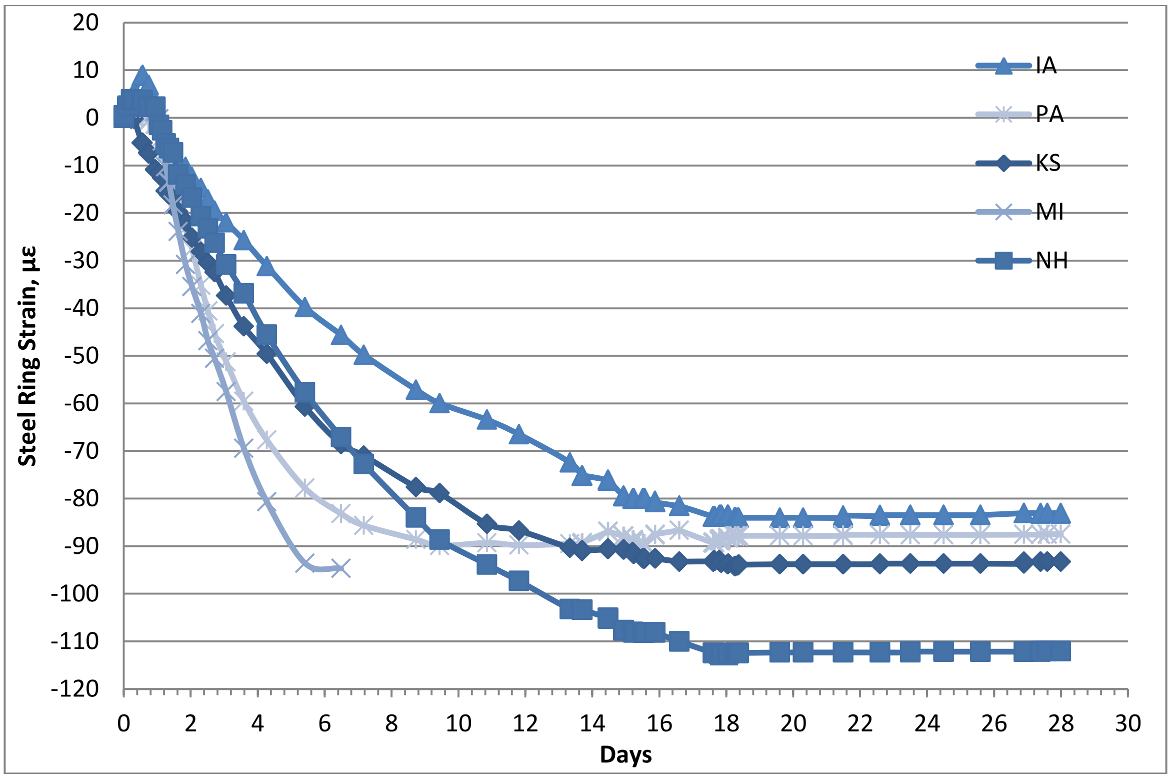

Figure 7. Strains of stell rings resulting from concrete shrinkage

Besides the length change, average strain rate factor can be used to evaluate the drying shrinkage in an unrestrained condition (Lomboy et al. 2010). Table 9 compares the shrinkage rate factors obtained from unrestrained prisms and restrained rings: the relative order obtained from the two tests is in good agreement – IA< KS< PA< NH< MI.

Table 9. Average strain rate factor

Mix	Average strain rate factor α (strain×10^{-6}/day$^{1/2}$)	
	Concrete prisms	Restrained rings
PA	83.0	34.0
NH	102.9	35.8
KS	81.2	26.1
MI	118.9	51.5
IA	34.0	23.1

Figure 8 shows cracking potential (Θ_{CR}) values of the concrete mixes. It was observed that only the Michigan mixture cracked, and that was when Θ_{CR} reached 2.1.

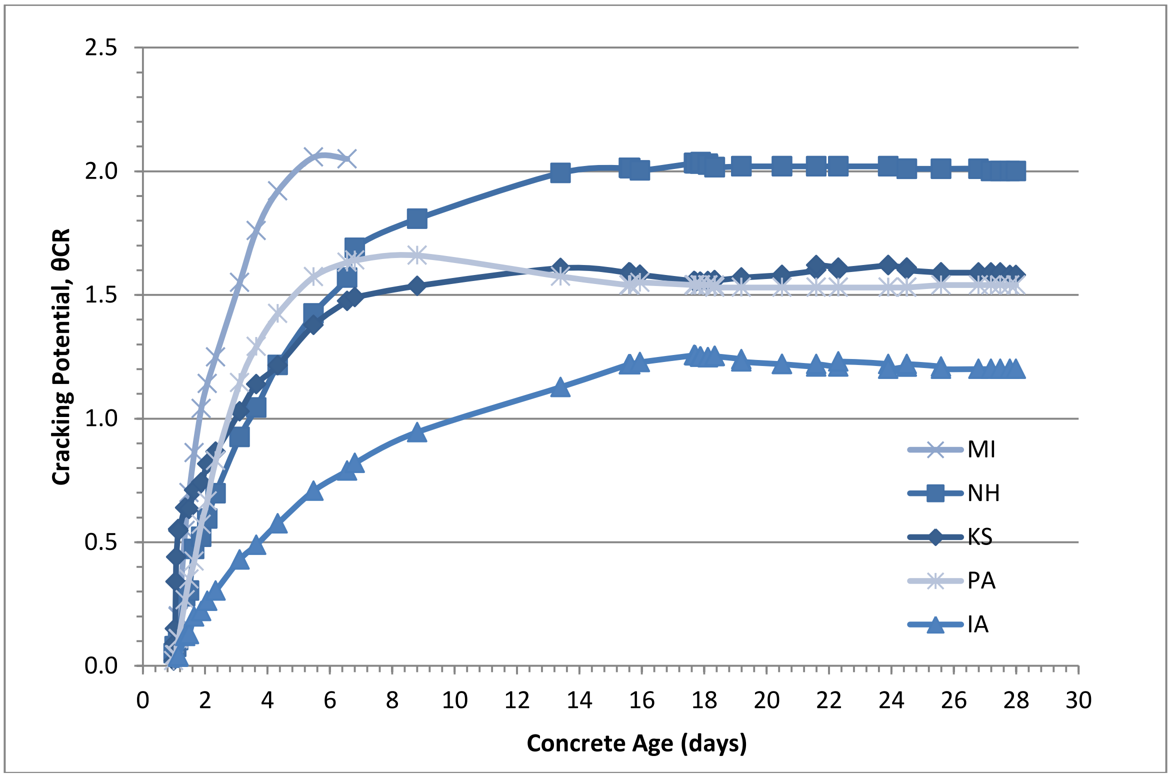

Figure 8. Shrinkage stress-to-tensile strength ratio (cracking potential Θ_{CR}) of restrained concrete rings with time

The cracking potential value of NH mixture was very close to MI mixture, but did not crack. This is attributed to fiber reinforcement in the NH mixture.

Salt Scaling Test

Specimens were rated on a scale of 0 to 5, with 0 having no scaling and 5 having severe scaling. Scaling rates are consistent with Phase II final report (Tikalsky et al. 2011). The average visual ratings of three specimens assigned to each field mixture after 50 cycles are given in Table 10.

Table 10. Visual condition of specimen

Mixture ID	KS	IA	PA	NH	NY	CA
Cycle 50	3	4	2	3	2	2

Slight surface scaling was seen in all field mixtures tested after 50 cycles. Mixtures with supplementary cementitious materials generally performed well in reducing the severity of the surface scaling except Iowa mixture using Class C fly ash.

Rapid Chloride Permeability, Porosity, and Air Void Analysis

Concrete cylinders were cast in the field and tested in accordance with ASTM C1202 in the laboratory for chloride ion penetration at 56 days. Table 11 summarizes the results and classifications for each mixture. All the field mixtures in this study had high chloride penetration resistance.

The boiling-water saturation technique described in ASTM C642 was used to measure the permeable pore space or voids (permeable porosity) in hardened concrete. Table 11 summarizes the porosity results for five field mixtures. Test results agreed well with chloride ion penetrability.

The air void system of hardened concrete samples was measured using the Rapid Air method. Table 11 shows the average air void test results. A spacing factor ≤ 0.20 mm measured using microscopical methods is an indication of a good concrete freeze-thaw resistance.

Table 11. Summary of chloride ion penetrability, porosity, and air void structure of hardened concrete

	Standard	UT	KS	MI	IA	PA	NH	NY	CA
Chloride ion penetrability at 56 days, coulombs	ASTM C1202	1800 (low)	500 (very low)	1000 (low)	1200 (low)	1800 (low)	1000 (low)	1200 (low)	1300 (low)
Porosity by boil test, %	ASTM C642	-	-	6.1	5.8	7.6	-	5.9	6.4
Air content, %	Rapid Air	-	7.4	2.2*	-	-	-	4.4	7.9
Specific surface, mm^{-1}		-	16.9	24.7	-	-	-	48.2	38.2
Spacing factor, mm		-	0.231	0.328	-	-	-	0.110	0.097

* MI hardened air data were not consistent with field data.

Owner and Contractor Feedback

In general, contractors and owners reported being satisfied with the performance of their concrete both in the fresh and hardened states. No mixture related difficulties were experienced. Specific feedback is summarized in the following:

- Utah
  - Excellent workability and finishing properties
  - Excellent rheological properties for the paving machine
  - Smooth day of paving with no problems
  - No cracking was found at 100 days after casting and outside of pavement joints
  - No scaling or freeze-thaw damage occurred after the first two winters
- Kansas
  - Workability and finishing properties were satisfactory
  - Use of the ternary mixture allowed the contactor to place a full depth deck in one pour instead of two pours traditionally
- Pennsylvania
  - Workability and finishing properties were satisfactory
  - Only some minor cracking was observed over the pier at four months after the bridge deck was constructed
- California
  - No materials difficulties experienced during construction
  - Some surface loss observed after the first winter on one section. This pavement is exposed to studded tires in winter.

KEY FINDINGS

In order to provide preliminary design and test results for concrete study, multiple paste and mortar mixtures composed of ordinary cements, binary system, and ternary system were developed and tested in this project.

The following points may be considered the key findings of the work:

- Ternary mixtures can be developed for any application and have a high probability of performing satisfactorily
- Performance will vary depending on the system selected
- Each mixture should be designed for the intended purpose

- Limits to dosage or type of SCM should be based on performance rather than a recipe (prescriptive) approach
- Performance can largely be predicted based on the available information, prior experience, and relative proportions of the individual components
- Materials intended for the field should be tested in laboratory trials. Do not substitute admixtures or SCMs in the field without trial batches
- Activities are driven by incentives; therefore specifications and financial incentives should carefully consider what is really wanted and when it is needed
- Increasing SCM content reduces environmental impacts
- There is a need for improved performance test methods with appropriate specification limits
- Innovative approaches to testing and evaluation such as the Wenner Probe and calorimetry were used and proved in this work
- There is still a need for an effective means of testing the air void system in real time, and assessing the ingredients and proportions of a sample of fresh concrete
- Systems have to be competitive in the marketplace to find acceptance
- Education and demonstration projects are critical to moving forward

OTHER IMPACTS

This research project provided quantitative information needed to make sound engineering judgments pertaining to the selection and use of SCMs in conjunction with portland or blended cements in ternary mixtures. This information can lead to a more effective utilization of supplementary materials and/or blended cements enhancing the life-cycle performance and cost of transportation pavements and structures.

In addition, a number of other impacts were realized in the execution of the work. These include a significant number of academic products:

1. Doctoral Graduates:
    - Tyson Rupnow (Iowa State University, 2008)
    - Pratanu Ghosh (University of Utah, 2011)
    - Shannon Hanson (University of Utah, 2013)
2. Masters Graduates:
    - Alison Marie St. Clair (Pennsylvania State University, 2007)
    - Mohamad Siddiqui (University of Utah, 2009)
    - Stephanie Marquez (University of Utah, 2011)
    - Xuhao Wang (Iowa State University, 2011)
3. Publications:
    a. Rupnow, T. D., Schaefer, V. R., Wang, K., and Tikalsky, P. J.; "Effects of Different Air Entraining Agents (AEA), Supplementary Cementitious Materials (SCM), and Water Reducing Agent (WR) on the Air Void Structure of Fresh Mortar," International Conference on Optimizing Paving Concrete Mixtures and Accelerated Concrete Pavement Construction and Rehabilitation,

FHWA/ACI/ACPA, Nov. 6-9, 2007.
b. St. Clair, A. M.; “Effect of Cementitious Combinations on Strength Development up to 28 Days and Shrinkage in Mortars,” Master Thesis, Pennsylvania State University, August 2007.
c. Rupnow, T. D.; “Evaluation of Laboratory and Field Techniques to Improve Portland Cement Concrete Performance,” Doctor of Philosophy Dissertation, Iowa State University, 2007.
d. Tikalsky, P., Schaefer, V., Wang, K., Scheetz, B., Rupnow, T., St. Clair, A., Siddiqi, M., and Marquez, S.; “Development of Performance Properties of Ternary Mixes: Phase I Final Report”, Report No. Pooled Fund Study TPF-5(117), Ames: Center for Transportation Research and Education, Iowa State University, December, 2007.
e. Marquez, S. A.; “Carbon Dioxide Signatures for Ternary Concrete Mixtures,” Master of Science Thesis in Civil Engineering, University of Utah, Salt Lake City, August, 2009.
f. Rupnow, T. D., Schaefer, V. R., and Wang, K.; “Evaluation of a Quick Heat Generation Index Test for Characterization of Cementitious Materials,” Transitioning from Fluid to Solid: Re-Examining the Behavior of Concrete at Early Ages, Proceeding ACI Convention, San Antonio, Texas, March 14-18, 2009.
g. Rupnow T. D., Wang, K., Schaefer, V., and Tikalsky, P.; “A Simple Method for Characterizing and Predicting Temperature Behavior of Ternary Cementitious Systems,” Journal of Construction and Building Materials, Elsevier Press, Vol. 25, 11/2010. 2290-2297.
h. Ghosh, P.; and Tikalsky, P. J.; “Effect of Ternary Cementitious Systems on Conductivity and Diffusion Coefficients,” 12th International Conference on Durability of Building Materials and Components,” ASTM-CIB-RILEM, Porto, Portugal, pp. 1609-1616, April 12-15, 2011.
i. Wang, X.; “Drying Shrinkage of Ternary Blends in Mortar and Concrete.” Master of Science Thesis in Civil Engineering Materials, Iowa State University, Ames, IA, 2011.
j. Wang, X., Taylor, P., Bektas, F., Wang, K., and Tikalsky P; “Drying Shrinkage Behavior of Mortars Made with Ternary Blends.” Paper presented at Mid-Continent Transportation Research Symposium, Ames, IA, August, 2011.
k. Tikalsky, P., Taylor, P., Hanson, S., Ghosh, P.; “Development of Performance Properties of Ternary Mixes: Phase II Final Report”, Report No. DTFH61-06-H-00011 Work Plan 12 Pooled Fund Study TPF-5(117), Ames: National Center for Concrete Pavement Technology, March 2011.
l. Wang, X., Taylor, P., Bektas, F., Wang, K., and Tikalsky P; “Drying Shrinkage Behavior of Mortars Made with Ternary Blends.” Paper presented at Transportation Research Board and accepted for publication in Transportation Research Record: Journal of the Transportation Research Board, Washington D.C., 2012.

As noted earlier, a number of promising test methods were also used and found to be effective in the work. These included the following methods:

1. The Wenner Probe was used to assess surface resistivity of concrete. This test is rapid, cost effective and has been adopted by more than one state department of transportation as an acceptance tool.
2. Semi-adiabatic calorimetry provides an effective means of assessing whether potential incompatibilities may occur between the ingredients of a mixture. Regular testing of materials on delivery will also flag changes in composition or behavior reducing the risk of unanticipated behavior at the batch plant or paving machine.

GUIDE SPECIFICATION

One of the deliverables for the project was a guide specification. Based on the overall findings discussed above, the guide specification should primarily be based on specifying performance rather than depending on prescriptive limits on amounts or types of cementitious materials used in a mixture.

The following clauses are therefore suggested for insertion into a specification:

- Ternary mixtures of cementitious materials are permitted
- Cementitious materials shall comply with their respective specifications:
    - Portland cement – ASTM C 150 or AASHTO M85
    - Blended cements – ASTM C 595 or AASHTO M 240
    - Hydraulic cements – ASTM C 1157
    - Fly ash – ASTM C 618 or AASHTO M 295
    - Slag cement ASTM C 989 or AASHTO M 302
    - Silica fume ASTM C 1240
- Concrete performance shall meet the following performance requirements based on trial batches:
    - Minimum air content [5%] […%] after placement
    - Slump shall be selected by the contractor. Delivered batches may not vary from the selected value by more than 1 in.
    - Shrinkage tested in accordance with ASTM C 157 modified as follows:
        - Soak samples for 7 days instead of 28
        - Initial reading to be taken at the end of soaking
        - Final reading to be taken of 28 days drying
        - Maximum shrinkage shall be [500 microstrain] [… microstrain]
    - Minimum surface resistivity shall be [10 kΩ/cm][… kΩ/cm] at 28 days
    - Comply with the requirements of AASHTO Recommended Practice PP 65-11, "Standard Practice for Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete"

- Sulfate expansion shall be less than 0.05% at 6 months when tested in accordance with ASTM C1012

- For paving applications, the mixture shall be evaluated using Hiperpav to verify that early cracking is not likely for the weather expected during construction
- Materials sources may not be changed without trial batches
- Materials dosages may not vary by more than 5% of total cementitious without trial batches
- Water may not be added to mixtures after initial mixing
- w/cm shall be selected based on the results of the trial batches to meet performance requirements. Delivered concrete w/cm shall not exceed the selected value based on batch tickets.

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APPENDICES: FIELD DEMONSTRATION REPORTS (ALPHABETIC ORDER)

Appendices for the Field Demonstration reports follow as outlined here:

Appendix	State
A and B	CA (2 reports)
C	IA
D	KS
E	MI
F	NH
G	NY
H	PA
I	UT

APPENDIX A. FIELD APPLICATION OF TERNARY MIXTURES: RECONSTRUCTION OF RIGID PAVEMENT IN CALIFORNIA

State Report
June 2012

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The research team at the National Concrete Pavement Technology Center at Iowa State University sincerely thanks the California Department of Transportation (Caltrans) and the Federal Highway Administration Mobile Concrete Laboratory for their cooperation, as well as Lehigh Heidelberg Cement Group, Salt River Materials Group—Phoenix Cement Co., and Teichert Construction Co. for supplying the equipment and materials.

INTRODUCTION

This document reports the activities and observations of the research group that performed on-site testing of a ternary mixture placed on the I-80 rigid pavement reconstruction project in Emigrant Gap, California. The cementitious system was composed of Type II-V cement from Lehigh Heidelberg Cement Group, Grade 120 slag cement from the same source, and Class F fly ash from Salt River Materials Group. This work is part of a comprehensive study that aims to improve the performance of concrete mixtures through use of ternary cementitious blends. This is the field demonstration phase that intends to provide consulting to the participating states and contractors on the use and field management of ternary mixtures. A mobile concrete laboratory (MCL) equipped for on-site cement and concrete testing was provided by the Federal Highway Administration (FHWA) to collect data and field observations. The MCL was invited to the project by Mr. Phil Zink and Dr. Dulce Feldman of the California Department of Transportation (Caltrans).

PROJECT INFORMATION

- I-80 Pavement Reconstruction, Emigrant Gap, California
- Contractor: Teichert Construction
- The original pavement was 8 in. jointed plain concrete pavement (JPCP). An 11-mile section was reconstructed on the eastbound I-80 from Emigrant Gap to Yuba Gap. Four of the 11 miles were reconstructed as continuously reinforced concrete pavement (CRCP), which was predominately used on the three lane section, and the remainder was reconstructed as JPCP using a ternary mixture.
- Reconstructed pavement information: 12 ft wide lanes, 10 ft shoulders, 14 in. thick, dense graded asphalt bond breaker with varying thickness (2.5 in. to 6 in.) between existing pavement and new rigid pavement to accommodate final grade.

Figure 1. I-80 rigid pavement reconstruction, Emigrant Gap, California

SITE LOCATION

An area in the central mix plant was prepared by the contractor for National Concrete Pavement Technology Center (National CP Tech Center) and FHWA crews to prepare samples. The 11-mile reconstruction section of the project is highlighted (points A and B) in Figure 2. The samples for fresh and hardened concrete property tests were prepared near Emigrant Gap.

Figure 2. Project location (Eastbound Lane)

SAMPLING AND TESTING ACTIVITIES

Safety concerns and limited access meant that testing could not be conducted at the point of placement. The mobile lab arrived at the plant during the CRCP construction on September 21, 2011. The National CP Tech Center crew arrived at job site on September 27, 2011. The project schedule (i.e., concrete placement, sampling, and testing) are shown in Table 1. The National CP Tech Center crew participated in sampling/testing activities on September 28, 2011, during the construction of the JPCP section. The samples were brought back to the plant site in 5 gallon buckets where all the field testing and casting took place. Hardened concrete specimens were transported to Iowa State University on September 30, 2011, for further testing. The following tests were conducted either in the field or in the laboratory:

- Semi-adiabatic calorimetry test
- Kelly-Ball test, unit weight, temperature, and air content of fresh concrete — 3 tests (ASTM C 360, ASTM C 138, ASTM C 1064, ASTM C 231)
- Microwave w/c ratio — 1 test (AASHTO T 318)
- Initial set and final set of concrete — 1 test (ASTM C 403)
- Compressive strength, splitting tensile strength, static modulus of elasticity — 4 in. × 8 in. cylinders at 3, 7, 28, and 56 days (ASTM C 39, ASTM C 496, ASTM C 469)
- Rapid chloride permeability — 4 in. × 8 in. cylinders at 56 days (ASTM C 1202)
- Salt scaling — 3 slabs (ASTM C 672)
- Free shrinkage best — 2 beams (ASTM C 157-mortar test)
- Surface resistivity test by FHWA's mobile lab crew — 4 in. × 8 in. cylinders at 28 and 56 days (AASHTO TP 95)

OBSERVATIONS OF THE RESEARCH TEAM

The following observations were made in the field work:

- GOMACO GHP 2800 slip form paver equipped with dowel bar inserter and GOMACO TC600 texturing/curing machine were used.
- The concrete was mixed at a central mix plant (Teichert Construction) and transported by ready-mix trucks. Figure 3 to 5 show pictures of the central mix plant and the aggregate stockpiles at the plant site, which was situated at the Nayak Road exit on I-80.

Figure 3. Concrete batch plant

Figure 4. Central mix plant

Figure 5. Aggregate stockpiles

- The mix design was approved by Caltrans material bureau. The accepted mix proportions are given in the Project Data section.
- The cementitious materials comprised a Type II-V cement from Lehigh Heidelberg Cement Group, a Grade 120 slag cement from the same source, and a Class F fly ash from Salt River Materials Group. The coarse aggregate was 1 in. and 1.5 in. river gravel, and fine aggregate was washed concrete sand. Both of them were from Teichert Construction, Hallwood, California.
- Setting time of the mix was determined using a single sample; initial and final sets occurred at 6.37 hours and 7.47 hours, respectively.
- According to the Workability Factor & Coarseness Factor graph (in the final Project Data section of this report), combined aggregate gradation for this project fell out of the well-graded region due to the high coarseness factor, i.e., 76.2. From Combined Percent Retained Curve, the aggregate gradation is good except the aggregate retained on 3/4 in. sieve causes a dip in the curve. However, these did not adversely affect workability and hardened properties of the mixture, as observed in the field and in the laboratory tests. The 0.45 Power Curve plot indicates a very good gradation of combined aggregate.
- The fresh concrete tests included Kelly-Ball, unit weight, and water-cementitious materials ratio by microwave, and concrete temperature. During the construction, a single set of samples was tested by the National CP Tech Center crew at 9:50 am and two sets were tested by the FHWA crew at 1:09 pm and 4:16 pm. Table 1 lists the fresh concrete properties and environmental conditions recorded during the testing process.
- Figures 6 to 13 illustrate activities from the site visit.

Table 1. Ambient conditions and fresh concrete properties of I-80 rigid pavement reconstruction project

Sample Information & Identification			Environmental Conditions				Fresh Concrete Workability Properties			Pressure Air
Sample Date	Sample Time	Sample Comments	Relative Humidity (%)	Ambient Temp. (˚F)	Wind Speed (mph)	Conc. Temp. (probe) (˚F)	Slump (in)	Unit Weight (lb/ft^3)	Microwave W/C Ratio (%)	% Air Content
9/28/11	9:50 AM	cp tech center sample taken at truck discharge	40.0	78.0	2.0	76.5	0.75	151.00	0.45	3.5
9/28/11	1:09 PM	FHWA MCL crew	-	-	-	82.0	1.25	150.10	-	4.2
9/28/11	4:16 PM	FHWA MCL crew	-	-	-	85.0	1.25	148.90	-	4.1

Figure 6. Concrete being discharged at central mix plant

Figure 7. FHWA's mobile laboratory

Figure 8. Concrete passing through the paver

Figure 9. GOMACO GHP 2800 slipform concrete paver

Figure 10. Dowel bar inserter

Figure 11. Concrete surface being sealed by Auto-Float

Figure 12. Texturing/curing machine

Figure 13. Specimen preparation

- The weather conditions recorded are given in Figures 14 to 16. The relative humidity ranged from 17 to 67 percent; the ambient temperature ranged from 59˚F to 79˚F; and the wind speed varied from 0 mph to 8 mph during the recorded period.

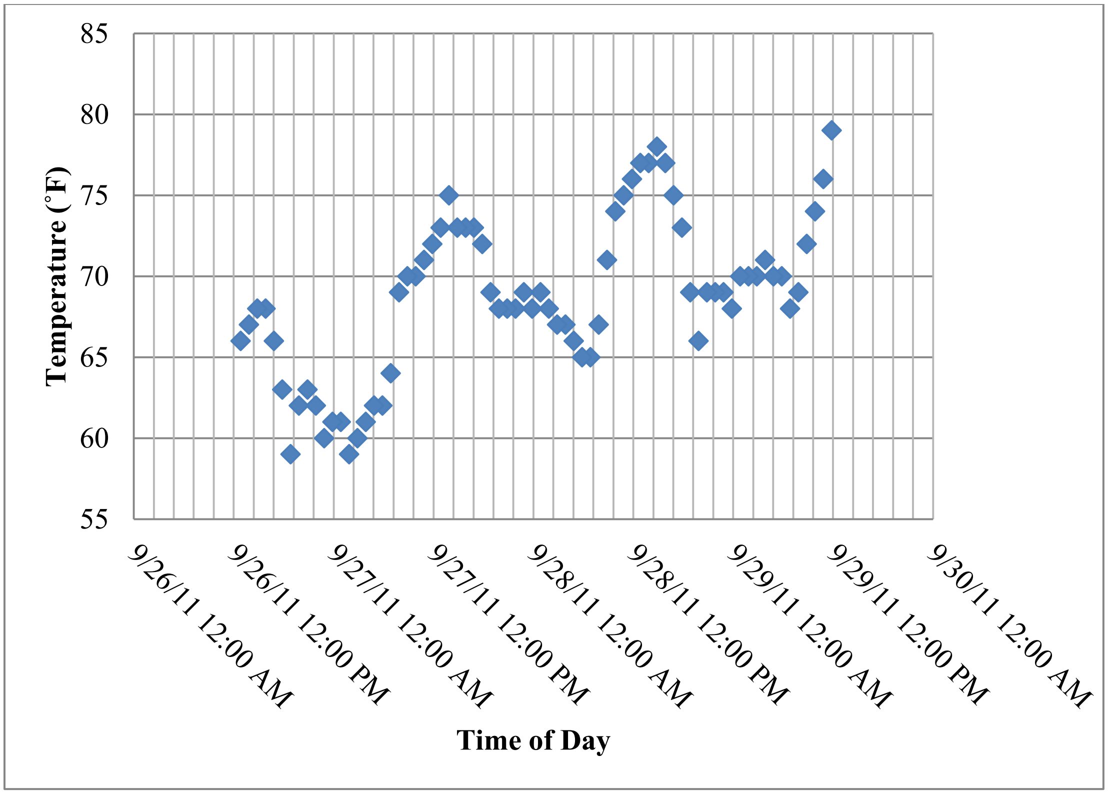


Figure 14. Ambient temperature

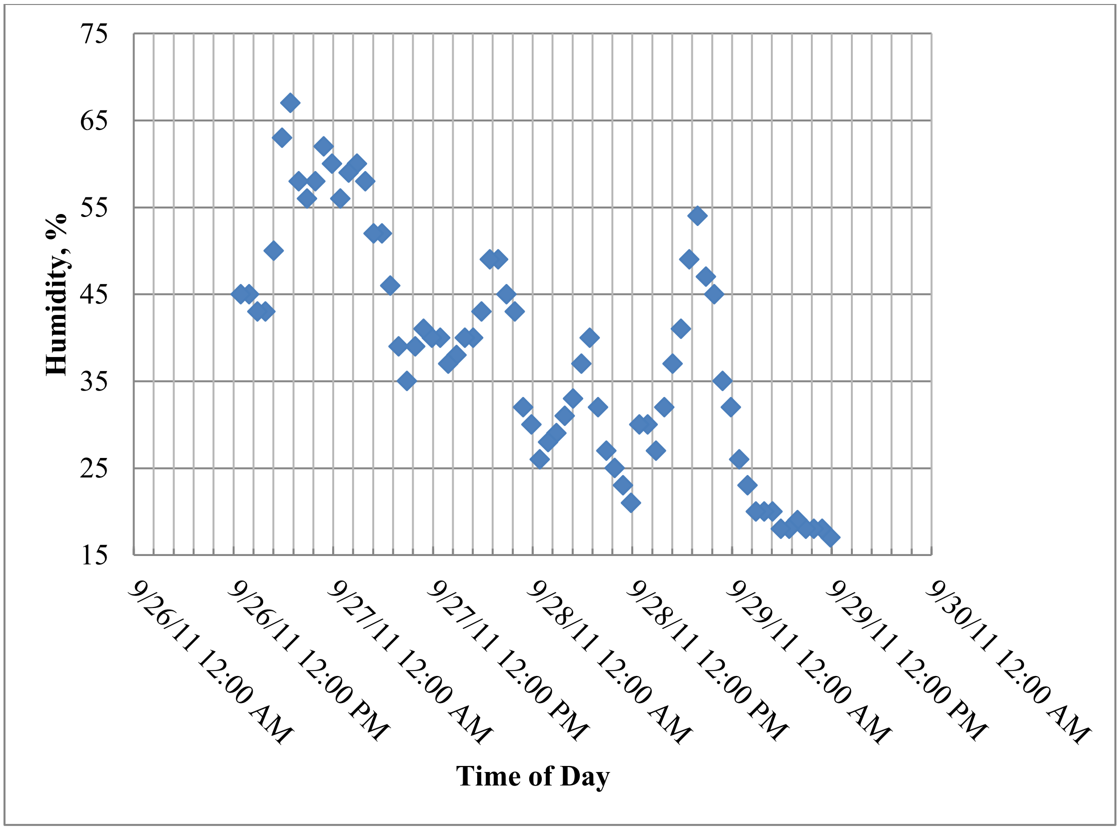


Figure 15. Relative humidity

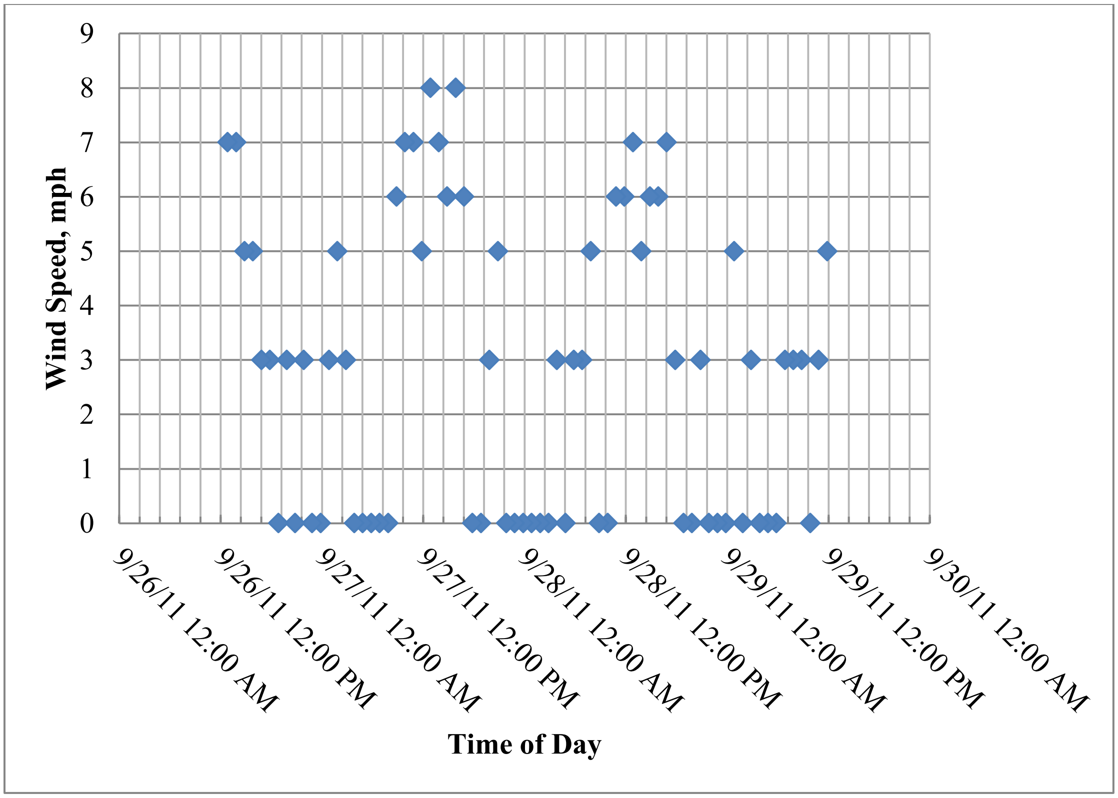


Figure 16. Wind speed

- A surface resistivity meter was used to evaluate the electrical resistivity of water saturated concrete to indicate permeability. The advantage of this test is that it is fast (less than five minutes) and does not require any sample preparation. Figure 17 shows the pictures of RCPT and resistivity tests. Table 2 gives the classification of chloride ion penetration by RCPT and surface resistivity test results.
- The 56-day resistivity was 15.2 kOhm-cm.

Figure 17. Rapid chloride permeability test (left) and surface resistivity meter (right)

Table 2. Classification according to Rapid Chloride Ion Penetration (ASTM C1202) and Surface Resistivity Tests in accordance with AASHTO TP 95

Chloride Ion Penetration	ASTM C 1202	Surface Resistivity Test
	RCP Test Charges Passed (Columbs)	4 in. × 8 in. Cylinder (KOhm-cm)
High	> 4,000	< 12
Moderate	2000-4000	12 - 21
Low	1000-2000	21 - 37
Very Low	100-1000	37 - 254
Negligible	<100	> 254

- The C1202 test results are shown in Table 3.
- The porosity value obtained by the boiling test (ASTM C 642) is given in Table 3.
- The strength development 28/7-day f_c ratio and some other significant hardened concrete properties are reported in Table 3.
- Compressive strength, splitting tensile strength, and modulus of elasticity results (ASTM C 39, ASTM C 496, and ASTM C 469) are given in Table 4, and development curves are plotted in Figures 18 to Figure 20.

Table 3. Properties of hardened concrete

Tests	Results		
7-day compressive strength, psi		3,080	
28-day compressive strength, psi		3,901	
Rapid chloride permeability, coulombs	Sample 1 1423	Sample 2 1135	Average 1279
Strength development 28/7 day fc ratio		1.27	
Mortar shrinkage μ-strain at 28 days		1050	
Porosity by boil Test, %		6.4	

Table 4. Mechanical properties of ternary concrete mix used in the project

Location	Age, days	Compressive Strength, psi	Splitting Tensile Strength, psi	Modulus Of Elasticity, psi
California	0	0	0	0.00E+00
	3	2,250	273	2.95E+06
	7	3,080	348	3.65E+06
	28	3,901	380	4.40E+06
	56	4,855	483	4.65E+06

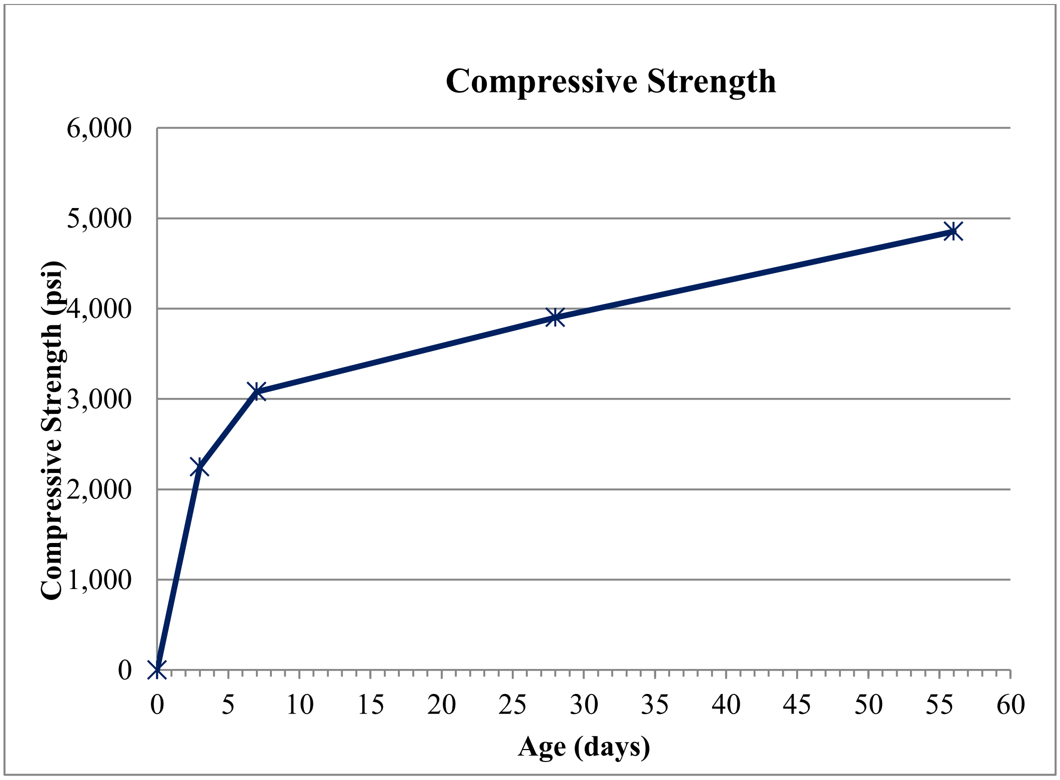


Figure 18. Compressive strength development with time

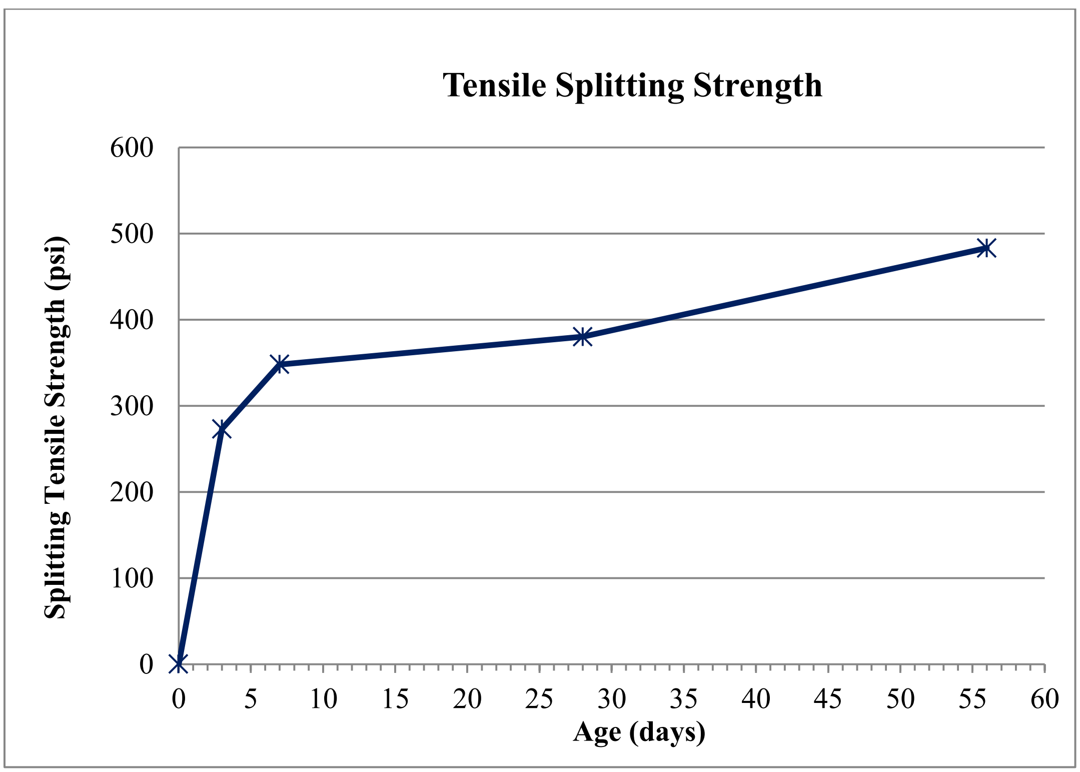


Figure 19. Tensile splitting strength development with time

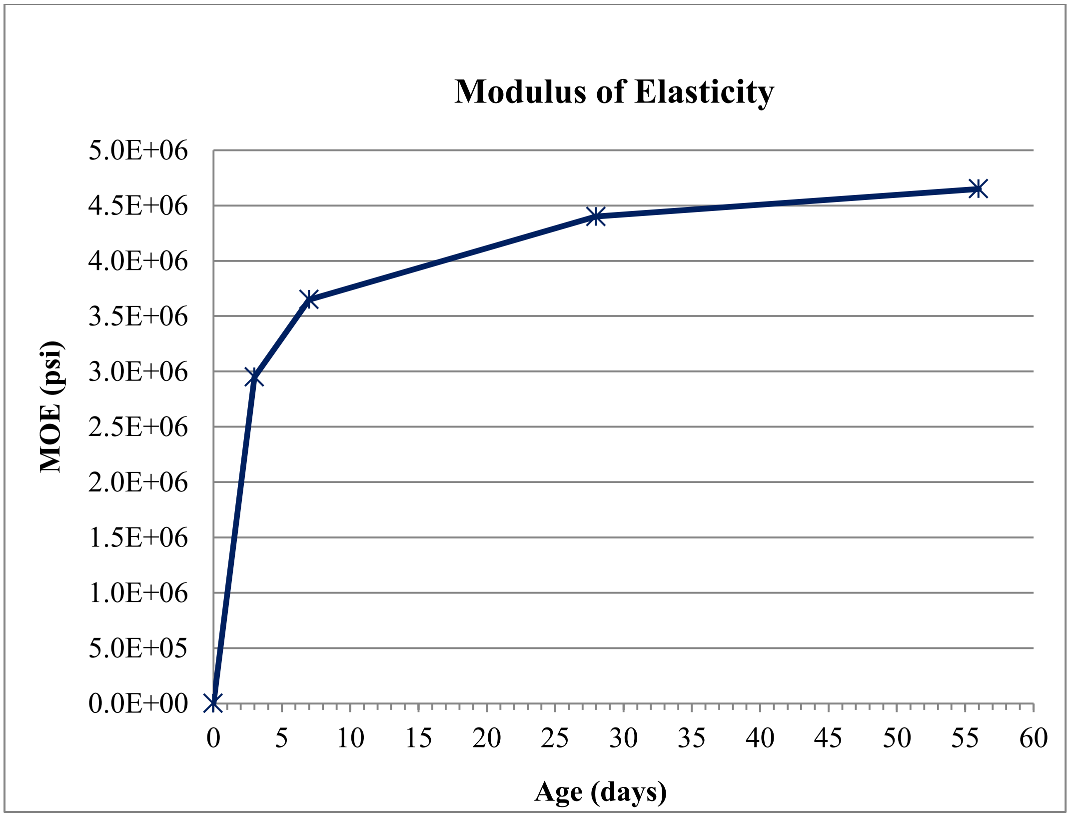


Figure 20. Modulus of elasticity development with time

- A free shrinkage test (ASTM C 157) using mortar was conducted in the laboratory. Two beams were cast on site, moist cured for seven days and then moved to a dry room at 23˚C and 50 percent relative humidity. The drying shrinkage results are given in Table 5 and also plotted in Figure 21.

Table 5. Free shrinkage test results

California Project Free Shrinkage Test (ASTM C 157)				
Dry Time	**Beam 1 change%**	**Beam 2 change %**	**Average**	**µ-strain**
1	-0.034	-0.030	-0.032	-320
4	-0.074	-0.068	-0.071	-710
7	-0.087	-0.085	-0.086	-860
14	-0.092	-0.093	-0.092	-920
28	-0.114	-0.096	-0.105	-1050
56	-0.135	-0.113	-0.124	-1125

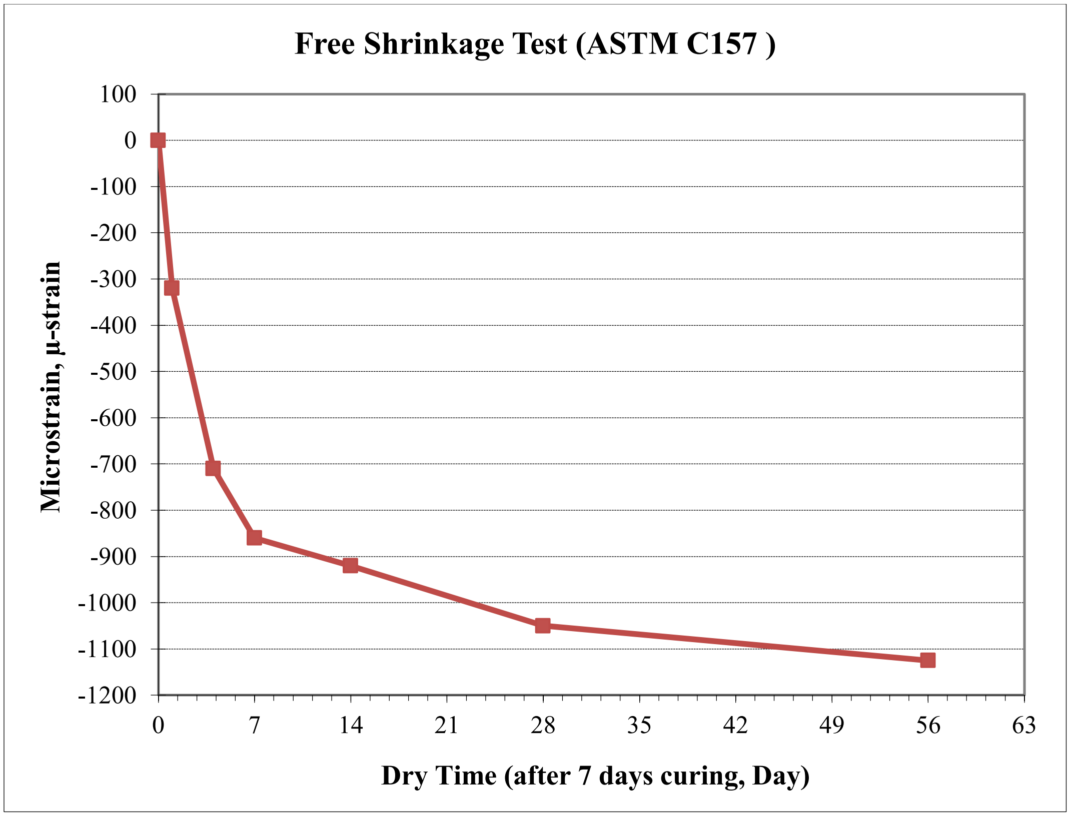


Figure 21. Free shrinkage of prisms (ASTM C 157)

- The air void test (rapid air test) results for three samples from the same batch are given in Table 6. The spacing factors were acceptable.

Table 6. Air void structure results

	Air content, %	Specific surface, mm^{-1}	Spacing factor, mm
CA cyl.1 side 1	7.29	42.36	0.093
CA cyl.2 side 1	8.84	39.38	0.083
CA cyl.2 side 2	7.52	32.91	0.116
Average	7.88	38.22	0.097

- A calorimetry test was conducted using an AdiaCal device. The test equipment and results are shown in Figure 22 and 23. The test was recorded from 9:50 AM and the peak value reached about 105°F at 14.6 hours.

Figure 22. AdiaCal calorimetry test equipment for heat of hydration of concrete

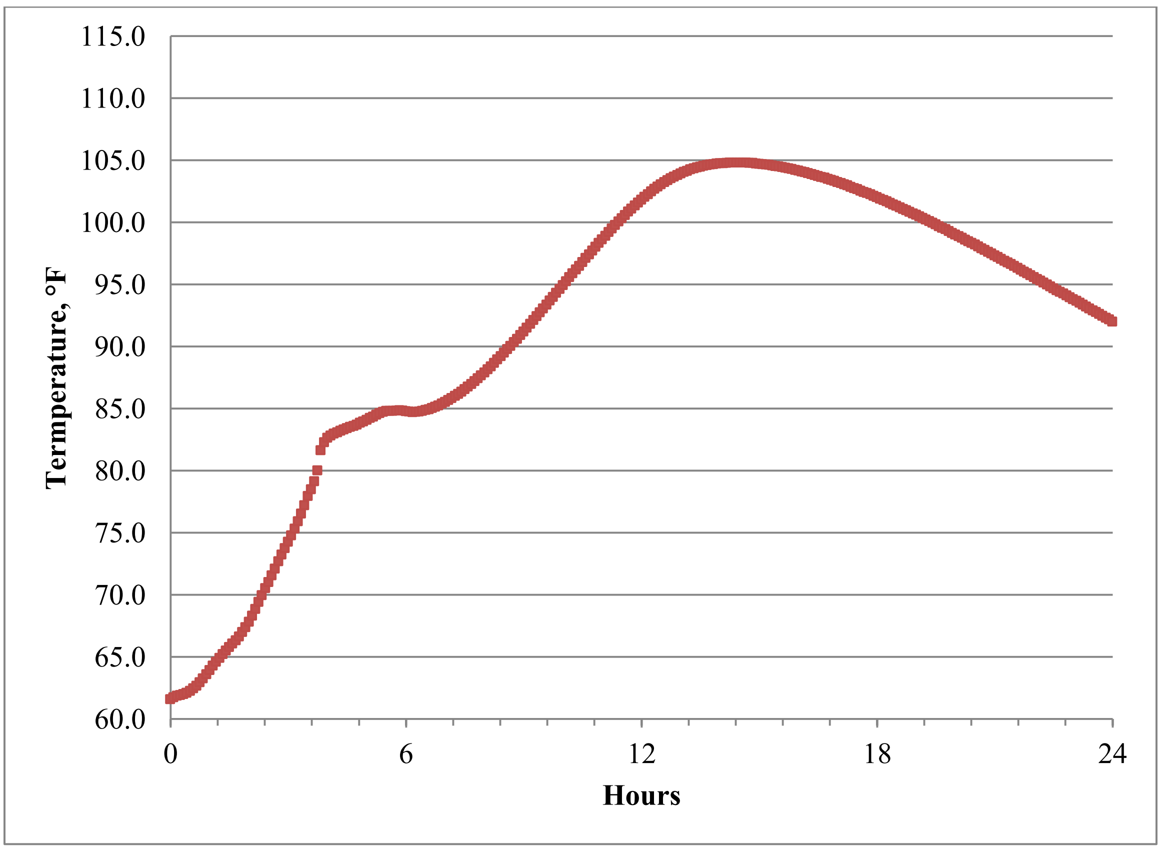


Figure 23. Calorimetry test results

- A salt scaling test (ASTM C 672) was performed: A photograph after the 50th cycle is shown in Figure 24. The visual ratings assigned to each specimen are given in Table 7.

Table 7. Salt scaling test visual condition of specimen

CA salt scaling specimens	Condition of surface					
	Cycle 5	Cycle 10	Cycle 15	Cycle 20	Cycle 25	Cycle 50
No. 1	1	1	1	2	2	2
No. 2	1	1	1	2	2	2
No. 3	1	1	1	2	2	2

Figure 24. CA salt scaling sample after 50th freeze-thaw cycle

PROJECT DATA

The following test data are provided for information only; comments and conclusions will be reported in the comprehensive Phase III report of the pooled fund project *Development of Performance Properties of Ternary Mixtures.*

Mix Design & Misc. Info.

General Information

Project:	CalTrans Contract 03-2C8604, I-80 Pavement Reconstuction, Emigrant Gap , CA
Contractor:	Teichert Construction
Mix Description:	675 lb Cementitious
Mix ID:	LB11-0039
Date(s) of Placement:	9/28/11

Cementitious Materials	Source	Type	Spec. Gravity	lb/yd^3	% Replacement by Mass
Portland Cement:	Lehigh Heidelberg Cement Group	Type II-V	3.150	452	
GGBFS:	Lehigh Heidelberg Cement Group	Grade 120	2.930	169	25.04%
Fly Ash:	Salt River Materials Group - Phoenix Cement Co.	Class F	2.060	54	8.00%
Silica Fume:					
Other Pozzolan:					
				675	**lb/yd^3**
				7.2	**sacks/yd^3**

Aggregate Information	Source	Type	Spec. Gravity SSD	Moisture(%)	% Passing #4
Coarse Aggregate:	Teichert, Hallwood	River gravel, 1"	2.750	1.30%	3.0%
Intermediate Aggregate #1:	Teichert, Hallwood	River gravel, 1.5"	2.760	1.10%	1.0%
Intermediate Aggregate #2:					
Fine Aggregate #1:	Teichert, Hallwood	Washed concrete sand	2.640	1.90%	96.0%

Coarse Aggregate %:	31.8%
Intermediate Aggregate #1%:	30.1%
Intermediate Aggregate #2%:	
Fine Aggregate #1 %:	38.1%

Mix Proportion Calculations

Water/Cementitious Materials Ratio:	0.370
Air Content:	5.50%

	Volume (ft^3)	Batch Weights SSD (lb/yd^3)	Spec. Gravity	Absolute Volume (%)
Portland Cement:	2.300	452	3.150	8.517%
GGBFS:	0.924	169	2.930	3.424%
Fly Ash:	0.420	54	2.060	1.556%
Silica Fume:				
Other Pozzolan:				
Coarse Aggregate:	5.681	975	2.750	21.041%
Intermediate Aggregate #1:	5.377	926	2.760	19.916%
Intermediate Aggregate #2:				
Fine Aggregate #1:	6.806	1,130	2.640	25.209%
Water:	4.006	250	1.000	14.839%
Air:	1.485			5.500%
	27.000	**3,956**		**100.000%**
	Unit Weight (lb/ft^3)	**146.5**	**Paste**	**33.835%**
			Mortar	**58.866%**

Admixture Information	Source/Description	oz/yd^3	oz/cwt
Air Entraining Admix.:	BASF Pave Air 90	20.30	3.01
Admix. #1:	BASF MASTERPAVE Plus Type A WR	33.80	5.01
Admix. #2:			
Admix. #3:			

AVA Information	Absolute Volume (%)
Air Free Paste:	28.335%
Air Free Mortar:	53.366%

TWINING

Corporate Headquarters 2883 East Spring Street, Suite 300, Long Beach, CA 90806
Laboratory 3310 Airport Way, Long Beach, CA 90806
Phone 562.426.3355 / Fax 562.426.6424 / Web twininginc.com

STATEMENT OF CONCRETE MIX DESIGN *Conversion to inch-pound units* Date: 28-Apr-11
FOR QUALIFICATION BY FIELD TRIAL BATCH (1), (2), (4), (5)

Client:	TEICHERT CONSTRUCTION ATTN: MR. GREG BARTHOLOMEW 4401 DULUTH AVE. ROSEVILL, CA 95678
Project:	CALTRANS CONTRACT 03-2C8604 RTE-80, NEVADA COUNTY EMIGRANT GAP
Architect:	-----
Engineer:	-----
Contractor:	TEICHERT CONSTRUCTION
Subcontractor:	-----
Supplier:	TEICHERT CONSTRUCTION

Mix Design #:	**LB11-0039 (Revised for X-values)**
Max. Size Aggregate:	1.5 in.
Design MOR: (1)	570 psi in 28 days; 650 in 42 days
Penetration:	1 in. (1.5 in. maximum)
Slump:	N/A
Placement Method:	Place
Mix Design Method:	ACI 211.1, Caltrans Standards Specifications (1)
Material Source:	
Cement:	Portland Cement Type II/V, Lehigh Permanente
Fly Ash Class F:	Class F, Cholla, Four Corners
GGBFS:	Grade 120, Lehigh
WCS	Teichert, Hallwood
1" MSA, 1.5" MSA	Teichert, Hallwood

The Supplier is responsible for compliance of materials used to ASTM & CalTrans standards.

PRIMARY AGGREGATE GRADATION
(% Passing US Standard Sieve)

Size	WCS	#4	L.W.	#3	#2	Comb.
Agg%:	38.1		0.0	31.8	30.1	100
2"	100			100	100	100
1.5"	100			100	100	100
1"	100			100	45	83
0.75"	100			85	16	70
0.5"	100			44	5	54
0.375"	100			25	2	47
#4	96			3	1	38
#8	77			1		30
#16	60					23
#30	43					16
#50	22					8
#100	7					3
#200	2.0					1
F.M.	2.95			6.86	7.81	5.66

CONCRETE MIX DESIGN FOR 1 CUBIC YARD (SSD BASIS)

Material		Sp.G.	Abs.Vol. (cu.ft.)	Batch Wt. (lb.)
Cement:	**4.81** Sacks	3.15	2.30	**452**
Fly Ash Class F:		2.06	0.42	**54**
GGBFS:		2.93	0.92	**169**
Washed Concrete Sand:		2.66	6.81	**1130**
#4 (0.375") Aggregate:		0.00	0.00	**0**
#3 (1") Aggregate:		2.75	5.68	**975**
#2 (1.5") Aggregate:		2.76	5.37	**926**
L.W.:		0.00	0.00	**0**
pcf ; Loose Volume			[**0.0**]	
Air:	5.5 %	----	1.49	----
Design Water:	30.0 gals.	1.00	4.00	250

Admixture. (3)

MASTER PAVE PLUS	5.0 fl.oz./100# cmt+P	**33.8** fl.oz.
PAVE AIR 90	3.0 fl.oz./100# cmt+P	**20.3** fl.oz.

PERTINENT PROPERTIES:

Est. Unit Weight, pcf:	Cementitious Factor:	W/(C+FA+SF):
Plastic 147	7.18 sk./cu.yd.	0.37 by weight
	8.0 % FA; 25.0 % GGBFS	4.18 gal/sack

Location in Structure: Pavement

NOTES:
(1) The mix is designed for field trial batch, testing ages are 10, 21, and 28 days.
(2) During the field trial batching we recommend to test the mix for setting time, strength gain in early age, and maturity.
(3) Dosage rate of Pave Air 90 shall be adjusted to produce the design air content.
(4) Laboratory shrinkage (AASHTO T160) and coefficient of thermal expansion data (AASHTO T336) are pending.
(5) The proportions of the cementitious blend are subject to acceptance of the Resident Engineer.

X-Values:

WCS		1"x#4 (2)		1.5"x3/4"		Amount of material passing 0.375" (9.5 mm) sieve and retained on # 8 (2.36 mm) sieve:
# 16	X= *62 preset*	0.75"	X= *85*	1"	X= *41 preset*	*17*
# 30	X= *42 preset*	0.375"	X= *23 preset*			
# 50	X= *22*					

X-values for WCS & 1"x#4 rock are based on the proposed individual gradations provided by Teichert and are subject to review by the same.
X-value for primary aggregate size 1.5"x0.75" is a preset value and is subject to review by Teichert.

Prepared by: Tom Carter

Reviewed by: Paul Soltis, RCE

PROFESSIONAL ENGINEER
PAUL C. SOLTIS
Exp. 12/31/12
STATE OF CAL

CA - Ternary Mixtures

Sample Information:

Project: CalTrans Contract 03-2C8604, I-80 Pavement Reconstuction, Emigrant Gap , CA

Date: 09/28/11
Time: 9:50 AM

Type of Paving: Interstate Pavement Reconstruction
Placement: slip form

Sta: 461+55
Latitude: n/a
Longitude: n/a

Mix ID: LB11-0039
Truck IDs: #27 load

Sample Location Mark & Comments: Sample brought to the plant site in 5 gallon buckets at 10:05 am

Environmental Conditions:

Dew Point: 51.0
Relative Humidity: 40%

Wind Speed: 2.0
Ambient Temp.: 78.0

Concrete Properties:

Base/Soil Temp. (internal)(ºF): n/a
Base Temp. (surface)(ºF): n/a

Microwave Water Content Samples: √
Calorimetry (ADIACAL Cylinders): 6

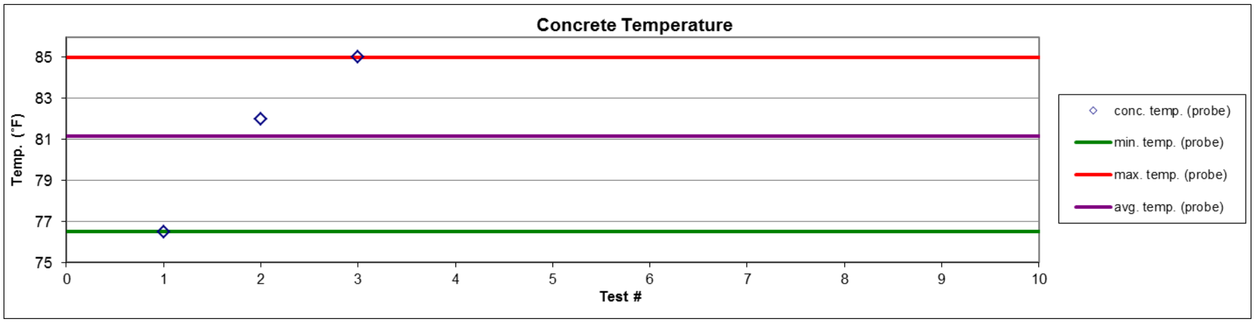
Set-Time (ASTMC403) Mortar Samples: √
Cylinder for RCP & Perm. Voids Boil Test: use adiacal

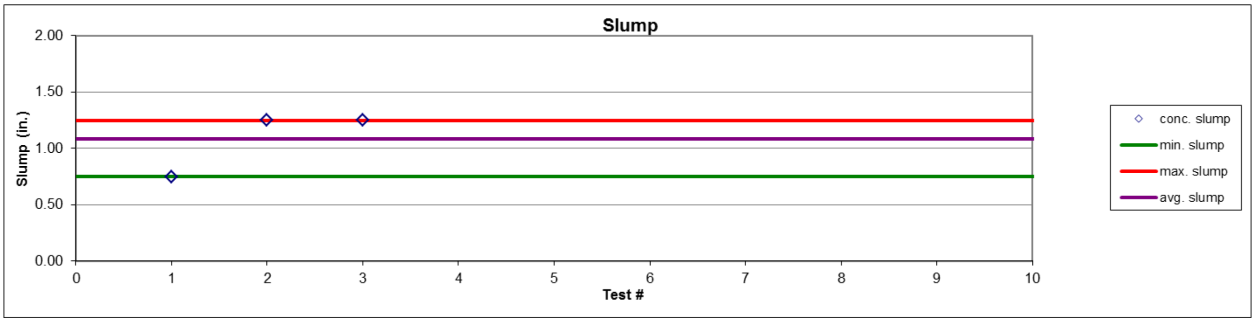
Scaling Blocks: 3

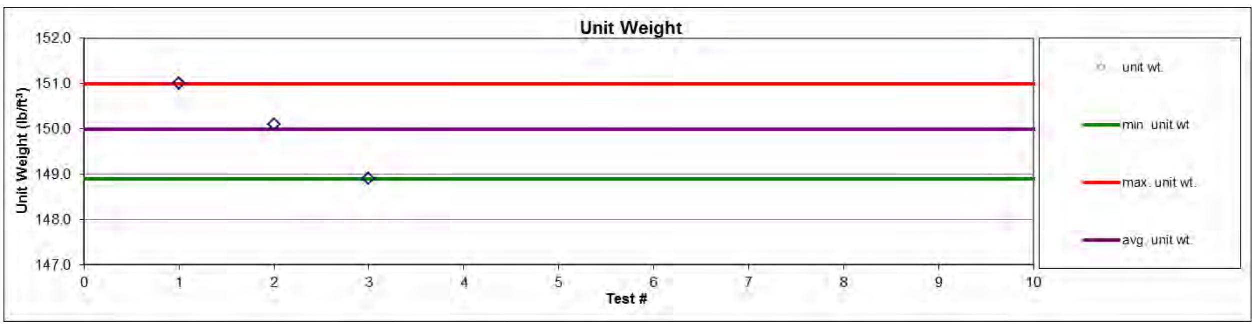
Compressive, Tensile & MOR Cylinders: 24

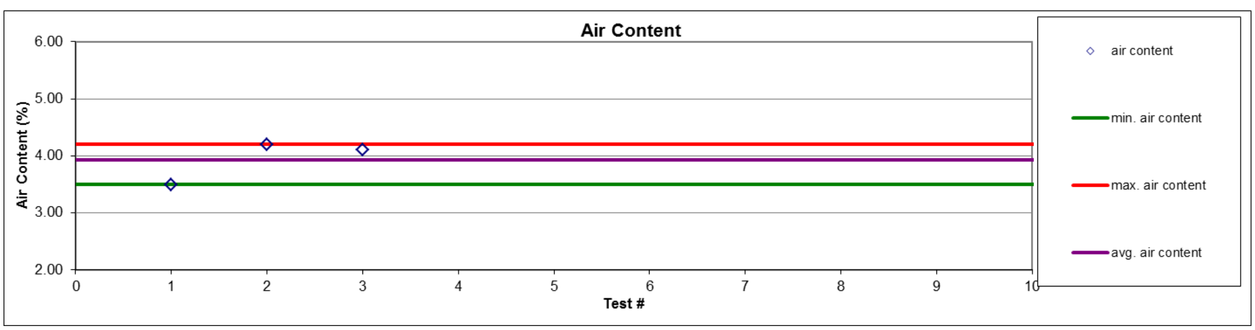
Shrinkage Beams: 2

Concrete Temp.(ºF):	76.5
Slump (in.):	0.75
Air Content:	3.5%
Unit Weight (lb/ft^3):	151.0


Concrete Temperature
Temp. (°F)
Test #
conc. temp. (probe)
min. temp. (probe)
max. temp. (probe)
avg. temp. (probe)


Slump
Slump (in.)
Test #
conc. slump
min. slump
max. slump
avg. slump


Unit Weight
Unit Weight (lb/ft³)
Test #
unit wt.
min. unit wt.
max. unit wt.
avg. unit wt.

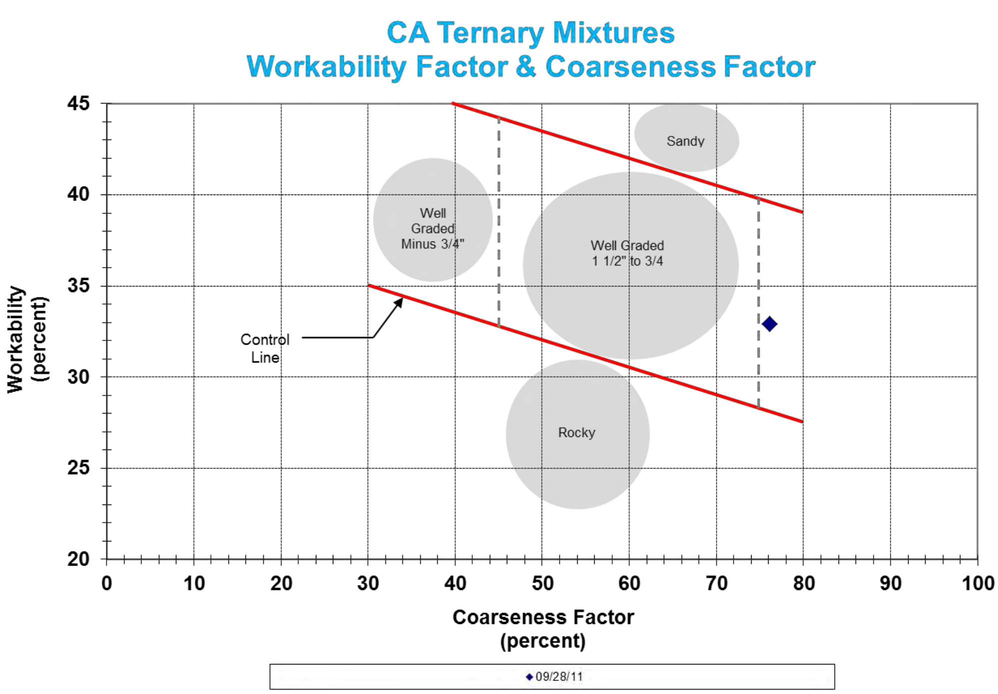

Air Content
Air Content (%)
Test #
air content
min. air content
max. air content
avg. air content

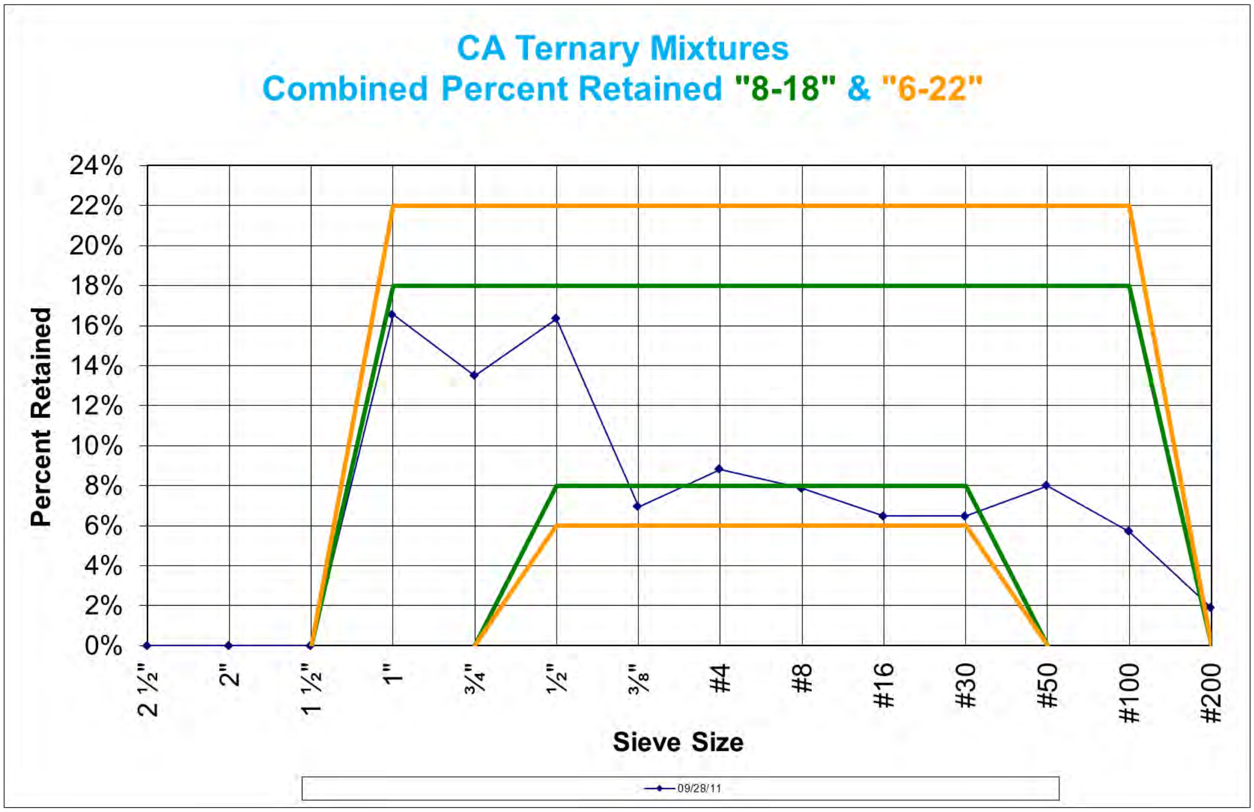
Project:	CalTrans Contract 03-2C8604, I-80 Pavement Reconstuction, Emigrant Gap , CA
Mix ID:	LB11-0039
Sample Comments:	
Test Date:	09/28/11

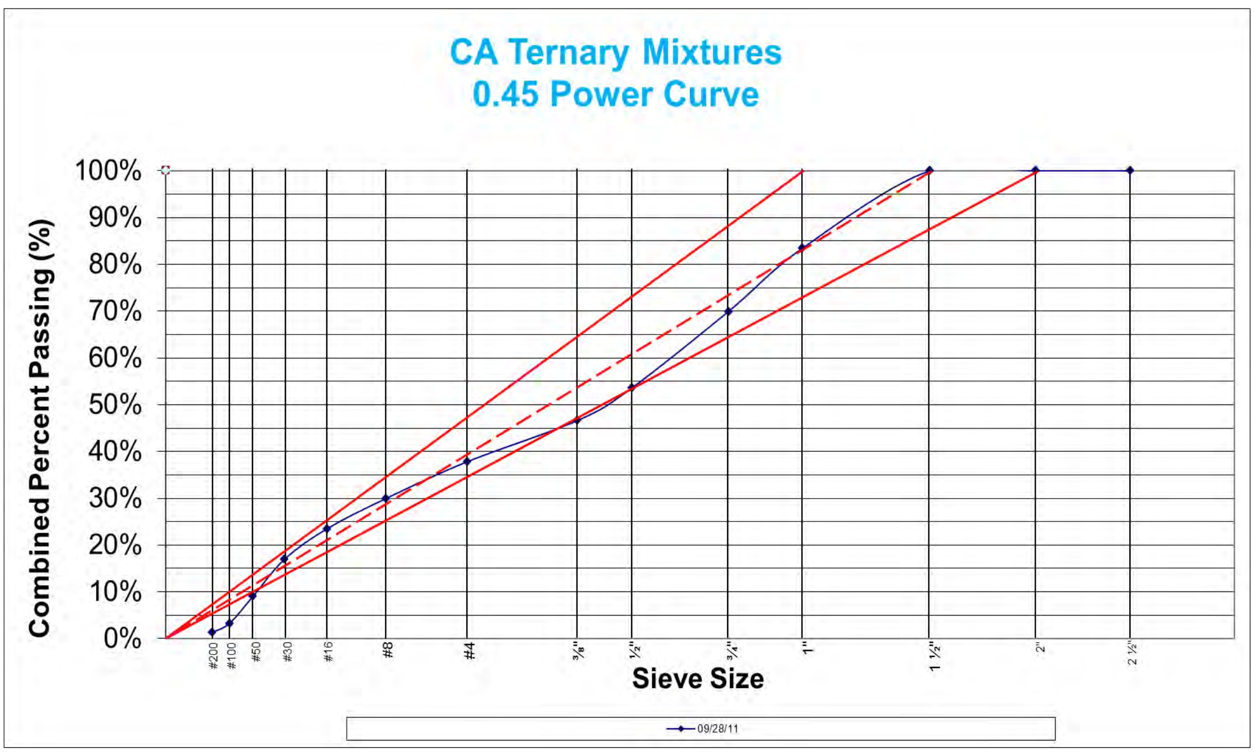
Total Cementitious Material:		675 lb/yd^3		
Agg. Ratios:	31.80%	30.10%	38.10%	100.00%

Sieve	Coarse	Intermediate	Fine #1	Fine #2	Combined % Retained	Combined % Retained On Each Sieve	Combined % Passing
2 ½"	100.0%	100.0%	100.0%		0%	0%	100%
2"	100.0%	100.0%	100.0%		0%	0%	100%
1 ½"	100.0%	100.0%	100.0%		0%	0%	100%
1"	100.0%	45.0%	100.0%		17%	17%	83%
¾"	85.0%	16.0%	100.0%		30%	13%	70%
½"	44.0%	5.0%	100.0%		46%	16%	54%
⅜"	25.0%	2.0%	100.0%		53%	7%	47%
#4	3.0%	1.0%	96.0%		62%	9%	38%
#8	1.0%	1.0%	77.0%		70%	8%	30%
#16	1.0%	1.0%	60.0%		77%	6%	23%
#30	1.0%	1.0%	43.0%		83%	6%	17%
#50	1.0%	1.0%	22.0%		91%	8%	9%
#100	1.0%	1.0%	7.0%		97%	6%	3%
#200	1.0%	1.0%	2.0%		98.6%	1.9%	1.4%

Workability Factor: 32.9
Coarseness Factor: 76.2




CA Ternary Mixtures
Combined Percent Retained "8-18" & "6-22"
Percent Retained
24%
22%
20%
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
2 ½"
2"
1 ½"
1"
¾"
½"
⅜"
#4
#8
#16
#30
#50
#100
#200
Sieve Size
09/28/11


CA Ternary Mixtures
0.45 Power Curve
Combined Percent Passing (%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
#200
#100
#50
#30
#16
#8
#4
⅜"
½"
¾"
1"
1 ½"
2"
2 ½"
Sieve Size
09/28/11

California - Ternary Mixtures

Set Time ASTM C 403

Project: CalTrans Contract 03-2C8604, I-80 Pavement Reconstuction, Emigrant Gap , CA

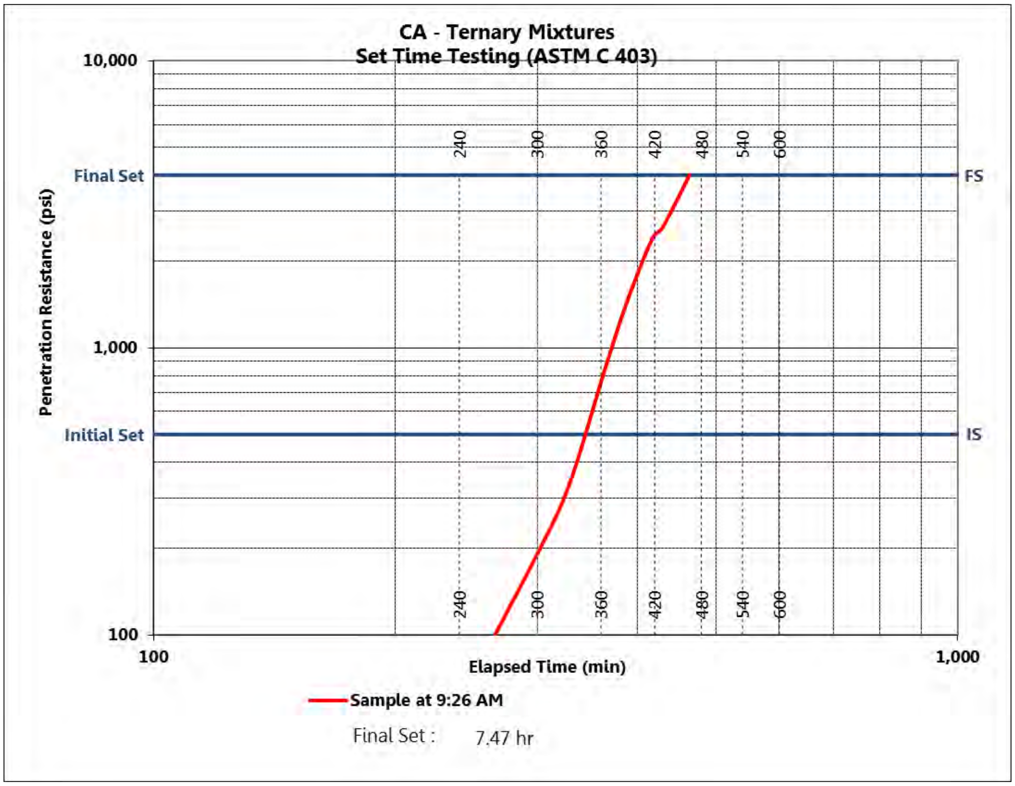
Date: 09/28/11 Start Time: 9:26 AM

Sta: n/a

Test Data

Penetration Time (xx:xx-24 hr format)	Time (min)	Needle # (1,2,4,10,20 or 40)	Force (lb)	Penetration Resistance (psi)	Sample Temp. (ºF)
1:30 PM	244.00	1	64	64.00	77.7
2:25 PM	299.00	2	94	188.00	76.6
2:55 PM	329.00	4	84	336.00	76.5
3:30 PM	364.00	10	84	840.00	76.3
3:55 PM	389.00	20	74	1480.00	76.6
4:23 PM	417.00	40	60	2400.00	77.7
4:36 PM	430.00	40	66	2640.00	78.4
5:10 PM	464.00	40	100	4000.00	80.2

Initial Set (at 500 psi PR)	estimated times using forecast function	**382**	minutes	**6.37**	hours
Final Set (at 4,000 psi PR)		**448**	minutes	**7.47**	hours



CA - Ternary Mixtures
Set Time Testing (ASTM C 403)
10,000
Final Set
1,000
Initial Set
100
Penetration Resistance (psi)
FS
IS
240
300
360
420
480
540
600
100
1,000
Elapsed Time (min)
Sample at 9:26 AM
Final Set : 7.47 hr

California - Ternary Mixtures

Microwave Water Content Worksheet

Project: CalTrans 03-2C8604, I-80 Pavement Reconstuction, Emigrant Gap , CA
Date: 09/28/11 Time: 9:50 AM
Sta: n/a

Test Data

Mass of tray+cloth+block+fresh test sample, W_F (g)	3,680.1
Mass of tray+cloth+block, W_S(g)	2,188.7
Mass of tray+cloth+dry sample, W_D (g) (5mins)	3,642.7
Mass of tray+cloth+dry sample, W_D (g) (7 mins)	3,614.0
Mass of tray+cloth+dry sample, W_D (g) (9 mins)*	3,588.3
Mass of tray+cloth+dry sample, W_D (g) (11 mins)*	3,569.3
Mass of tray+cloth+dry sample, W_D (g) (13 mins)*	3,563.2
Mass of tray+cloth+dry sample, W_D (g) (15 mins)*	3,559.3
Mass of tray+cloth+dry sample, W_D (g) (17 mins)*	3,556.5
Mass of tray+cloth+dry sample, W_D (g) (19 mins)*	3,554.0
Mass of tray+cloth+dry sample, W_D (g) (Final)**	3,554.0
Water content percentage, W_C (%)	**8.5%**
Unit weight of fresh concrete, UW (lb/ft^3)***	151.0
Total water content, W_T, (lb/yd^3)	**344.7**
Total cementitious weight (lb/yd^3)	675
Fine aggregate weight (lb/yd^3)	1130
Coarse Aggregate weight (lb/yd^3)	975
Intermediate Aggregate weight (lb/yd^3)	926
Fine aggregate absorption (%)	1.90%
Coarse aggregate absorption (%)	1.30%
Intermediate aggregate absorption (%)	1.10%
w/c	**0.445**

* If necessary (stop if the weight loss is less than 1g)
** Mass at test termination
***From unit weight test

Sample ID:	ternary CA cylinder 1 side 1		
Sample Size (mm x mm):	80 x 80	Length Traversed (mm):	2413.1
Paste Content (%):	28.80	Area Traversed (mm x mm):	70 x 70

Chord Length Distribution - Table

Class No.	Chord size (microns)	Number of Chords in Class	Number of Chords in Percent	Air Content in Class	Cumulated Air Content	Chord length frequency	Air content, fraction	
1	0-10	212	11.37	0.070	0.070	0.11	0.070	0.00-0.01
2	10-20	637	34.17	0.370	0.440	0.34	0.370	0.01-0.02
3	20-30	259	34.17	0.270	0.710	0.14	0.270	0.02-0.03
4	30-40	124	6.65	0.180	0.890	0.07	0.180	0.03-0.04
5	40-50	106	5.69	0.190	1.080	0.06	0.190	0.04-0.05
6	50-60	62	3.33	0.140	1.220	0.03	0.140	0.05-0.06
7	60-80	88	4.72	0.260	1.480	0.05	0.260	0.06-0.08
8	80-100	62	3.33	0.230	1.710	0.03	0.230	0.08-0.10
9	100-120	36	1.93	0.170	1.880	0.02	0.170	0.10-0.12
10	120-140	24	1.29	0.130	2.010	0.01	0.130	0.12-0.14
11	140-160	35	1.88	0.220	2.230	0.02	0.220	0.14-0.16
12	160-180	15	0.80	0.110	2.330	0.01	0.110	0.16-0.18
13	180-200	21	1.13	0.170	2.500	0.01	0.170	0.18-0.20
14	200-220	14	0.75	0.120	2.620	0.01	0.120	0.20-0.22
15	220-240	17	0.91	0.160	2.780	0.01	0.160	0.22-0.24
16	240-260	10	0.54	0.100	2.880	0.01	0.100	0.24-0.26
17	260-280	8	0.43	0.090	2.970	0.00	0.090	0.26-0.28
18	280-300	16	0.86	0.190	3.160	0.01	0.190	0.28-0.30
19	300-350	11	0.59	0.150	3.310	0.01	0.150	0.30-0.35
20	350-400	12	0.64	0.190	3.500	0.01	0.190	0.35-0.40
21	400-450	12	0.64	0.210	3.710	0.01	0.210	0.40-0.45
22	450-500	6	0.32	0.120	3.830	0.00	0.120	0.45.0.50
23	500-1000	51	2.74	1.460	4.020	0.03	1.460	0.50-1.00
24	1000-1500	13	0.70	0.650	5.930	0.01	0.650	1.00-1.50
25	1500-2000	3	0.16	0.220	6.160	0.00	0.220	1.50-2.00
26	2000-2500	7	0.38	0.660	6.820	0.00	0.660	2.00-2.50
27	2500-3000	0	0.00	0.000	6.820	0.00	0.000	2.50-3.00
28	3000-4000	3	0.16	0.470	7.290	0.00	0.470	3.00-4.00
						1864		

Air Content (%):	7.29
Specific Surface (mm^{-1}):	42.36
Spacing Factor (mm):	0.093
Void Frequency (mm^{-1}):	0.770
Average Chord Length (mm):	0.094
Paste to Air Ratio:	3.95

Sample ID: ternary CA cylinder 2 side 1

Sample Size (mm x mm):	80 x 80	Length Traversed (mm):	2413.1
Paste Content (%):	28.80	Area Traversed (mm x mm):	70 x 70

Chord Length Distribution - Table

Class No.	Chord size (microns)	Number of Chords in Class	Number of Chords in Percent	Air Content in Class	Cumulated Air Content	Chord length frequency	Air content, fraction	
1	0-10	217	10.34	0.080	0.080	0.10	0.080	0.00-0.01
2	10-20	671	31.97	0.390	0.470	0.32	0.390	0.01-0.02
3	20-30	327	31.97	0.340	0.810	0.16	0.340	0.02-0.03
4	30-40	132	6.29	0.190	1.000	0.06	0.190	0.03-0.04
5	40-50	94	4.48	0.170	1.170	0.04	0.170	0.04-0.05
6	50-60	82	3.91	0.190	1.360	0.04	0.190	0.05-0.06
7	60-80	111	5.29	0.320	1.670	0.05	0.320	0.06-0.08
8	80-100	83	3.95	0.310	1.980	0.04	0.310	0.08-0.10
9	100-120	47	2.24	0.210	2.190	0.02	0.210	0.10-0.12
10	120-140	39	1.86	0.210	2.400	0.02	0.210	0.12-0.14
11	140-160	36	1.72	0.220	2.620	0.02	0.220	0.14-0.16
12	160-180	20	0.95	0.140	2.770	0.01	0.140	0.16-0.18
13	180-200	16	0.76	0.130	2.890	0.01	0.130	0.18-0.20
14	200-220	21	1.00	0.180	3.080	0.01	0.180	0.20-0.22
15	220-240	12	0.57	0.110	3.190	0.01	0.110	0.22-0.24
16	240-260	10	0.48	0.100	3.290	0.00	0.100	0.24-0.26
17	260-280	14	0.67	0.160	3.450	0.01	0.160	0.26-0.28
18	280-300	8	0.38	0.100	3.540	0.00	0.100	0.28-0.30
19	300-350	26	1.24	0.350	3.900	0.01	0.350	0.30-0.35
20	350-400	13	0.62	0.200	4.100	0.01	0.200	0.35-0.40
21	400-450	15	0.71	0.270	4.370	0.01	0.270	0.40-0.45
22	450-500	15	0.71	0.300	4.660	0.01	0.300	0.45.0.50
23	500-1000	51	2.43	1.470	4.880	0.02	1.470	0.50-1.00
24	1000-1500	19	0.91	0.960	7.090	0.01	0.960	1.00-1.50
25	1500-2000	10	0.48	0.720	7.810	0.00	0.720	1.50-2.00
26	2000-2500	7	0.33	0.630	8.450	0.00	0.630	2.00-2.50
27	2500-3000	2	0.10	0.230	8.670	0.00	0.230	2.50-3.00
28	3000-4000	1	0.05	0.160	8.840	0.00	0.160	3.00-4.00
						2099		

Air Content (%):	8.84
Specific Surface (mm^{-1}):	39.38
Spacing Factor (mm):	0.083
Void Frequency (mm^{-1}):	0.870
Average Chord Length (mm):	0.102
Paste to Air Ratio:	3.26

Sample ID: **ternary CA cylinder 2 side 2**

Sample Size (mm x mm):	80 x 80	Length Traversed (mm):	2413.1
Paste Content (%):	28.80	Area Traversed (mm x mm):	70 x 70

Chord Length Distribution - Table

Class No.	Chord size (microns)	Number of Chords in Class	Number of Chords in Percent	Air Content in Class	Cumulated Air Content	Chord length frequency	Air content, fraction	
1	0-10	119	7.97	0.040	0.040	0.08	0.040	0.00-0.01
2	10-20	400	26.79	0.240	0.280	0.27	0.240	0.01-0.02
3	20-30	230	26.79	0.240	0.520	0.15	0.240	0.02-0.03
4	30-40	97	6.50	0.140	0.660	0.06	0.140	0.03-0.04
5	40-50	105	7.03	0.190	0.850	0.07	0.190	0.04-0.05
6	50-60	63	4.22	0.140	0.990	0.04	0.140	0.05-0.06
7	60-80	69	4.62	0.200	1.190	0.05	0.200	0.06-0.08
8	80-100	50	3.35	0.190	1.380	0.03	0.190	0.08-0.10
9	100-120	53	3.55	0.240	1.620	0.04	0.240	0.10-0.12
10	120-140	32	2.14	0.170	1.790	0.02	0.170	0.12-0.14
11	140-160	23	1.54	0.140	1.930	0.02	0.140	0.14-0.16
12	160-180	24	1.61	0.170	2.100	0.02	0.170	0.16-0.18
13	180-200	24	1.61	0.190	2.280	0.02	0.190	0.18-0.20
14	200-220	15	1.00	0.130	2.410	0.01	0.130	0.20-0.22
15	220-240	16	1.07	0.150	2.560	0.01	0.150	0.22-0.24
16	240-260	10	0.67	0.100	2.670	0.01	0.100	0.24-0.26
17	260-280	9	0.60	0.100	2.770	0.01	0.100	0.26-0.28
18	280-300	8	0.54	0.100	2.870	0.01	0.100	0.28-0.30
19	300-350	20	1.34	0.270	3.130	0.01	0.270	0.30-0.35
20	350-400	18	1.21	0.280	3.410	0.01	0.280	0.35-0.40
21	400-450	15	1.00	0.260	3.680	0.01	0.260	0.40-0.45
22	450-500	9	0.60	0.180	3.850	0.01	0.180	0.45.0.50
23	500-1000	52	3.48	1.470	4.160	0.03	1.470	0.50-1.00
24	1000-1500	16	1.07	0.790	6.110	0.01	0.790	1.00-1.50
25	1500-2000	5	0.33	0.370	6.470	0.00	0.370	1.50-2.00
26	2000-2500	11	0.74	1.040	7.520	0.01	1.040	2.00-2.50
27	2500-3000	0	0.00	0.000	7.520	0.00	0.000	2.50-3.00
28	3000-4000	0	0.00	0.000	7.520	0.00	0.000	3.00-4.00
						1493		

Air Content (%):	7.52
Specific Surface (mm^{-1}):	32.91
Spacing Factor (mm):	0.116
Void Frequency (mm^{-1}):	0.620
Average Chord Length (mm):	0.122
Paste to Air Ratio:	3.83

PROOVE it

ASTM C 1202-97

TEST CO.
File name = Prooveit user logo.jpg located in application directory.

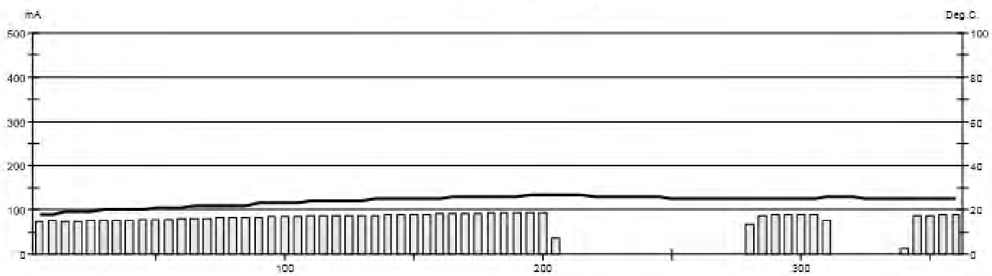
Test-compagny
Testing street 45
CompagnyCity
Some Country

Your own logo.
size=20x80mm

GERMANN INSTRUMENTS
DENMARK
USA

Test report

Voltage Used:	60
Testing time:	06:00 hour
Charge passed:	1309
Adjusted Charge passed:	1135
Permeability class:	Low
Instrument number:	023907
Channel number:	1
Report date:	12/1/2011
Testing by:	---
Reference:	CA T MIX
Sample diameter:	102
Comment:	---



Time	°C	mA	Time	°C	mA	Time	°C	mA	Time	°C	mA
00:05	18	74.1	01:35	23	84.4	03:05	26	93.1	04:35	25	0.1
00:10	18	75.6	01:40	23	85.0	03:10	26	93.3	04:40	25	66.3
00:15	19	74.3	01:45	23	85.6	03:15	27	93.6	04:45	25	88.0
00:20	19	74.5	01:50	24	86.2	03:20	27	93.9	04:50	25	88.5
00:25	19	75.4	01:55	24	86.5	03:25	27	35.5	04:55	25	88.9
00:30	20	75.8	02:00	24	86.6	03:30	27	0.0	05:00	25	89.0
00:35	20	76.0	02:05	24	86.9	03:35	27	0.0	05:05	25	88.3
00:40	20	76.3	02:10	24	87.6	03:40	26	0.0	05:10	26	75.6
00:45	20	77.2	02:15	25	87.3	03:45	26	0.0	05:15	26	0.0
00:50	21	78.2	02:20	25	88.8	03:50	26	0.0	05:20	26	0.0
00:55	21	78.9	02:25	25	89.1	03:55	26	0.0	05:25	25	0.0
01:00	21	79.6	02:30	25	89.8	04:00	26	0.0	05:30	25	0.0
01:05	22	80.4	02:35	25	90.3	04:05	26	0.0	05:35	25	0.0
01:10	22	81.2	02:40	25	91.0	04:10	25	0.0	05:40	25	13.7
01:15	22	81.8	02:45	26	91.2	04:15	25	0.0	05:45	25	87.5
01:20	22	82.4	02:50	26	91.7	04:20	25	0.1	05:50	25	87.9
01:25	22	83.1	02:55	26	92.2	04:25	25	0.1	05:55	25	88.4
01:30	23	83.7	03:00	26	92.7	04:30	25	0.1	06:00	25	88.8

PROOVE it

ASTM C 1202-97

EST CO.
File name – Prooveit user logo.jpg located in application directory.

Test-compagny
Testing street 45
CompagnyCity
Some Country

Your own logo.
size=20x80mm

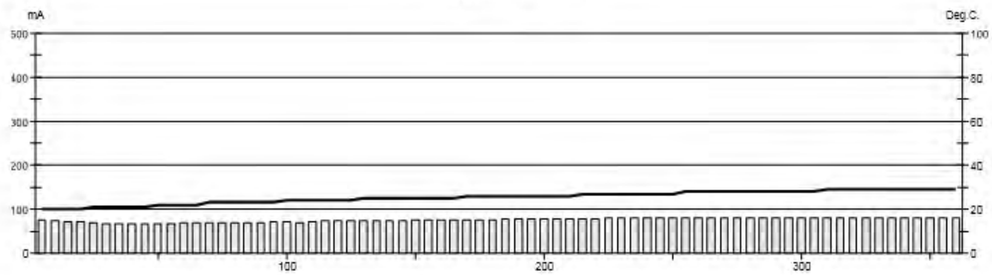
GERMANN INSTRUMENTS

DENMARK
Phone: +45 3967 7117
Fax: +45 3967 3167

USA
Phone: (847)329-9999
Fax: (847)329-8888

Test report

Voltage Used:	60
Testing time:	06:00 hour
Charge passed:	1640
Adjusted Charge passed:	1423
Permeability class:	Low
Instrument number:	023907
Channel number:	2
Report date:	12/1/2011
Testing by:	---
Reference:	CA T MIX
Sample diameter:	102
Comment:	---



Time	°C	mA	Time	°C	mA	Time	°C	mA	Time	°C	mA
00:05	20	76.7	01:35	23	70.4	03:05	26	77.5	04:35	28	80.8
00:10	20	74.6	01:40	24	70.9	03:10	26	77.4	04:40	28	81.0
00:15	20	71.1	01:45	24	69.4	03:15	26	77.3	04:45	28	81.3
00:20	20	70.5	01:50	24	72.5	03:20	26	78.0	04:50	28	81.3
00:25	21	68.4	01:55	24	72.8	03:25	26	78.4	04:55	28	81.4
00:30	21	66.9	02:00	24	73.1	03:30	26	78.7	05:00	28	81.4
00:35	21	66.4	02:05	24	73.4	03:35	27	78.9	05:05	28	81.4
00:40	21	66.1	02:10	25	73.8	03:40	27	79.1	05:10	29	81.4
00:45	21	66.2	02:15	25	74.1	03:45	27	79.3	05:15	29	81.4
00:50	22	66.8	02:20	25	74.4	03:50	27	79.5	05:20	29	81.3
00:55	22	67.8	02:25	25	74.7	03:55	27	79.7	05:25	29	81.4
01:00	22	68.9	02:30	25	74.9	04:00	27	79.9	05:30	29	81.4
01:05	22	69.0	02:35	25	75.2	04:05	27	80.1	05:35	29	81.3
01:10	23	68.8	02:40	25	75.4	04:10	27	80.3	05:40	29	81.3
01:15	23	69.0	02:45	25	75.8	04:15	28	80.4	05:45	29	81.3
01:20	23	69.3	02:50	26	76.2	04:20	28	80.6	05:50	29	81.3
01:25	23	69.5	02:55	26	76.7	04:25	28	80.7	05:55	29	81.1
01:30	23	70.0	03:00	26	76.8	04:30	28	80.8	06:00	29	80.9

APPENDIX B. FIELD APPLICATION OF TERNARY MIXTURES: ASSESSMENT OF CEMENTITIOUS COMBINATIONS USED IN CALIFORNIA DEMONSTRATION PROJECT

State Report
June 2012

Research Team
Peter Taylor
Paul Tikalsky
Kejin Wang
Gary Fick
Xuhao Wang

Sponsored through
Federal Highway Administration DTFH61-06-H-00011 Work Plan 19
FHWA Pooled Fund Study TPF-5(117): California, Illinois, Iowa (lead state), Kansas, Mississippi, New Hampshire, Oklahoma, Pennsylvania, Utah, Wisconsin;
American Coal Ash Association, American Concrete Pavement Association, Headwaters Resources, Portland Cement Association, Slag Cement Association

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through funds provided by the Iowa Department of Transportation
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Institute for Transportation
(InTrans Project 09-361)

A report from
National Concrete Pavement Technology Center
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Fax: 515-294-0467
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ACKNOWLEDGMENTS

The research team at the National Concrete Pavement Technology Center at Iowa State University sincerely thanks the California Department of Transportation (Caltrans) and the Federal Highway Administration Mobile Concrete Laboratory for their cooperation, as well as Lehigh Heidelberg Cement Group, Salt River Materials Group—Phoenix Cement Co., and Teichert Construction Co. for supplying the materials.

INTRODUCTION

This document is a report of laboratory work carried out to review the performance of cementitious blends used on the I-80 reconstruction demonstration project at Emigrant Gap, California in October 2011.

During the preconstruction stage, it had been reported that strength gains using the originally specified ternary mixture (8% fly ash and 35% slag cement) were unacceptably slow. The purpose of this laboratory work was to investigate whether changes to some of the cementitious materials would have improved performance.

MATERIALS

Cementitious materials were obtained from the construction site during a visit by staff from the National Concrete Pavement Technology Center in October 2011.

These comprised the following:

- Type II/V cement, Lehigh Permanente
- Grade 120 slag cement, Salt River Materials
- Class F fly ash, Lehigh Southwest

In addition, a high alkali cement (~1.0% Na_2O_{eq}) was used from laboratory stocks, along with chemical grade NaOH.

MIXTURES AND TESTS

Eighteen mortar mixtures were prepared in accordance with ASTM C 109, as discussed below.

The original specification called for a ternary mixture containing 8% fly ash and 35% slag cement. The mixture used in construction had a slag cement content that was reduced to 25%. To assess the various combinations, six mixtures were prepared containing the following blends:

- 100% portland cement (100P)
- 92% portland cement, 8% fly ash (8FA)
- 75% portland cement, 25% slag cement (25SL)
- 65% portland cement, 35% slag cement (25SL)
- 67% portland cement, 8% fly ash 25% slag cement (8FA25SL)
- 57% portland cement, 8% fly ash 35% slag cement (8FA35SL)

In addition, the same six mixtures were repeated using the high alkali cement in place of the material obtained from the site. The mixtures were labeled with a post-script of “Hi”. The purpose of this work was to assess whether a high alkali cement would have performed better.

Finally, the original six mixtures were repeated with additional sodium hydroxide added to accelerate the system. The NaOH dosage was calculated at 0.5% Na_2O_{eq} by mass of cement. These mixtures were labeled with a post-script of "NaOH". The purpose of this work was to assess whether increasing the alkalinity of the system would accelerate early hydration.

Cube (2 in.) strengths were determined at 3, 7, and 28 days of age. In addition, temperature rise of selected mixtures was monitored by placing thermocouples at the center of insulated 3 by 6 in. cylinders.

RESULTS

The strength data are presented in Table 1 and Figure 1.

The temperature rise results are shown in Figures 2 and 3.

DISCUSSION

The following observations may be extracted from the strength data:

- For the mixtures made with the original cement:
    - The 3- and 7-day strengths of all were not significantly affected by the type or amount of supplementary cementitious material. This is to be expected because early strengths are typically controlled by the cement hydration.
    - The 7-day strengths were not significantly higher than the 3-day results.
    - Typically there was doubling strength between 7 and 28 days. This is not typical of portland cement systems, but may be related to the low alkali / low C_3A chemistry of the cement used.
    - The highest 28-day strengths were achieved by the mixtures containing slag cement.
- For the high alkali cement system:
    - Strengths at 3 days and 7 days were generally higher than the original cement, but at 28 days, strengths were generally lower.
    - The lowest early strength was the ternary mixture containing 35% slag cement.
    - Strength gain rates were more typical to those normally observed.
    - Supplementary cementitious materials had more of an effect on this system than on the others.
- For the added alkali system:
    - Strengths at 3 days and 7 days were generally higher than the original cement, but at 28 days, strengths were generally lower.
    - The lowest early strengths were the binary mixtures containing fly ash.
    - The highest 28-day strengths were achieved by the mixtures containing slag cement.
- Between cement systems:

- Early strengths were lowest for the original cement system, but the 28-day strengths were the highest.
- Use of 35% slag cement was observed to reduce 3-day strength in all cases, while 25% dosage had less of an effect.

Therefore, while use of an alternative cement may have improved early strength gain, so reducing risk of early cracking, longer term strength was not as high. Decreasing the slag cement dosage from 35 to 25% did appear to improve early strengths, thus reducing the impact of early strength.

Table 1. Compressive cube strength data in psi

	3-day				7-day				28-day			
	1	2	3	Ave.	1	2	3	Ave.	1	2	3	Ave.
100P	3081	3916	4083	3690	4475	4287	4389	4380	6533	8054	8299	7630
8FA	3997	2986	3793	3590	4116	3907	3943	3990	6896	6410	8033	7110
25Sl	3595	3610	3656	3620	3899	4592	4401	4300	7662	8276	7923	7950
35Sl	3776	3736	3739	3750	4167	3765	4617	4180	8875	9021	8793	8900
8Fa25Sl	3810	3698	3634	3710	3950	4030	4341	4110	8671	8771	8698	8710
8Fa35Sl	3125	3000	2946	3020	3685	3850	3692	3740	8361	9067	8840	8760
100P NaOH	3859	4103	4271	4080	5651	5093	5389	5380	6126	7415	6845	6800
8FA NaOH	3744	3526	3468	3580	4680	4190	4656	4510	5944	6215	6853	6340
25Sl NaOH	4022	3882	4054	3990	5659	5030	5434	5370	7554	8049	7786	7800
35Sl NaOH	3755	3823	3754	3780	5500	5662	5333	5500	7284	7439	7326	7350
8Fa25Sl NaOH	3524	3426	3568	3510	5057	5148	5097	5100	7191	7502	7328	7340
8Fa35Sl NaOH	3149	3101	3159	3140	5109	5010	4980	5030	7742	7425	7598	7590
100P Hi	4677	4805	4627	4700	5525	6049	6052	5880	8189	7163	8005	7790
8FA Hi	4083	3567	4234	3960	5696	5055	5239	5330	7437	7428	7504	7460
25Sl Hi	4316	4028	3709	4020	6158	6130	5923	6070	7778	7926	8117	7940
35Sl Hi	3784	3375	3767	3640	5445	5440	5509	5460	7420	7488	7392	7430
8Fa25Sl Hi	4100	3998	4021	4040	5799	5951	5836	5860	7862	8144	7929	7980
8Fa35Sl Hi	2646	2630	3001	2760	5920	5708	5898	5840	7515	8559	7522	7870

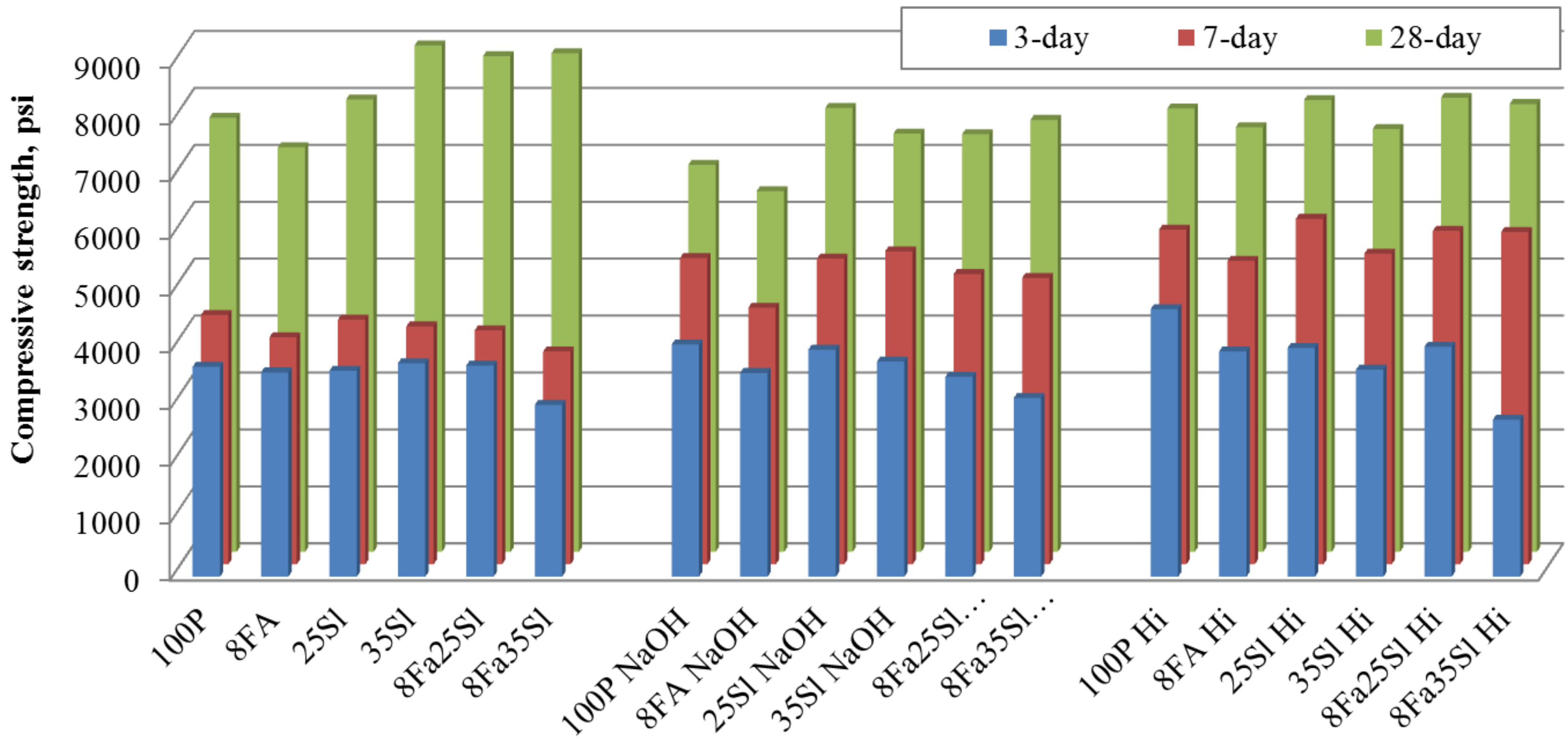

Figure 1. Graphical representation of strength data

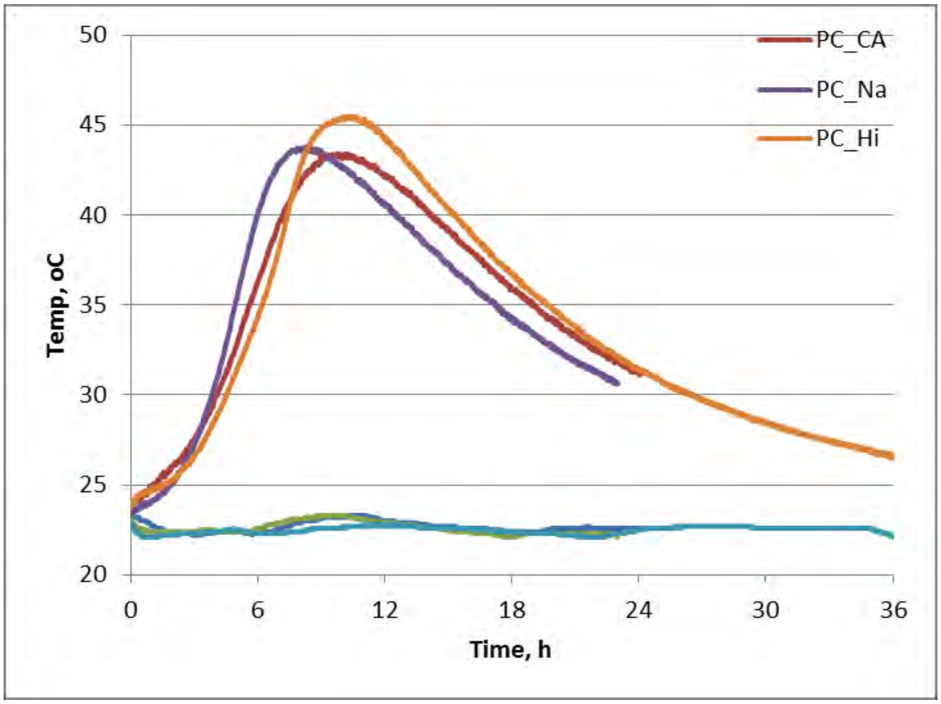

Figure 2. Temperature data for straight portland mixtures

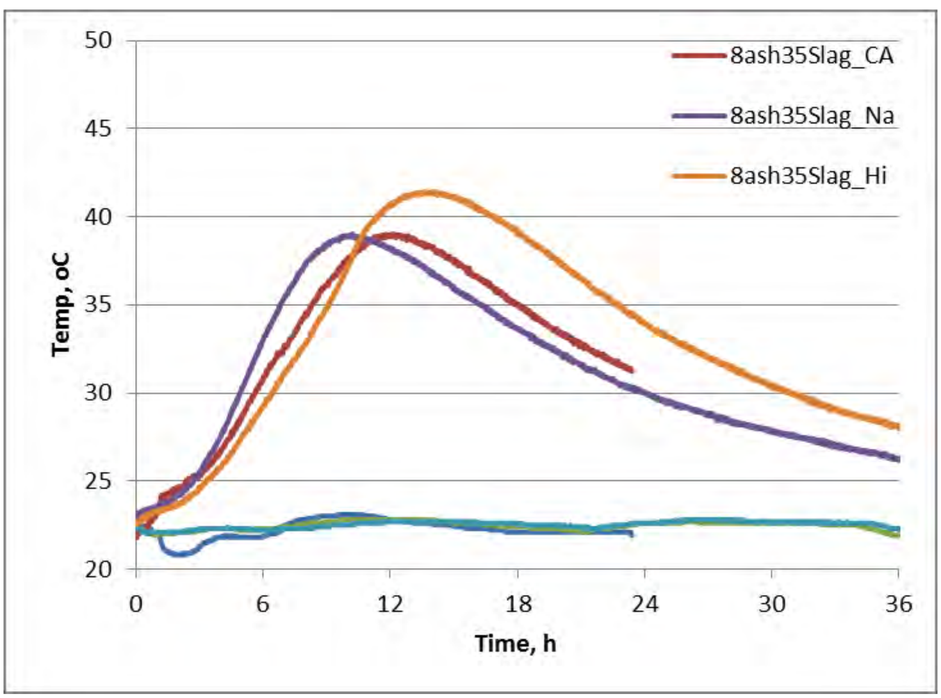

Figure 3. Temperature data for ternary mixtures with 35% slag cement

The following observations may be extracted from the temperature data:

- Initial setting times do not seem to be significantly impacted between the systems tested.
- Temperature rise is notably higher in the mixtures containing the high alkali cement.
- Slag cement suppressed peak temperatures, as expected.
- The temperature peak is earliest in the mixtures containing added alkali.
- No signs of incompatibilities were observed.

CONCLUSION

Based on the data obtained from this work, selection of 25% slag cement content in the mixtures appears to have been an appropriate decision for the materials available.

APPENDIX C.
FIELD APPLICATION OF TERNARY MIXTURES: CONSTRUCTION OF A RIGID PAVEMENT IN IOWA

State Report
June 2010

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ACKNOWLEDGMENTS

The research team at the National Concrete Pavement Technology Center, Iowa State University, sincerely thanks the Iowa Deportment of Transportation for providing the cooperation and the McCarthy Improvement Company for supplying the materials and equipment. All of the contributions from the job site and concrete design company are also gratefully acknowledged.

INTRODUCTION

This document is a report of the activities and observations of a research team that performed on-site testing of a ternary mixture placed on an interstate pavement in Iowa. The cementitious system comprised a Type 1P cement (25% fly ash) blended with 15% Class C fly ash. The purpose of this research project is a comprehensive study of how supplementary cementitious materials can be used to improve the performance of concrete mixtures when used in ternary blends.

This is the third phase of a project that intends to provide consulting to states and contractors with the use and field management of ternary mixtures. A state-of-the-art 44 ft. portland cement concrete (PCC) mobile laboratory equipped for on-site cement and concrete testing was provided by the National CP Tech Center to collect data and field observations.

PROJECT INFORMATION

- Project No. ESIMX-029-5(100)95-1S-43
- Monona County, Iowa
- Contractor: McCarthy Improvement Co.
- I-29 Grade/Replace, Monona, Iowa
- Rigid Pavement Improvement (Southbound of Interstate 29 in Iowa) (Figure 1)

Figure 1. Interstate 29 in Iowa (southbound)

SITE LOCATION

An area at the bridge site was prepared by the contractor for the PCC mobile lab. The location of the project (on Interstate 29 near the city of Onawa, Iowa) and the mobile lab is shown in Figure 2.

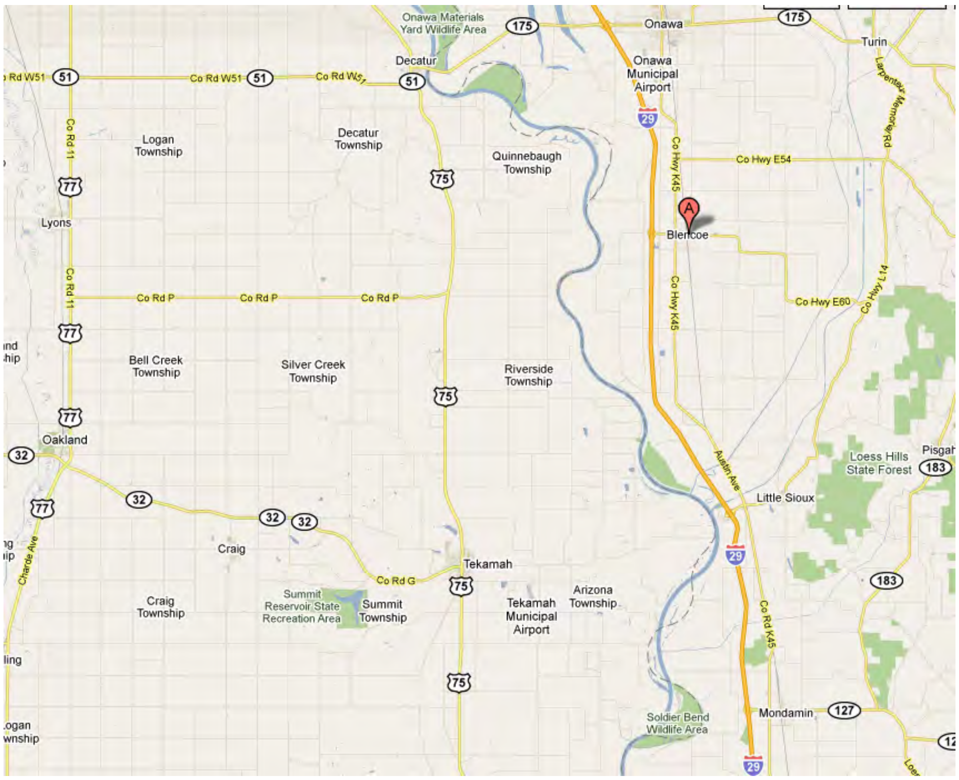


Figure 2. Project and mobile lab location

SAMPLING AND TESTING ACTIVITIES

The mobile lab arrived on site on June 1, 2010. Concrete placement, sampling, and testing took place on June 7, 2010. Hardened samples were transported to Iowa State University on June 8, 2010, for further testing. The following tests were conducted in the field or in the laboratory:

- Calorimetry test (ASTM C 1679)
- Slump, unit weight, temperature, and air content of fresh concrete: 1 test (ASTM C 143, ASTM C 138, ASTM C 231)
- Microwave w/c ratio: 1 test (AASHTO T 318)
- Initial set and final set of concrete: 1 test (ASTM C 403)
- Compressive strength, splitting tensile strength, static modulus of elasticity: 4 in. x 8 in. cylinders at 1 day, 3 days, 7 days, 28 days, and 56 days (ASTM C 39, ASTM C 496, ASTM C 469)
- Rapid chloride permeability: 4 in. x 8 in. cylinders at 56 days (ASTM C 1202)

- Porosity analysis (boil test) of hardened concrete: 4 in. x 8 in. cylinders (ASTM C 642)
- Salt scaling: 3 samples (ASTM C 672)
- Shrinkage: 3 beams (ASTM C 157)
- Restrained rings: 4 samples (ASTM C 1581)

OBSERVATIONS OF THE RESEARCH TEAM

The following observations were made in this field testing:

- The sub-base for the entire project was recycled material: the old concrete slab had been crushed to create a granular sub-base of approximately 8–10 in. thick.
- The sub-grade was also a recycled section: the old asphalt overlay was crushed into a sub-grade of 12 in. thick. All was installed on a 1% grade to the outside.
- Slab dimensions were 11 in. by 26 ft for the mainline, and 7 in. by 6 or 8 ft for shoulders, which were tied to the mainline by #4 bars.
- For the mainline pavement, the contractor used a Guntert-Zimmerman 8500, while Gomaco Commander with a side kit was used for the shoulders.
- One and a half-inch dowel bars were used in baskets placed every 20 feet. The transverse joints were 1/4 in. wide and approximately 2 in. deep, cut using early-entry saws. The center longitudinal joint was 1/8 in. wide by approximately 3.5 in. deep, cut using conventional water-cooled saws.
- The concrete was supplied from a fixed batch plant and was delivered to the job site in tandem trucks. The mix design was from the McCarthy Improvement Company and approved by the Iowa DOT. The specific accepted mix proportions are given in the Project Data section. The plant had a 90-second mix time. Once in the truck, the mix had to be placed on the ground within 60 minutes without segregation.
- Workability and coarseness factors were 34.5 and 64.9, respectively. The combined aggregate gradation fell in the well-graded region (see Project Data). Similarly, the Combined Percent Retained Curve indicated a well graded system (see Project Data).
- The weather condition at the job site was recorded for a period of eight days from June 1st to June 8th. Data is shown in Figures 3 through 5. The relative humidity ranged between 21% and 89%. The ambient temperature ranged from 48˚F to 88˚F. The wind speed varied from 3 mph to 20 mph.
- The fresh concrete properties testing included slump, unit weight, and water-cementitious materials ratio measured by microwave. Due to unexpected weather, only one group of samples was tested during the construction period. The slump was 2.0 in. The unit weight was 135.6 lb/ft^3. The water- cementitious material ratio was 0.35.
- The air content was 8.75% from the one test conducted at the batch plant, which was slightly higher than the specified minimum, 6%.
- The setting time of the mix was determined as a single measurement: initial set occurred at 2.32 hours, and the final set was achieved at 8.41 hours.

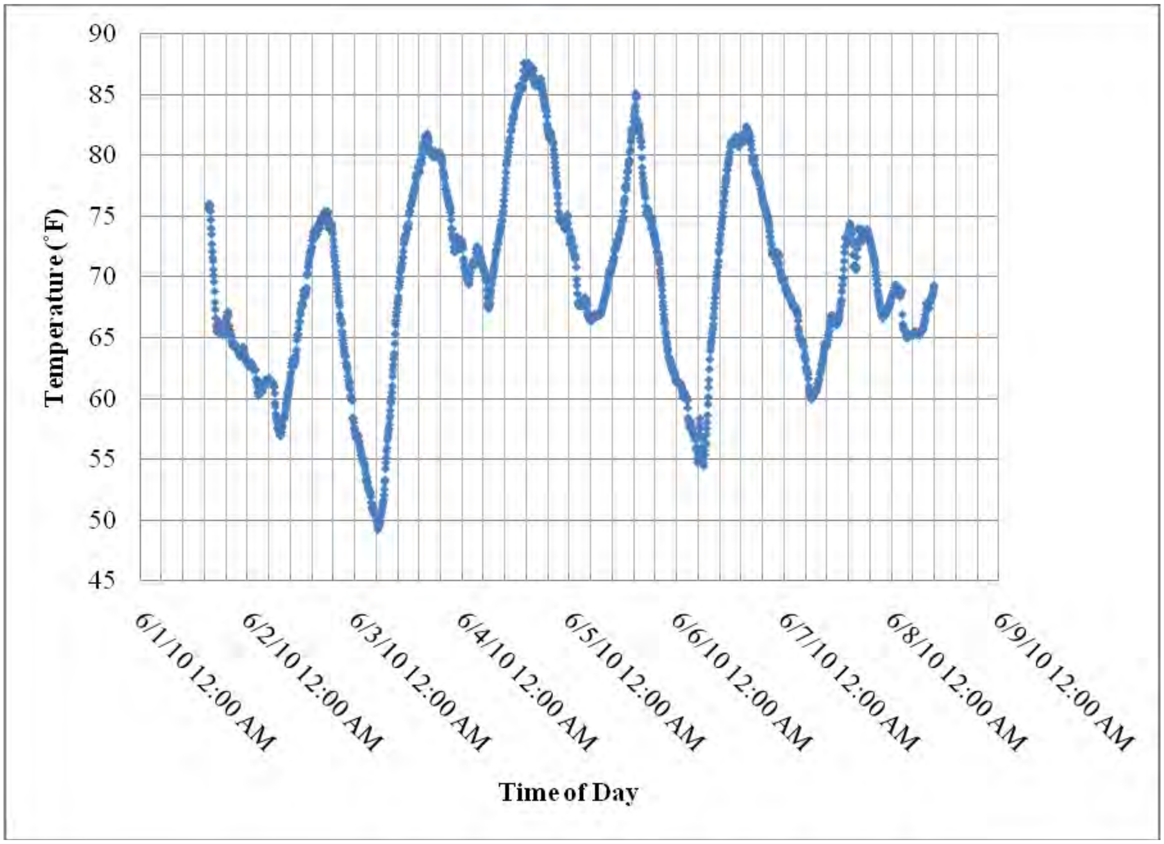


Figure 3. Ambient temperature versus time of day

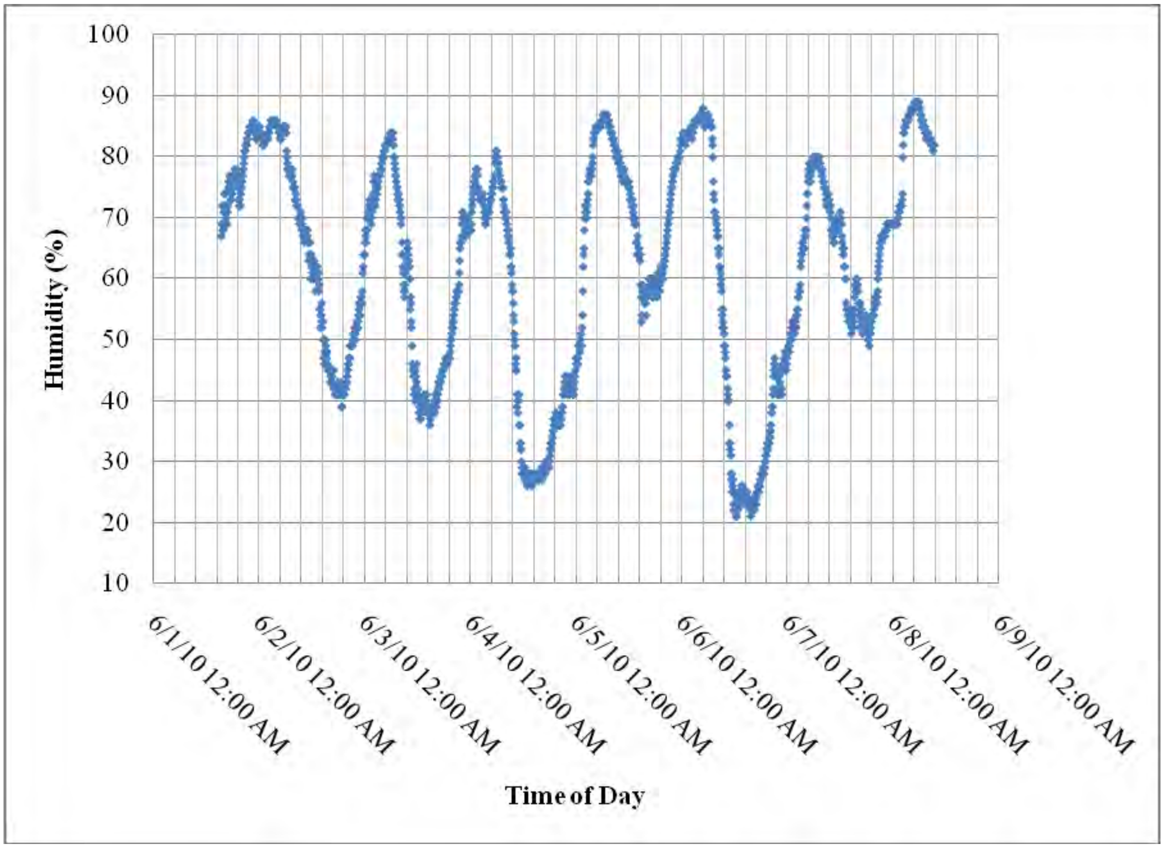


Figure 4. Relative humidity versus time of day

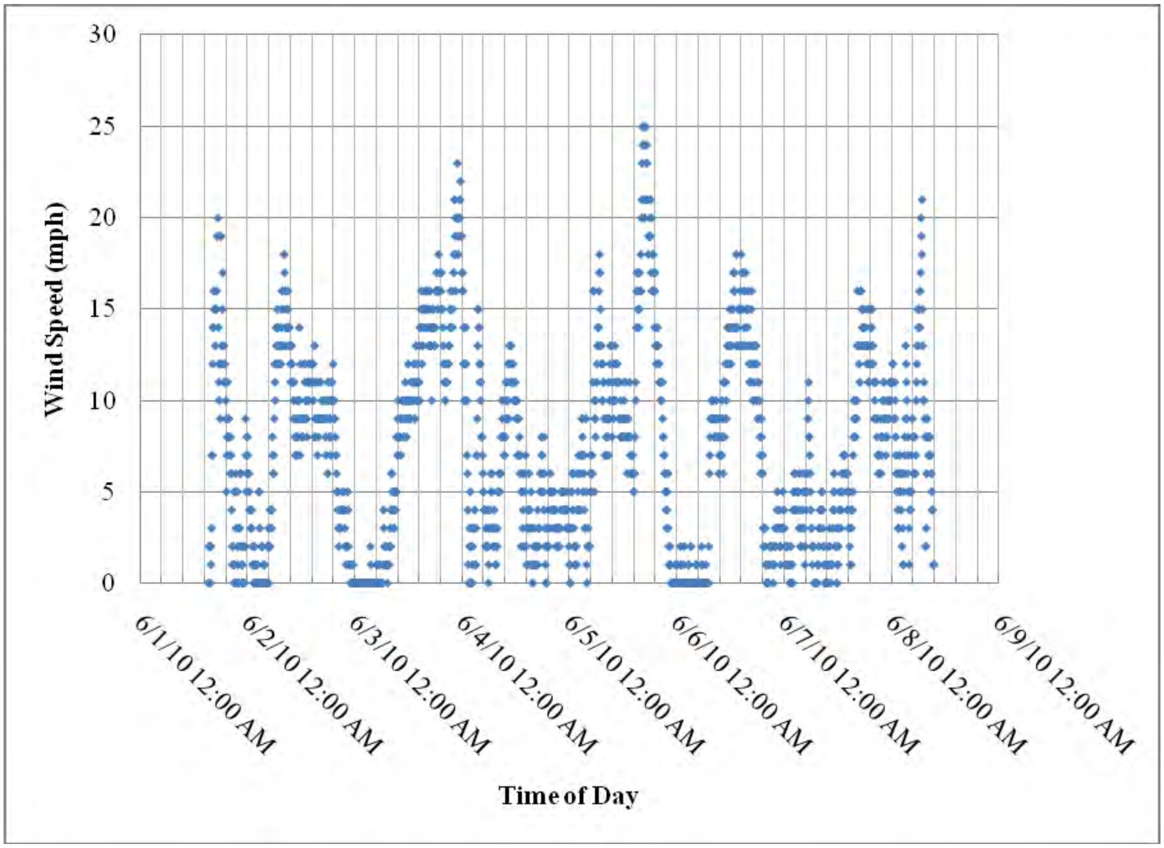
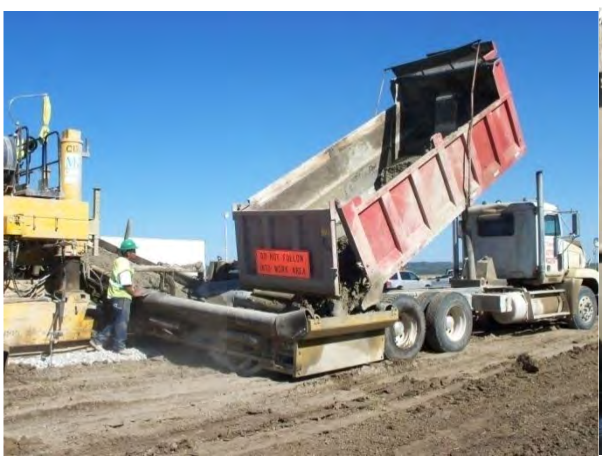
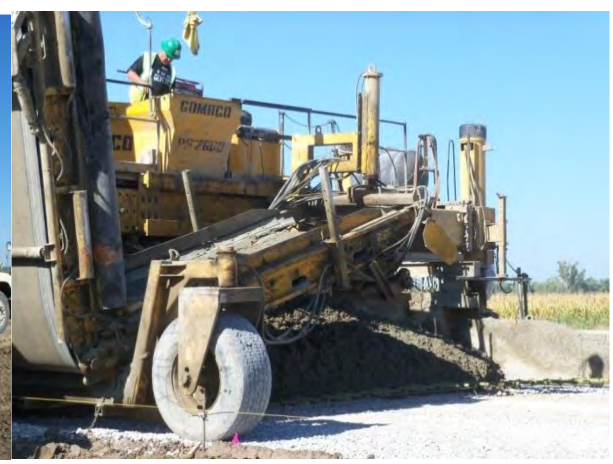


Figure 5. Wind speed versus time of day

- Figures 6 through 11 illustrate some activities during the testing process.





Figures 6 and 7. Concrete being dumped into a belt placer and spread by the placer

Figures 8 and 9. Concrete passing through the paver

Figures 10 and 11. Concrete being finished and curing compound being applied

- The rapid chloride permeability test measures the electrical conductance of a concrete sample as its resistance to chloride ion penetration. The test results shown in Table 1 indicate a classification of “very low” chloride permeability, according to ASTM C1202.
- The compressive strengths at 7 and 28 days and the 28/7 days strength development ratio are reported in Table 1.
- The porosity values obtained by the boiling test (ASTM C 642) results are given in Table 1.
- Compressive strength, splitting tensile strength, and modulus of elasticity results (ASTM C 39, ASTM C 496, and ASTM C 469) are given in Table 2, and development curves are plotted in Figures 12 through Figure 14.

Table 1. Properties of hardened concrete

Tests	Results			
7-day compressive strength, psi	4860			
28-day compressive strength, psi	5960			
Volume of permeable pore space, %	Sample 1 5.56	Sample 2 5.68	Sample 3 6.18	Average 5.81
Rapid chloride permeability, coulombs	Sample 1 980	Sample 2 1413		Average 1197
Strength development 28/7 day fc ratio	1.23			
Shrinkage microstrain @ 28 days, in/in	183.3			
Average stress rate by restrained ring test, psi/day	28.21			

Table 2. Summation of strength and modulus of elasticity

Location	Age, Days	Compressive Strength, psi	Splitting Tensile Strength, psi	Modulus of Elasticity, psi
IA	1	2,660	322	4.75E+06
	3	4,650	339	5.30E+06
	7	4,860	452	5.10E+06
	28	5,960	478	5.75E+06
	56	8,110	599	5.70E+06

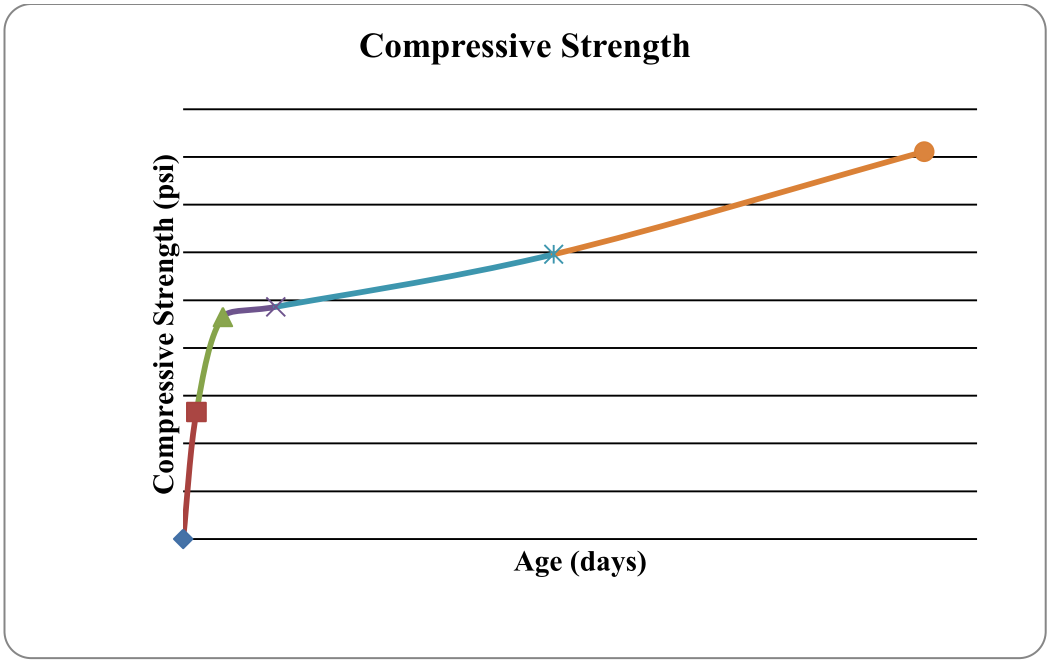


Figure 12. Compressive strength development with time

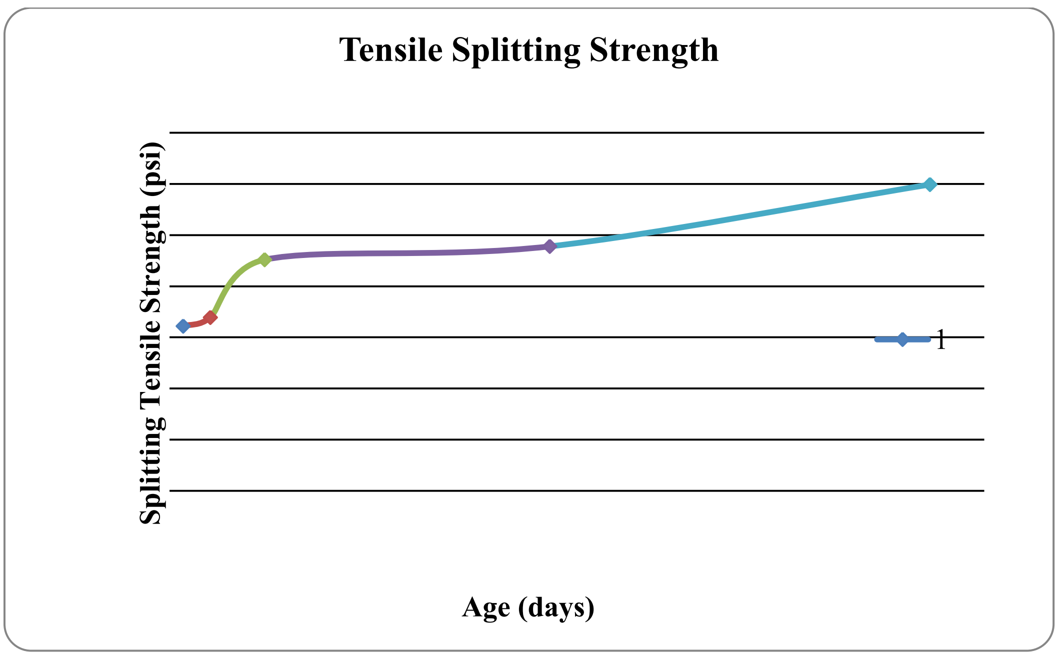


Figure 13. Tensile splitting strength development with time

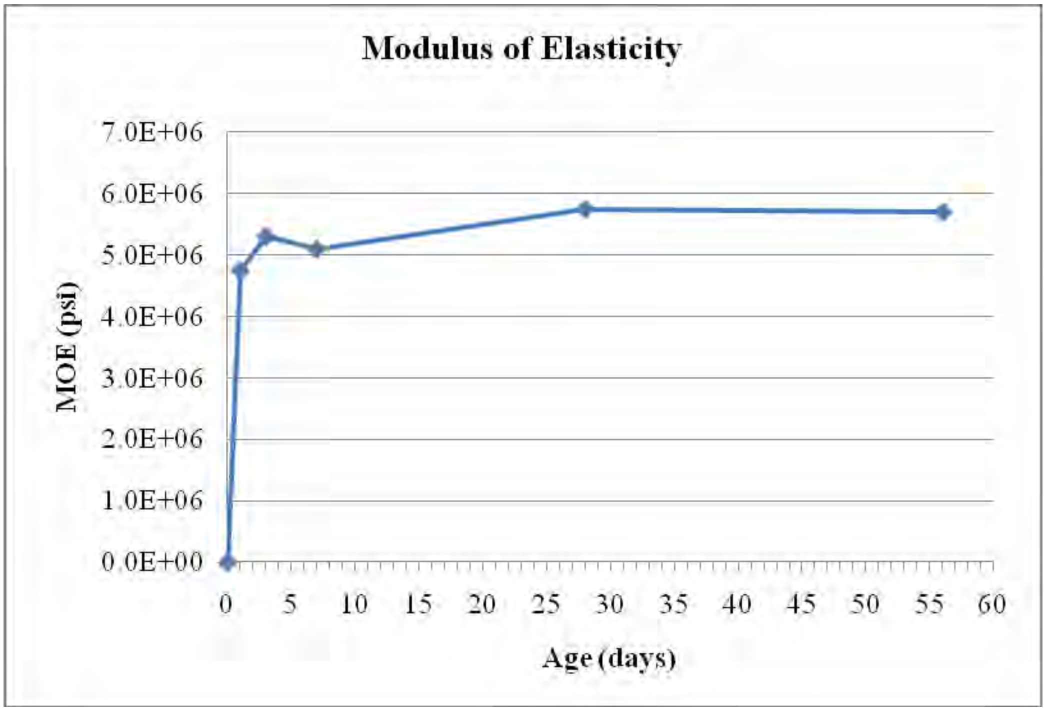


Figure 14. Modulus of elasticity development with time

- A free shrinkage test (ASTM C 157) was conducted in the laboratory. Three concrete beams were wet cured for seven days and then moved to a dry room at 23˚C and 50% relative humidity. The drying shrinkage results are given in Table 3 and also plotted in Figure 15.

Table 3. Free shrinkage test results

IA Project Free Shrinkage Test (ASTM C 157)					
Dry Time	**Beam 1 change%**	**Beam 2 change %**	**Beam 3 change %**	**Average**	**Microstrain**
0	0.000	0.000	0.000	0.000	0.000
1	-0.011	-0.010	-0.010	-0.010	-103.3
4	-0.010	-0.008	-0.008	-0.009	-86.7
7	-0.005	-0.005	0.000	-0.003	-33.3
14	-0.011	-0.012	-0.006	-0.010	-96.7
28	-0.017	-0.024	-0.014	-0.018	-183.3
56	-0.027	-0.031	-0.029	-0.029	-290.0

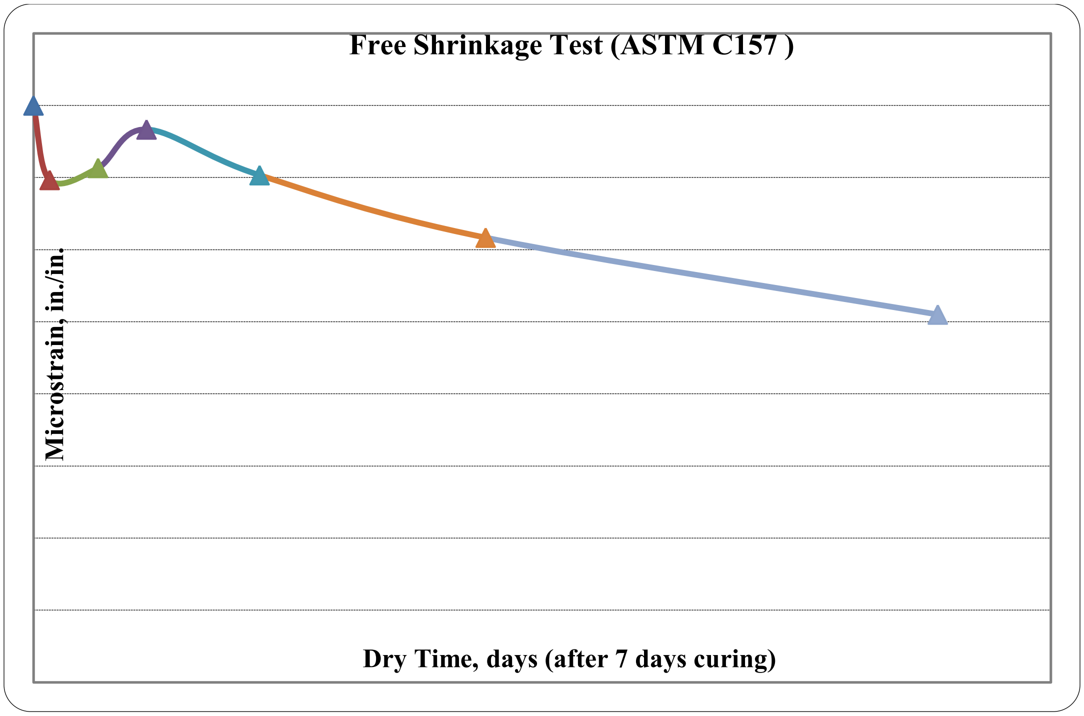


Figure 15. Free shrinkage of prisms (ASTM C 157)

- A restrained shrinkage test was conducted based on ASTM C 1581. Four rings were cast. The rings were demolded and the top surface was covered with paraffin wax 24 hours from casting. The rings were allowed to dry at 23˚C and 50% relative humidity immediately after demolding. Strains in the steel rings were recorded every 10 minutes for up to 28 days, or until the concrete cracked. The configuration of restrained concrete rings is shown in Figure 16. The cracking potential is listed in Table 4 and shown graphically in Figure 17. The cracking potential is classified as "moderate high," based on the average stress rate.

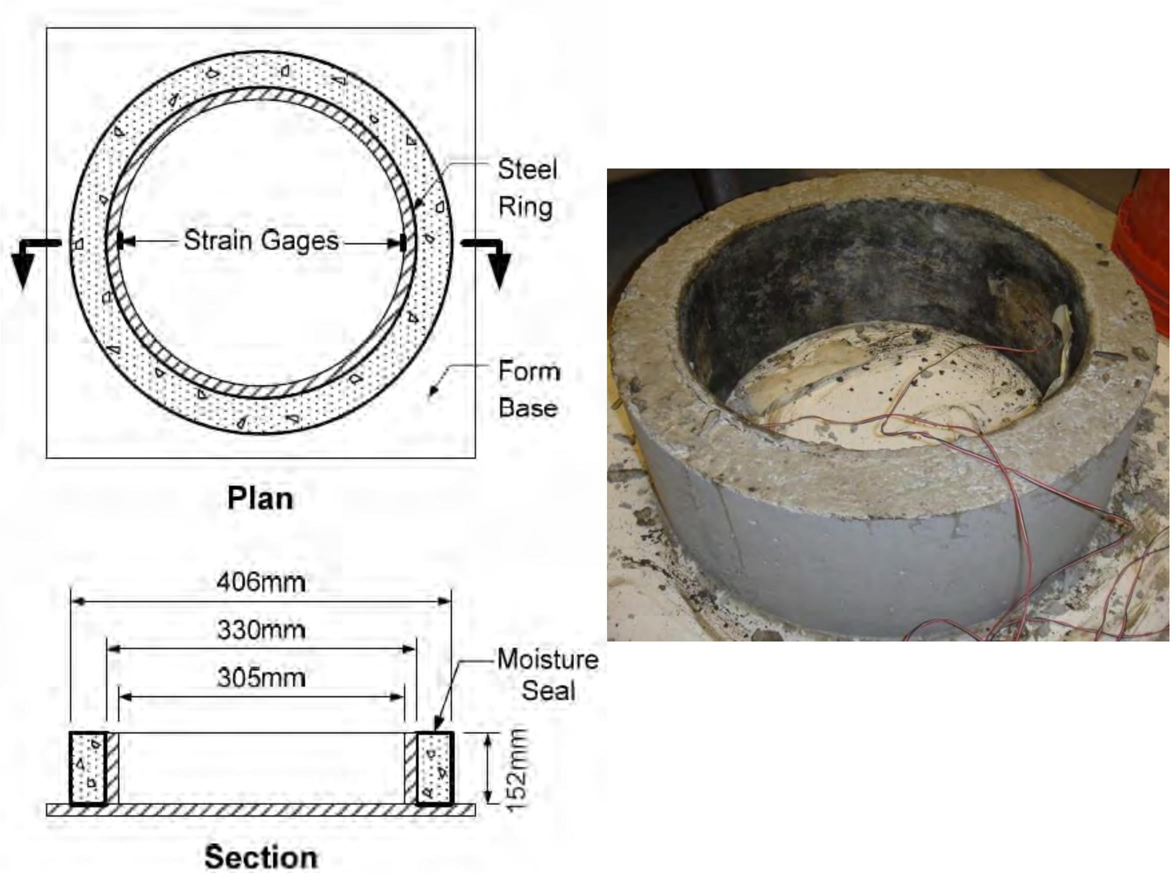


Figure 16. Configuration of restrained concrete ring samples

Table 4. Cracking potential and average stress rate (ASTM C 1581)

Cracking Potential for IA Project (ASTM C 1581)				
	Ring 1	Ring 2	Ring 3	Ring 4
Strain rate factor (in./in.x10^{-6})/hours$^{1/2}$	-4.89	-4.23	-4.47	-5.27
G (psi)	10.47x10 6	10.47x10 6	10.47x10 6	10.47x10 6
Absolute value of α_{avg} (in./in.10^{-6})/day$^{1/2}$	23.10			
Elapsed time, tr (hours)	441.0	441.0	441.0	441.0
Elapsed time, tr (days)	18.4	18.4	18.4	18.4
Stress rate, q (psi/day) $q=GI\alpha_{avg}I/2\sqrt{t_r}$	28.2	28.2	28.2	28.2
Average stress rate, q (psi/day) $q=GI\alpha_{avg}I/2\sqrt{t_r}$	**28.21**			
Potential for cracking classification (ASTM 1581)	**Moderate-high (25≤ q < 50)**			

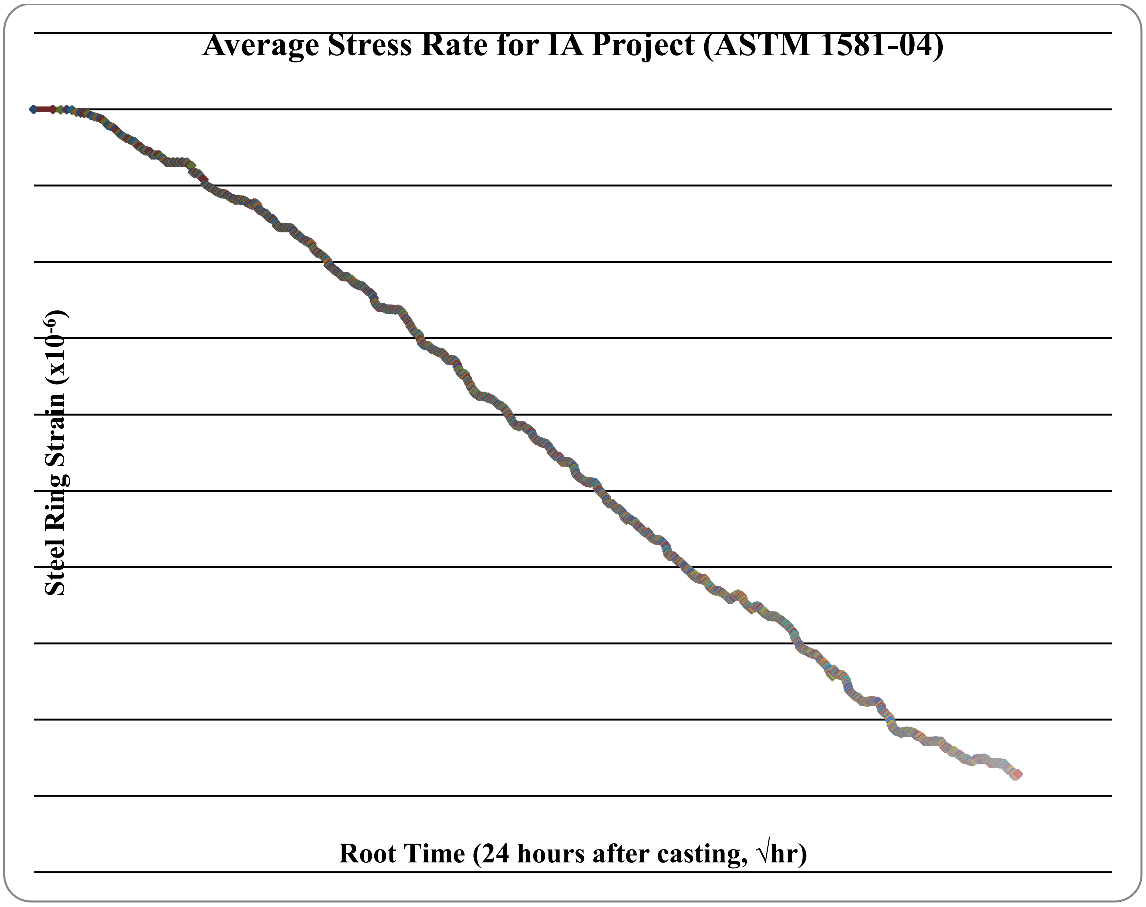


Figure 17. Average stress rate for KS project

- A salt scaling test (ASTM C 672) was performed: the specimens were subjected to 16 to18 hours freezing and then allowed to thaw at 23 ± 2.0˚C and a relative humidity of 45 to 55% for 6 to 8 hours. A 4% calcium chloride solution was used for conditioning. Visual rating was done every 5 freeze-thaw cycles for up to 50 cycles. The surface was rated on a scale of 0 to 5, with 0 having no scaling, 1 having very slight scaling of 3 mm depth maximum without coarse aggregate visible, 2 having slight to moderate scaling, 3 having moderate scaling with some coarse aggregate visible, 4 having moderate to severe scaling, and 5 having severe scaling with coarse aggregate visible over entire surface. The photograph after the 50th cycle was taken and shown in Figure 18. The visual ratings assigned to each specimen for cycles 0, 5, 10, 15, 20, 25, and 50 are given in Table 5.

Table 5. Salt scaling test visual condition of specimen

IA Salt Scaling Samples	Condition of Surface Cycle 5	Cycle 10	Cycle 15	Cycle 20	Cycle 25	Cycle 50
No. 1	1	1	2	2	2	4
No. 2	1	1	2	2	2	4
No. 3	1	1	2	2	2	4

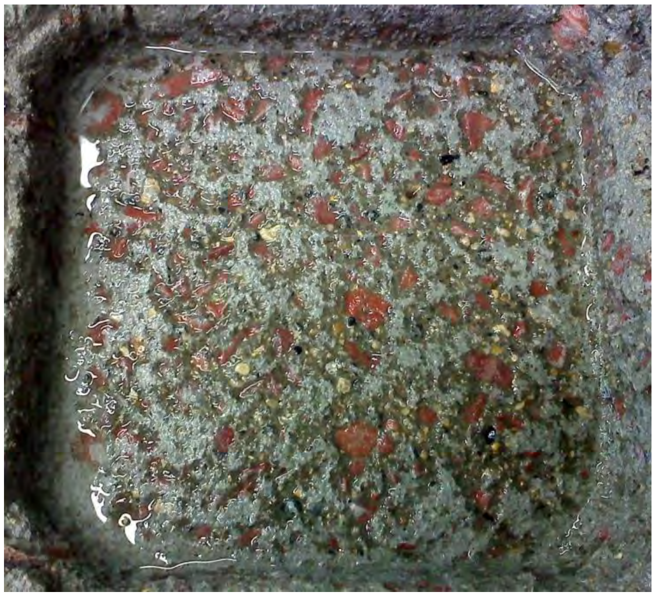


Figure 18. IA salt scaling sample after 50th freeze-thaw cycle

PROJECT DATA

The following test data is provided for information only; comments and conclusions will be reported in the comprehensive Phase III report of the pooled fund project *Development of Performance Properties of Ternary Mixtures.*

Mix Design & Misc. Info.

General Information

Project:	I-29 Grade/Replace Monona Co
Contractor:	McCarthy Improvement Company
Mix Description:	562 lb Cementitious
Mix ID:	ESIMX-029-5(100)951S-43
Date(s) of Placement:	6/7/2010

Cementitious Materials	Source	Type	Spec. Gravity	lb/yd^3	% Replacement by Mass
Portland Cement:	PC0008 Ash Grove Louisville, NE	1P (25)	2.950	478	
GGBFS:					
Fly Ash:	FA004C Headwater Resources Concil Bluffs, I	Class C	2.620	84	14.95%
Silica Fume:					
Other Pozzolan:					
				562	**lb/yd^3**
				6.0	**sacks/yd^3**

Aggregate Information	Source	Type	Spec. Gravity SSD	Absorption (%)	% Passing #4
Coarse Aggregate:	ASD010 Everist, Inc. Dell Rapids, SD	Quartzite	2.640	0.30%	0.7%
Intermediate Aggregate #1:	A18528 Higman S&G Washta, IA	P-Gravel	2.670	1.60%	39.0%
Intermediate Aggregate #2:					
Fine Aggregate #1:	A18528 Higman S&G Washta, IA	Natural Sand	2.650	0.80%	99.0%

Coarse Aggregate %:	51.0%
Intermediate Aggregate #1%:	9.0%
Intermediate Aggregate #2%:	
Fine Aggregate #1 %:	40.0%

Mix Proportion Calculations

Water/Cementitious Materials Ratio:	0.400
Air Content:	6.00%

	Volume (ft^3)	Batch Weights SSD (lb/yd^3)	Spec. Gravity	Absolute Volume (%)
Portland Cement:	2.597	478	2.950	9.617%
GGBFS:				
Fly Ash:	0.514	84	2.620	1.903%
Silica Fume:				
Other Pozzolan:				
Coarse Aggregate:	9.520	1,568	2.640	35.260%
Intermediate Aggregate #1:	1.680	280	2.670	6.222%
Intermediate Aggregate #2:				
Fine Aggregate #1:	7.467	1,235	2.650	27.655%
Water:	3.603	225	1.000	13.343%
Air:	1.620			6.000%
	27.000	**3,870**		**100.000%**
	Unit Weight (lb/ft^3)	**143.3**	**Paste**	**30.863%**
			Mortar	**60.915%**

Admixture Information	Source/Description	oz/yd^3	oz/cwt
Air Entraining Admix.:	Eucild AEA 92/ AEA	1.00	0.18
Admix. #1:	Euclid Eucon Retardent 100/ Retarder	1.50	0.27
Admix. #2:	Euclid Eucon WR/ Water Reducer	4.00	0.71
Admix. #3:			

AVA Information	Absolute Volume (%)
Air Free Paste:	24.863%
Air Free Mortar:	54.915%

Iowa - Ternary Mixtures

Sample Information:

Project: I-29 @ Blencoe

Date: 7-Jun-10

Time: 1:15 PM

Type of Paving:

Direction of Paving:

Sta:

Latitude:

Longitude:

Mix ID:

Truck IDs:

Sample Location Mark & Comments:

Environmental Conditions:

Dew Point:

Relative Humidity: 65%

Wind Speed:

Ambient Temp.: 72.0

Concrete Properties:

Base/Soil Temp. (internal)(°F):

Base Temp. (surface)(°F):

Microwave Water Content Samples:

Calorimetry (ADIACAL Cylinders): 4

Set-Time (ASTMC403) Mortar Samples:

Cylinder for RCP & Perm. Voids Boil Test: use adiacal

Scaling Blocks: 3

Concrete Temp.(°F):	74.1
Slump (in.):	2.00
Air Content:	8.8%
Unit Weight (lb/ft^3):	135.6

Compressive, Tensile & MOR Cylinders: 30

Shrinkage Beams: 3

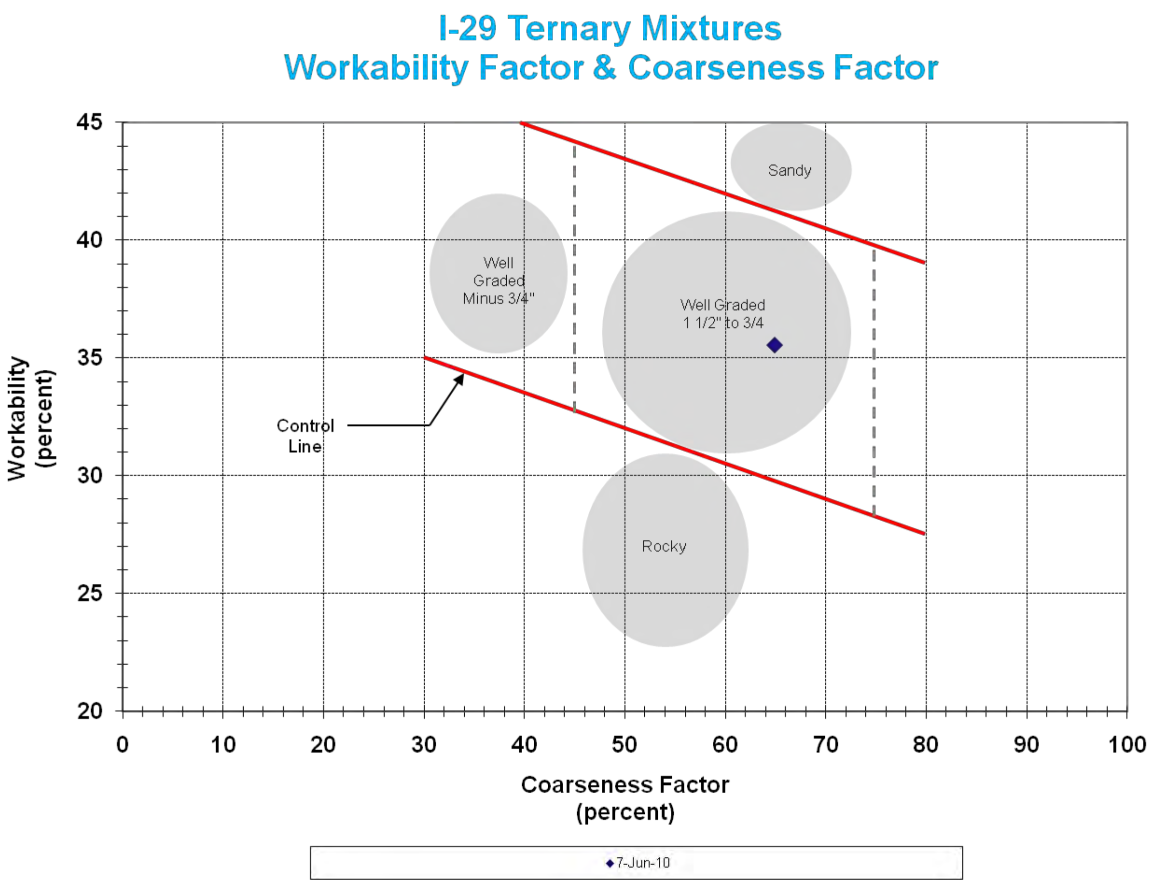
Project: I-29 Grade/Replace Monona Co @ Blencoe
Mix ID: CDM
Sample Comments:
Test Date: 7-Jun-10

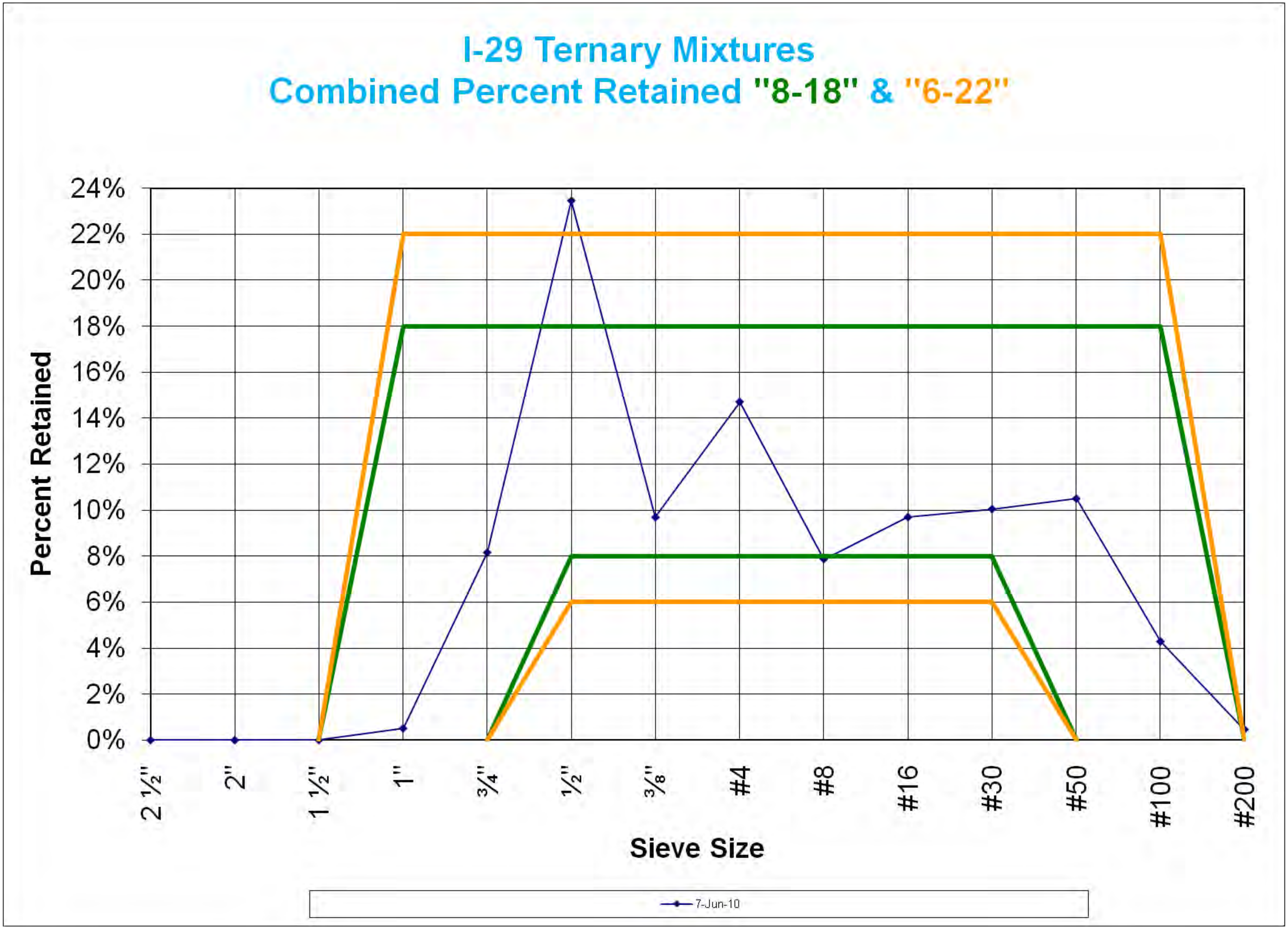
otal Cementitious Material: 562 lb/yd^3

Agg. Ratios:	51.00%	9.00%	40.00%		100.00%

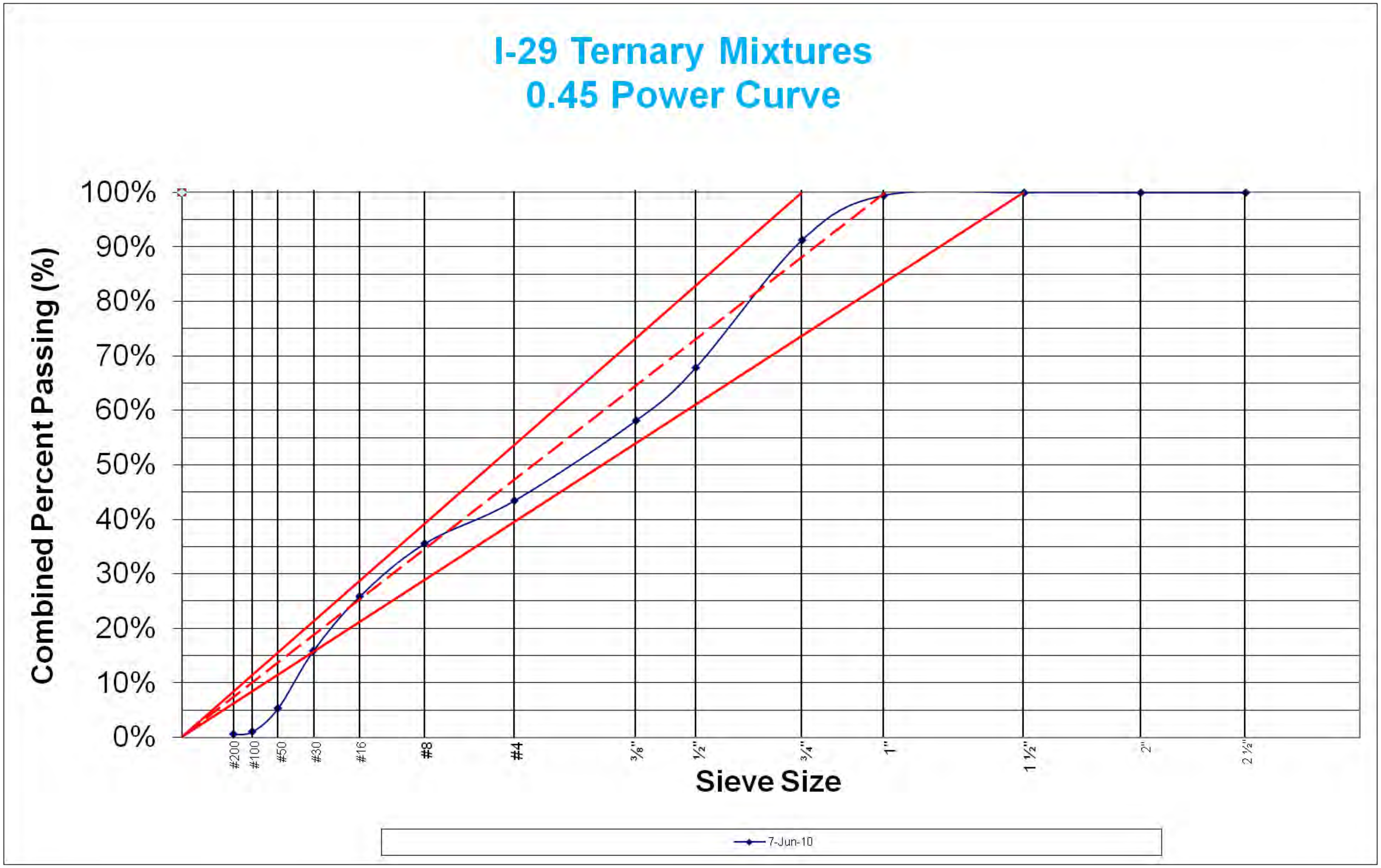
Sieve	Coarse	Intermediate	Fine #1	Fine #2	Combined % Retained	Combined % Retained On Each Sieve	Combined % Passing
2 ½"	100%	100%	100%		0%	0%	100%
2"	100%	100%	100%		0%	0%	100%
1 ½"	100%	100%	100%		0%	0%	100%
1"	99%	100%	100%		1%	1%	99%
¾"	83%	100%	100%		9%	8%	91%
½"	37%	100%	100%		32%	23%	68%
⅜"	18%	100%	100%		42%	10%	58%
#4	1%	39%	99%		57%	15%	43%
#8	1%	6%	87%		64%	8%	36%
#16	1%	5%	63%		74%	10%	26%
#30	1%	4%	38%		84%	10%	16%
#50	1%	3%	12%		95%	10%	5%
#100	1%	2%	1%		99%	4%	1%
#200	0.7%	0.5%	0.5%		99.4%	0.5%	0.6%

Workability Factor: 35.5
Coarseness Factor: 64.9





I-29 Ternary Mixtures
Combined Percent Retained "8-18" & "6-22"
24%
22%
20%
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
Percent Retained
2 ½"
2"
1 ½"
1"
¾"
½"
⅜"
#4
#8
#16
#30
#50
#100
#200
Sieve Size
7-Jun-10



I-29 Ternary Mixtures
0.45 Power Curve
Combined Percent Passing (%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
#200
#100
#50
#30
#16
#8
#4
3/8"
1/2"
3/4"
1"
1 1/2"
2"
2 1/2"
Sieve Size
7-Jun-10

Iowa - Ternary Mixtures

Set Time ASTM C 403

Project: I-29 Grade/Replace Monona Co

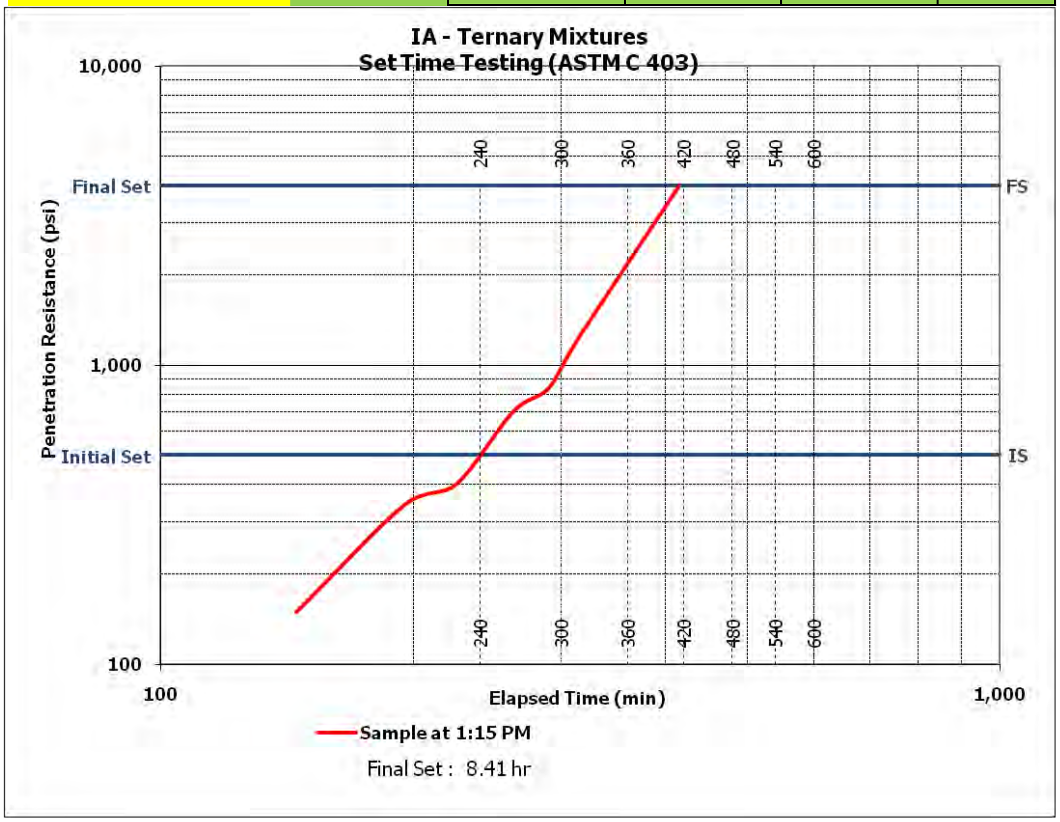
Date: 7-Jun-10 Start Time: 1:15 PM

Sta: n/a

Test Data

Penetration Time (xx:xx-24 hr format)	Time (min)	Needle # (1,2,4,10,20 or 40)	Force (lb)	Penetration Resistance (psi)	Sample Temp. (ºF)
3:40 PM	145.00	1	149	149.00	n/a
4:30 PM	195.00	4	85	340.00	n/a
5:00 PM	225.00	10	40	400.00	n/a
5:38 PM	263.00	10	70	700.00	n/a
6:05 PM	290.00	20	42	840.00	n/a
6:30 PM	315.00	20	62	1240.00	n/a
8:10 PM	415.00	40	100	4000.00	n/a
					n/a
					n/a

Initial Set (at 500 psi PR)	estimated times using forecast function	**139**	minutes	**2.32**	hours
Final Set (at 4,000 psi PR)		**505**	minutes	**8.41**	hours



Iowa - Ternary Mixtures

Boil Test (ASTM C 642)

IA #1		
A	944.4	g
B	966.61	g
C	967.18	g
D	557.5	g
P	1	g/cm³
g1	2.3052	g/cm³
g2	2.4409	g/cm³
Volume of permeable pore space (voids), %		**5.5604**
IA #2		
A	982.7	g
B	1006.28	g
C	1006.91	g
D	581.1	g
P	1	g/cm³
g1	2.3078	g/cm³
g2	2.4470	g/cm³
Volume of permeable pore space (voids), %		**5.6856**
IA #3		
A	1017.7	g
B	1044.53	g
C	1045.46	g
D	596.2	g
P	1	g/cm³
g1	2.2653	g/cm³
g2	2.4145	g/cm³
Volume of permeable pore space (voids), %		**6.1791**

PROOVE it

ASTM C 1202-97

TEST CO.

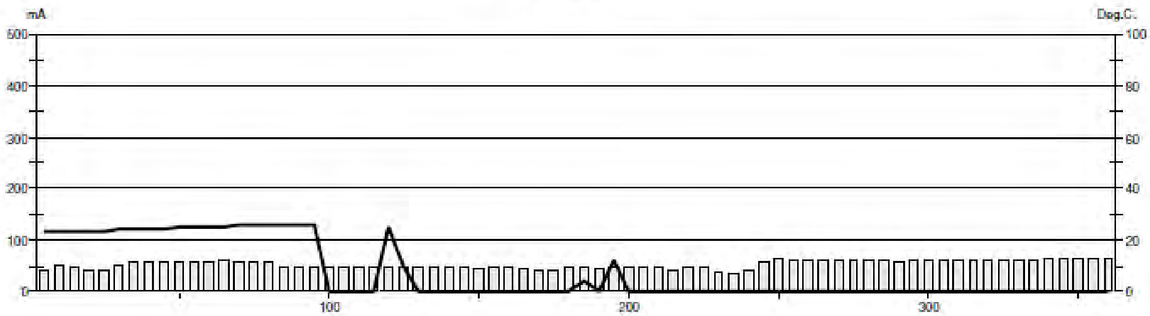
Test-compagny
Testing street 45
CompagnyCity
Some Country

Your own logo,
size=20x80mm

GERMANN INSTRUMENTS
DENMARK
USA

Test report

Voltage Used:	60
Testing time:	06:00 hour
Charge passed:	1130
Adjusted Charge passed:	980
Permeability class:	Very Low
Instrument number:	023907
Channel number:	1
Report date:	8/3/2010
Testing by:	PJM
Reference:	IA ternary 56day #1
Sample diameter:	102
Comment:	---



Time	°C	mA	Time	°C	mA	Time	°C	mA	Time	°C	mA
00:05	23	42.1	01:35	26	46.0	03:05	4	47.0	04:35	0	59.3
00:10	23	50.3	01:40	0	47.3	03:10	0	44.8	04:40	0	59.3
00:15	23	46.5	01:45	0	47.4	03:15	12	46.4	04:45	0	59.4
00:20	23	42.0	01:50	0	47.9	03:20	0	49.1	04:50	0	59.1
00:25	23	42.2	01:55	0	48.3	03:25	0	48.7	04:55	0	59.8
00:30	24	50.6	02:00	25	48.7	03:30	0	48.4	05:00	0	60.4
00:35	24	59.1	02:05	10	49.1	03:35	0	40.1	05:05	0	59.7
00:40	24	58.5	02:10	0	48.8	03:40	0	45.9	05:10	0	59.9
00:45	24	56.8	02:15	0	47.8	03:45	0	46.7	05:15	0	60.2
00:50	25	56.5	02:20	0	47.5	03:50	0	37.5	05:20	0	60.8
00:55	25	55.9	02:25	0	46.4	03:55	0	35.1	05:25	0	61.1
01:00	25	57.9	02:30	0	45.3	04:00	0	40.6	05:30	0	61.3
01:05	25	59.7	02:35	0	48.6	04:05	0	56.4	05:35	0	61.3
01:10	26	59.0	02:40	0	48.4	04:10	0	61.4	05:40	0	61.4
01:15	26	58.4	02:45	0	45.6	04:15	0	59.8	05:45	0	61.5
01:20	26	55.8	02:50	0	41.0	04:20	0	59.6	05:50	0	61.9
01:25	26	50.0	02:55	0	41.8	04:25	0	59.6	05:55	0	61.9
01:30	26	48.0	03:00	0	46.6	04:30	0	59.4	06:00	0	61.7

APPENDIX D.
FIELD APPLICATION OF TERNARY MIXTURES: CONSTRUCTION OF A BRIDGE DECK IN KANSAS

State Report
October2009

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ACKNOWLEDGMENTS

The research team at the National Concrete Pavement Technology Center at Iowa State University sincerely thanks the Kansas Department of Transportation for their cooperation, and Penny's Concrete and Ames Construction Inc. for supplying the materials and equipment.

INTRODUCTION

This document is a report of the activities and observations of a research team that performed on-site testing of a ternary mixture placed on a bridge deck in Kansas. The purpose of this research project is a comprehensive study of how supplementary cementitious materials can be used to improve the performance of concrete mixtures when used in ternary blends. This is the third phase of a project that intends to provide consulting to states and contractors on the use and field management of ternary mixtures. A state-of-the-art 44 ft long portland cement concrete (PCC) mobile laboratory equipped for on-site cement and concrete testing was provided by the National Concrete Pavement Technology Center (National CP Tech Center) to collect data and field observations.

PROJECT INFORMATION

- Project No. K 7888-01
- Douglas County, Kansas
- Contractor: Ames Construction
- US 59 northbound bridge approximately 1.5 miles south of US 56
- Bridge deck placement (3 span—structural steel girders with concrete deck) (Figure 1)

Figure 1. US 59 bridges (southbound-left and northbound-right)

SITE LOCATION

An area at the bridge site was prepared by the contractor for the PCC mobile lab. The location of the project site and the mobile lab is shown in Figure 2.

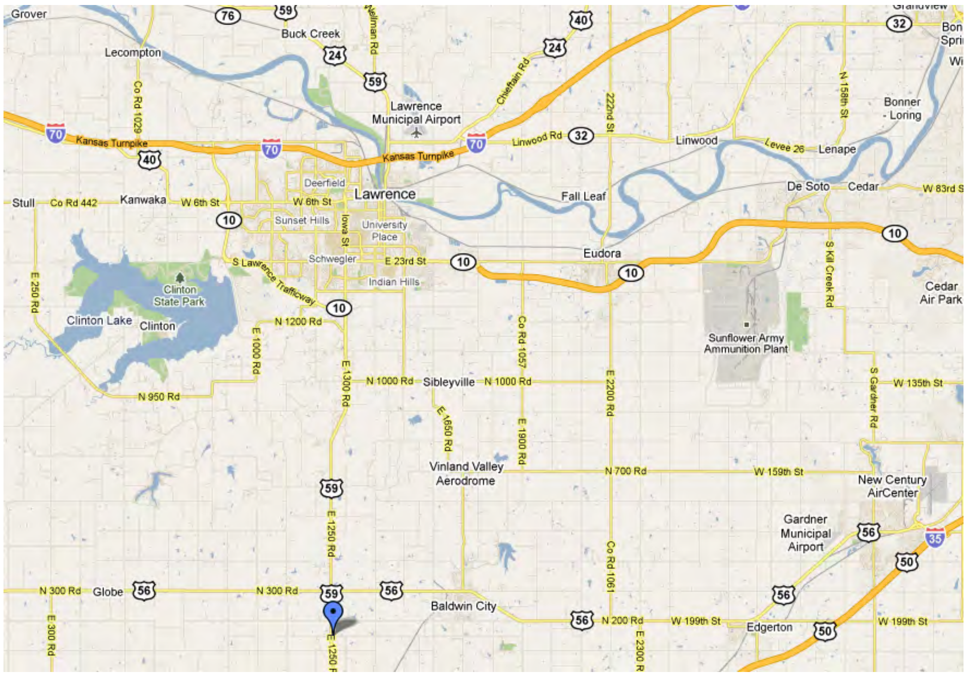


Figure 2. Project and mobile lab location

SAMPLING AND TESTING ACTIVITIES

The mobile lab arrived on site on October 27, 2009. Concrete placement, sampling, and testing took place on October 28, 2009. Hardened samples were transported to Iowa State University on October 29, 2009, for further testing. The following tests were conducted either in the field or in the laboratory:

- Calorimetry test (ASTM C 1679)
- Slump, unit weight, temperature, and air content of fresh concrete: 2 tests (ASTM C 143, ASTM C 138, ASTM C 231)
- Microwave w/c ratio: 2 tests (AASHTO T 318)
- Air void analyzer, Taylor et al. (2006)
- Initial set and final set of concrete: 1 test (ASTM C 403)
- Compressive strength, splitting tensile strength, static modulus of elasticity: 4 in. x 8 in. cylinders at 1 day, 3 days, 7 days, 28 days, and 56 days (ASTM C 39, ASTM C 496, ASTM C 469)
- Rapid chloride permeability: 4 in. x 8 in. cylinders at 56 days (ASTM C 1202)
- Air void analysis of hardened concrete: 4 in. x 8 in. cylinders (ASTM C 457)
- Porosity analysis (boil test) of hardened concrete: 4 in. x 8 in. cylinders (ASTM C 642)

- Free shrinkage test: 3 beams (ASTM C 157)
- Restrained rings: 4 samples (ASTM C 1581)

OBSERVATIONS OF THE RESEARCH TEAM

The following observations were made in this field study:

- The overall deck thickness was 8.5 in. The cover for the top mat of epoxy-coated grade 60 steel was 3 in., and the cover from the top surface for the bottom mat of steel was 6.5 in.
- Removable wood formwork was used in the deck construction.
- The concrete was mixed at a central mix plant (Penny's concrete) and transported by ready-mix trucks.
- The mix design was from Ames Construction Inc. and approved by the Kansas Department of Transportation (KDOT). The accepted mix proportions are given in the Project Data section of this report.
- Cementitious materials included Type I/II cement (Buzzi Unicem), grade 120 slag cement (Holcim), and silica fume (WR Grace). Two types of coarse granite aggregate were used together with a natural sand as fine aggregate.
- Setting time of the mix was determined as a single measurement: initial set occurred at 3.66 hours and the final set was achieved at 11.66 hours.
- According to the Workability Factor & Coarseness Factor graph (see Project Data section), combined aggregate gradation for this project fell in the well-graded region. However, from 0.45 Power Curve and Combined Percent Retained Curve, the aggregate gradation was slightly lacking in the amount of material retained on the #8 sieve. This did not adversely affect workability or hardened properties of the mixture, as observed in the field.
- A brief summary of weather conditions recorded by the PCC mobile lab is tabulated in Table 1 and presented graphically in Figures 3 through 5. The relative humidity ranged from 60% to 84%; the ambient temperature ranged from 48˚F to 62˚F; the wind speed varied from 2.4 mph to 11.2 mph; the concrete temperature ranged from 55.0˚F to 66˚F during the recorded period (i.e., from 8 a.m. to 11:30 a.m.).

Table 1. Ambient conditions of US 59 bridge deck project

Kansas - Ternary Mixtures

US-59 Bridge Deck

Sample Information & Identification			Environmental Conditions			
Sample Date	Sample Time	Sample Comments	Relative Humidity (%)	Ambient Temp. (˚F)	Wind Speed (mph)	Conc. Temp. (probe) (˚F)
28-Oct-09	8:03 AM	kdot sample taken at pump discharge	65.0	48.0	2.4	55.0
28-Oct-09	8:20 AM	cp tech center sample taken at truck discharge	81.0	48.0	8.0	60.0
28-Oct-09	8:25 AM	kdot sample taken at pump discharge	84.0	49.0	4.5	62.0
28-Oct-09	9:20 AM	kdot sample taken at pump discharge	79.0	51.0	4.5	61.0
28-Oct-09	8:40 AM	kdot sample taken at pump discharge	81.0	53.0	11.2	62.0
28-Oct-09	10:10 AM	kdot sample taken at pump discharge	70.0	57.0	6.0	65.0
28-Oct-09	10:50 AM	cp tech center sample taken at truck discharge	60.0	57.0	5.0	62.6
28-Oct-09	11:04 AM	kdot sample taken at pump discharge	65.0	58.0	5.5	65.0
28-Oct-09	11:28 AM	kdot sample taken at pump discharge	62.0	62.0	3.5	66.0

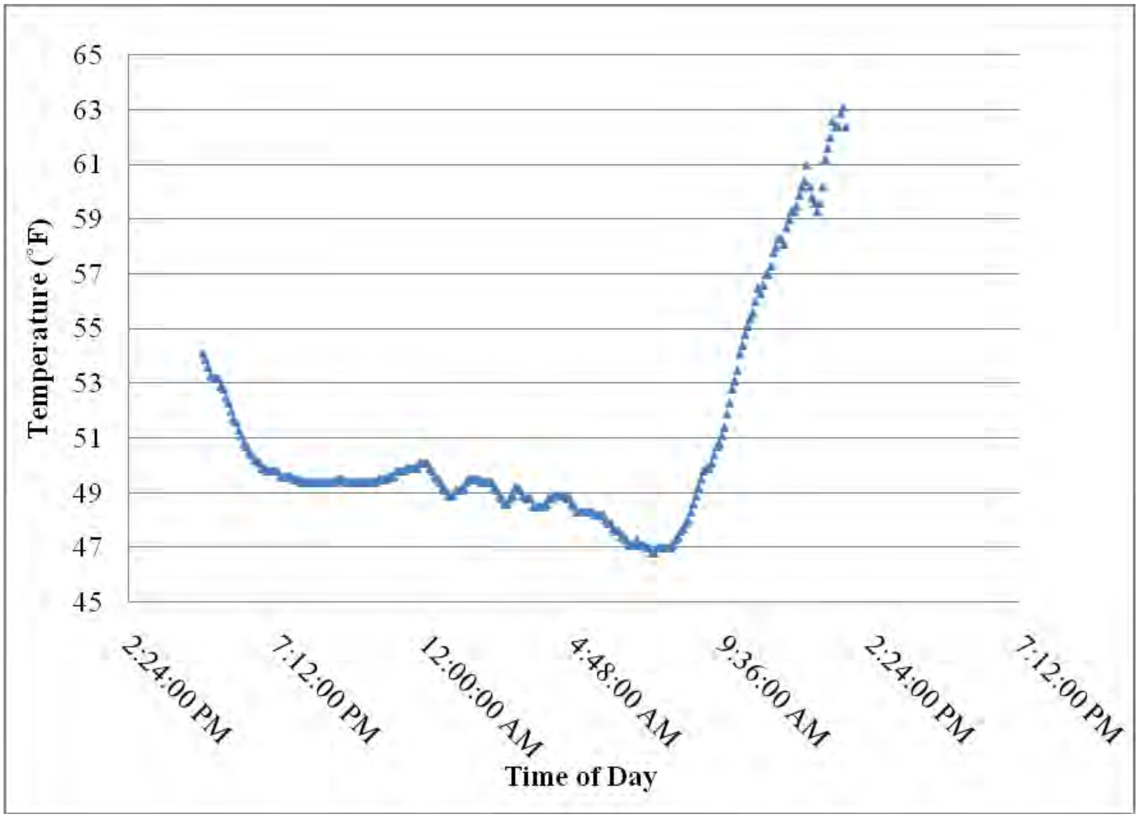


Figure 3. Ambient temperature versus time of day

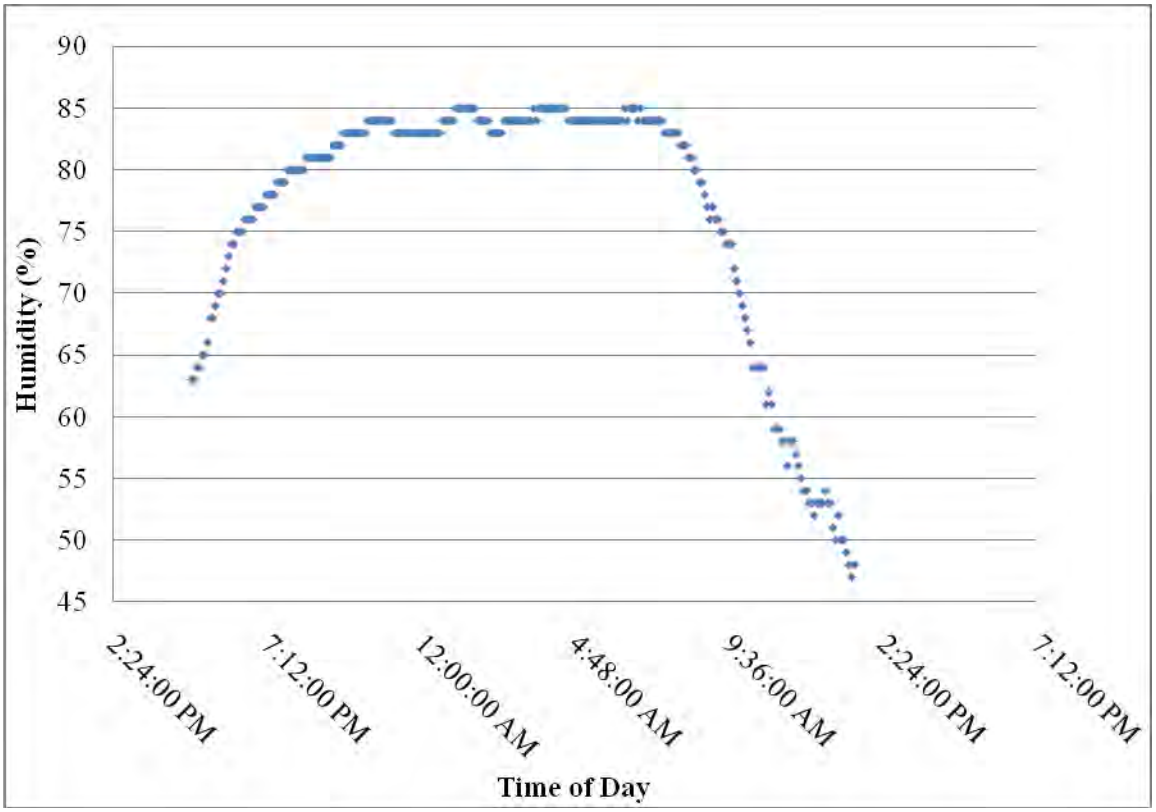


Figure 4. Relative humidity versus time of day

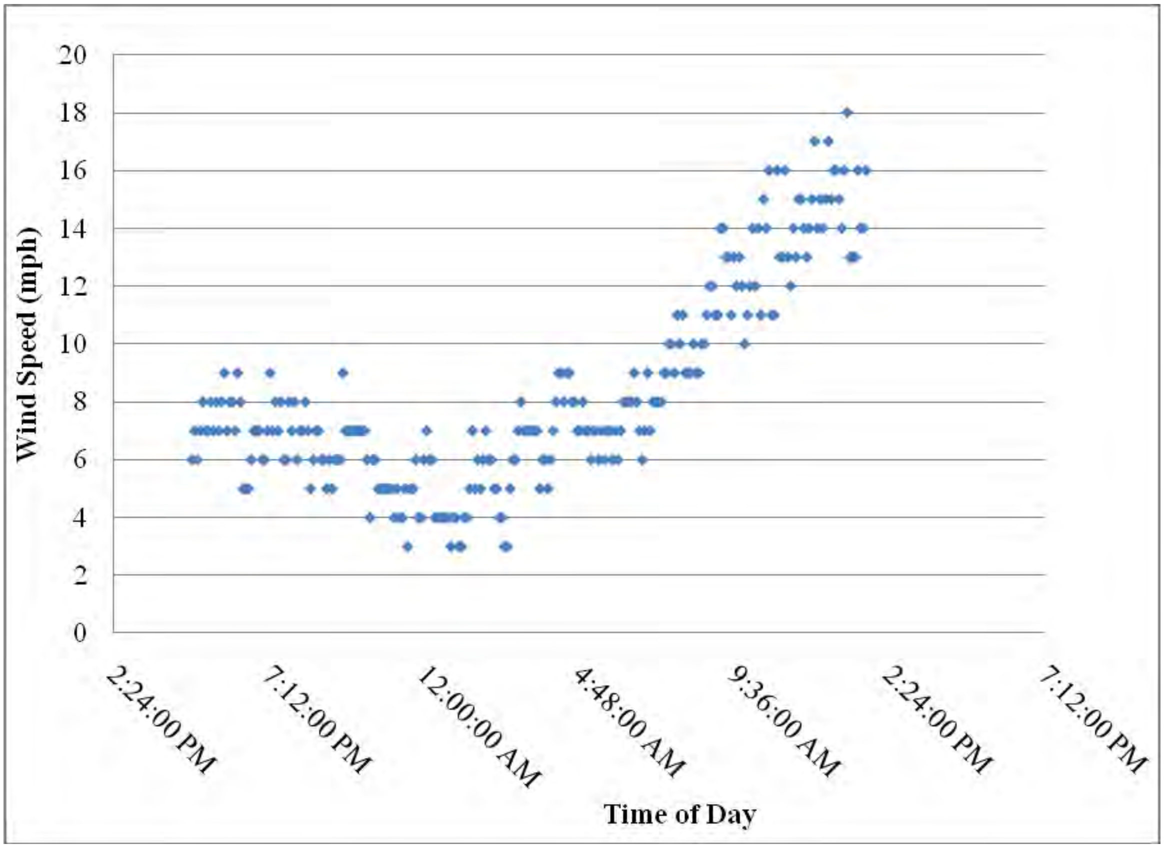


Figure 5. Wind speed versus time of day

- Figures 6 through 10 illustrate some activities during the testing process.

Figure 6. KDOT crew collecting samples

Figure 7. Construction crew placing concrete, pouring and vibrating

Figure 8. Preparing concrete cylinder samples **Figure 9. CP Tech Center PCC mobile lab**

Figure 10. Concrete being placed and vibrated

- The fresh concrete tests included slump cone, unit weight, and water-cementitious materials ratio by microwave. Nine groups of samples were tested during the construction period. Slump results varied from a maximum of 7.5 in. to a minimum of 3.0 in. The unit weight ranged from 142.4 lb/ft^3 to 135.6 lb/ft^3, with an average value of 138.9 lb/ft^3. Two microwave w-cm ratio tests were performed at 8:20 a.m. and 10:50 a.m., and the results were 0.44 and 0.45, respectively. The design value was 0.42. The data are provided in the Project Data section of this report.
- The air content ranged from 5.2% to 9.0%, with an average of 7.3% over the nine tests conducted. The specified minimum was 6.5%.
- The air void test (rapid air test) results for 14 samples from the same concrete mix are given in Table 2. A spacing factor ≤ 0.20 mm measured using microscopical methods is an indication of a good concrete freeze-thaw resistance. Based on this criterion, the spacing factors were acceptable in 7 out of 14 samples.

Table 2. Air void structure results

Sample ID	Air Content (%)	Specific Surface (mm^{-1})	Spacing Factor (mm)
A-1-122-S1	8.92	18.78	0.161
A-1-122-S2	9.59	16.63	0.169
A-1-122-S3	8.59	16.96	0.185
A-2-122-S1	13.19	15.56	0.132
A-2-122-S2	10.99	14.15	0.174
A-2-122-S3	11.77	16.35	0.140
A-2-122-S4	12.3	14.40	0.153
B-1-133-S1	3.62	21.50	0.259
B-1-133-S2	5.10	14.46	0.329
B-1-133-S3	3.88	16.33	0.330
B-1-133-S4	3.43	17.17	0.332
B-2-129-S1	3.97	17.60	0.303
B-2-129-S2	4.02	19.40	0.273
B-2-129-S3	4.40	17.43	0.292

- The rapid chloride permeability test measured the electrical conductance of a concrete sample as its resistance to chloride ion penetration. The test results shown in Table 3 indicate a classification of "very low" permeability of chloride.
- The strength development 28/7-day f_c ratios are reported in Table 3.
- Compressive strength, splitting tensile strength, and modulus of elasticity results (ASTM C 39, ASTM C 496, and ASTM C 469) are given in Table 4, and development curves are plotted in Figures 11 through 13.
- The porosity values obtained by the boiling test (ASTM C 642) results are given in Table 3.
- The feedback from the contractor on workability and finishing properties was positive. Traditionally, KDOT has constructed bridge decks in two pours: a binary mixture approximately 6 in. thick, which is later capped with an approximate 2 in. high-density silica fume mixture. However, the ternary mixture allowed the contractor to place a full-depth deck in one pour.

Table 3. Properties of hardened concrete

	7-day Compressive Strength, (psi)	28-day Compressive Strength, (psi)	56-day Compressive Strength, (psi)	Rapid Chloride Permeability, (coulombs)	Porosity, (%)	Strength Development 28/7-day fc Ratio
A-1-122-S1 A-1-122-S2 A-1-122-S3	2100	5010	6020	532	8.3	2.39
A-2-122-S1 A-2-122-S2 A-2-122-S3 A-2-122-S4	2170	4950	5790	471	7.9	2.28
B-1-133-S1 B-1-133-S2 B-1-133-S3 B-1-133-S4	3300	5880	6470	468	4.5	1.78
B-2-129-S1 B-2-129-S2 B-2-129-S3	3150	5400	6640	449	3.7	1.71

Table 4. Summation of strength and modulus of elasticity

Location	Age, Days	Compressive Strength, psi	Splitting Tensile Strength, psi	Modulus of Elasticity, psi
KS	1	820	114	4.1E+06
	3	1,750	270	4.8E+06
	7	3,050	417	5.3E+06
	28	6,110	484	5.8E+06
	56	6,610	522	5.4E+06

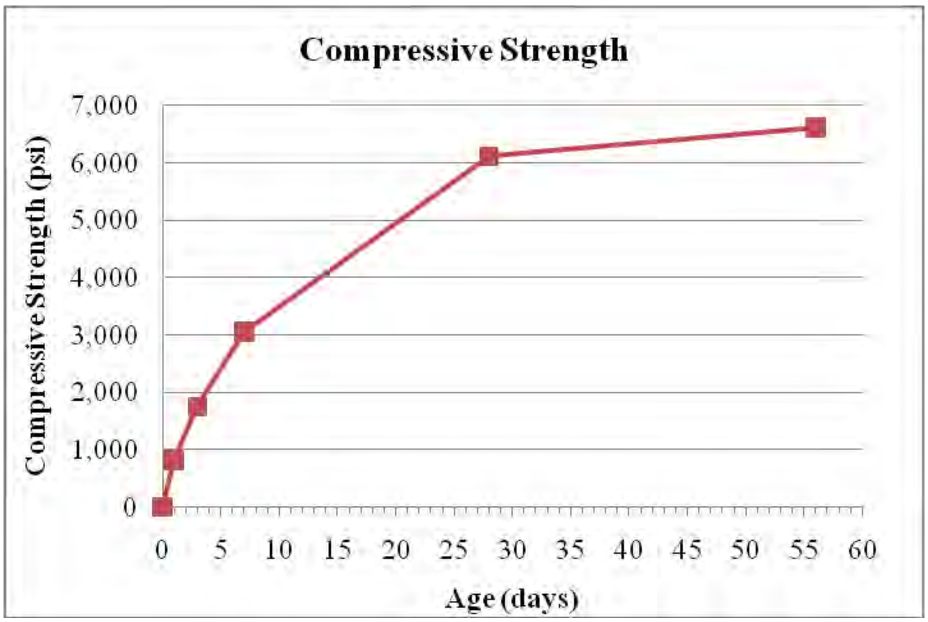


Figure 11. Compressive strength development with time

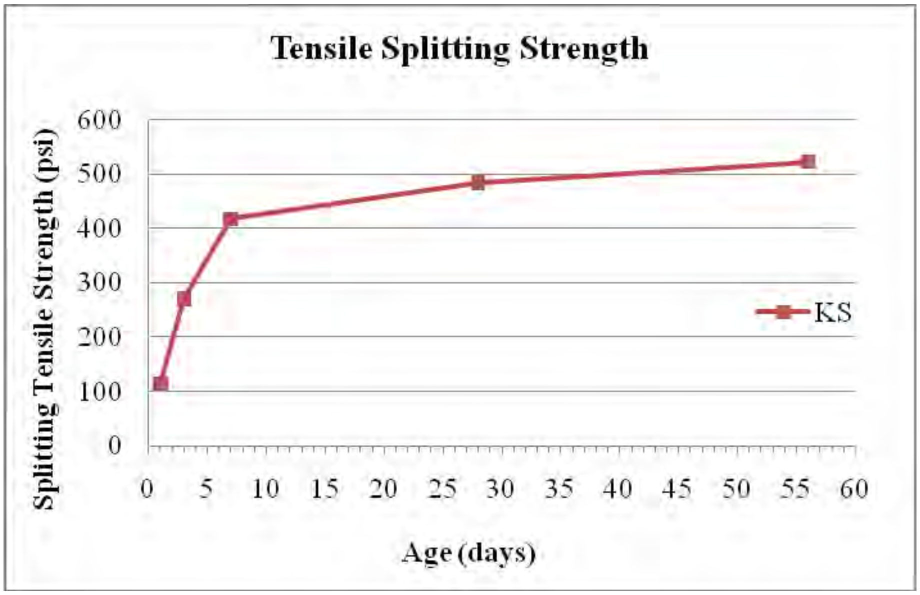


Figure 12. Tensile splitting strength development with time

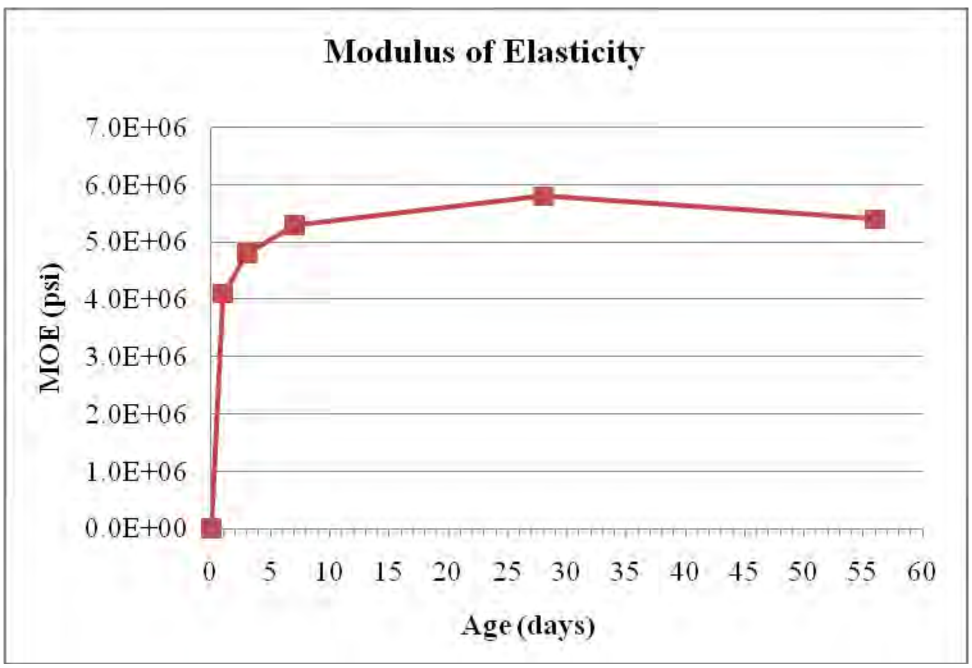


Figure 13. Modulus of elasticity development with time

- The free shrinkage test (ASTM C 157) was conducted in the laboratory. Three concrete beams were wet cured for seven days and then moved to a dry room at 23˚C and 50% relative humidity. The drying shrinkage results are given in Table 5 and also plotted in Figure 14.

Table 5. Free shrinkage test results

	Free Shrinkage (ASTM C 157)				
Dry Time	Beam 1 Change%	Beam 2 Change %	Beam 3 Change %	Average	Microstrain
1	-0.001	0.004	0.000	0.001	10.0
4	-0.008	-0.003	-0.002	-0.004	-43.3
7	0.000	-0.009	-0.01	-0.006	-63.3
14	-0.031	-0.038	-0.039	-0.036	-360.0
28	-0.039	-0.044	-0.042	-0.042	-416.7
56	-0.050	-0.056	-0.047	-0.051	-510.0

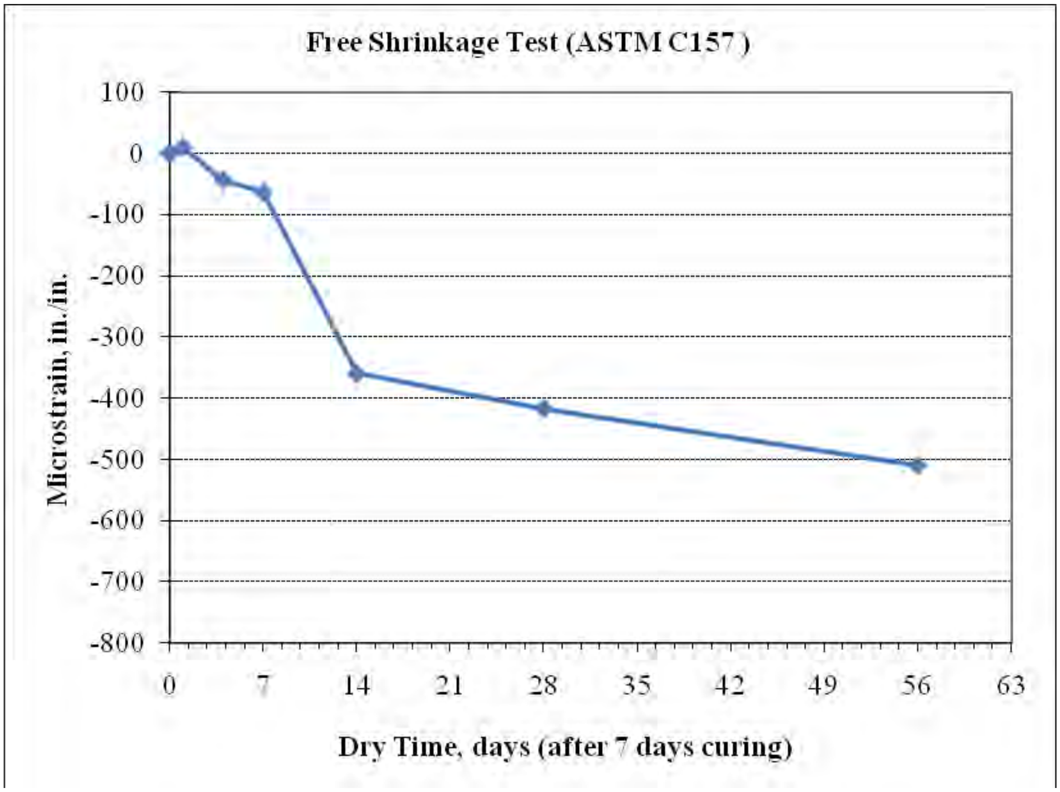


Figure 14. Free shrinkage test results (ASTM C 157)

- The restrained shrinkage test was conducted based on ASTM C 1581. Four rings were cast. The rings were demolded, and the top surface was covered with paraffin wax 24 hours from casting. The rings were allowed to dry at 23˚C and 50% relative humidity immediately after demolding. Strains in the steel rings were recorded every 10 minutes for up to 28 days, or until the concrete cracked. The configuration of restrained concrete rings is shown in Figure 15. The cracking potential is listed in Table 6 and shown graphically in Figure 16. The cracking potential is classified as “moderate high,” based on the average stress rate.

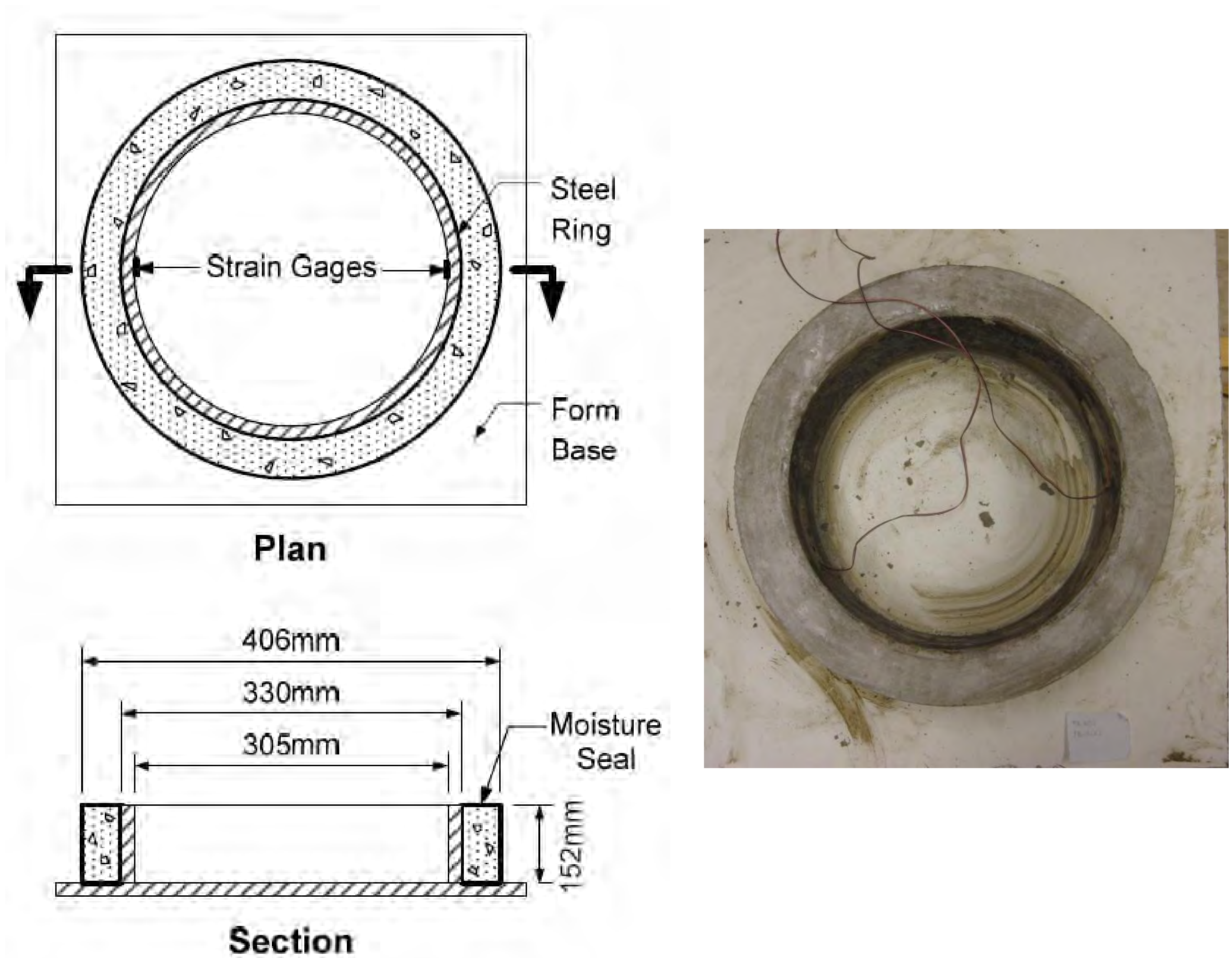


Figure 15. Configuration of restrained concrete ring samples

Table 6. Cracking potential and average stress rate (ASTM C 1581)

Cracking Potential for KS Project (ASTM C 1581)			
	Ring 1	Ring 2	Ring 3
Strain rate factor (in./in.x10^{-6})/hours$^{1/2}$	-5.09	-5.70	-5.21
G (psi)	10.47x10^6	10.47x10^6	10.47x10^6
Absolute value of α_{avg} (in./in.10^{-6})/day$^{1/2}$		26.13	
Elapsed time, tr (hours)	424.0	302.9	302.9
Elapsed time, tr (days)	17.7	12.6	12.6
Stress rate, q (psi/day) $q=G I \alpha_{avg} I/2\sqrt{t_r}$	32.5	38.5	38.5
Average stress rate, q (psi/day) $q=G I \alpha_{avg} I/2\sqrt{t_r}$		**36.52**	
Potential for cracking classification (ASTM 1581)		**Moderate-high (25≤ q < 50)**	

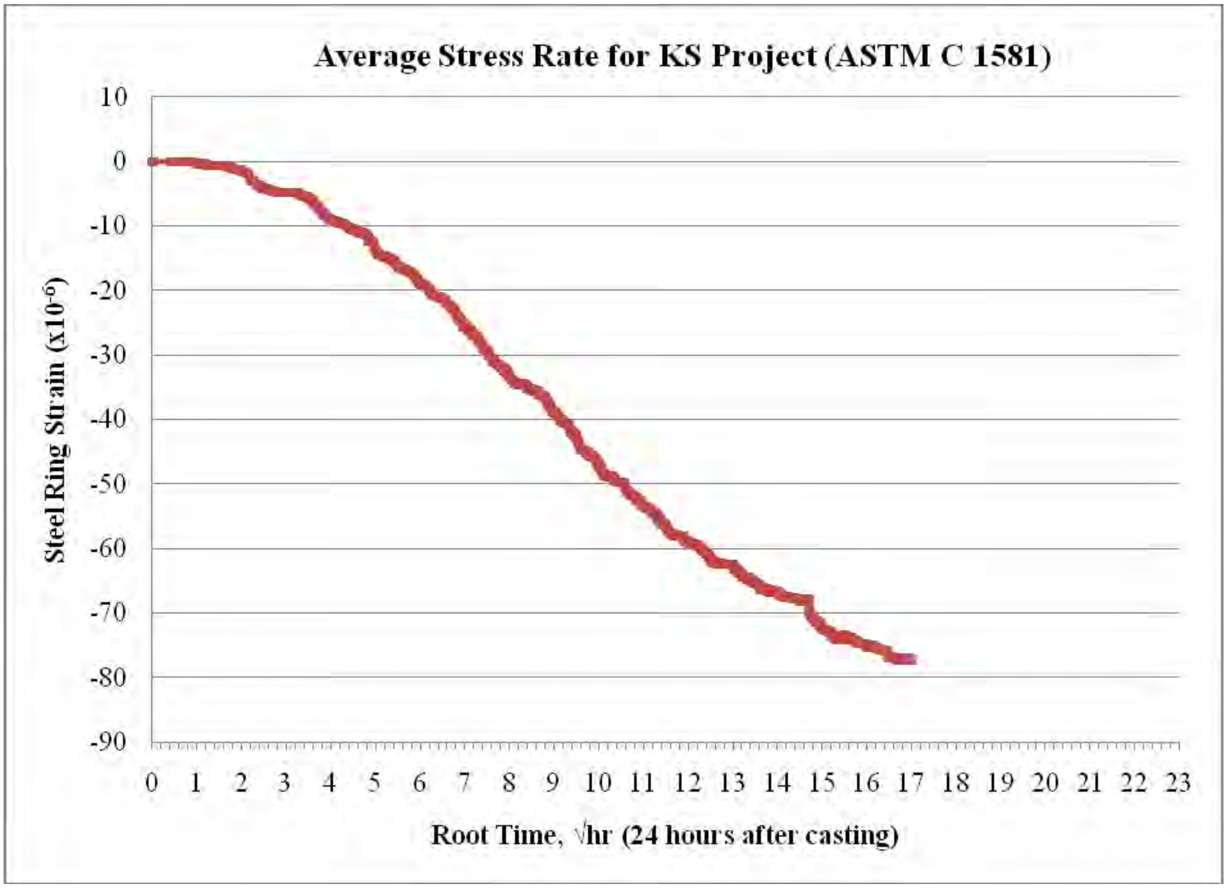


Figure 16. Strain of steel rings resulting from concrete shrinkage

PROJECT DATA

The following test data is provided for information only; comments and conclusions will be reported in the comprehensive Phase III report of the pooled fund project *Development of Performance Properties of Ternary Mixtures.*

Mix Design & Misc. Info.

General Information

Project:	Kansas - Ternary Mixtures
Contractor:	Ames
Mix Description:	535 lb Cementitious
Mix ID:	1PL5046A
Date(s) of Placement:	10/28/2009

Cementitious Materials

	Source	Type	Spec. Gravity	lb/yd^3	% Replacement by Mass
Portland Cement:	Buzzi Unicem	I/II	3.150	321	
GGBFS:	Holcim		2.870	187	34.95%
Fly Ash:					
Silica Fume:	WR Grace		2.250	27	5.05%
Other Pozzolan:					
				535	**lb/yd^3**
				5.7	**sacks/yd^3**

Aggregate Information

	Source	Type	Spec. Gravity SSD	Absorption (%)	% Passing #4
Coarse Aggregate:	Granite Mountain - Ark.	Granite	2.600	0.80%	3.0%
Intermediate Aggregate #1:	Granite Mountain - Ark.	Granite	2.600	0.80%	5.0%
Intermediate Aggregate #2:					
Fine Aggregate #1:	Penny's	Natural Sand	2.610	0.70%	99.0%

Coarse Aggregate %:	45.0%
Intermediate Aggregate #1%:	15.2%
Intermediate Aggregate #2%:	
Fine Aggregate #1 %:	39.8%

Mix Proportion Calculations

Water/Cementitious Materials Ratio:	0.420
Air Content:	6.50%

	Volume (ft^3)	Batch Weights SSD (lb/yd^3)	Spec. Gravity	Absolute Volume (%)
Portland Cement:	1.633	321	3.150	6.048%
GGBFS:	1.044	187	2.870	3.867%
Fly Ash:				
Silica Fume:	0.192	27	2.250	0.712%
Other Pozzolan:				
Coarse Aggregate:	8.449	1,371	2.600	31.291%
Intermediate Aggregate #1:	2.854	463	2.600	10.569%
Intermediate Aggregate #2:				
Fine Aggregate #1:	7.472	1,217	2.610	27.675%
Water:	3.601	225	1.000	13.337%
Air:	1.755			6.500%
	27.000	**3,810**		**100.000%**
	Unit Weight (lb/ft^3)	**141.1**	**Paste**	**30.465%**
			Mortar	**59.330%**

Admixture Information

	Source/Description	oz/yd^3	oz/cwt
Air Entraining Admix.:	Daravair 1400 AEA	4.00	0.75
Admix. #1:	ADVA 140M Full Range WR	1.00	0.19
Admix. #2:	Daraset 200 Type C accelerator	1.00	0.19
Admix. #3:	Recover Type D Retarder	1.00	0.19

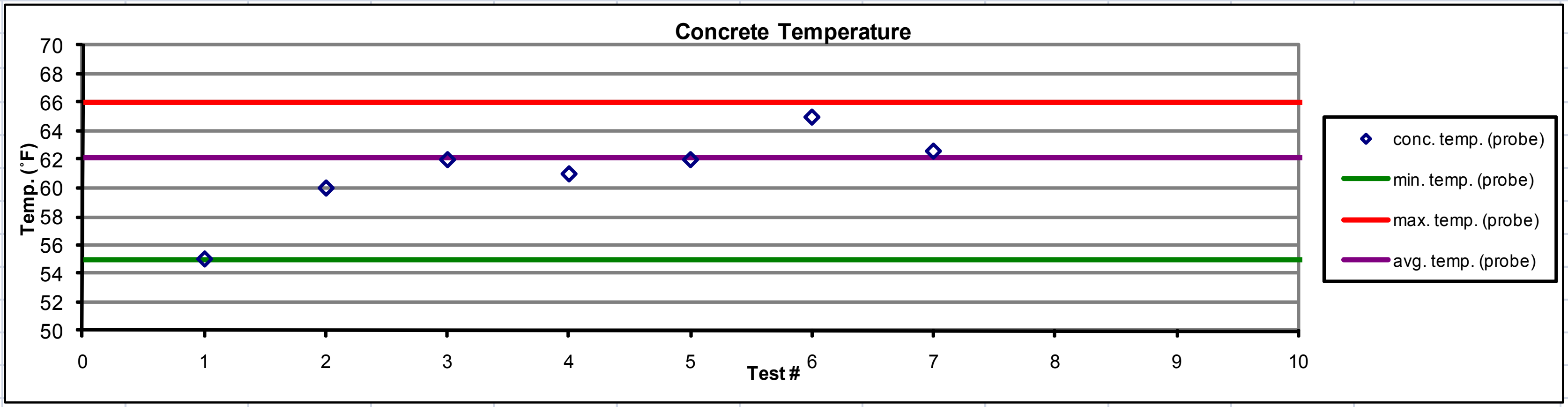
AVA Information

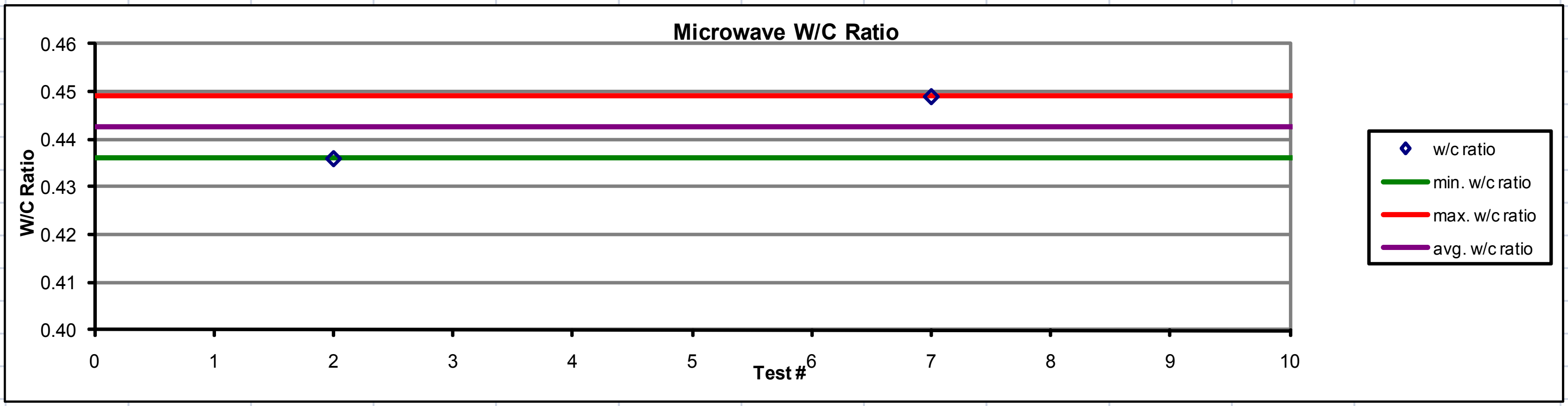
	Absolute Volume (%)
Air Free Paste:	23.965%
Air Free Mortar:	52.830%

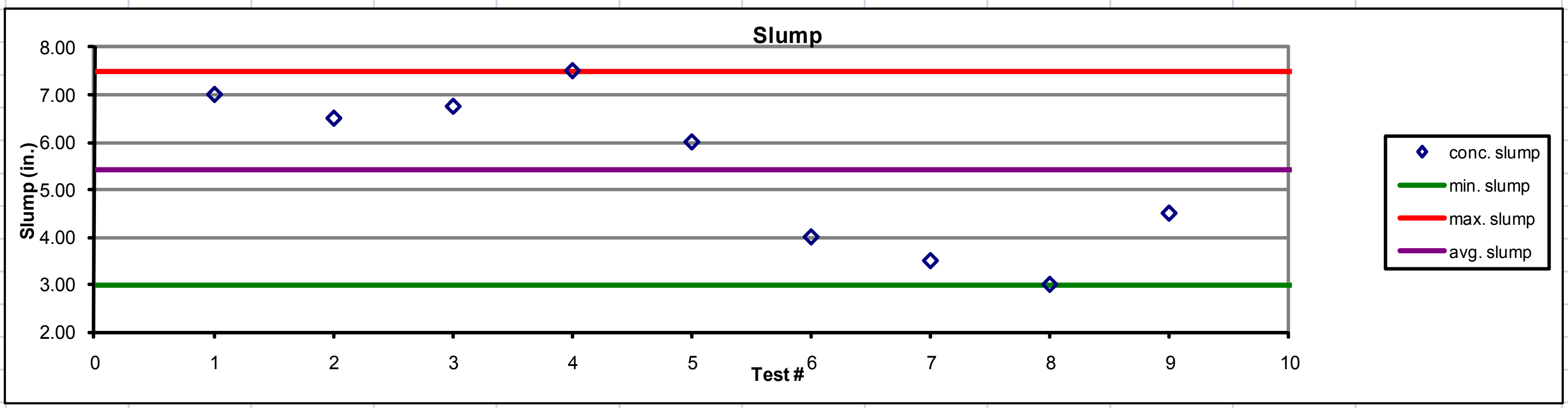
Kansas - Ternary Mixtures

US-59 Bridge Deck

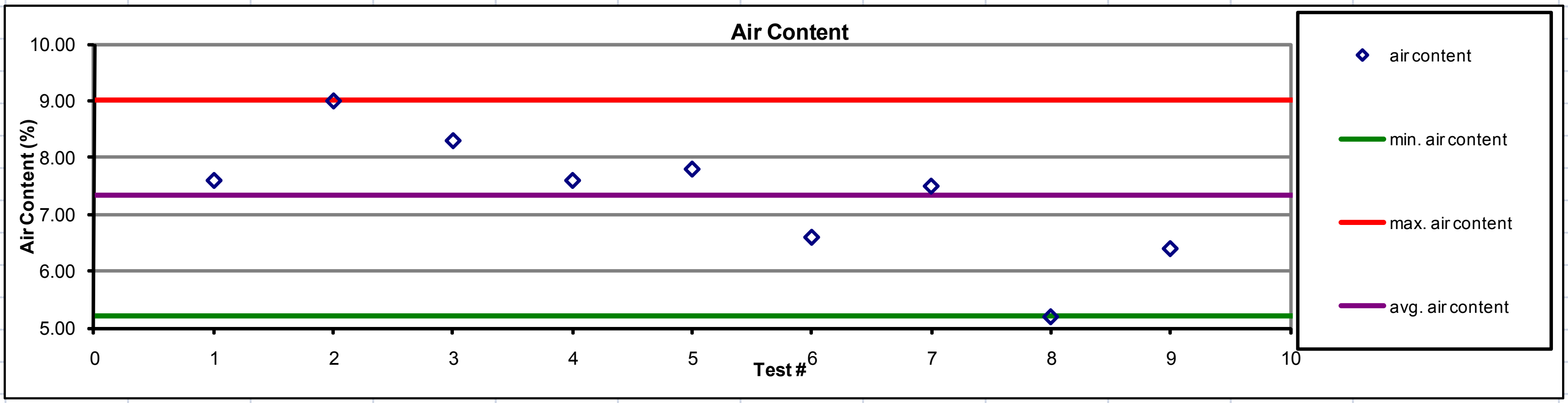
Sample Information & Identification			Environmental Conditions				Fresh Concrete Workability Properties			Pressure Air
Sample Date	Sample Time	Sample Comments	Relative Humidity (%)	Ambient Temp. (˚F)	Wind Speed (mph)	Conc. Temp. (probe) (˚F)	Slump (in)	Unit Weight (lb/ft^3)	Microwave W/C Ratio (%)	% Air Content
28-Oct-09	8:03 AM	kdot sample taken at pump discharge	65.0	48.0	2.4	55.0	7.00	137.8	n/a	7.6
28-Oct-09	8:20 AM	cp tech center sample taken at truck discharge	81.0	48.0	8.0	60.0	6.50	135.6	0.44	9.0
28-Oct-09	8:25 AM	kdot sample taken at pump discharge	84.0	49.0	4.5	62.0	6.75	136.4	n/a	8.3
28-Oct-09	9:20 AM	kdot sample taken at pump discharge	79.0	51.0	4.5	61.0	7.50	137.8	n/a	7.6
28-Oct-09	8:40 AM	kdot sample taken at pump discharge	81.0	53.0	11.2	62.0	6.00	138.8	n/a	7.8
28-Oct-09	10:10 AM	kdot sample taken at pump discharge	70.0	57.0	6.0	65.0	4.00	140.4	n/a	6.6
28-Oct-09	10:50 AM	cp tech center sample taken at truck discharge	60.0	57.0	5.0	62.6	3.50	139.8	0.45	7.5
28-Oct-09	11:04 AM	kdot sample taken at pump discharge	65.0	58.0	5.5	65.0	3.00	142.4	n/a	5.2
28-Oct-09	11:28 AM	kdot sample taken at pump discharge	62.0	62.0	3.5	66.0	4.50	140.8	n/a	6.4


Concrete Temperature
Temp. (°F)
70
68
66
64
62
60
58
56
54
52
50
0
1
2
3
4
5
6
7
8
9
10
Test #
conc. temp. (probe)
min. temp. (probe)
max. temp. (probe)
avg. temp. (probe)


Microwave W/C Ratio
W/C Ratio
0.46
0.45
0.44
0.43
0.42
0.41
0.40
0
1
2
3
4
5
6
7
8
9
10
Test #
w/c ratio
min. w/c ratio
max. w/c ratio
avg. w/c ratio


Slump
Slump (in.)
8.00
7.00
6.00
5.00
4.00
3.00
2.00
0
1
2
3
4
5
6
7
8
9
10
Test #
conc. slump
min. slump
max. slump
avg. slump


Unit Weight
Unit Weight (lb/ft³)
145.0
144.0
143.0
142.0
141.0
140.0
139.0
138.0
137.0
136.0
135.0
0
1
2
3
4
5
6
7
8
9
10
Test #
unit wt.
min. unit wt.
max. unit wt.
avg. unit wt.


Air Content
Air Content (%)
10.00
9.00
8.00
7.00
6.00
5.00
0
1
2
3
4
5
6
7
8
9
10
Test #
air content
min. air content
max. air content
avg. air content

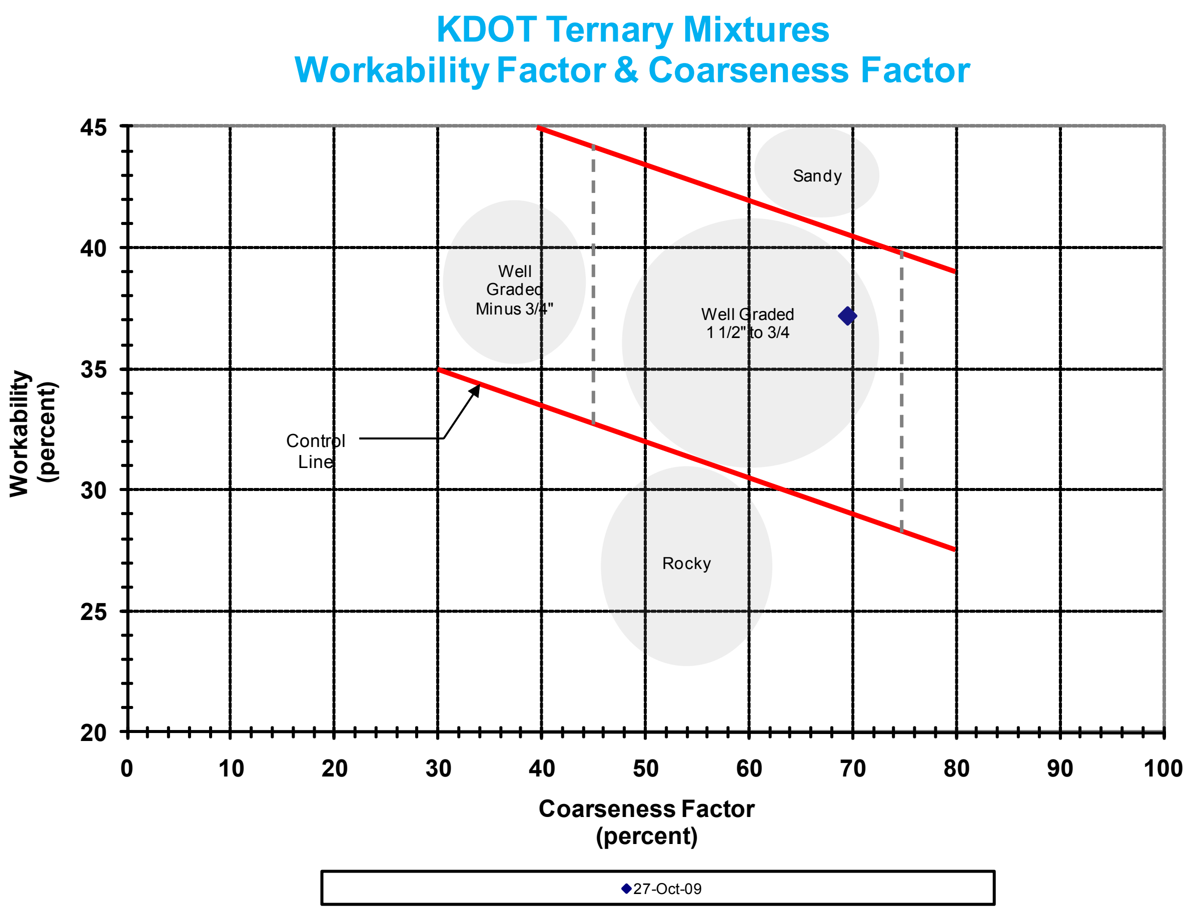
Workability Factor & Coarseness Factor

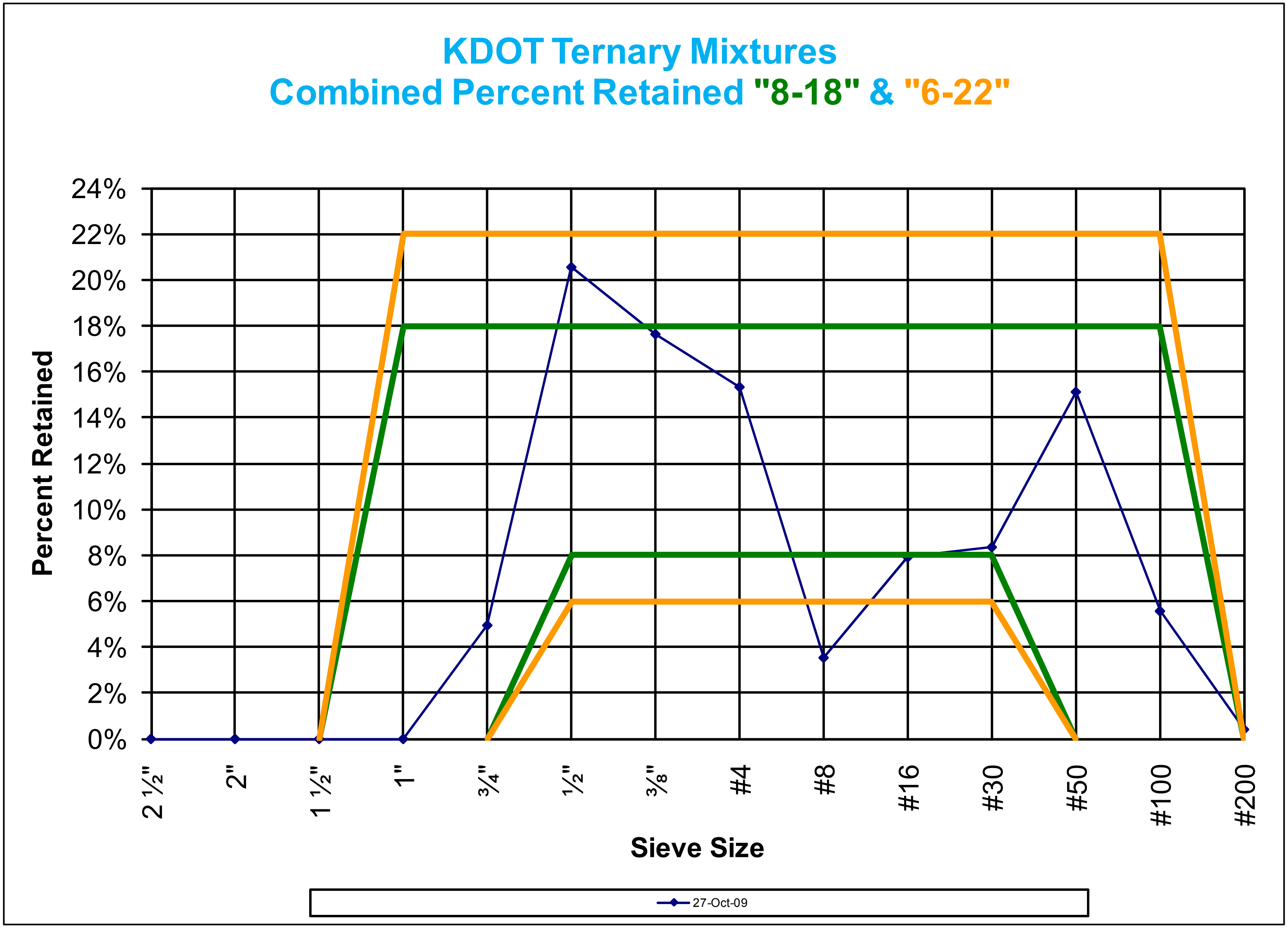
Project: KDOT Ternary Mixtures
Mix ID: Bridge Deck
Sample Comments: KDOT Data
Test Date: 27-Oct-09

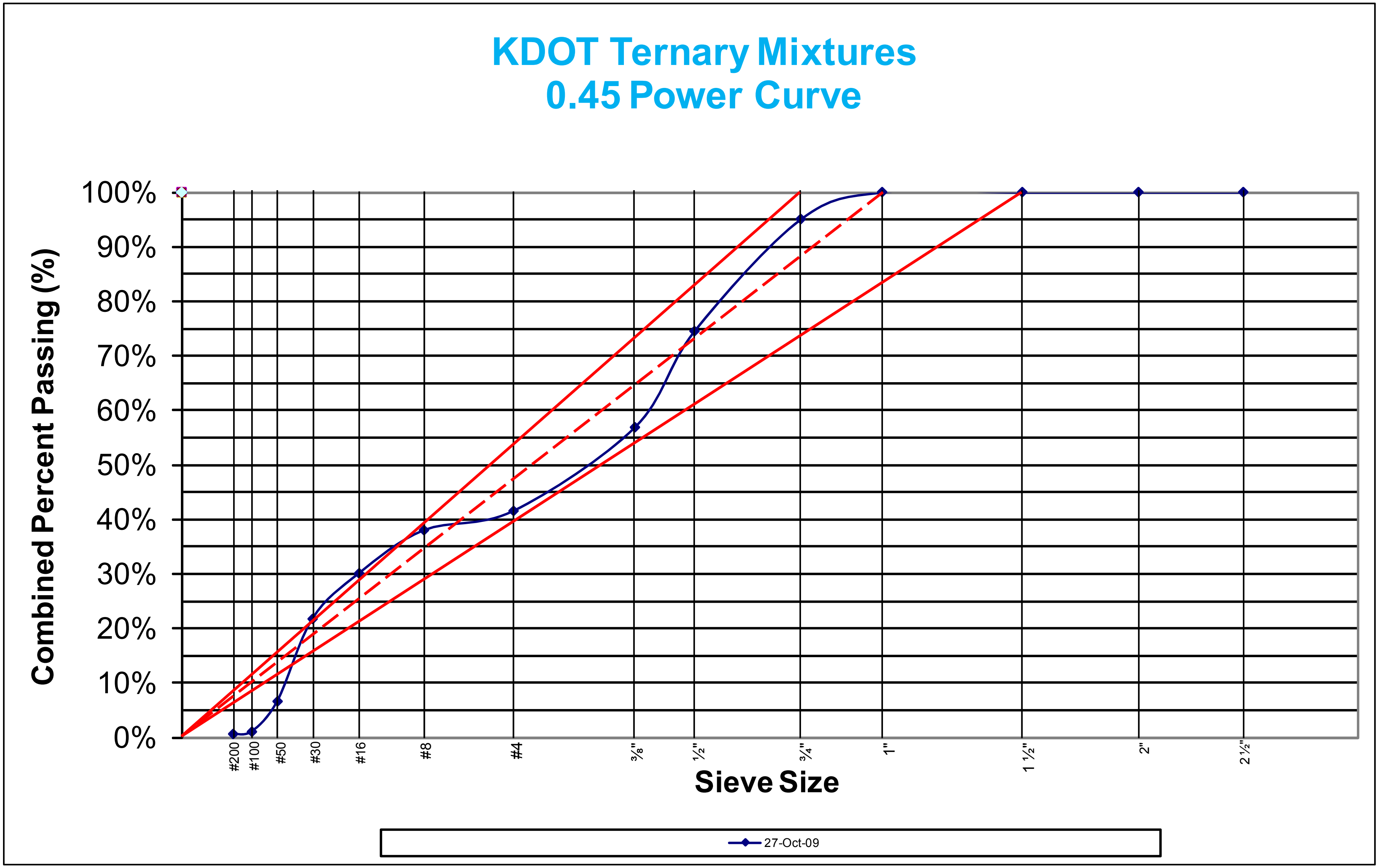
Total Cementitious Material:		535 lb/yd^3		
Agg. Ratios:	45.00%	15.20%	39.80%	100.00%

Sieve	Coarse	Intermediate	Fine #1	Fine #2	Combined % Retained	Combined % Retained On Each Sieve	Combined % Passing
2 ½"	100%	100%	100%		0%	0%	100%
2"	100%	100%	100%		0%	0%	100%
1 ½"	100%	100%	100%		0%	0%	100%
1"	100%	100%	100%		0%	0%	100%
¾"	89%	100%	100%		5%	5%	95%
½"	45%	95%	100%		26%	21%	74%
⅜"	21%	50%	100%		43%	18%	57%
#4	3%	5%	99%		58%	15%	42%
#8	2%	3%	92%		62%	4%	38%
#16	1%	1%	74%		70%	8%	30%
#30	1%	1%	53%		78%	8%	22%
#50	1%	1%	15%		93%	15%	7%
#100	1%	1%	1%		99%	6%	1%
#200	0.7%	1.0%	0.3%		99.4%	0.4%	0.6%

Workability Factor: 37.2
Coarseness Factor: 69.6




KDOT Ternary Mixtures
Combined Percent Retained "8-18" & "6-22"
Percent Retained
24%
22%
20%
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
2 ½"
2"
1 ½"
1"
¾"
½"
⅜"
#4
#8
#16
#30
#50
#100
#200
Sieve Size
27-Oct-09


KDOT Ternary Mixtures
0.45 Power Curve
Combined Percent Passing (%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
#200
#100
#50
#30
#16
#8
#4
3/8"
1/2"
3/4"
1"
1 1/2"
2"
2 1/2"
Sieve Size
27-Oct-09

Kansas - Ternary Mixtures

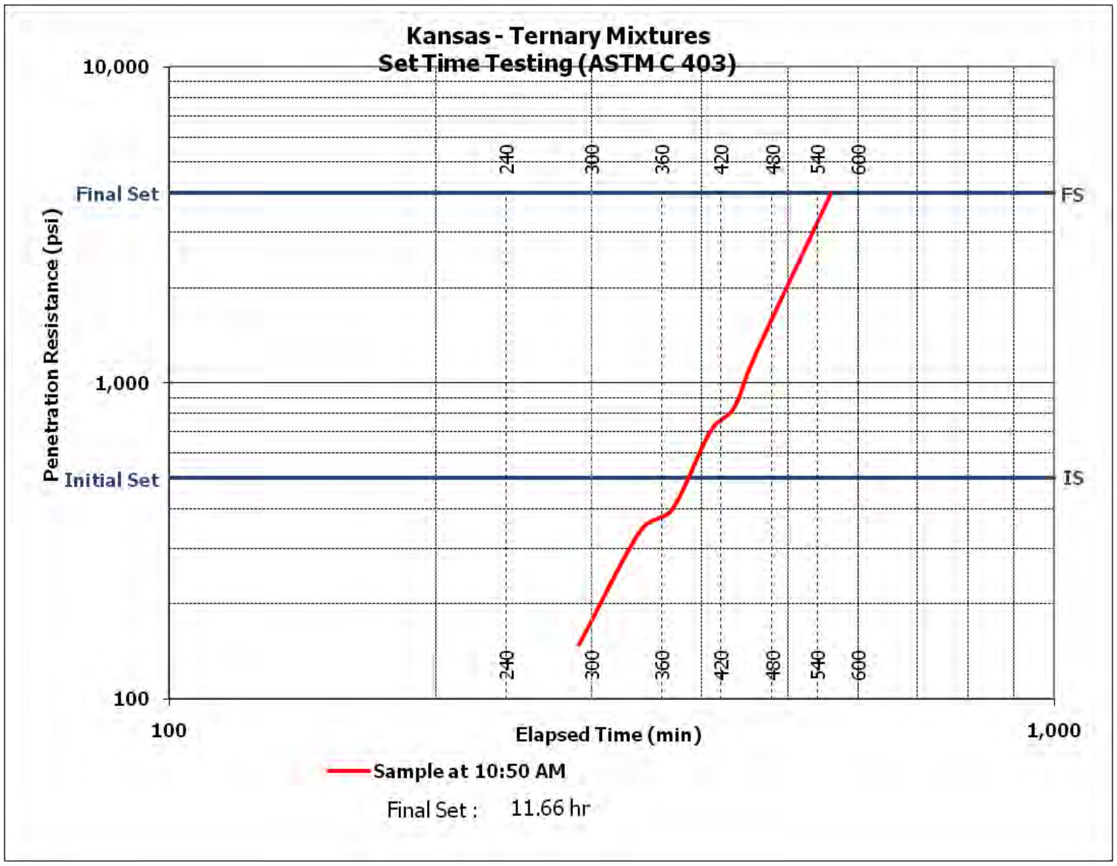
Set Time ASTM C 403

Project: US-59 Bridge Deck
Date: 28-Oct-09 Start Time: 10:50 AM
Sta: n/a

Test Data

Penetration Time (xx:xx-24 hr format)	Time (min)	Needle # (1,2,4,10,20 or 40)	Force (lb)	Penetration Resistance (psi)	Sample Temp. (°F)
3:40 PM	290.00	1	149	149.00	n/a
4:30 PM	340.00	4	85	340.00	n/a
5:00 PM	370.00	10	40	400.00	n/a
5:38 PM	408.00	10	70	700.00	n/a
6:05 PM	435.00	20	42	840.00	n/a
6:30 PM	460.00	20	62	1240.00	n/a
8:10 PM	560.00	40	100	4000.00	n/a
					n/a
					n/a

Initial Set (at 500 psi PR)	estimated times using forecast function	**220**	minutes	**3.66**	hours
Final Set (at 4,000 psi PR)		**700**	minutes	**11.66**	hours



Kansas - Ternary Mixtures
Set Time Testing (ASTM C 403)
10,000
1,000
100
Final Set
Initial Set
Penetration Resistance (psi)
FS
IS
240
300
360
420
480
540
600
100
1,000
Elapsed Time (min)
Sample at 10:50 AM
Final Set : 11.66 hr

Kansas - Ternary Mixtures

Microwave Water Content Worksheet

Project: US-59 Bridge Deck

Date: 28-Oct-09 Time: 8:20 AM

Sta: n/a

Test Data

Mass of tray+cloth+block+fresh test sample, W_F (g)	3,703.6
Mass of tray+cloth+block, W_S(g)	2,203.4
Mass of tray+cloth+dry sample, W_D (g) (5mins)	3,662.2
Mass of tray+cloth+dry sample, W_D (g) (7 mins)	3,611.0
Mass of tray+cloth+dry sample, W_D (g) (9 mins)*	3,603.2
Mass of tray+cloth+dry sample, W_D (g) (11 mins)*	3,601.1
Mass of tray+cloth+dry sample, W_D (g) (13 mins)*	3,599.6
Mass of tray+cloth+dry sample, W_D (g) (15 mins)*	3,598.8
Mass of tray+cloth+dry sample, W_D (g) (17 mins)*	3,598.5
Mass of tray+cloth+dry sample, W_D (g) (Final)**	3,598.5
Water content percentage, W_C (%)	**7.0%**
Unit weight of fresh concrete, UW (lb/ft^3)***	135.6
Total water content, W_T, (lb/yd^3)	**256.6**
Total cementitious weight (lb/yd^3)	535
Fine aggregate weight (lb/yd^3)	1211
Coarse Aggregate weight (lb/yd^3)	1369
Intermediate Aggregate weight (lb/yd^3)	463
Fine aggregate absorption (%)	0.70%
Coarse aggregate absorption (%)	0.80%
Intermediate aggregate absorption (%)	0.80%
w/c	**0.436**

* If necessary (stop if the weight loss is less than 1g)

** Mass at test termination

***From unit weight test

Kansas - Ternary Mixtures

Microwave Water Content Worksheet

Project: US-59 Bridge Deck

Date: 28-Oct-09 Time: 10:50 AM

Sta: n/a

Test Data

Mass of tray+cloth+block+fresh test sample, W_F (g)	3,707.8
Mass of tray+cloth+block, W_S(g)	2,203.2
Mass of tray+cloth+dry sample, W_D (g) (5mins)	3,668.0
Mass of tray+cloth+dry sample, W_D (g) (7 mins)	3,635.2
Mass of tray+cloth+dry sample, W_D (g) (9 mins)*	3,613.5
Mass of tray+cloth+dry sample, W_D (g) (11 mins)*	3,605.7
Mass of tray+cloth+dry sample, W_D (g) (13 mins)*	3,603.8
Mass of tray+cloth+dry sample, W_D (g) (15 mins)*	3,602.9
Mass of tray+cloth+dry sample, W_D (g) (17 mins)*	
Mass of tray+cloth+dry sample, W_D (g) (Final)**	3,602.9
Water content percentage, W_C (%)	**7.0%**
Unit weight of fresh concrete, UW (lb/ft^3)***	139.8
Total water content, W_T, (lb/yd^3)	**263.1**
Total cementitious weight (lb/yd^3)	535
Fine aggregate weight (lb/yd^3)	1211
Coarse Aggregate weight (lb/yd^3)	1369
Intermediate Aggregate weight (lb/yd^3)	463
Fine aggregate absorption (%)	0.70%
Coarse aggregate absorption (%)	0.80%
Intermediate aggregate absorption (%)	0.80%
w/c	**0.449**

* If necessary (stop if the weight loss is less than 1g)

** Mass at test termination

***From unit weight test

Kansas - Ternary Mixtures

Compressive Strength Results

Catalog # KS ternary

Mix ID # 85T1P/15C

Date Cast: 28-Oct-09

Time Cast: 11 a.m.

		1					2					3				
			Load	Diameter	Load Rate	f'c		Load	Diameter	Load Rate	f'c		Load	Diameter	Load Rate	f'c
Date Tested	Operator	Time of Test	(lb)	(in)	(lb/sec)	(psi)	Time of Test	(lb)	(in)	(lb/sec)	(psi)	Time of Test	(lb)	(in)	(lb/sec)	(psi)
4-Nov-09	PJM	7day	41,490	4.00		3,300	7day	39,630	4.00		3,150	7day				3,225
				4.01		0			4.02		0					0
		28 day	74,310	4.01		5,880	28 day	68,180	4.01		5,400	28 day				5,640
		56 day	81,290	4.00		6,470	56 day	83,460	4.00		6,640	56 day				6,555

Kansas - Ternary Mixtures

Boil Test (ASTM C 642)

KS A-1			KS B-1		
A	1032.5	g	A	1216.8	g
B	1061.86	g	B	1239.58	g
C	1072.3	g	C	1241.36	g
D	594.1	g	D	694.4	g
P	1	g/cm³	P	1	g/cm³
g1	2.1591	g/cm³	g1	2.2247	g/cm³
g2	2.3552	g/cm³	g2	2.3292	g/cm³
Volume of permeable pore space (voids), %		**8.3229**	Volume of permeable pore space (voids), %		**4.4903**

KS A-2			KS B-2		
A	1203.3	g	A	1207.8	g
B	1234.8	g	B	1227	g
C	1247.16	g	C	1227.71	g
D	694.8	g	D	695.1	g
P	1	g/cm³	P	1	g/cm³
g1	2.1785	g/cm³	g1	2.2677	g/cm³
g2	2.3664	g/cm³	g2	2.3558	g/cm³
Volume of permeable pore space (voids), %		**7.9405**	Volume of permeable pore space (voids), %		**3.7382**

Sample ID: CAST CYL A- 1 - 122 - S2

Sample Size (mm x mm	80 x 90	Length Traversed (mm):	2413.1
Paste Content (%):	27.00	Area Traversed (mm x mm):	70 x 80

Chord Length Distribution - Table

Class No.	Chord size (microns)	Number of Chords in Class	Number of Chords in Percent	Air Content in Class	Cumulated Air Content	Chord length frequency	Air content, fraction	
1	0-10	22	2.29	0.010	0.010	0.02	0.010	0.00-0.01
2	10-20	56	5.82	0.040	0.040	0.06	0.040	0.01-0.02
3	20-30	38	5.82	0.040	0.080	0.04	0.040	0.02-0.03
4	30-40	32	3.33	0.050	0.130	0.03	0.050	0.03-0.04
5	40-50	49	5.09	0.090	0.220	0.05	0.090	0.04-0.05
6	50-60	34	3.53	0.080	0.300	0.04	0.080	0.05-0.06
7	60-80	57	5.93	0.170	0.460	0.06	0.170	0.06-0.08
8	80-100	66	6.86	0.240	0.710	0.07	0.240	0.08-0.10
9	100-120	64	6.65	0.290	1.000	0.07	0.290	0.10-0.12
10	120-140	52	5.41	0.280	1.280	0.05	0.280	0.12-0.14
11	140-160	45	4.68	0.280	1.560	0.05	0.280	0.14-0.16
12	160-180	32	3.33	0.220	1.780	0.03	0.220	0.16-0.18
13	180-200	40	4.16	0.320	2.100	0.04	0.320	0.18-0.20
14	200-220	33	3.43	0.290	2.390	0.03	0.290	0.20-0.22
15	220-240	42	4.37	0.400	2.790	0.04	0.400	0.22-0.24
16	240-260	32	3.33	0.330	3.120	0.03	0.330	0.24-0.26
17	260-280	21	2.18	0.240	3.350	0.02	0.240	0.26-0.28
18	280-300	21	2.18	0.250	3.600	0.02	0.250	0.28-0.30
19	300-350	37	3.85	0.500	4.100	0.04	0.500	0.30-0.35
20	350-400	32	3.33	0.500	4.600	0.03	0.500	0.35-0.40
21	400-450	25	2.60	0.440	5.030	0.03	0.440	0.40-0.45
22	450-500	16	1.66	0.310	5.350	0.02	0.310	0.45.0.50
23	500-1000	82	8.52	2.230	5.870	0.09	2.230	0.50-1.00
24	1000-1500	22	2.29	1.090	8.670	0.02	1.090	1.00-1.50
25	1500-2000	9	0.94	0.640	9.310	0.01	0.640	1.50-2.00
26	2000-2500	3	0.31	0.280	9.590	0.00	0.280	2.00-2.50
27	2500-3000	0	0.00	0.000	9.590	0.00	0.000	2.50-3.00
28	3000-4000	0	0.00	0.000	9.590	0.00	0.000	3.00-4.00
						962		

Air Content (%):	9.59
Specific Surface (mm^{-1}):	16.63
Spacing Factor (mm):	0.169
Void Frequency (mm^{-1}):	0.400
Average Chord Length (n	0.240
Paste to Air Ratio:	2.82

Sample ID: CAST CYL A- 1 - 122 - S3

Sample Size (mm x mm	90 x 85	Length Traversed (mm):	2413.1
Paste Content (%):	27.00	Area Traversed (mm x mm):	80 x 75

Chord Length Distribution - Table

Class No.	Chord size (microns)	Number of Chords in Class	Number of Chords in Percent	Air Content in Class	Cumulated Air Content	Chord length frequency	Air content, fraction	
1	0-10	11	1.25	0.000	0.000	0.01	0.000	0.00-0.01
2	10-20	39	4.44	0.020	0.030	0.04	0.020	0.01-0.02
3	20-30	47	4.44	0.050	0.080	0.05	0.050	0.02-0.03
4	30-40	37	4.21	0.050	0.130	0.04	0.050	0.03-0.04
5	40-50	39	4.44	0.070	0.200	0.04	0.070	0.04-0.05
6	50-60	40	4.55	0.090	0.290	0.05	0.090	0.05-0.06
7	60-80	73	8.30	0.210	0.510	0.08	0.210	0.06-0.08
8	80-100	63	7.17	0.240	0.740	0.07	0.240	0.08-0.10
9	100-120	52	5.92	0.240	0.980	0.06	0.240	0.10-0.12
10	120-140	49	5.57	0.260	1.240	0.06	0.260	0.12-0.14
11	140-160	45	5.12	0.280	1.520	0.05	0.280	0.14-0.16
12	160-180	32	3.64	0.230	1.750	0.04	0.230	0.16-0.18
13	180-200	39	4.44	0.310	2.060	0.04	0.310	0.18-0.20
14	200-220	32	3.64	0.280	2.330	0.04	0.280	0.20-0.22
15	220-240	23	2.62	0.220	2.550	0.03	0.220	0.22-0.24
16	240-260	19	2.16	0.200	2.750	0.02	0.200	0.24-0.26
17	260-280	30	3.41	0.340	3.090	0.03	0.340	0.26-0.28
18	280-300	14	1.59	0.170	3.260	0.02	0.170	0.28-0.30
19	300-350	38	4.32	0.510	3.770	0.04	0.510	0.30-0.35
20	350-400	27	3.07	0.420	4.190	0.03	0.420	0.35-0.40
21	400-450	26	2.96	0.450	4.640	0.03	0.450	0.40-0.45
22	450-500	12	1.37	0.230	4.880	0.01	0.230	0.45.0.50
23	500-1000	66	7.51	1.920	5.010	0.08	1.920	0.50-1.00
24	1000-1500	16	1.82	0.800	7.600	0.02	0.800	1.00-1.50
25	1500-2000	4	0.46	0.300	7.900	0.00	0.300	1.50-2.00
26	2000-2500	2	0.23	0.190	8.100	0.00	0.190	2.00-2.50
27	2500-3000	2	0.23	0.220	8.320	0.00	0.220	2.50-3.00
28	3000-4000	2	0.23	0.270	8.590	0.00	0.270	3.00-4.00
						879		

Air Content (%):	8.59
Specific Surface (mm^{-1}):	16.96
Spacing Factor (mm):	0.185
Void Frequency (mm^{-1}):	0.360
Average Chord Length (r	0.236
Paste to Air Ratio:	3.14

Sample Size (mm x mm	75 x 100	Length Traversed (mm):	2413.1
Paste Content (%):	27.00	Area Traversed (mm x mm):	65 x 90

Chord Length Distribution - Table

Class No.	Chord size (microns)	Number of Chords in Class	Number of Chords in Percent	Air Content in Class	Cumulated Air Content	Chord length frequency	Air content, fraction	
1	0-10	31	2.50	0.010	0.010	0.03	0.010	0.00-0.01
2	10-20	107	8.64	0.070	0.080	0.09	0.070	0.01-0.02
3	20-30	70	8.64	0.070	0.150	0.06	0.070	0.02-0.03
4	30-40	43	3.47	0.060	0.210	0.03	0.060	0.03-0.04
5	40-50	54	4.36	0.100	0.310	0.04	0.100	0.04-0.05
6	50-60	41	3.31	0.090	0.410	0.03	0.090	0.05-0.06
7	60-80	65	5.25	0.190	0.590	0.05	0.190	0.06-0.08
8	80-100	69	5.57	0.260	0.850	0.06	0.260	0.08-0.10
9	100-120	56	4.52	0.250	1.110	0.05	0.250	0.10-0.12
10	120-140	69	5.57	0.370	1.480	0.06	0.370	0.12-0.14
11	140-160	41	3.31	0.250	1.740	0.03	0.250	0.14-0.16
12	160-180	41	3.31	0.290	2.020	0.03	0.290	0.16-0.18
13	180-200	40	3.23	0.310	2.340	0.03	0.310	0.18-0.20
14	200-220	30	2.42	0.260	2.600	0.02	0.260	0.20-0.22
15	220-240	41	3.31	0.390	2.990	0.03	0.390	0.22-0.24
16	240-260	22	1.78	0.230	3.220	0.02	0.230	0.24-0.26
17	260-280	32	2.58	0.360	3.570	0.03	0.360	0.26-0.28
18	280-300	21	1.70	0.250	3.820	0.02	0.250	0.28-0.30
19	300-350	59	4.77	0.800	4.620	0.05	0.800	0.30-0.35
20	350-400	43	3.47	0.670	5.290	0.03	0.670	0.35-0.40
21	400-450	40	3.23	0.700	5.990	0.03	0.700	0.40-0.45
22	450-500	36	2.91	0.710	6.700	0.03	0.710	0.45.0.50
23	500-1000	153	12.36	4.380	7.220	0.12	4.380	0.50-1.00
24	1000-1500	24	1.94	1.190	12.270	0.02	1.190	1.00-1.50
25	1500-2000	5	0.40	0.370	12.650	0.00	0.370	1.50-2.00
26	2000-2500	1	0.08	0.090	12.740	0.00	0.090	2.00-2.50
27	2500-3000	4	0.32	0.450	13.190	0.00	0.450	2.50-3.00
28	3000-4000	0	0.00	0.000	13.190	0.00	0.000	3.00-4.00
						1238		

Air Content (%):	13.19
Specific Surface (mm^{-1}):	15.56
Spacing Factor (mm):	0.132
Void Frequency (mm^{-1}):	0.510
Average Chord Length (r	0.257
Paste to Air Ratio:	2.05

Sample ID: CAST CYL A-2-122-S2

Sample Size (mm x mm	90 x 80	Length Traversed (mm):	2413.1
Paste Content (%):	27.00	Area Traversed (mm x mm):	80 x 70

Chord Length Distribution - Table

Class No.	Chord size (microns)	Number of Chords in Class	Number of Chords in Percent	Air Content in Class	Cumulated Air Content	Chord length frequency	Air content, fraction	
1	0-10	9	0.96	0.000	0.000	0.01	0.000	0.00-0.01
2	10-20	37	3.94	0.020	0.030	0.04	0.020	0.01-0.02
3	20-30	48	3.94	0.050	0.080	0.05	0.050	0.02-0.03
4	30-40	31	3.30	0.040	0.120	0.03	0.040	0.03-0.04
5	40-50	36	3.84	0.070	0.190	0.04	0.070	0.04-0.05
6	50-60	34	3.62	0.080	0.270	0.04	0.080	0.05-0.06
7	60-80	61	6.50	0.180	0.440	0.07	0.180	0.06-0.08
8	80-100	53	5.65	0.200	0.640	0.06	0.200	0.08-0.10
9	100-120	52	5.54	0.240	0.880	0.06	0.240	0.10-0.12
10	120-140	41	4.37	0.220	1.100	0.04	0.220	0.12-0.14
11	140-160	39	4.16	0.240	1.340	0.04	0.240	0.14-0.16
12	160-180	35	3.73	0.250	1.590	0.04	0.250	0.16-0.18
13	180-200	31	3.30	0.250	1.830	0.03	0.250	0.18-0.20
14	200-220	31	3.30	0.270	2.110	0.03	0.270	0.20-0.22
15	220-240	30	3.20	0.290	2.390	0.03	0.290	0.22-0.24
16	240-260	20	2.13	0.210	2.600	0.02	0.210	0.24-0.26
17	260-280	17	1.81	0.190	2.790	0.02	0.190	0.26-0.28
18	280-300	27	2.88	0.320	3.110	0.03	0.320	0.28-0.30
19	300-350	50	5.33	0.670	3.790	0.05	0.670	0.30-0.35
20	350-400	51	5.44	0.790	4.580	0.05	0.790	0.35-0.40
21	400-450	33	3.52	0.580	5.160	0.04	0.580	0.40-0.45
22	450-500	19	2.03	0.370	5.530	0.02	0.370	0.45.0.50
23	500-1000	119	12.69	3.300	6.120	0.13	3.300	0.50-1.00
24	1000-1500	22	2.35	1.110	9.940	0.02	1.110	1.00-1.50
25	1500-2000	6	0.64	0.430	10.370	0.01	0.430	1.50-2.00
26	2000-2500	3	0.32	0.280	10.650	0.00	0.280	2.00-2.50
27	2500-3000	3	0.32	0.330	10.990	0.00	0.330	2.50-3.00
28	3000-4000	0	0.00	0.000	10.990	0.00	0.000	3.00-4.00
						938		

Air Content (%):	10.99
Specific Surface (mm^{-1}):	14.15
Spacing Factor (mm):	0.174
Void Frequency (mm^{-1}):	0.390
Average Chord Length (r	0.283
Paste to Air Ratio:	2.46

Sample ID: CAST CYL A-2-122-S3

Sample Size (mm x mm	75 x 90	Length Traversed (mm):	2413.1
Paste Content (%):	27.00	Area Traversed (mm x mm):	65 x 80

Chord Length Distribution - Table

Class No.	Chord size (microns)	Number of Chords in Class	Number of Chords in Percent	Air Content in Class	Cumulated Air Content	Chord length frequency	Air content, fraction	
1	0-10	29	2.50	0.010	0.010	0.02	0.010	0.00-0.01
2	10-20	101	8.70	0.060	0.070	0.09	0.060	0.01-0.02
3	20-30	75	8.70	0.080	0.150	0.06	0.080	0.02-0.03
4	30-40	52	4.48	0.080	0.230	0.04	0.080	0.03-0.04
5	40-50	43	3.70	0.080	0.310	0.04	0.080	0.04-0.05
6	50-60	40	3.45	0.090	0.400	0.03	0.090	0.05-0.06
7	60-80	73	6.29	0.210	0.610	0.06	0.210	0.06-0.08
8	80-100	63	5.43	0.240	0.850	0.05	0.240	0.08-0.10
9	100-120	64	5.51	0.290	1.140	0.06	0.290	0.10-0.12
10	120-140	49	4.22	0.260	1.400	0.04	0.260	0.12-0.14
11	140-160	43	3.70	0.270	1.670	0.04	0.270	0.14-0.16
12	160-180	46	3.96	0.320	1.990	0.04	0.320	0.16-0.18
13	180-200	31	2.67	0.240	2.230	0.03	0.240	0.18-0.20
14	200-220	29	2.50	0.250	2.490	0.02	0.250	0.20-0.22
15	220-240	26	2.24	0.250	2.740	0.02	0.250	0.22-0.24
16	240-260	32	2.76	0.330	3.070	0.03	0.330	0.24-0.26
17	260-280	22	1.89	0.240	3.310	0.02	0.240	0.26-0.28
18	280-300	30	2.58	0.360	3.670	0.03	0.360	0.28-0.30
19	300-350	38	3.27	0.510	4.180	0.03	0.510	0.30-0.35
20	350-400	37	3.19	0.570	4.750	0.03	0.570	0.35-0.40
21	400-450	36	3.10	0.640	5.390	0.03	0.640	0.40-0.45
22	450-500	40	3.45	0.790	6.170	0.03	0.790	0.45.0.50
23	500-1000	137	11.80	3.990	6.700	0.12	3.990	0.50-1.00
24	1000-1500	16	1.38	0.810	10.980	0.01	0.810	1.00-1.50
25	1500-2000	4	0.34	0.270	11.250	0.00	0.270	1.50-2.00
26	2000-2500	2	0.17	0.190	11.430	0.00	0.190	2.00-2.50
27	2500-3000	3	0.26	0.340	11.770	0.00	0.340	2.50-3.00
28	3000-4000	0	0.00	0.000	11.770	0.00	0.000	3.00-4.00
						1161		

Air Content (%):	11.77
Specific Surface (mm^{-1}):	16.35
Spacing Factor (mm):	0.140
Void Frequency (mm^{-1}):	0.480
Average Chord Length (r	0.245
Paste to Air Ratio:	2.29

Sample ID: CAST CYL A-2-122-S4

Sample Size (mm x mm	90 x 80	Length Traversed (mm):	2413.1
Paste Content (%):	27.00	Area Traversed (mm x mm):	80 x 70

Chord Length Distribution - Table

Class No.	Chord size (microns)	Number of Chords in Class	Number of Chords in Percent	Air Content in Class	Cumulated Air Content	Chord length frequency	Air content, fraction	
1	0-10	11	1.03	0.000	0.000	0.01	0.000	0.00-0.01
2	10-20	62	5.81	0.040	0.040	0.06	0.040	0.01-0.02
3	20-30	62	5.81	0.070	0.110	0.06	0.070	0.02-0.03
4	30-40	40	3.75	0.060	0.170	0.04	0.060	0.03-0.04
5	40-50	38	3.56	0.070	0.230	0.04	0.070	0.04-0.05
6	50-60	45	4.21	0.100	0.340	0.04	0.100	0.05-0.06
7	60-80	69	6.46	0.200	0.540	0.06	0.200	0.06-0.08
8	80-100	60	5.62	0.220	0.760	0.06	0.220	0.08-0.10
9	100-120	67	6.27	0.300	1.060	0.06	0.300	0.10-0.12
10	120-140	46	4.31	0.250	1.310	0.04	0.250	0.12-0.14
11	140-160	42	3.93	0.260	1.570	0.04	0.260	0.14-0.16
12	160-180	48	4.49	0.340	1.910	0.04	0.340	0.16-0.18
13	180-200	30	2.81	0.230	2.140	0.03	0.230	0.18-0.20
14	200-220	28	2.62	0.240	2.380	0.03	0.240	0.20-0.22
15	220-240	26	2.43	0.240	2.630	0.02	0.240	0.22-0.24
16	240-260	35	3.28	0.360	2.990	0.03	0.360	0.24-0.26
17	260-280	20	1.87	0.220	3.210	0.02	0.220	0.26-0.28
18	280-300	19	1.78	0.230	3.440	0.02	0.230	0.28-0.30
19	300-350	51	4.78	0.700	4.140	0.05	0.700	0.30-0.35
20	350-400	23	2.15	0.360	4.500	0.02	0.360	0.35-0.40
21	400-450	33	3.09	0.580	5.080	0.03	0.580	0.40-0.45
22	450-500	31	2.90	0.610	5.680	0.03	0.610	0.45.0.50
23	500-1000	135	12.64	3.840	6.400	0.13	3.840	0.50-1.00
24	1000-1500	32	3.00	1.540	11.060	0.03	1.540	1.00-1.50
25	1500-2000	9	0.84	0.660	11.710	0.01	0.660	1.50-2.00
26	2000-2500	4	0.37	0.360	12.070	0.00	0.360	2.00-2.50
27	2500-3000	2	0.19	0.230	12.300	0.00	0.230	2.50-3.00
28	3000-4000	0	0.00	0.000	12.300	0.00	0.000	3.00-4.00
						1068		

Air Content (%):	12.30
Specific Surface (mm^{-1}):	14.40
Spacing Factor (mm):	0.153
Void Frequency (mm^{-1}):	0.440
Average Chord Length (r	0.278
Paste to Air Ratio:	2.20

Sample ID: CAST CYL B-1-133-S1

Sample Size (mm x mm):	120 x 80	Length Traversed (mm):	2413.1
Paste Content (%):	27.00	Area Traversed (mm x mm):	100 x 70

Chord Length Distribution - Table

Class No.	Chord size (microns)	Number of Chords in Class	Number of Chords in Percent	Air Content in Class	Cumulated Air Content	Chord length frequency	Air content, fraction	
1	0-10	8	1.71	0.000	0.000	0.02	0.000	0.00-0.01
2	10-20	47	10.02	0.030	0.030	0.10	0.030	0.01-0.02
3	20-30	22	10.02	0.020	0.050	0.05	0.020	0.02-0.03
4	30-40	22	4.69	0.030	0.090	0.05	0.030	0.03-0.04
5	40-50	30	6.40	0.050	0.140	0.06	0.050	0.04-0.05
6	50-60	21	4.48	0.050	0.190	0.04	0.050	0.05-0.06
7	60-80	42	8.96	0.120	0.310	0.09	0.120	0.06-0.08
8	80-100	36	7.68	0.130	0.440	0.08	0.130	0.08-0.10
9	100-120	18	3.84	0.080	0.530	0.04	0.080	0.10-0.12
10	120-140	23	4.90	0.120	0.650	0.05	0.120	0.12-0.14
11	140-160	16	3.41	0.100	0.750	0.03	0.100	0.14-0.16
12	160-180	12	2.56	0.080	0.840	0.03	0.080	0.16-0.18
13	180-200	20	4.26	0.160	1.000	0.04	0.160	0.18-0.20
14	200-220	22	4.69	0.190	1.190	0.05	0.190	0.20-0.22
15	220-240	11	2.35	0.100	1.290	0.02	0.100	0.22-0.24
16	240-260	13	2.77	0.140	1.430	0.03	0.140	0.24-0.26
17	260-280	7	1.49	0.080	1.510	0.01	0.080	0.26-0.28
18	280-300	8	1.71	0.100	1.600	0.02	0.100	0.28-0.30
19	300-350	21	4.48	0.280	1.890	0.04	0.280	0.30-0.35
20	350-400	18	3.84	0.280	2.170	0.04	0.280	0.35-0.40
21	400-450	10	2.13	0.180	2.350	0.02	0.180	0.40-0.45
22	450-500	6	1.28	0.120	2.470	0.01	0.120	0.45.0.50
23	500-1000	30	6.40	0.820	2.600	0.06	0.820	0.50-1.00
24	1000-1500	4	0.85	0.200	3.490	0.01	0.200	1.00-1.50
25	1500-2000	2	0.43	0.130	3.620	0.00	0.130	1.50-2.00
26	2000-2500	0	0.00	0.000	3.620	0.00	0.000	2.00-2.50
27	2500-3000	0	0.00	0.000	3.620	0.00	0.000	2.50-3.00
28	3000-4000	0	0.00	0.000	3.620	0.00	0.000	3.00-4.00
						469		

Air Content (%):	3.62
Specific Surface (mm^{-1}):	21.50
Spacing Factor (mm):	0.259
Void Frequency (mm^{-1}):	0.190
Average Chord Length (mm):	0.186
Paste to Air Ratio:	7.46

Sample ID: CAST CYL   B-1-133-S2

Sample Size (mm x mm):	90 x 100	Length Traversed (mm):	2413.1
Paste Content (%):	27.00	Area Traversed (mm x mm):	80 x 90

Chord Length Distribution - Table

Class No.	Chord size (microns)	Number of Chords in Class	Number of Chords in Percent	Air Content in Class	Cumulated Air Content	Chord length frequency	Air content, fraction	
1	0-10	6	1.35	0.000	0.000	0.01	0.000	0.00-0.01
2	10-20	33	7.42	0.020	0.020	0.07	0.020	0.01-0.02
3	20-30	21	7.42	0.020	0.040	0.05	0.020	0.02-0.03
4	30-40	14	3.15	0.020	0.060	0.03	0.020	0.03-0.04
5	40-50	21	4.72	0.040	0.100	0.05	0.040	0.04-0.05
6	50-60	16	3.60	0.040	0.140	0.04	0.040	0.05-0.06
7	60-80	26	5.84	0.070	0.210	0.06	0.070	0.06-0.08
8	80-100	30	6.74	0.110	0.330	0.07	0.110	0.08-0.10
9	100-120	20	4.49	0.090	0.420	0.04	0.090	0.10-0.12
10	120-140	11	2.47	0.060	0.480	0.02	0.060	0.12-0.14
11	140-160	16	3.60	0.100	0.570	0.04	0.100	0.14-0.16
12	160-180	21	4.72	0.150	0.720	0.05	0.150	0.16-0.18
13	180-200	15	3.37	0.120	0.840	0.03	0.120	0.18-0.20
14	200-220	17	3.82	0.150	0.990	0.04	0.150	0.20-0.22
15	220-240	10	2.25	0.090	1.080	0.02	0.090	0.22-0.24
16	240-260	23	5.17	0.240	1.320	0.05	0.240	0.24-0.26
17	260-280	13	2.92	0.150	1.470	0.03	0.150	0.26-0.28
18	280-300	11	2.47	0.130	1.600	0.02	0.130	0.28-0.30
19	300-350	19	4.27	0.250	1.850	0.04	0.250	0.30-0.35
20	350-400	18	4.04	0.280	2.130	0.04	0.280	0.35-0.40
21	400-450	6	1.35	0.110	2.240	0.01	0.110	0.40-0.45
22	450-500	14	3.15	0.270	2.510	0.03	0.270	0.45.0.50
23	500-1000	48	10.79	1.340	2.710	0.11	1.340	0.50-1.00
24	1000-1500	6	1.35	0.300	4.150	0.01	0.300	1.00-1.50
25	1500-2000	5	1.12	0.340	4.490	0.01	0.340	1.50-2.00
26	2000-2500	0	0.00	0.000	4.490	0.00	0.000	2.00-2.50
27	2500-3000	2	0.45	0.230	4.720	0.00	0.230	2.50-3.00
28	3000-4000	3	0.67	0.380	5.100	0.01	0.380	3.00-4.00
						445		

Air Content (%):	5.10
Specific Surface (mm^{-1}):	14.46
Spacing Factor (mm):	0.329
Void Frequency (mm^{-1}):	0.180
Average Chord Length (mm):	0.277
Paste to Air Ratio:	5.29

Sample ID: CAST CYL B-1-133-S3

Sample Size (mm x mm):	80 x 110	Length Traversed (mm):	2413.1
Paste Content (%):	27.00	Area Traversed (mm x mm):	70 x 90

Chord Length Distribution - Table

Class No.	Chord size (microns)	Number of Chords in Class	Number of Chords in Percent	Air Content in Class	Cumulated Air Content	Chord length frequency	Air content, fraction	
1	0-10	10	2.62	0.000	0.000	0.03	0.000	0.00-0.01
2	10-20	41	10.73	0.020	0.030	0.11	0.020	0.01-0.02
3	20-30	20	10.73	0.020	0.050	0.05	0.020	0.02-0.03
4	30-40	16	4.19	0.020	0.070	0.04	0.020	0.03-0.04
5	40-50	14	3.66	0.030	0.100	0.04	0.030	0.04-0.05
6	50-60	11	2.88	0.020	0.120	0.03	0.020	0.05-0.06
7	60-80	21	5.50	0.060	0.180	0.05	0.060	0.06-0.08
8	80-100	28	7.33	0.100	0.290	0.07	0.100	0.08-0.10
9	100-120	11	2.88	0.050	0.340	0.03	0.050	0.10-0.12
10	120-140	10	2.62	0.050	0.390	0.03	0.050	0.12-0.14
11	140-160	15	3.93	0.090	0.480	0.04	0.090	0.14-0.16
12	160-180	15	3.93	0.110	0.590	0.04	0.110	0.16-0.18
13	180-200	19	4.97	0.150	0.740	0.05	0.150	0.18-0.20
14	200-220	10	2.62	0.090	0.820	0.03	0.090	0.20-0.22
15	220-240	13	3.40	0.120	0.950	0.03	0.120	0.22-0.24
16	240-260	13	3.40	0.130	1.080	0.03	0.130	0.24-0.26
17	260-280	12	3.14	0.130	1.220	0.03	0.130	0.26-0.28
18	280-300	16	4.19	0.190	1.410	0.04	0.190	0.28-0.30
19	300-350	15	3.93	0.200	1.600	0.04	0.200	0.30-0.35
20	350-400	10	2.62	0.150	1.760	0.03	0.150	0.35-0.40
21	400-450	10	2.62	0.180	1.930	0.03	0.180	0.40-0.45
22	450-500	7	1.83	0.140	2.070	0.02	0.140	0.45.0.50
23	500-1000	28	7.33	0.750	2.240	0.07	0.750	0.50-1.00
24	1000-1500	9	2.36	0.480	3.300	0.02	0.480	1.00-1.50
25	1500-2000	7	1.83	0.490	3.790	0.02	0.490	1.50-2.00
26	2000-2500	1	0.26	0.090	3.880	0.00	0.090	2.00-2.50
27	2500-3000	0	0.00	0.000	3.880	0.00	0.000	2.50-3.00
28	3000-4000	0	0.00	0.000	3.880	0.00	0.000	3.00-4.00
						382		

Air Content (%):	3.88
Specific Surface (mm^{-1}):	16.33
Spacing Factor (mm):	0.330
Void Frequency (mm^{-1}):	0.160
Average Chord Length (mm):	0.245
Paste to Air Ratio:	6.96

Sample ID: CAST CYL B-1-133-S4

Sample Size (mm x mm):	100 x 90	Length Traversed (mm):	2413.1
Paste Content (%):	27.00	Area Traversed (mm x mm):	90 x 80

Chord Length Distribution - Table

Class No.	Chord size (microns)	Number of Chords in Class	Number of Chords in Percent	Air Content in Class	Cumulated Air Content	Chord length frequency	Air content, fraction	
1	0-10	13	3.66	0.000	0.000	0.04	0.000	0.00-0.01
2	10-20	48	13.52	0.030	0.030	0.14	0.030	0.01-0.02
3	20-30	34	13.52	0.040	0.070	0.10	0.040	0.02-0.03
4	30-40	18	5.07	0.030	0.090	0.05	0.030	0.03-0.04
5	40-50	13	3.66	0.020	0.120	0.04	0.020	0.04-0.05
6	50-60	9	2.54	0.020	0.140	0.03	0.020	0.05-0.06
7	60-80	21	5.92	0.060	0.200	0.06	0.060	0.06-0.08
8	80-100	15	4.23	0.060	0.250	0.04	0.060	0.08-0.10
9	100-120	18	5.07	0.080	0.340	0.05	0.080	0.10-0.12
10	120-140	10	2.82	0.050	0.390	0.03	0.050	0.12-0.14
11	140-160	11	3.10	0.070	0.460	0.03	0.070	0.14-0.16
12	160-180	7	1.97	0.050	0.510	0.02	0.050	0.16-0.18
13	180-200	8	2.25	0.060	0.570	0.02	0.060	0.18-0.20
14	200-220	11	3.10	0.100	0.670	0.03	0.100	0.20-0.22
15	220-240	10	2.82	0.090	0.760	0.03	0.090	0.22-0.24
16	240-260	6	1.69	0.060	0.820	0.02	0.060	0.24-0.26
17	260-280	8	2.25	0.090	0.910	0.02	0.090	0.26-0.28
18	280-300	7	1.97	0.080	0.990	0.02	0.080	0.28-0.30
19	300-350	11	3.10	0.150	1.140	0.03	0.150	0.30-0.35
20	350-400	12	3.38	0.190	1.330	0.03	0.190	0.35-0.40
21	400-450	12	3.38	0.210	1.540	0.03	0.210	0.40-0.45
22	450-500	8	2.25	0.160	1.700	0.02	0.160	0.45.0.50
23	500-1000	31	8.73	0.830	1.850	0.09	0.830	0.50-1.00
24	1000-1500	7	1.97	0.340	2.870	0.02	0.340	1.00-1.50
25	1500-2000	5	1.41	0.370	3.250	0.01	0.370	1.50-2.00
26	2000-2500	2	0.56	0.180	3.430	0.01	0.180	2.00-2.50
27	2500-3000	0	0.00	0.000	3.430	0.00	0.000	2.50-3.00
28	3000-4000	0	0.00	0.000	3.430	0.00	0.000	3.00-4.00
						355		

Air Content (%):	3.43
Specific Surface (mm^{-1}):	17.17
Spacing Factor (mm):	0.332
Void Frequency (mm^{-1}):	0.150
Average Chord Length (mm):	0.233
Paste to Air Ratio:	7.87

Sample Size (mm x mm):	80 x 90	Length Traversed (mm):	2413.1
Paste Content (%):	27.00	Area Traversed (mm x mm):	70 x 80

Chord Length Distribution - Table

Class No.	Chord size (microns)	Number of Chords in Class	Number of Chords in Percent	Air Content in Class	Cumulated Air Content	Chord length frequency	Air content, fraction	
1	0-10	13	3.08	0.000	0.000	0.03	0.000	0.00-0.01
2	10-20	36	8.53	0.020	0.030	0.09	0.020	0.01-0.02
3	20-30	25	8.53	0.030	0.050	0.06	0.030	0.02-0.03
4	30-40	19	4.50	0.030	0.080	0.05	0.030	0.03-0.04
5	40-50	20	4.74	0.040	0.120	0.05	0.040	0.04-0.05
6	50-60	19	4.50	0.040	0.160	0.05	0.040	0.05-0.06
7	60-80	32	7.58	0.090	0.250	0.08	0.090	0.06-0.08
8	80-100	29	6.87	0.110	0.360	0.07	0.110	0.08-0.10
9	100-120	15	3.55	0.070	0.430	0.04	0.070	0.10-0.12
10	120-140	20	4.74	0.110	0.540	0.05	0.110	0.12-0.14
11	140-160	22	5.21	0.140	0.670	0.05	0.140	0.14-0.16
12	160-180	26	6.16	0.180	0.860	0.06	0.180	0.16-0.18
13	180-200	16	3.79	0.130	0.980	0.04	0.130	0.18-0.20
14	200-220	18	4.27	0.160	1.140	0.04	0.160	0.20-0.22
15	220-240	5	1.18	0.050	1.190	0.01	0.050	0.22-0.24
16	240-260	5	1.18	0.050	1.240	0.01	0.050	0.24-0.26
17	260-280	9	2.13	0.100	1.340	0.02	0.100	0.26-0.28
18	280-300	8	1.90	0.100	1.430	0.02	0.100	0.28-0.30
19	300-350	12	2.84	0.160	1.600	0.03	0.160	0.30-0.35
20	350-400	5	1.18	0.080	1.670	0.01	0.080	0.35-0.40
21	400-450	10	2.37	0.180	1.850	0.02	0.180	0.40-0.45
22	450-500	8	1.90	0.160	2.010	0.02	0.160	0.45.0.50
23	500-1000	37	8.77	1.010	2.290	0.09	1.010	0.50-1.00
24	1000-1500	4	0.95	0.190	3.210	0.01	0.190	1.00-1.50
25	1500-2000	5	1.18	0.390	3.590	0.01	0.390	1.50-2.00
26	2000-2500	3	0.71	0.280	3.870	0.01	0.280	2.00-2.50
27	2500-3000	1	0.24	0.100	3.970	0.00	0.100	2.50-3.00
28	3000-4000	0	0.00	0.000	3.970	0.00	0.000	3.00-4.00
						422		

Air Content (%):	3.97
Specific Surface (mm^{-1}):	17.60
Spacing Factor (mm):	0.303
Void Frequency (mm^{-1}):	0.170
Average Chord Length (mm):	0.227
Paste to Air Ratio:	6.80

Sample ID: CAST CYL B-2-129-S3

Sample Size (mm x mm): 80 x 90 Length Traversed (mm): 2413.1

Paste Content (%): 27.00 Area Traversed (mm x mm): 70 x 80

Chord Length Distribution - Table

Class No.	Chord size (microns)	Number of Chords in Class	Number of Chords in Percent	Air Content in Class	Cumulated Air Content	Chord length frequency	Air content, fraction	
1	0-10	14	3.02	0.000	0.000	0.03	0.000	0.00-0.01
2	10-20	36	7.78	0.020	0.030	0.08	0.020	0.01-0.02
3	20-30	37	7.78	0.040	0.060	0.08	0.040	0.02-0.03
4	30-40	13	2.81	0.020	0.080	0.03	0.020	0.03-0.04
5	40-50	23	4.97	0.040	0.120	0.05	0.040	0.04-0.05
6	50-60	20	4.32	0.050	0.170	0.04	0.050	0.05-0.06
7	60-80	38	8.21	0.110	0.280	0.08	0.110	0.06-0.08
8	80-100	27	5.83	0.100	0.380	0.06	0.100	0.08-0.10
9	100-120	23	4.97	0.100	0.490	0.05	0.100	0.10-0.12
10	120-140	24	5.18	0.130	0.620	0.05	0.130	0.12-0.14
11	140-160	17	3.67	0.110	0.720	0.04	0.110	0.14-0.16
12	160-180	20	4.32	0.140	0.860	0.04	0.140	0.16-0.18
13	180-200	18	3.89	0.140	1.000	0.04	0.140	0.18-0.20
14	200-220	7	1.51	0.060	1.060	0.02	0.060	0.20-0.22
15	220-240	10	2.16	0.100	1.160	0.02	0.100	0.22-0.24
16	240-260	10	2.16	0.110	1.260	0.02	0.110	0.24-0.26
17	260-280	4	0.86	0.050	1.310	0.01	0.050	0.26-0.28
18	280-300	7	1.51	0.080	1.390	0.02	0.080	0.28-0.30
19	300-350	12	2.59	0.160	1.550	0.03	0.160	0.30-0.35
20	350-400	14	3.02	0.210	1.770	0.03	0.210	0.35-0.40
21	400-450	12	2.59	0.210	1.980	0.03	0.210	0.40-0.45
22	450-500	15	3.24	0.300	2.270	0.03	0.300	0.45.0.50
23	500-1000	51	11.02	1.430	2.470	0.11	1.430	0.50-1.00
24	1000-1500	7	1.51	0.350	4.060	0.02	0.350	1.00-1.50
25	1500-2000	2	0.43	0.160	4.220	0.00	0.160	1.50-2.00
26	2000-2500	2	0.43	0.190	4.400	0.00	0.190	2.00-2.50
27	2500-3000	0	0.00	0.000	4.400	0.00	0.000	2.50-3.00
28	3000-4000	0	0.00	0.000	4.400	0.00	0.000	3.00-4.00
						463		

Air Content (%): 4.40

Specific Surface (mm^{-1}): 17.43

Spacing Factor (mm): 0.292

Void Frequency (mm^{-1}): 0.190

Average Chord Length (mm): 0.229

Paste to Air Ratio: 6.14

Kansas - Ternary Mixtures

Rapid Chloride Permeability

PROOVE it

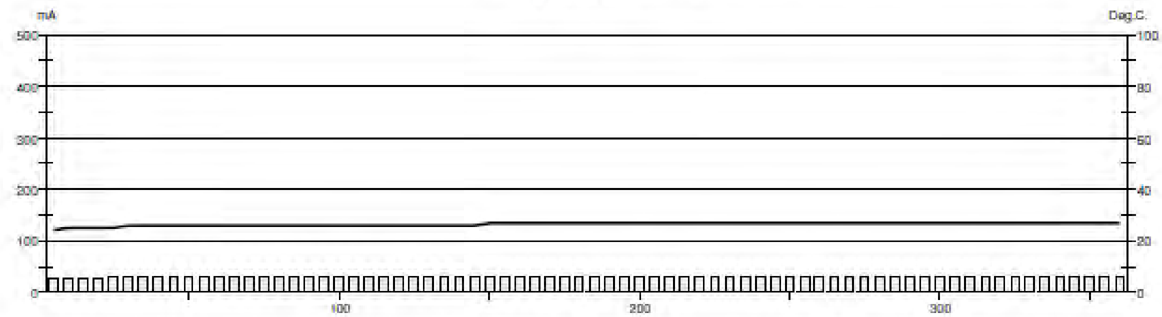
ASTM C 1202-97

Test-compagny
Testing street 45
CompagnyCity
Some Country

GERMANN INSTRUMENTS
DENMARK
USA

Test report

Voltage Used:	60
Testing time:	06:00 hour
Charge passed:	613
Adjusted Charge passed:	532
Permeability class:	Very Low
Instrument number:	023907
Channel number:	1
Report date:	12/22/2009
Testing by:	PJM
Reference:	KS ternary A-1
Sample diameter:	102
Comment:	—



Time	°C	mA	Time	°C	mA	Time	°C	mA	Time	°C	mA
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00:10	25	26.9	01:40	26	28.9	03:10	27	28.2	04:40	27	28.5
00:15	25	26.9	01:45	26	28.8	03:15	27	28.2	04:45	27	28.9
00:20	25	27.4	01:50	26	28.7	03:20	27	28.2	04:50	27	28.8
00:25	25	28.0	01:55	26	28.6	03:25	27	28.4	04:55	27	28.8
00:30	26	28.1	02:00	26	28.5	03:30	27	28.9	05:00	27	28.7
00:35	26	28.3	02:05	26	28.4	03:35	27	28.9	05:05	27	28.6
00:40	26	28.3	02:10	26	28.5	03:40	27	28.9	05:10	27	28.4
00:45	26	28.5	02:15	26	28.4	03:45	27	28.8	05:15	27	28.3
00:50	26	28.4	02:20	26	28.4	03:50	27	28.7	05:20	27	28.2
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01:00	26	28.4	02:30	27	28.3	04:00	27	28.5	05:30	27	28.1
01:05	26	28.6	02:35	27	28.3	04:05	27	28.4	05:35	27	28.1
01:10	26	28.9	02:40	27	28.3	04:10	27	28.3	05:40	27	28.1
01:15	26	29.1	02:45	27	28.2	04:15	27	28.3	05:45	27	28.1
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01:25	26	29.1	02:55	27	28.3	04:25	27	28.5	05:55	27	28.2
01:30	26	29.1	03:00	27	28.3	04:30	27	28.4	06:00	27	28.9

Kansas - Ternary Mixtures

Rapid Chloride Permeability

PROOVE it

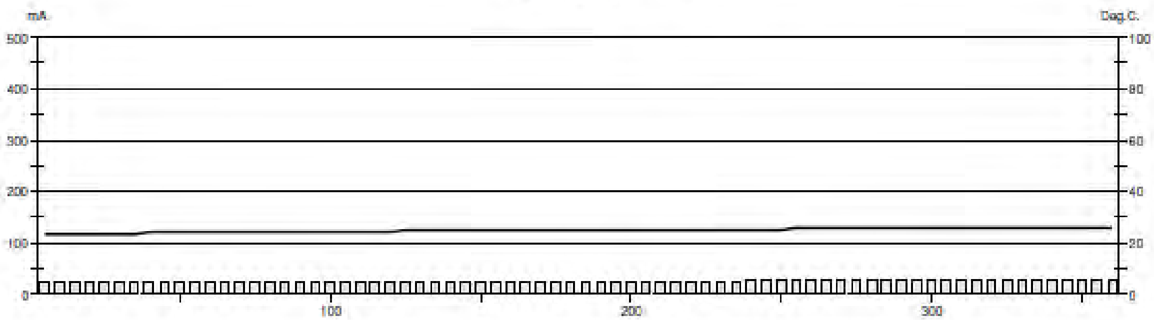
ASTM C 1202-97

Test-compagny
Testing street 45
CompagnyCity
Some Country

GERMANN INSTRUMENTS

Test report

Voltage Used:	60
Testing time:	06:00 hour
Charge passed:	543
Adjusted Charge passed:	471
Permeability class:	Very Low
Instrument number:	023907
Channel number:	2
Report date:	12/22/2009
Testing by:	PJM
Reference:	KS ternary A-2
Sample diameter:	102
Comment:	---



Time	°C	mA	Time	°C	mA	Time	°C	mA	Time	°C	mA
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00:10	23	24.4	01:40	24	24.8	03:10	25	25.3	04:40	26	25.7
00:15	23	24.4	01:45	24	24.8	03:15	25	25.4	04:45	26	25.7
00:20	23	24.3	01:50	24	24.8	03:20	25	25.4	04:50	26	25.7
00:25	23	24.3	01:55	24	24.8	03:25	25	25.4	04:55	26	25.7
00:30	23	24.2	02:00	24	24.9	03:30	25	25.4	05:00	26	25.7
00:35	23	24.2	02:05	25	24.9	03:35	25	25.4	05:05	26	25.7
00:40	24	24.2	02:10	25	25.0	03:40	25	25.4	05:10	26	25.7
00:45	24	24.3	02:15	25	25.1	03:45	25	25.5	05:15	26	25.7
00:50	24	24.2	02:20	25	25.1	03:50	25	25.5	05:20	26	25.7
00:55	24	24.1	02:25	25	25.1	03:55	25	25.5	05:25	26	25.7
01:00	24	24.2	02:30	25	25.1	04:00	25	25.7	05:30	26	25.7
01:05	24	24.2	02:35	25	25.3	04:05	25	25.7	05:35	26	25.7
01:10	24	24.2	02:40	25	25.2	04:10	25	25.7	05:40	26	25.7
01:15	24	24.3	02:45	25	25.2	04:15	26	25.7	05:45	26	25.7
01:20	24	24.4	02:50	25	25.2	04:20	26	25.8	05:50	26	25.8
01:25	24	24.5	02:55	25	25.3	04:25	26	25.9	05:55	26	25.8
01:30	24	24.5	03:00	25	25.4	04:30	26	25.9	06:00	26	25.7

Kansas - Ternary Mixtures

Rapid Chloride Permeability

PROOVE it

ASTM C 1202-97

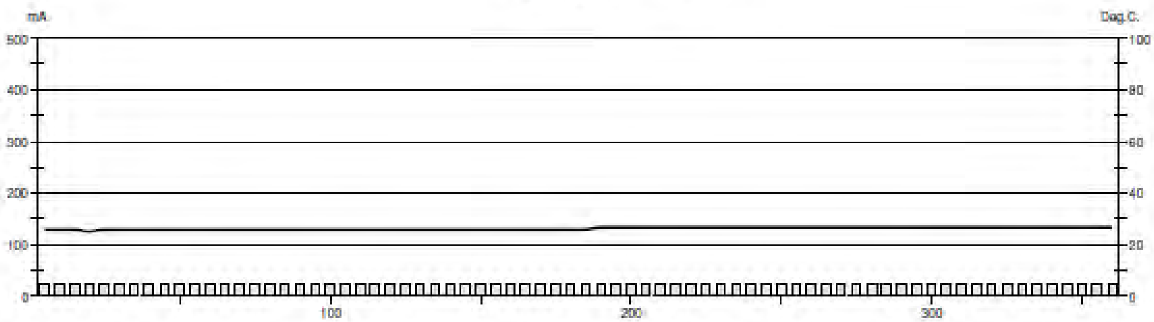
TEST CO.

Test-compagny
Testing street 45
CompagnyCity
Some Country

GERMANN INSTRUMENTS

Test report

Voltage Used:	60
Testing time:	06:00 hour
Charge passed:	539
Adjusted Charge passed:	468
Permeability class:	Very Low
Instrument number:	023907
Channel number:	3
Report date:	12/22/2009
Testing by:	PJM
Reference:	KS Ternary B-1
Sample diameter:	102
Comment:	---



Time	°C	mA	Time	°C	mA	Time	°C	mA	Time	°C	mA
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00:10	26	24.8	01:40	26	24.9	03:10	27	24.8	04:40	27	25.2
00:15	26	24.6	01:45	26	24.9	03:15	27	24.8	04:45	27	25.2
00:20	25	24.6	01:50	26	24.9	03:20	27	24.8	04:50	27	25.2
00:25	26	24.7	01:55	26	24.9	03:25	27	24.8	04:55	27	25.2
00:30	26	24.7	02:00	26	24.9	03:30	27	24.8	05:00	27	25.2
00:35	26	24.7	02:05	26	24.9	03:35	27	24.9	05:05	27	25.1
00:40	26	24.7	02:10	26	24.9	03:40	27	25.1	05:10	27	25.1
00:45	26	24.7	02:15	26	24.9	03:45	27	25.1	05:15	27	25.1
00:50	26	24.7	02:20	26	24.8	03:50	27	25.1	05:20	27	25.1
00:55	26	24.7	02:25	26	24.8	03:55	27	25.1	05:25	27	25.3
01:00	26	24.7	02:30	26	24.8	04:00	27	25.1	05:30	27	25.3
01:05	26	24.7	02:35	26	24.8	04:05	27	25.2	05:35	27	25.3
01:10	26	24.7	02:40	26	24.7	04:10	27	25.2	05:40	27	25.3
01:15	26	24.7	02:45	26	24.7	04:15	27	25.2	05:45	27	25.4
01:20	26	24.9	02:50	26	24.7	04:20	27	25.2	05:50	27	25.4
01:25	26	24.9	02:55	26	24.7	04:25	27	25.2	05:55	27	25.4
01:30	26	24.9	03:00	26	24.7	04:30	27	25.2	06:00	27	25.4

Kansas - Ternary Mixtures

Rapid Chloride Permeability

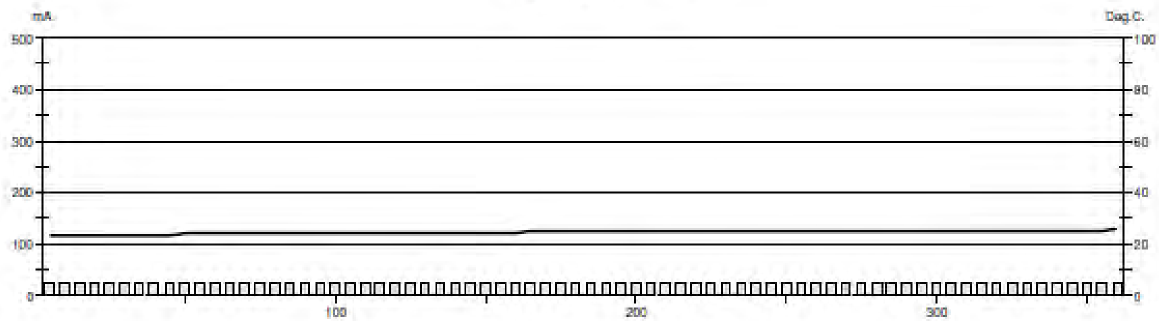
ASTM C 1202-97

Test-compagny
Testing street 45
CompagnyCity
Some Country

Your own logo.
size=20x80mm

Test report

Voltage Used:	60
Testing time:	06:00 hour
Charge passed:	518
Adjusted Charge passed:	449
Permeability class:	Very Low
Instrument number:	023907
Channel number:	4
Report date:	12/22/2009
Testing by:	PJM
Reference:	KS Ternary B-2
Sample diameter:	102
Comment:	---



Time	°C	mA	Time	°C	mA	Time	°C	mA	Time	°C	mA
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00:15	23	23.7	01:45	24	23.3	03:15	25	23.8	04:45	25	24.7
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APPENDIX E. FIELD APPLICATION OF TERNARY MIXTURES: CONSTRUCTION OF A BRIDGE DECK IN MICHIGAN

State Report
December 2009

Research Team
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American Coal Ash Association, American Concrete Pavement Association, Headwaters Resources, Portland Cement Association, Slag Cement Association

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ACKNOWLEDGMENTS

The research team at the National Concrete Pavement Technology Center at Iowa State University sincerely thanks the Michigan Department of Transportation for their cooperation, and Anlaan Company for supplying the equipment and materials.

INTRODUCTION

This document is a report of the activities and observations of a ternary mixture placed on the I-94 Riverside Drive bridge deck in Battle Creek, Michigan. The cementitious system comprised a Type I cement, Grade 100 slag cement, and silica fume. The purpose of this research project is a comprehensive study of how supplementary cementitious materials can be used to improve the performance of concrete mixtures when used in ternary blends. This is the third phase of a project that intends to provide consulting to states and contractors on the use and field management of ternary mixtures. Samples were delivered by the Michigan Department of Transportation (MDOT) and tested under laboratory conditions.

PROJECT INFORMATION

- Project: Full deck reconstruction with Lafarge Tercem 3000 Blended
- I-94, Riverside Drive, Battle Creek, Michigan
- Contractor: Anlaan Contracting
- Bridge deck placement (Figure 1)

Figure 1. I-94 Riverside drive bridge deck placement

SITE LOCATION

The location of the project is shown in Figure 2.

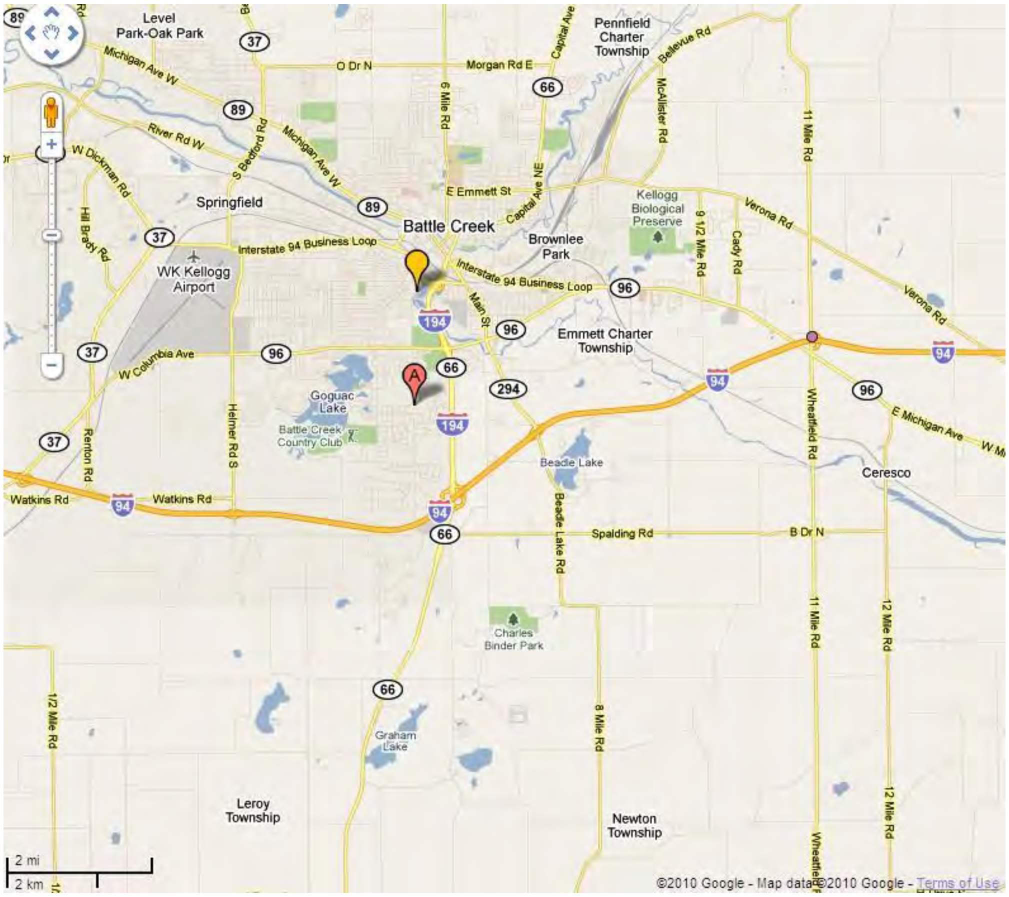

Figure 2. Project location

SAMPLING AND TESTING ACTIVITIES

Concrete placement, sampling, and testing took place on December 18, 2009. Hardened samples were transported to Iowa State University on December 30, 2010, for further testing. The following tests were conducted either in the field or in the laboratory:

- Slump, unit weight, air content, and temperature of fresh concrete: 1 test (ASTM C 143, ASTM C 138, ASTM C 231, ASTM C 1064)
- Compressive strength, splitting tensile strength, static modulus of elasticity: 4 in. x 8 in. cylinders at 1 day, 3 days, 7 days, 28 days, and 56 days (ASTM C 39, ASTM C 496, ASTM C 469)
- Rapid chloride permeability: 4 in. x 8 in. cylinders at 56 days (ASTM C 1202)
- Air void analysis of hardened concrete: 4 in. x 8 in. cylinders (ASTM C 457)
- Free shrinkage test: 4 beams (ASTM C 157)
- Restrained rings: 4 samples (ASTM C 1581)

OBSERVATIONS OF THE RESEARCH TEAM

The following additional information was obtained:

- Two types of coarse aggregate were used: one type was MDOT gradation 6AA high-calcium limestone with 1.73% absorption, and the other was MDOT gradation 29A granite with 2.33% absorption. One type of fine aggregate, MDOT gradation 2NS natural sand with 1.2% absorption, was used in the concrete. A Micro-Air Type AE air entraining agent, Delvo retarding agent (ASTM Type D), and Rheobuild 1000 (Type MR) water reducer were used as chemical admixtures in order to achieve a better performance. All chemical admixtures are from the chemical company BASF.
- Eight temperature sensors were used to track the concrete and ambient temperatures. Table 1 lists the names of the sensors and a description of the location for each sensor. The specific locations of the eight sensors are illustrated in Figures 3 through 6. The temperature sensor data reported by MDOT are shown in Figure 7.

Table 1. Description of locations for each temperature sensor

Sensor	Location/Description
Ambient (Figure 3)	Approximately 200' from structure, tied to a tree to protect from sunlight and exhaust
#640 (Figure 4)	Mid-structure, on bottom mat, over a metal form
#641 (Figure 4)	Mid-structure, on top mat, over a metal form
#642 (Figure 5)	Where wood forms meet the fascia beam, on bottom mat
#643 (Figure 5)	Where wood forms meet the fascia beam, on top mat
#644 (Figure 4)	Mid-structure south of #640 & #641, on top mat, over middle of beam
#646 (Figure 6)	Cure box, placed between cylinders
#647 (Figure 6)	Inside a cylinder

Figure 3. Ambient sensor location

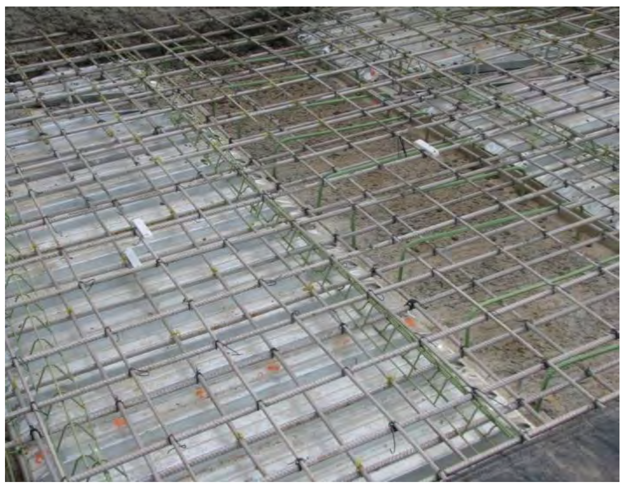

Figure 4. Locations of sensors #640, #641, and #644

Figure 5. Locations of sensors #642 and #643

Figure 6. Locations of sensors #646 and #647

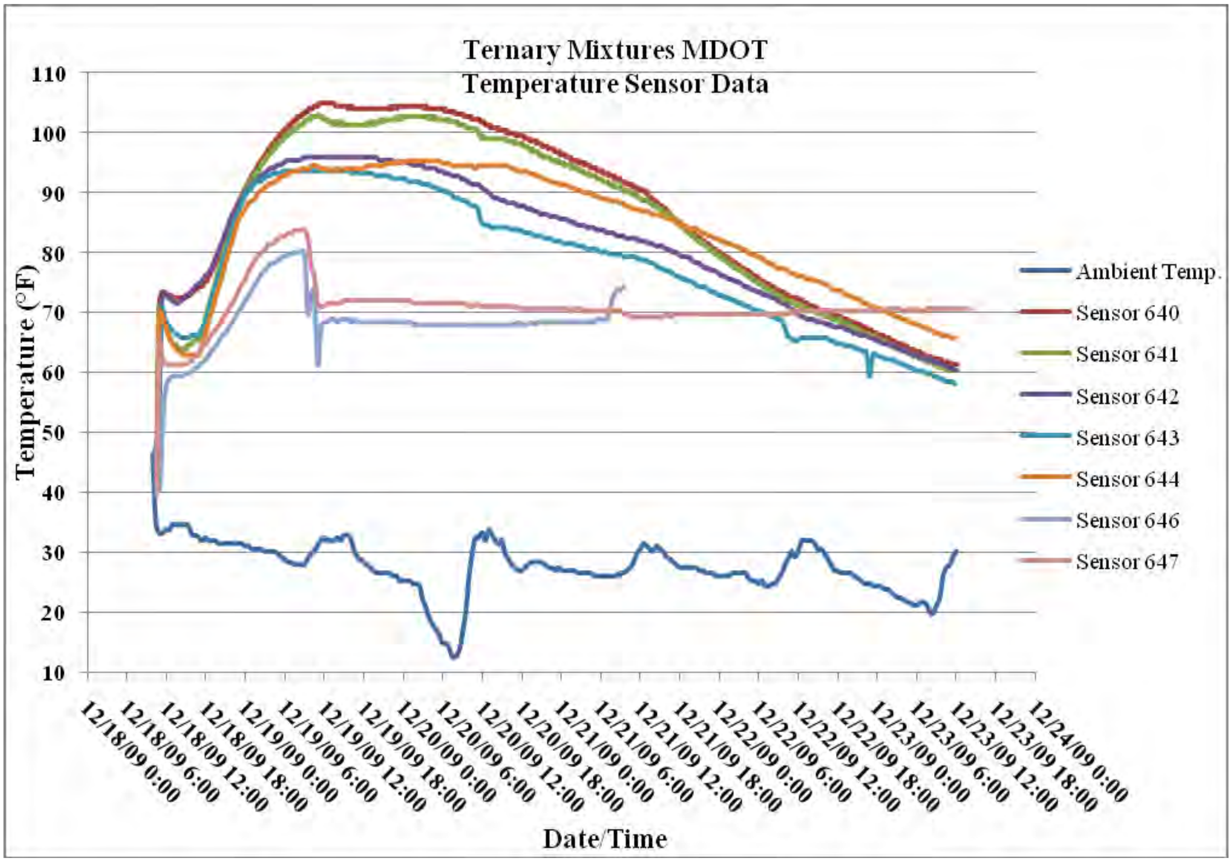

Figure 7. Temperature sensor data from MDOT

- The fresh concrete tests included slump cone, unit weight, and temperature measurement. MDOT staff and consultant inspectors conducted the tests on site: the slump was 4 in.; unit weight was 147.2 lb/ft3; concrete placement temperature was 81˚F; and the ambient temperature was 33˚F.
- Figures 8 through 11 illustrate several activities during the testing process.

Figure 8. Concrete being placed

Figure 9. Concrete being finished

Figure 10. Concrete heated tent enclosure below the deck

Figure 11. Curing blankets for concrete curing

- The air void test (Rapid Air Test) results for 10 samples, which were tested by the National CP Tech Center, are given in Table 2. The average results for each cylinder are less than the expected values. Two of the cylinders have lower specific surface results than desired.

Table 2. Air void test results conducted by the National CP Tech Center

Sample ID	Air Content (%)	Specific Surface (mm^{-1})	Spacing Factor (mm)
Cylinder 1-1	1.99	24.72	0.308
Cylinder 1-2	1.18	27.11	0.352
Cylinder 1-3	3.27	12.89	0.475
Cylinder 2-1	1.92	19.66	0.394
Cylinder 2-2	1.94	19.09	0.404
Cylinder 2-3	1.26	26.13	0.355
Cylinder 2-4	1.44	22.56	0.388
Cylinder 3-1	2.95	33.39	0.192
Cylinder 3-2	3.60	26.68	0.220
Cylinder 3-3	2.81	34.98	0.187

- The strength development as 28/7-day compressive strength ratios is reported in Table 3.
- The rapid chloride permeability test measures the electrical conductance of a concrete sample as its resistance to chloride ion penetration. The test results shown in Table 3 indicate a classification of "very low" chloride permeability according to ASTM C1202.

Table 3. Properties of hardened concrete

Tests	Results			
7-day compressive strength, psi	3050			
28-day compressive strength, psi	6110			
Rapid chloride permeability, coulombs	Sample 1 977	Sample 2 1040	Sample 3 987	Average 1001
Strength development 28/7 day fc ratio	2.00			
Shrinkage microstrain @ 28 days, in/in	756.7			
Average stress rate by restrained ring test, psi/day	92.63			

- Compressive strength, splitting tensile strength, and modulus of elasticity results (ASTM C 39, ASTM C 496, and ASTM C 469) are tabulated in Table 4 and also plotted in Figures 12 to 14.

Table 4. Summation of strength and modulus of elasticity

Location	Age, days	Compressive Strength, psi	Splitting Tensile Strength, psi	Modulus of Elasticity, psi
MI	1	820	163	4.10E+06
	3	1,750	275	4.80E+06
	7	3,050	324	5.30E+06
	28	6,110	517	5.80E+06
	56	6,610	598	5.40E+06

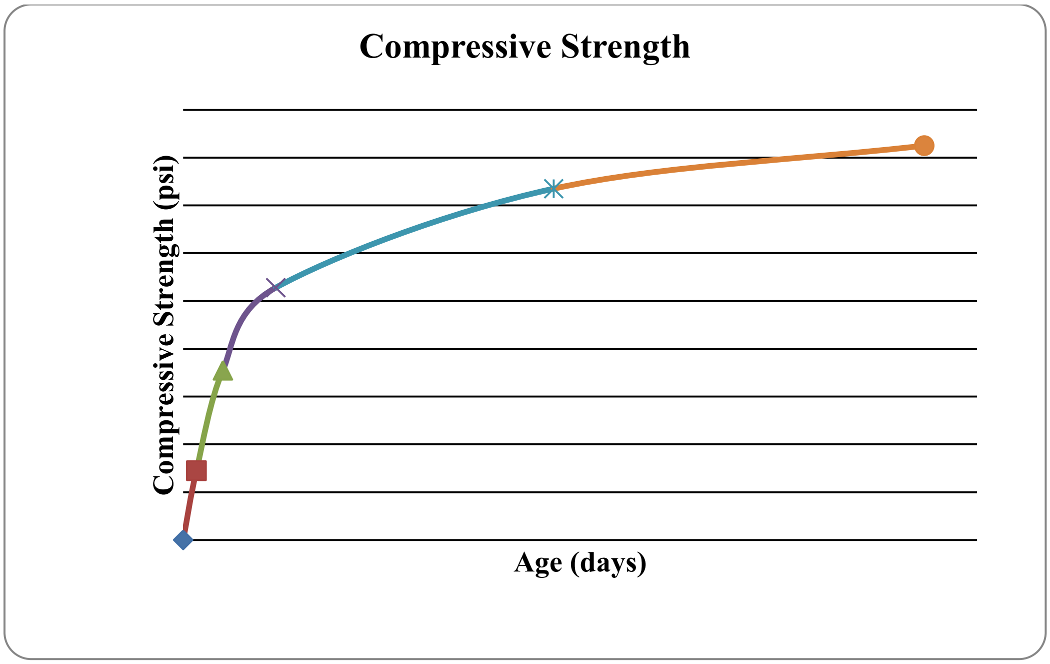

Figure 12. Compressive strength development with time

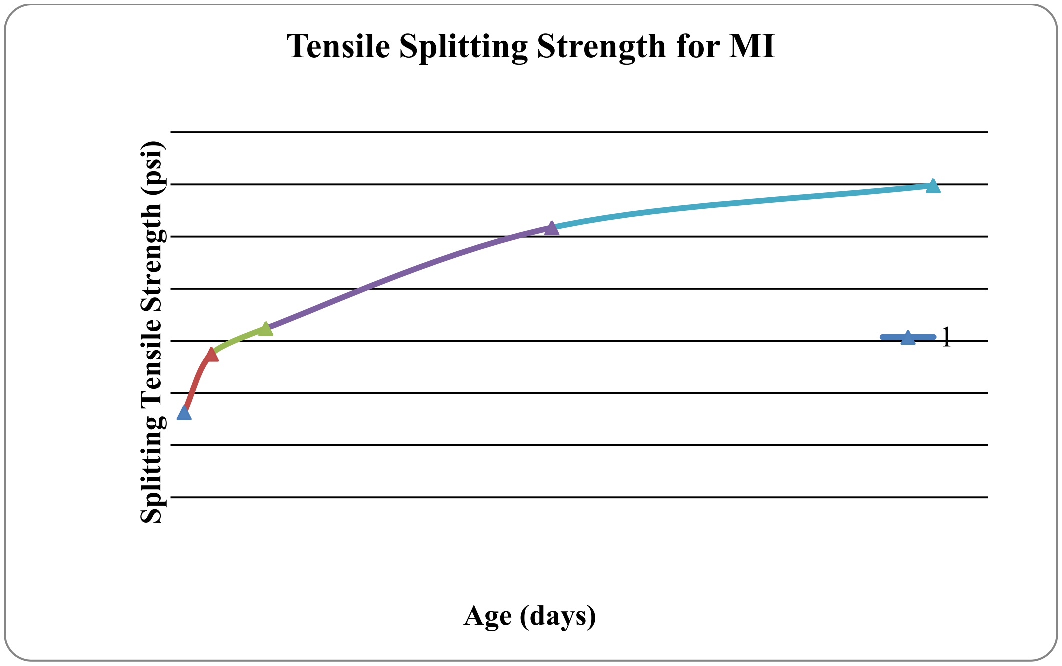

Figure 13. Tensile splitting strength development with time

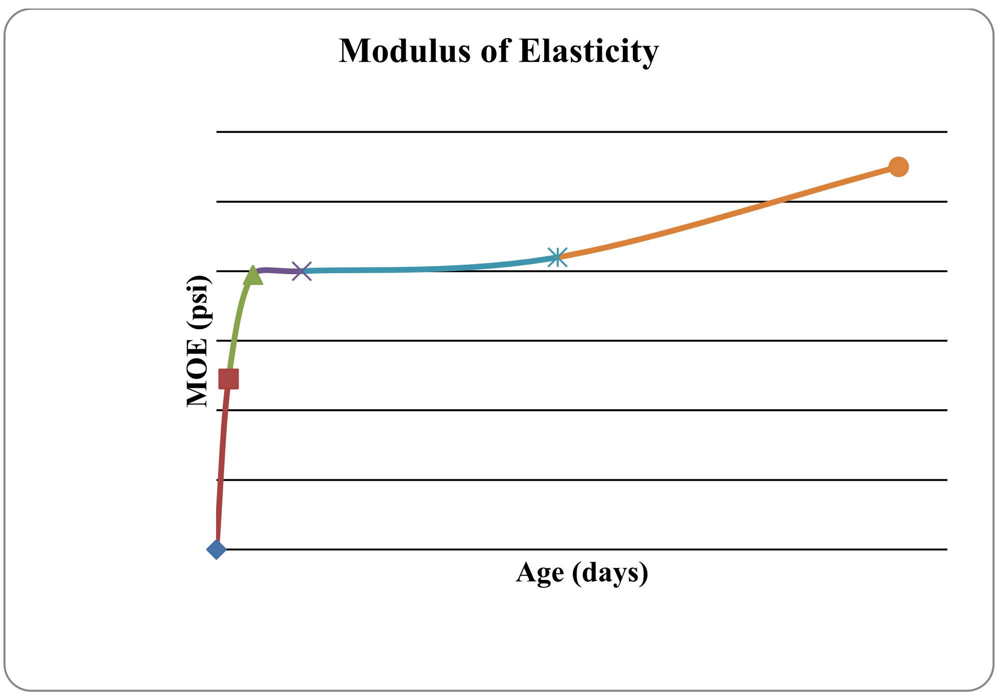

Figure 14. Modulus of elasticity development with time

- A free shrinkage test (ASTM C 157) was conducted in the laboratory. Three concrete beams were wet cured for seven days and then moved to a dry room at 23˚C and 50% relative humidity. The drying shrinkage results are given in Table 5 and are also plotted in Figure 15.

Table 5. Free shrinkage test results

MI Project Free Shrinkage Test (ASTM C 157)					
Dry Time	Beam 1 change%	Beam 2 change %	Beam 3 change %	Average	Microstrain
1	-0.002	-0.001	-0.005	-0.003	-26.7
4	-0.015	-0.015	-0.020	-0.017	-166.7
7	-0.073	-0.051	-0.045	-0.056	-563.3
14	-0.080	-0.064	-0.068	-0.071	-706.7
28	-0.089	-0.067	-0.071	-0.076	-756.7
56	-0.077	-0.070	-0.080	-0.076	-756.7

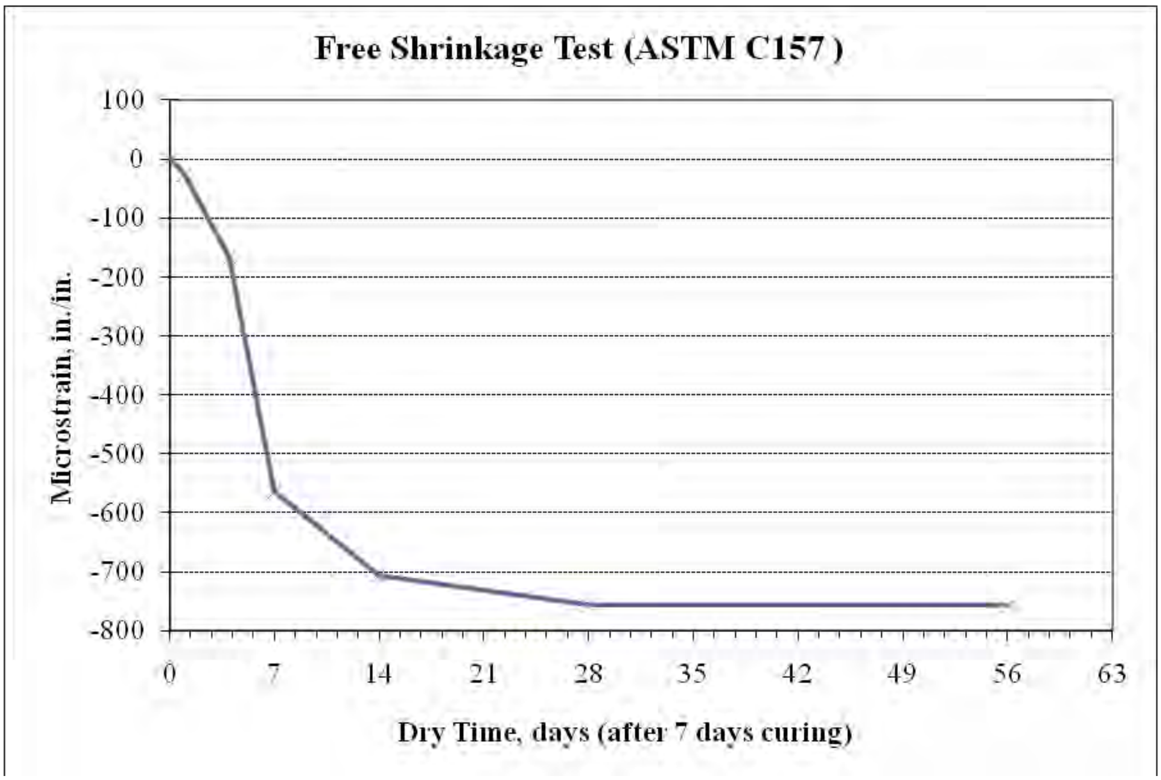

Figure 15. Free shrinkage of prisms (ASTM C 157)

- A restrained shrinkage test was conducted based on ASTM C 1581. Four rings were cast. The rings were demolded and the top surface was covered with paraffin wax 24 hours after casting. The rings were allowed to dry at 23˚C and 50% relative humidity immediately after demolding. Strains in the steel rings were recorded every 10 minutes for up to 28 days, or until the concrete cracked. The configuration of restrained concrete rings is shown in Figure 16. The cracking potential is listed in Table 6 and shown graphically in Figure 17. The cracking potential is classified as "moderate high" based on the average stress rate.

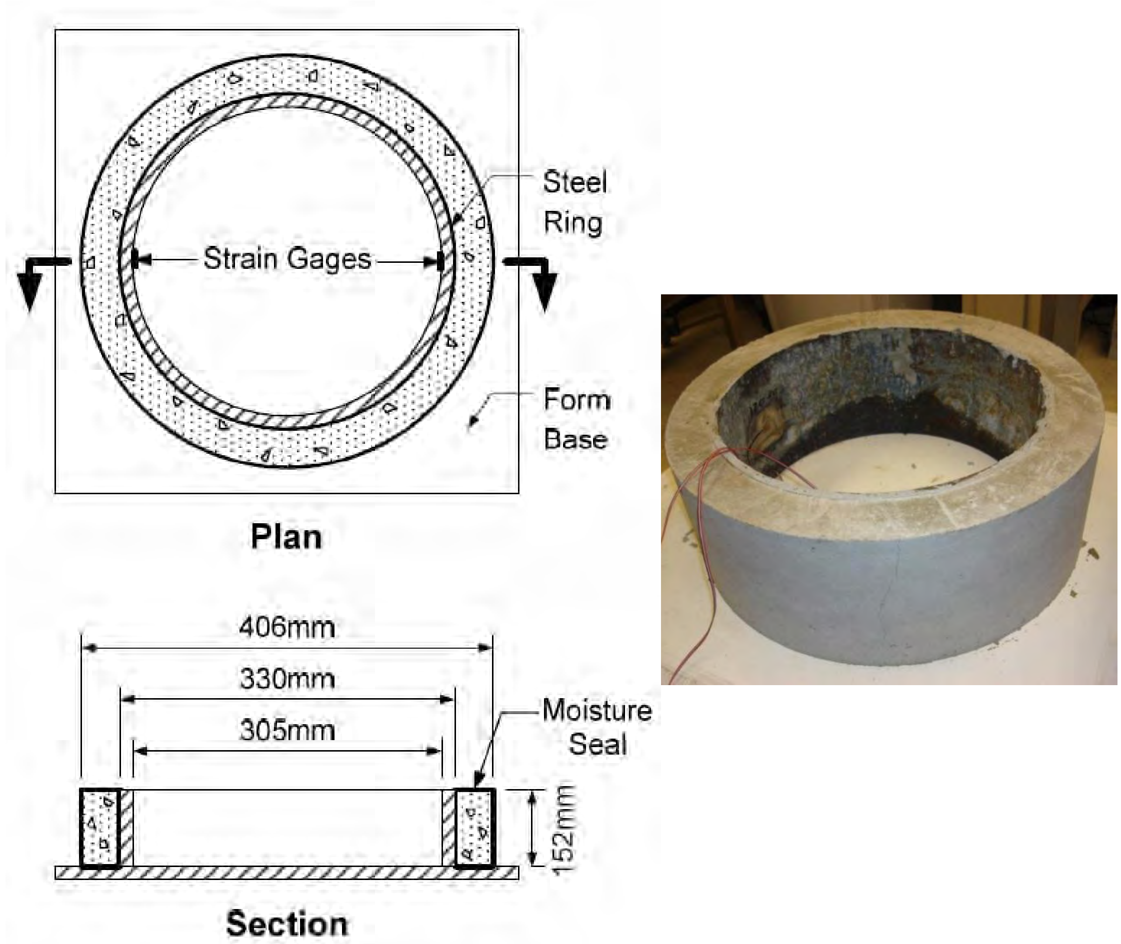

Figure 16. Configuration of restrained concrete ring samples

Table 6. Cracking potential and average stress rate (ASTM C 1581)

Cracking Potential for MI Project (ASTM C 1581)			
	Ring 1	Ring 2	Ring 3
Strain rate factor (in./in.x10^{-6})/hours$^{1/2}$	-11.57	-10.48	-9.47
G (psi)	10.47×10^{6}	10.47×10^{6}	10.47×10^{6}
Absolute value of α_{avg} (in./in.10^{-6})/day$^{1/2}$		51.47	
Elapsed time, tr (hours)	176.0	138.0	400.0
Elapsed time, tr (days)	7.3	5.8	16.7
Stress rate, q (psi/day) $q=G I \alpha_{avg} I/2\sqrt{t_r}$	99.5	112.4	66.0
Average stress rate, q (psi/day) $q=G I \alpha_{avg} I/2\sqrt{t_r}$		**92.63**	
Potential for cracking classification (ASTM 1581)		**High (50≤ q)**	

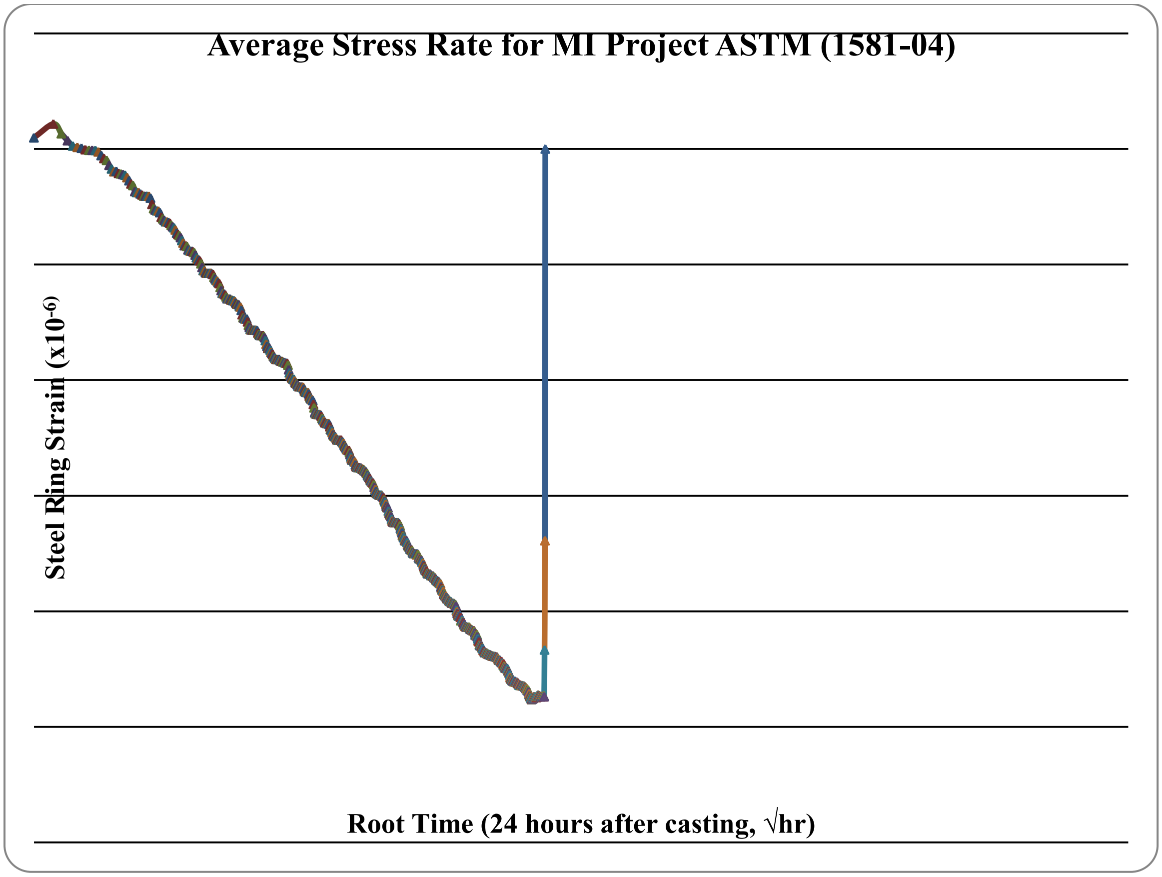

Figure 17. Strains of steel rings resulting from concrete shrinkage

PROJECT DATA

The following test data are provided for information only; comments and conclusions will be reported in the comprehensive Phase III report of the pooled fund project *Development of Performance Properties of Ternary Mixtures.*

Mix Design & Misc. Info.

General Information

Project:	MI - Ternary Mixtures
Contractor:	
Mix Description:	600 lb Cementitious
Mix ID:	1PL5046A
Date(s) of Placement:	10/28/2009

Cementitious Materials

Cementitious Materials	Source	Type	Spec. Gravity	lb/yd³	% Replacement by Mass
Portland Cement:	Buzzi Unicem	I	3.150	426	
GGBFS:			2.870	150	25.00%
Fly Ash:					
Silica Fume:			2.250	24	4.00%
Other Pozzolan:					
				600	**lb/yd³**
				6.4	**sacks/yd³**

Aggregate Information

Aggregate Information	Source	Type	Spec. Gravity SSD	Absorption (%)	% Passing #4
Coarse Aggregate:	6AA	High calcium limestone	2.700	1.73%	3.0%
Intermediate Aggregate #1:	29A	Granite	2.600	2.33%	5.0%
Intermediate Aggregate #2:					
Fine Aggregate #1:	2NS	Natural Sand	2.610	1.20%	99.0%

Coarse Aggregate %:	48.3%
Intermediate Aggregate #1%:	10.1%
Intermediate Aggregate #2%:	
Fine Aggregate #1 %:	41.6%

Mix Proportion Calculations

Water/Cementitious Materials Ratio:	0.380
Air Content:	6.50%

	Volume (ft³)	Batch Weights SSD (lb/yd³)	Spec. Gravity	Absolute Volume (%)
Portland Cement:	2.167	426	3.150	8.030%
GGBFS:	0.838	150	2.870	3.103%
Fly Ash:				
Silica Fume:	0.171	24	2.250	0.633%
Other Pozzolan:				
Coarse Aggregate:	8.895	1,435	2.700	32.954%
Intermediate Aggregate #1:	1.854	299	2.600	6.871%
Intermediate Aggregate #2:				
Fine Aggregate #1:	7.657	1,234	2.610	28.369%
Water:	3.654	228	1.000	13.537%
Air:	1.755			6.502%
	26.991	**3,796**		**100.000%**
	Unit Weight (lb/ft³)	**140.6**	**Paste**	**31.806%**
			Mortar	**61.224%**

Admixture Information

Admixture Information	Source/Description	oz/yd³	oz/cwt
Air Entraining Admix.:	Micro-Air (type AR)	11.40	1.90
Admix. #1:	Delvo (Type D)	18.00	3.00
Admix. #2:	Rheobuild 1000 (Type MR)	54.00	9.00
Admix. #3:			

AVA Information

AVA Information	Absolute Volume (%)
Air Free Paste:	25.304%
Air Free Mortar:	54.721%

PROOVE it

ASTM C 1202-97

TEST CO.

File name = Proovelt user logo.jpg located in application directory.

Your own logo. size=20x80mm

Test-compagny
Testing street 45
CompagnyCity
Some Country

GERMANN INSTRUMENTS
DENMARK
USA

Test report

Voltage Used:	60
Testing time:	06:00 hour
Charge passed:	977
Adjusted Charge passed:	848
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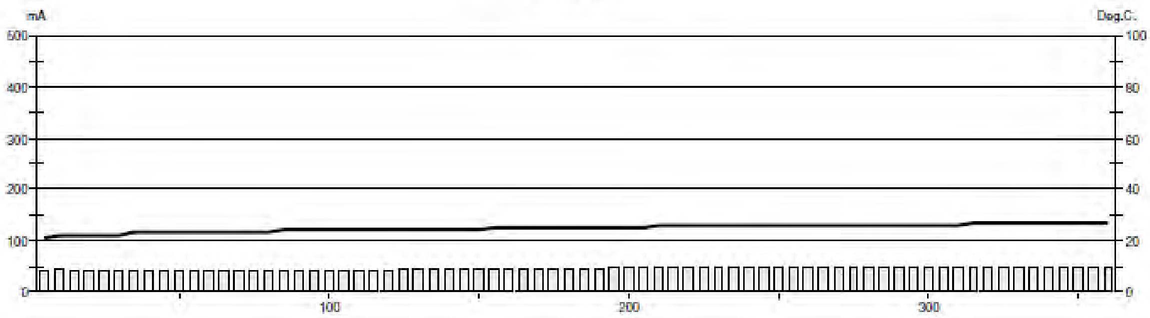
Comment:	---



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ASTM C 1202-97

Test-compagny
Testing street 45
CompagnyCity
Some Country

GERMANN INSTRUMENTS

Test report

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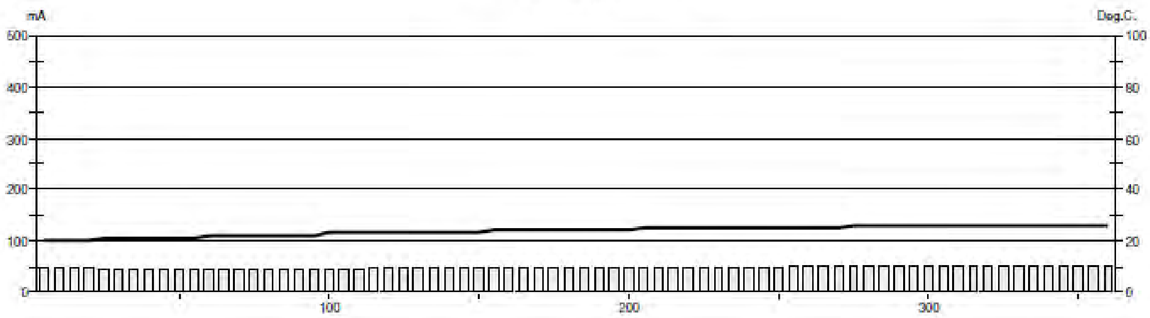
Comment:	---



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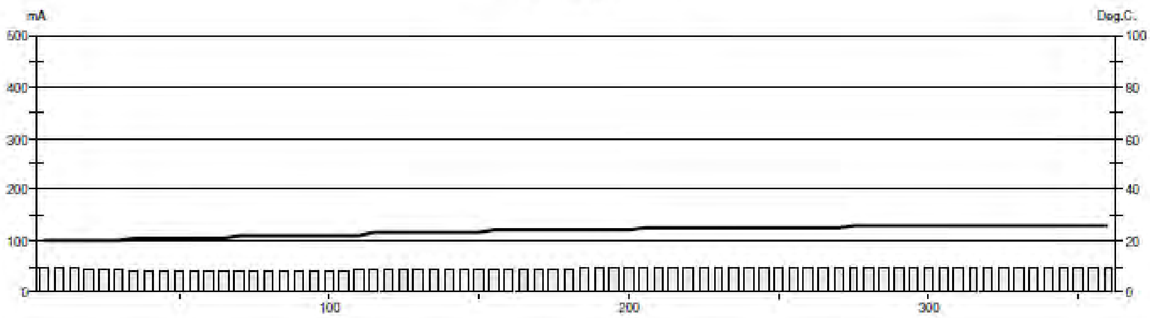
ASTM C 1202-97

Test-compagny
Testing street 45
CompagnyCity
Some Country

GERMANN INSTRUMENTS
DENMARK
Phone: +45 3967 7117
Fax: +45 3967 3107
USA
Phone: (847)329-9999
Fax: (847)329-8888

Test report

Voltage Used:	60
Testing time:	06:00 hour
Charge passed:	987
Adjusted Charge passed:	856
Permeability class:	Very Low
Instrument number:	023907
Channel number:	3
Report date:	2/11/2010
Testing by:	PJM
Reference:	MI Ternary 3
Sample diameter:	102
Comment:	---



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00:30	20	43.8	02:00	23	43.7	03:30	25	46.2	05:00	26	47.9
00:35	21	43.0	02:05	23	43.8	03:35	25	46.4	05:05	26	48.0
00:40	21	42.4	02:10	23	43.8	03:40	25	46.5	05:10	26	48.2
00:45	21	42.0	02:15	23	43.9	03:45	25	46.8	05:15	26	48.1
00:50	21	42.0	02:20	23	44.1	03:50	25	46.7	05:20	26	48.1
00:55	21	42.1	02:25	23	44.3	03:55	25	46.8	05:25	26	48.3
01:00	21	42.1	02:30	23	44.5	04:00	25	46.9	05:30	26	48.3
01:05	21	42.1	02:35	24	44.6	04:05	25	47.2	05:35	26	48.3
01:10	22	42.2	02:40	24	44.8	04:10	25	47.5	05:40	26	48.5
01:15	22	42.3	02:45	24	45.1	04:15	25	47.4	05:45	26	48.5
01:20	22	42.5	02:50	24	45.1	04:20	25	47.3	05:50	26	48.5
01:25	22	42.8	02:55	24	45.2	04:25	25	47.4	05:55	26	48.5
01:30	22	42.8	03:00	24	45.4	04:30	25	47.7	06:00	26	48.5

Sample ID: Cast cyl Cylinder 1-1

Sample Size (mm x mm):	85 x 90	Length Traversed (mm):	2413.1
Paste Content (%):	30.20	Area Traversed (mm x mm):	75 x 80

Chord Length Distribution - Table

Class No.	Chord size (microns)	Number of Chords in Class	Number of Chords in Percent	Air Content in Class	Cumulated Air Content	Chord length frequency	Air content, fraction	
1	0-10	11	3.70	0.000	0.000	0.04	0.000	0.00-0.01
2	10-20	39	13.13	0.020	0.030	0.13	0.020	0.01-0.02
3	20-30	27	13.13	0.030	0.060	0.09	0.030	0.02-0.03
4	30-40	22	7.41	0.030	0.090	0.07	0.030	0.03-0.04
5	40-50	21	7.07	0.040	0.130	0.07	0.040	0.04-0.05
6	50-60	14	4.71	0.030	0.160	0.05	0.030	0.05-0.06
7	60-80	21	7.07	0.060	0.220	0.07	0.060	0.06-0.08
8	80-100	14	4.71	0.050	0.270	0.05	0.050	0.08-0.10
9	100-120	13	4.38	0.060	0.330	0.04	0.060	0.10-0.12
10	120-140	14	4.71	0.070	0.410	0.05	0.070	0.12-0.14
11	140-160	13	4.38	0.080	0.490	0.04	0.080	0.14-0.16
12	160-180	9	3.03	0.060	0.550	0.03	0.060	0.16-0.18
13	180-200	11	3.70	0.090	0.640	0.04	0.090	0.18-0.20
14	200-220	10	3.37	0.090	0.720	0.03	0.090	0.20-0.22
15	220-240	7	2.36	0.070	0.790	0.02	0.070	0.22-0.24
16	240-260	3	1.01	0.030	0.820	0.01	0.030	0.24-0.26
17	260-280	4	1.35	0.040	0.860	0.01	0.040	0.26-0.28
18	280-300	5	1.68	0.060	0.920	0.02	0.060	0.28-0.30
19	300-350	5	1.68	0.070	0.990	0.02	0.070	0.30-0.35
20	350-400	4	1.35	0.060	1.050	0.01	0.060	0.35-0.40
21	400-450	4	1.35	0.070	1.120	0.01	0.070	0.40-0.45
22	450-500	5	1.68	0.100	1.220	0.02	0.100	0.45.0.50
23	500-1000	12	4.04	0.360	1.280	0.04	0.360	0.50-1.00
24	1000-1500	9	3.03	0.410	1.990	0.03	0.410	1.00-1.50
25	1500-2000	0	0.00	0.000	1.990	0.00	0.000	1.50-2.00
26	2000-2500	0	0.00	0.000	1.990	0.00	0.000	2.00-2.50
27	2500-3000	0	0.00	0.000	1.990	0.00	0.000	2.50-3.00
28	3000-4000	0	0.00	0.000	1.990	0.00	0.000	3.00-4.00
						297		

Air Content (%):	1.99
Specific Surface (mm^{-1}):	24.72
Spacing Factor (mm):	0.308
Void Frequency (mm^{-1}):	0.120
Average Chord Length (mm):	0.162
Paste to Air Ratio:	15.18

Sample ID:	Cast cyl	Cylinder 1-2	
Sample Size (mm x mm):	80 x 95	Length Traversed (mm):	2413.1
Paste Content (%):	30.20	Area Traversed (mm x mm):	70 x 85

Chord Length Distribution - Table

Class No.	Chord size (microns)	Number of Chords in Class	Number of Chords in Percent	Air Content in Class	Cumulated Air Content	Chord length frequency	Air content, fraction	
1	0-10	10	5.18	0.000	0.000	0.05	0.000	0.00-0.01
2	10-20	21	10.88	0.010	0.020	0.11	0.010	0.01-0.02
3	20-30	20	10.88	0.020	0.040	0.10	0.020	0.02-0.03
4	30-40	18	9.33	0.030	0.060	0.09	0.030	0.03-0.04
5	40-50	14	7.25	0.030	0.090	0.07	0.030	0.04-0.05
6	50-60	15	7.77	0.030	0.130	0.08	0.030	0.05-0.06
7	60-80	17	8.81	0.050	0.170	0.09	0.050	0.06-0.08
8	80-100	19	9.84	0.070	0.240	0.10	0.070	0.08-0.10
9	100-120	6	3.11	0.030	0.270	0.03	0.030	0.10-0.12
10	120-140	5	2.59	0.030	0.300	0.03	0.030	0.12-0.14
11	140-160	4	2.07	0.020	0.320	0.02	0.020	0.14-0.16
12	160-180	5	2.59	0.040	0.360	0.03	0.040	0.16-0.18
13	180-200	3	1.55	0.020	0.380	0.02	0.020	0.18-0.20
14	200-220	2	1.04	0.020	0.400	0.01	0.020	0.20-0.22
15	220-240	5	2.59	0.050	0.450	0.03	0.050	0.22-0.24
16	240-260	1	0.52	0.010	0.460	0.01	0.010	0.24-0.26
17	260-280	3	1.55	0.030	0.490	0.02	0.030	0.26-0.28
18	280-300	3	1.55	0.040	0.530	0.02	0.040	0.28-0.30
19	300-350	6	3.11	0.080	0.610	0.03	0.080	0.30-0.35
20	350-400	2	1.04	0.030	0.640	0.01	0.030	0.35-0.40
21	400-450	2	1.04	0.040	0.680	0.01	0.040	0.40-0.45
22	450-500	3	1.55	0.060	0.730	0.02	0.060	0.45.0.50
23	500-1000	3	1.55	0.080	0.760	0.02	0.080	0.50-1.00
24	1000-1500	3	1.55	0.150	0.970	0.02	0.150	1.00-1.50
25	1500-2000	2	1.04	0.130	1.090	0.01	0.130	1.50-2.00
26	2000-2500	1	0.52	0.090	1.180	0.01	0.090	2.00-2.50
27	2500-3000	0	0.00	0.000	1.180	0.00	0.000	2.50-3.00
28	3000-4000	0	0.00	0.000	1.180	0.00	0.000	3.00-4.00
						193		

Air Content (%):	1.18
Specific Surface (mm^{-1}):	27.11
Spacing Factor (mm):	0.352
Void Frequency (mm^{-1}):	0.080
Average Chord Length (mm):	0.148
Paste to Air Ratio:	25.59

Sample ID:	Cast cyl	Cylinder 1-3	
Sample Size (mm x mm):	85 x 90	Length Traversed (mm):	2413.1
Paste Content (%):	30.20	Area Traversed (mm x mm):	75 x 80

Chord Length Distribution - Table

Class No.	Chord size (microns)	Number of Chords in Class	Number of Chords in Percent	Air Content in Class	Cumulated Air Content	Chord length frequency	Air content, fraction	
1	0-10	6	2.36	0.000	0.000	0.02	0.000	0.00-0.01
2	10-20	24	9.45	0.020	0.020	0.09	0.020	0.01-0.02
3	20-30	26	9.45	0.030	0.040	0.10	0.030	0.02-0.03
4	30-40	15	5.91	0.020	0.070	0.06	0.020	0.03-0.04
5	40-50	17	6.69	0.030	0.100	0.07	0.030	0.04-0.05
6	50-60	19	7.48	0.040	0.140	0.07	0.040	0.05-0.06
7	60-80	22	8.66	0.060	0.200	0.09	0.060	0.06-0.08
8	80-100	15	5.91	0.060	0.260	0.06	0.060	0.08-0.10
9	100-120	8	3.15	0.040	0.290	0.03	0.040	0.10-0.12
10	120-140	7	2.76	0.040	0.330	0.03	0.040	0.12-0.14
11	140-160	13	5.12	0.080	0.410	0.05	0.080	0.14-0.16
12	160-180	9	3.54	0.060	0.470	0.04	0.060	0.16-0.18
13	180-200	4	1.57	0.030	0.510	0.02	0.030	0.18-0.20
14	200-220	8	3.15	0.070	0.580	0.03	0.070	0.20-0.22
15	220-240	5	1.97	0.050	0.620	0.02	0.050	0.22-0.24
16	240-260	1	0.39	0.010	0.630	0.00	0.010	0.24-0.26
17	260-280	3	1.18	0.030	0.670	0.01	0.030	0.26-0.28
18	280-300	1	0.39	0.010	0.680	0.00	0.010	0.28-0.30
19	300-350	3	1.18	0.040	0.720	0.01	0.040	0.30-0.35
20	350-400	3	1.18	0.050	0.770	0.01	0.050	0.35-0.40
21	400-450	4	1.57	0.070	0.840	0.02	0.070	0.40-0.45
22	450-500	3	1.18	0.060	0.900	0.01	0.060	0.45.0.50
23	500-1000	16	6.30	0.470	0.940	0.06	0.470	0.50-1.00
24	1000-1500	6	2.36	0.290	1.660	0.02	0.290	1.00-1.50
25	1500-2000	7	2.76	0.530	2.180	0.03	0.530	1.50-2.00
26	2000-2500	4	1.57	0.350	2.530	0.02	0.350	2.00-2.50
27	2500-3000	0	0.00	0.000	2.530	0.00	0.000	2.50-3.00
28	3000-4000	5	1.97	0.730	3.270	0.02	0.730	3.00-4.00
						254		

Air Content (%):	3.27
Specific Surface (mm^{-1}):	12.89
Spacing Factor (mm):	0.475
Void Frequency (mm^{-1}):	0.110
Average Chord Length (mm):	0.310
Paste to Air Ratio:	9.24

Sample ID:	Cast cyl	Cylinder 2-1	
Sample Size (mm x mm):	80 x 90	Length Traversed (mm):	2413.1
Paste Content (%):	30.20	Area Traversed (mm x mm):	70 x 80

Chord Length Distribution - Table

Class No.	Chord size (microns)	Number of Chords in Class	Number of Chords in Percent	Air Content in Class	Cumulated Air Content	Chord length frequency	Air content, fraction	
1	0-10	1	0.44	0.000	0.000	0.00	0.000	0.00-0.01
2	10-20	30	13.16	0.020	0.020	0.13	0.020	0.01-0.02
3	20-30	20	13.16	0.020	0.040	0.09	0.020	0.02-0.03
4	30-40	13	5.70	0.020	0.060	0.06	0.020	0.03-0.04
5	40-50	12	5.26	0.020	0.080	0.05	0.020	0.04-0.05
6	50-60	14	6.14	0.030	0.110	0.06	0.030	0.05-0.06
7	60-80	15	6.58	0.040	0.160	0.07	0.040	0.06-0.08
8	80-100	14	6.14	0.050	0.210	0.06	0.050	0.08-0.10
9	100-120	16	7.02	0.070	0.280	0.07	0.070	0.10-0.12
10	120-140	6	2.63	0.030	0.310	0.03	0.030	0.12-0.14
11	140-160	7	3.07	0.040	0.360	0.03	0.040	0.14-0.16
12	160-180	8	3.51	0.060	0.410	0.04	0.060	0.16-0.18
13	180-200	6	2.63	0.050	0.460	0.03	0.050	0.18-0.20
14	200-220	2	0.88	0.020	0.480	0.01	0.020	0.20-0.22
15	220-240	5	2.19	0.050	0.530	0.02	0.050	0.22-0.24
16	240-260	4	1.75	0.040	0.570	0.02	0.040	0.24-0.26
17	260-280	6	2.63	0.070	0.630	0.03	0.070	0.26-0.28
18	280-300	7	3.07	0.080	0.720	0.03	0.080	0.28-0.30
19	300-350	9	3.95	0.120	0.840	0.04	0.120	0.30-0.35
20	350-400	6	2.63	0.090	0.930	0.03	0.090	0.35-0.40
21	400-450	2	0.88	0.040	0.960	0.01	0.040	0.40-0.45
22	450-500	3	1.32	0.060	1.020	0.01	0.060	0.45.0.50
23	500-1000	16	7.02	0.440	1.130	0.07	0.440	0.50-1.00
24	1000-1500	1	0.44	0.040	1.500	0.00	0.040	1.00-1.50
25	1500-2000	2	0.88	0.160	1.660	0.01	0.160	1.50-2.00
26	2000-2500	3	1.32	0.260	1.920	0.01	0.260	2.00-2.50
27	2500-3000	0	0.00	0.000	1.920	0.00	0.000	2.50-3.00
28	3000-4000	0	0.00	0.000	1.920	0.00	0.000	3.00-4.00
						228		

Air Content (%):	1.92
Specific Surface (mm^{-1}):	19.66
Spacing Factor (mm):	0.394
Void Frequency (mm^{-1}):	0.090
Average Chord Length (mm):	0.203
Paste to Air Ratio:	15.73

Sample ID:	Cast cyl	Cylinder 2-2	
Sample Size (mm x mm):	80 x 80	Length Traversed (mm):	2413.1
Paste Content (%):	30.20	Area Traversed (mm x mm):	70 x 80

Chord Length Distribution - Table

Class No.	Chord size (microns)	Number of Chords in Class	Number of Chords in Percent	Air Content in Class	Cumulated Air Content	Chord length frequency	Air content, fraction	
1	0-10	3	1.35	0.000	0.000	0.01	0.000	0.00-0.01
2	10-20	32	14.35	0.020	0.020	0.14	0.020	0.01-0.02
3	20-30	25	14.35	0.030	0.050	0.11	0.030	0.02-0.03
4	30-40	16	7.17	0.020	0.070	0.07	0.020	0.03-0.04
5	40-50	18	8.07	0.030	0.100	0.08	0.030	0.04-0.05
6	50-60	10	4.48	0.020	0.130	0.04	0.020	0.05-0.06
7	60-80	14	6.28	0.040	0.170	0.06	0.040	0.06-0.08
8	80-100	16	7.17	0.060	0.230	0.07	0.060	0.08-0.10
9	100-120	6	2.69	0.030	0.260	0.03	0.030	0.10-0.12
10	120-140	12	5.38	0.060	0.320	0.05	0.060	0.12-0.14
11	140-160	5	2.24	0.030	0.350	0.02	0.030	0.14-0.16
12	160-180	6	2.69	0.040	0.390	0.03	0.040	0.16-0.18
13	180-200	7	3.14	0.060	0.450	0.03	0.060	0.18-0.20
14	200-220	6	2.69	0.050	0.500	0.03	0.050	0.20-0.22
15	220-240	6	2.69	0.060	0.560	0.03	0.060	0.22-0.24
16	240-260	1	0.45	0.010	0.570	0.00	0.010	0.24-0.26
17	260-280	6	2.69	0.070	0.640	0.03	0.070	0.26-0.28
18	280-300	2	0.90	0.020	0.660	0.01	0.020	0.28-0.30
19	300-350	7	3.14	0.090	0.750	0.03	0.090	0.30-0.35
20	350-400	3	1.35	0.050	0.800	0.01	0.050	0.35-0.40
21	400-450	1	0.45	0.020	0.820	0.00	0.020	0.40-0.45
22	450-500	1	0.45	0.020	0.840	0.00	0.020	0.45.0.50
23	500-1000	10	4.48	0.250	0.940	0.04	0.250	0.50-1.00
24	1000-1500	4	1.79	0.220	1.300	0.02	0.220	1.00-1.50
25	1500-2000	2	0.90	0.130	1.440	0.01	0.130	1.50-2.00
26	2000-2500	1	0.45	0.100	1.540	0.00	0.100	2.00-2.50
27	2500-3000	1	0.45	0.110	1.650	0.00	0.110	2.50-3.00
28	3000-4000	2	0.90	0.290	1.940	0.01	0.290	3.00-4.00
						223		

Air Content (%):	1.94
Specific Surface (mm^{-1}):	19.09
Spacing Factor (mm):	0.404
Void Frequency (mm^{-1}):	0.090
Average Chord Length (mm):	0.209
Paste to Air Ratio:	15.57

Sample ID: Cast cyl Cylinder 2-3

Sample Size (mm x mm):	80 x 80	Length Traversed (mm):	2413.1
Paste Content (%):	30.20	Area Traversed (mm x mm):	70 x 70

Chord Length Distribution - Table

Class No.	Chord size (microns)	Number of Chords in Class	Number of Chords in Percent	Air Content in Class	Cumulated Air Content	Chord length frequency	Air content, fraction	
1	0-10	5	2.51	0.000	0.000	0.03	0.000	0.00-0.01
2	10-20	33	16.58	0.020	0.020	0.17	0.020	0.01-0.02
3	20-30	16	16.58	0.020	0.040	0.08	0.020	0.02-0.03
4	30-40	21	10.55	0.030	0.070	0.11	0.030	0.03-0.04
5	40-50	7	3.52	0.010	0.080	0.04	0.010	0.04-0.05
6	50-60	13	6.53	0.030	0.110	0.07	0.030	0.05-0.06
7	60-80	16	8.04	0.050	0.160	0.08	0.050	0.06-0.08
8	80-100	17	8.54	0.060	0.220	0.09	0.060	0.08-0.10
9	100-120	10	5.03	0.050	0.270	0.05	0.050	0.10-0.12
10	120-140	5	2.51	0.030	0.290	0.03	0.030	0.12-0.14
11	140-160	11	5.53	0.070	0.360	0.06	0.070	0.14-0.16
12	160-180	4	2.01	0.030	0.390	0.02	0.030	0.16-0.18
13	180-200	0	0.00	0.000	0.390	0.00	0.000	0.18-0.20
14	200-220	4	2.01	0.030	0.420	0.02	0.030	0.20-0.22
15	220-240	3	1.51	0.030	0.450	0.02	0.030	0.22-0.24
16	240-260	2	1.01	0.020	0.470	0.01	0.020	0.24-0.26
17	260-280	1	0.50	0.010	0.480	0.01	0.010	0.26-0.28
18	280-300	2	1.01	0.020	0.510	0.01	0.020	0.28-0.30
19	300-350	3	1.51	0.040	0.550	0.02	0.040	0.30-0.35
20	350-400	1	0.50	0.010	0.560	0.01	0.010	0.35-0.40
21	400-450	2	1.01	0.040	0.600	0.01	0.040	0.40-0.45
22	450-500	3	1.51	0.060	0.660	0.02	0.060	0.45.0.50
23	500-1000	17	8.54	0.460	0.720	0.09	0.460	0.50-1.00
24	1000-1500	3	1.51	0.150	1.260	0.02	0.150	1.00-1.50
25	1500-2000	0	0.00	0.000	1.260	0.00	0.000	1.50-2.00
26	2000-2500	0	0.00	0.000	1.260	0.00	0.000	2.00-2.50
27	2500-3000	0	0.00	0.000	1.260	0.00	0.000	2.50-3.00
28	3000-4000	0	0.00	0.000	1.260	0.00	0.000	3.00-4.00
						199		

Air Content (%):	1.26
Specific Surface (mm^{-1}):	26.13
Spacing Factor (mm):	0.355
Void Frequency (mm^{-1}):	0.080
Average Chord Length (mm):	0.153
Paste to Air Ratio:	23.97

Sample ID: Cast cyl Cylinder 2-4

Sample Size (mm x mm):	80 x 80	Length Traversed (mm):	2413.1
Paste Content (%):	30.20	Area Traversed (mm x mm):	70 x 70

Chord Length Distribution - Table

Class No.	Chord size (microns)	Number of Chords in Class	Number of Chords in Percent	Air Content in Class	Cumulated Air Content	Chord length frequency	Air content, fraction	
1	0-10	6	3.06	0.000	0.000	0.03	0.000	0.00-0.01
2	10-20	16	8.16	0.010	0.010	0.08	0.010	0.01-0.02
3	20-30	21	8.16	0.020	0.030	0.11	0.020	0.02-0.03
4	30-40	15	7.65	0.020	0.050	0.08	0.020	0.03-0.04
5	40-50	10	5.10	0.020	0.070	0.05	0.020	0.04-0.05
6	50-60	10	5.10	0.020	0.100	0.05	0.020	0.05-0.06
7	60-80	13	6.63	0.040	0.130	0.07	0.040	0.06-0.08
8	80-100	16	8.16	0.060	0.190	0.08	0.060	0.08-0.10
9	100-120	12	6.12	0.050	0.250	0.06	0.050	0.10-0.12
10	120-140	12	6.12	0.060	0.310	0.06	0.060	0.12-0.14
11	140-160	4	2.04	0.030	0.340	0.02	0.030	0.14-0.16
12	160-180	3	1.53	0.020	0.360	0.02	0.020	0.16-0.18
13	180-200	7	3.57	0.050	0.410	0.04	0.050	0.18-0.20
14	200-220	3	1.53	0.030	0.440	0.02	0.030	0.20-0.22
15	220-240	3	1.53	0.030	0.470	0.02	0.030	0.22-0.24
16	240-260	5	2.55	0.050	0.520	0.03	0.050	0.24-0.26
17	260-280	3	1.53	0.030	0.550	0.02	0.030	0.26-0.28
18	280-300	2	1.02	0.020	0.580	0.01	0.020	0.28-0.30
19	300-350	6	3.06	0.080	0.660	0.03	0.080	0.30-0.35
20	350-400	6	3.06	0.090	0.750	0.03	0.090	0.35-0.40
21	400-450	4	2.04	0.070	0.820	0.02	0.070	0.40-0.45
22	450-500	3	1.53	0.060	0.880	0.02	0.060	0.45.0.50
23	500-1000	11	5.61	0.320	0.900	0.06	0.320	0.50-1.00
24	1000-1500	5	2.55	0.250	1.440	0.03	0.250	1.00-1.50
25	1500-2000	0	0.00	0.000	1.440	0.00	0.000	1.50-2.00
26	2000-2500	0	0.00	0.000	1.440	0.00	0.000	2.00-2.50
27	2500-3000	0	0.00	0.000	1.440	0.00	0.000	2.50-3.00
28	3000-4000	0	0.00	0.000	1.440	0.00	0.000	3.00-4.00
						196		

Air Content (%):	1.44
Specific Surface (mm^{-1}):	22.56
Spacing Factor (mm):	0.388
Void Frequency (mm^{-1}):	0.080
Average Chord Length (mm):	0.177
Paste to Air Ratio:	20.97

Sample ID:	Cast cyl	Cylinder 3-1	
Sample Size (mm x mm):	70 x 70	Length Traversed (mm):	2413.1
Paste Content (%):	30.20	Area Traversed (mm x mm):	60 x 70

Chord Length Distribution - Table

Class No.	Chord size (microns)	Number of Chords in Class	Number of Chords in Percent	Air Content in Class	Cumulated Air Content	Chord length frequency	Air content, fraction	
1	0-10	18	3.03	0.010	0.010	0.03	0.010	0.00-0.01
2	10-20	67	11.28	0.040	0.050	0.11	0.040	0.01-0.02
3	20-30	86	11.28	0.090	0.140	0.14	0.090	0.02-0.03
4	30-40	69	11.62	0.100	0.240	0.12	0.100	0.03-0.04
5	40-50	59	9.93	0.110	0.350	0.10	0.110	0.04-0.05
6	50-60	38	6.40	0.090	0.430	0.06	0.090	0.05-0.06
7	60-80	54	9.09	0.150	0.590	0.09	0.150	0.06-0.08
8	80-100	39	6.57	0.150	0.730	0.07	0.150	0.08-0.10
9	100-120	26	4.38	0.120	0.850	0.04	0.120	0.10-0.12
10	120-140	21	3.54	0.110	0.970	0.04	0.110	0.12-0.14
11	140-160	18	3.03	0.110	1.080	0.03	0.110	0.14-0.16
12	160-180	8	1.35	0.060	1.140	0.01	0.060	0.16-0.18
13	180-200	13	2.19	0.100	1.240	0.02	0.100	0.18-0.20
14	200-220	10	1.68	0.090	1.320	0.02	0.090	0.20-0.22
15	220-240	3	0.51	0.030	1.350	0.01	0.030	0.22-0.24
16	240-260	6	1.01	0.060	1.410	0.01	0.060	0.24-0.26
17	260-280	8	1.35	0.090	1.500	0.01	0.090	0.26-0.28
18	280-300	1	0.17	0.010	1.510	0.00	0.010	0.28-0.30
19	300-350	9	1.52	0.120	1.630	0.02	0.120	0.30-0.35
20	350-400	6	1.01	0.090	1.730	0.01	0.090	0.35-0.40
21	400-450	4	0.67	0.070	1.800	0.01	0.070	0.40-0.45
22	450-500	4	0.67	0.080	1.880	0.01	0.080	0.45.0.50
23	500-1000	17	2.86	0.470	1.920	0.03	0.470	0.50-1.00
24	1000-1500	6	1.01	0.320	2.670	0.01	0.320	1.00-1.50
25	1500-2000	4	0.67	0.280	2.950	0.01	0.280	1.50-2.00
26	2000-2500	0	0.00	0.000	2.950	0.00	0.000	2.00-2.50
27	2500-3000	0	0.00	0.000	2.950	0.00	0.000	2.50-3.00
28	3000-4000	0	0.00	0.000	2.950	0.00	0.000	3.00-4.00
						594		

Air Content (%):	2.95
Specific Surface (mm^{-1}):	33.39
Spacing Factor (mm):	0.192
Void Frequency (mm^{-1}):	0.250
Average Chord Length (mm):	0.120
Paste to Air Ratio:	10.24

Sample ID: Cast cyl Cylinder 3-2

Sample Size (mm x mm):	80 x 80	Length Traversed (mm):	2413.1
Paste Content (%):	30.20	Area Traversed (mm x mm):	70 x 70

Chord Length Distribution - Table

Class No.	Chord size (microns)	Number of Chords in Class	Number of Chords in Percent	Air Content in Class	Cumulated Air Content	Chord length frequency	Air content, fraction	
1	0-10	17	2.93	0.010	0.010	0.03	0.010	0.00-0.01
2	10-20	58	10.00	0.030	0.040	0.10	0.030	0.01-0.02
3	20-30	76	10.00	0.080	0.120	0.13	0.080	0.02-0.03
4	30-40	38	6.55	0.050	0.180	0.07	0.050	0.03-0.04
5	40-50	38	6.55	0.070	0.240	0.07	0.070	0.04-0.05
6	50-60	47	8.10	0.110	0.350	0.08	0.110	0.05-0.06
7	60-80	63	10.86	0.180	0.530	0.11	0.180	0.06-0.08
8	80-100	42	7.24	0.160	0.690	0.07	0.160	0.08-0.10
9	100-120	20	3.45	0.090	0.780	0.03	0.090	0.10-0.12
10	120-140	22	3.79	0.120	0.900	0.04	0.120	0.12-0.14
11	140-160	18	3.10	0.110	1.010	0.03	0.110	0.14-0.16
12	160-180	17	2.93	0.120	1.130	0.03	0.120	0.16-0.18
13	180-200	13	2.24	0.100	1.230	0.02	0.100	0.18-0.20
14	200-220	10	1.72	0.090	1.320	0.02	0.090	0.20-0.22
15	220-240	9	1.55	0.090	1.410	0.02	0.090	0.22-0.24
16	240-260	6	1.03	0.060	1.470	0.01	0.060	0.24-0.26
17	260-280	4	0.69	0.040	1.510	0.01	0.040	0.26-0.28
18	280-300	6	1.03	0.070	1.590	0.01	0.070	0.28-0.30
19	300-350	17	2.93	0.230	1.810	0.03	0.230	0.30-0.35
20	350-400	7	1.21	0.110	1.920	0.01	0.110	0.35-0.40
21	400-450	9	1.55	0.160	2.080	0.02	0.160	0.40-0.45
22	450-500	7	1.21	0.140	2.220	0.01	0.140	0.45.0.50
23	500-1000	24	4.14	0.690	2.330	0.04	0.690	0.50-1.00
24	1000-1500	8	1.38	0.400	3.300	0.01	0.400	1.00-1.50
25	1500-2000	4	0.69	0.300	3.600	0.01	0.300	1.50-2.00
26	2000-2500	0	0.00	0.000	3.600	0.00	0.000	2.00-2.50
27	2500-3000	0	0.00	0.000	3.600	0.00	0.000	2.50-3.00
28	3000-4000	0	0.00	0.000	3.600	0.00	0.000	3.00-4.00
						580		

Air Content (%):	3.60
Specific Surface (mm^{-1}):	26.68
Spacing Factor (mm):	0.220
Void Frequency (mm^{-1}):	0.240
Average Chord Length (mm):	0.150
Paste to Air Ratio:	8.39

Sample ID:	Cast cyl	Cylinder 3-3	
Sample Size (mm x mm):	70 x 80	Length Traversed (mm):	2413.1
Paste Content (%):	30.20	Area Traversed (mm x mm):	60 x 70

Chord Length Distribution - Table

Class No.	Chord size (microns)	Number of Chords in Class	Number of Chords in Percent	Air Content in Class	Cumulated Air Content	Chord length frequency	Air content, fraction	
1	0-10	22	3.70	0.010	0.010	0.04	0.010	0.00-0.01
2	10-20	79	13.30	0.050	0.050	0.13	0.050	0.01-0.02
3	20-30	80	13.30	0.080	0.140	0.13	0.080	0.02-0.03
4	30-40	54	9.09	0.080	0.220	0.09	0.080	0.03-0.04
5	40-50	49	8.25	0.090	0.310	0.08	0.090	0.04-0.05
6	50-60	36	6.06	0.080	0.390	0.06	0.080	0.05-0.06
7	60-80	58	9.76	0.170	0.560	0.10	0.170	0.06-0.08
8	80-100	30	5.05	0.110	0.670	0.05	0.110	0.08-0.10
9	100-120	32	5.39	0.150	0.810	0.05	0.150	0.10-0.12
10	120-140	19	3.20	0.100	0.920	0.03	0.100	0.12-0.14
11	140-160	19	3.20	0.120	1.040	0.03	0.120	0.14-0.16
12	160-180	15	2.53	0.100	1.140	0.03	0.100	0.16-0.18
13	180-200	14	2.36	0.110	1.250	0.02	0.110	0.18-0.20
14	200-220	9	1.52	0.080	1.330	0.02	0.080	0.20-0.22
15	220-240	6	1.01	0.060	1.390	0.01	0.060	0.22-0.24
16	240-260	5	0.84	0.050	1.440	0.01	0.050	0.24-0.26
17	260-280	6	1.01	0.070	1.510	0.01	0.070	0.26-0.28
18	280-300	6	1.01	0.070	1.580	0.01	0.070	0.28-0.30
19	300-350	11	1.85	0.150	1.730	0.02	0.150	0.30-0.35
20	350-400	9	1.52	0.140	1.870	0.02	0.140	0.35-0.40
21	400-450	3	0.51	0.050	1.920	0.01	0.050	0.40-0.45
22	450-500	6	1.01	0.120	2.040	0.01	0.120	0.45.0.50
23	500-1000	24	4.04	0.670	2.060	0.04	0.670	0.50-1.00
24	1000-1500	2	0.34	0.110	2.810	0.00	0.110	1.00-1.50
25	1500-2000	0	0.00	0.000	2.810	0.00	0.000	1.50-2.00
26	2000-2500	0	0.00	0.000	2.810	0.00	0.000	2.00-2.50
27	2500-3000	0	0.00	0.000	2.810	0.00	0.000	2.50-3.00
28	3000-4000	0	0.00	0.000	2.810	0.00	0.000	3.00-4.00
						594		

Air Content (%):	2.81
Specific Surface (mm^{-1}):	34.98
Spacing Factor (mm):	0.187
Void Frequency (mm^{-1}):	0.250
Average Chord Length (mm):	0.114
Paste to Air Ratio:	10.75

APPENDIX F.
FIELD APPLICATION OF TERNARY MIXTURES: CONSTRUCTION OF A BRIDGE DECK IN NEW HAMPSHIRE

State Report
August 2010

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INTRODUCTION

This document is a report of the activities and observations of a research team that performed on-site testing of a ternary mixture placed on a small bridge in Epsom, New Hampshire. The cementitious system comprised a Type II cement, Grade 120 slag cement, and Class F fly ash. The purpose of this research project is a comprehensive study of how supplementary cementitious materials can be used to improve the performance of concrete mixtures when used in ternary blends.

This is the third phase of a project that intends to provide consulting to states and contractors on the use and field management of ternary mixtures. A state-of-the-art 44 ft portland cement concrete (PCC) mobile laboratory equipped for on-site cement and concrete testing was provided by the National Concrete Pavement Technology Center (National CP Tech Center) to collect data and field observations.

PROJECT INFORMATION

- The project was advertised in September 2009 for construction during 2010.
- Project No. Epsom 15266
- Located on NH Route 107, approximately thirteen miles east of Concord and one mile south of US Route 4.
- Contractor: Southern New Hampshire Poured Concrete Construction, Inc.
- Bridge is situated on a low volume, two-lane, rural road, 20 ft long by 30 ft wide.
- Bridge deck placement (the slab on the right with form is using ternary mixture while one on the left is using conventional binary mix for comparison purposes) (Figure 1)

Figure 1. Route 107 bridge deck in Epsom, New Hampshire

SITE LOCATION

An area at the bridge site was prepared by the contractor for the PCC mobile lab. The location of the project site and the mobile lab is shown Figure 2.

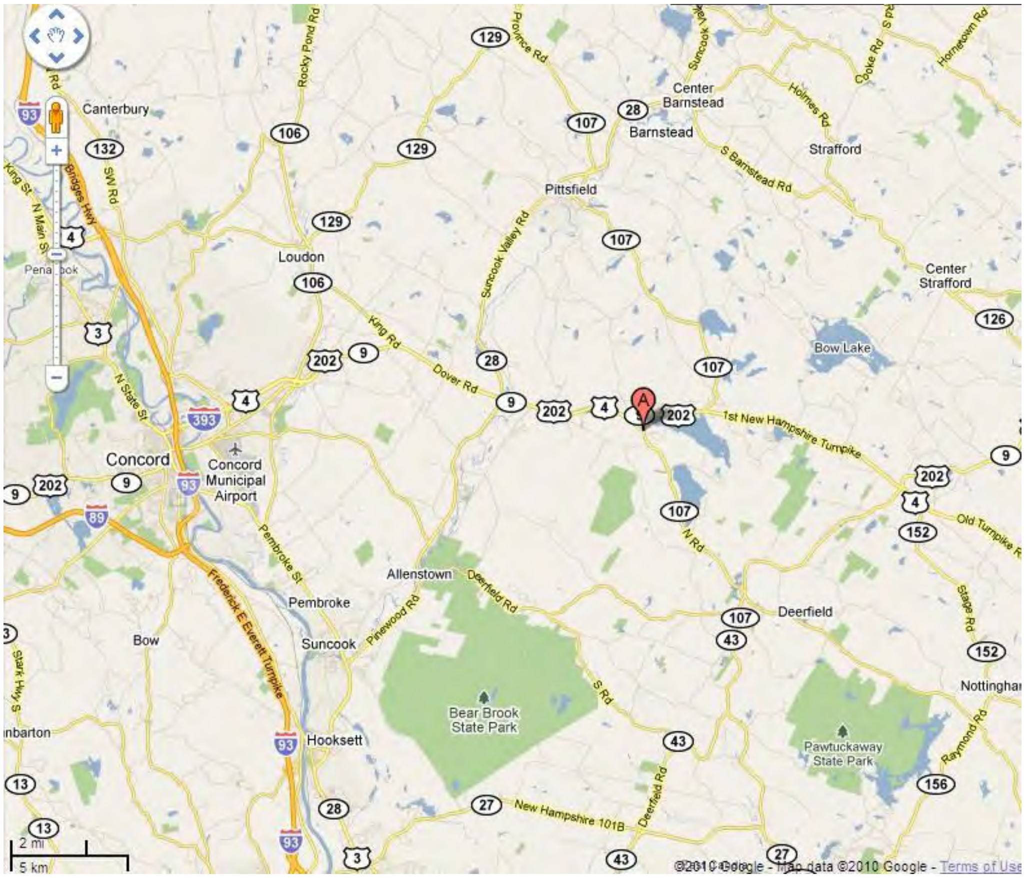


Figure 2. Project and mobile lab location

SAMPLING AND TESTING ACTIVITIES

The mobile lab arrived on site on August 9, 2010. Concrete placement, sampling, and testing took place on August 10, 2010. Hardened samples were transported to Iowa State University on August 14, 2010, for further testing. The following tests were conducted either in the field or in the laboratory:

- Calorimetry test (ASTM C 1679)
- Slump, unit weight, temperature, and air content of fresh concrete: 1 test (ASTM C 143, ASTM C 138, ASTM C 231)
- Microwave w/c ratio: 1 test (AASHTO T 318)
- Initial set and final set of concrete: 1 test (ASTM C 403)
- Compressive strength, splitting tensile strength, static modulus of elasticity: 4 in. x 8 in. cylinders at 1 day, 3 days, 7 days, 28 days, and 56 days (ASTM C 39, ASTM C 496, ASTM C 469)
- Rapid chloride permeability: 4 in. x 8 in. cylinders at 56 days (ASTM C 1202)
- Salt scaling: 3 samples (ASTM C 672)
- Free shrinkage best: 3 beams (ASTM C 157)
- Restrained rings: 4 samples (ASTM C 1581)

- Two i-buttons are buried on top and bottom layer of reinforcement to investigate maturity of concrete (ASTM C 1074)

OBSERVATIONS OF THE RESEARCH TEAM

The following observations were made in this field testing:

- The structure was originally designed to have a bituminous concrete wearing course, but the designer had revised it to have a bare deck for long-term observation purposes.
- The deck thickness was 23 in. The cover for top mat of epoxy-coated steel was approximately 5.125 inches and cover for bottom mat of steel was 1.5 inches.
- Removable wood formwork was used in the deck construction.
- All concrete was delivered in three concrete ready-mix trucks. During construction process, ready-mix trucks dumped concrete onto bridge deck. Concrete was manually spread out and vibrated by the construction crew.
- The mix design was prepared by Southern New Hampshire Poured Concrete Construction and approved by the New Hampshire Department of Transportation (NHDOT). The mix proportions are given in the project data section.
- The state of New Hampshire has alkali reactive aggregate, therefore the specifications require mixes to contain 50% slag or fly ash unless the aggregate has been tested to determine the required percentage to mitigate ASR. Most suppliers presently use fly ash from Brayton Point, Massachusetts. A 50% replacement of combined Grade 120 slag cement and Class F fly ash were used as supplementary cementitious material. Strux 90/40 polymer fibers were also used at a dosage of 7 lb/cubic yard.
- According to the workability factor and coarseness factor graph (see Project Data section of this report), combined aggregate gradation for this project falls in the well-graded region. Similarly, the combined percent retained curve indicates a well-graded system.
- The weather conditions recorded by the PCC mobile lab are given in Table 1 and in Figures 3 through 5. The relative humidity ranged from 72% to 79%; the ambient temperature ranged from 71.8˚F to 74.4˚F; the wind speed varied from 1 mph to 3 mph; the concrete temperature ranged from 80˚F to 83˚F during the recorded period.
- The fresh concrete tests included slump cone, unit weight, and water-cementitious materials ratio by microwave. During the construction, one set of samples was tested by the National CP Tech Center crew and four sets of testing were performed by the NHDOT crew. The slump result varied from 3.0 in. to 5.5 in. Five sets of unit weight of concrete were available and ranged from 136 lb/ft^3 (performed by NHDOT) to 141.18 lb/ft^3 (performed by the National CP Tech Center). The microwave water-cementitious ratio was found to be 0.43; the design value was 0.44. The data are provided in the Project Data section.
- The air content ranged from 6.6% to 8.8%, with an average of 7.4% over the five tests conducted. The specified minimum was 5%. It was noticed that the air content was reduced by adding 9 ounces of defoamer admixture during mixing. The data are provided in the Project Data section.
- Setting time of the mix was determined as a single measurement: initial set occurred at 5.24 hours and the final set was achieved at 8.12 hours.

Table 1. Ambient conditions of Route 107 Bridge Deck project in New Hampshire

New Hampshire - Ternary Mixtures

RT-107 Bridge Deck

Sample Information & Identification			Environmental Conditions			
Sample Date	Sample Time	Sample Comments	Relative Humidity (%)	Ambient Temp. (˚F)	Wind Speed (mph)	Conc. Temp. (probe) (˚F)
10-Aug-10	8:22 AM	NHDOT sample taken at pump discharge (quality control)	79.0	71.8	3.0	83.0
10-Aug-10	9:00 AM	NHDOT sample taken at pump discharge (quality control)	75.0	73.1	1.0	80.0
10-Aug-10	9:15 AM	cp tech center sample taken at truck discharge	72.0	74.0	2.0	82.2
10-Aug-10	9:17 AM	NHDOT sample taken at pump discharge (quality control)	72.0	74.4	3.0	81.0
10-Aug-10	9:28 AM	NHDOT sample taken at pump discharge (quality control)	72.0	74.4	1.0	81.0

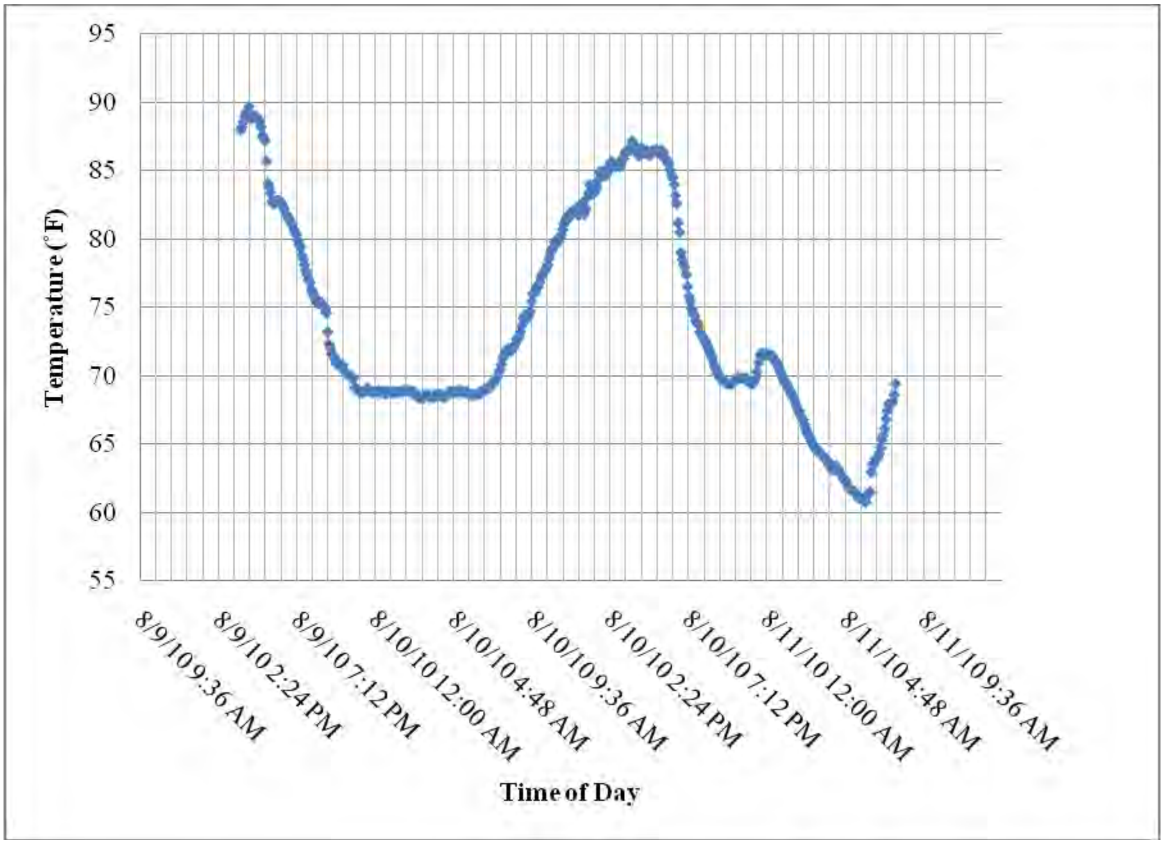


Figure 3. Ambient temperature versus time of day

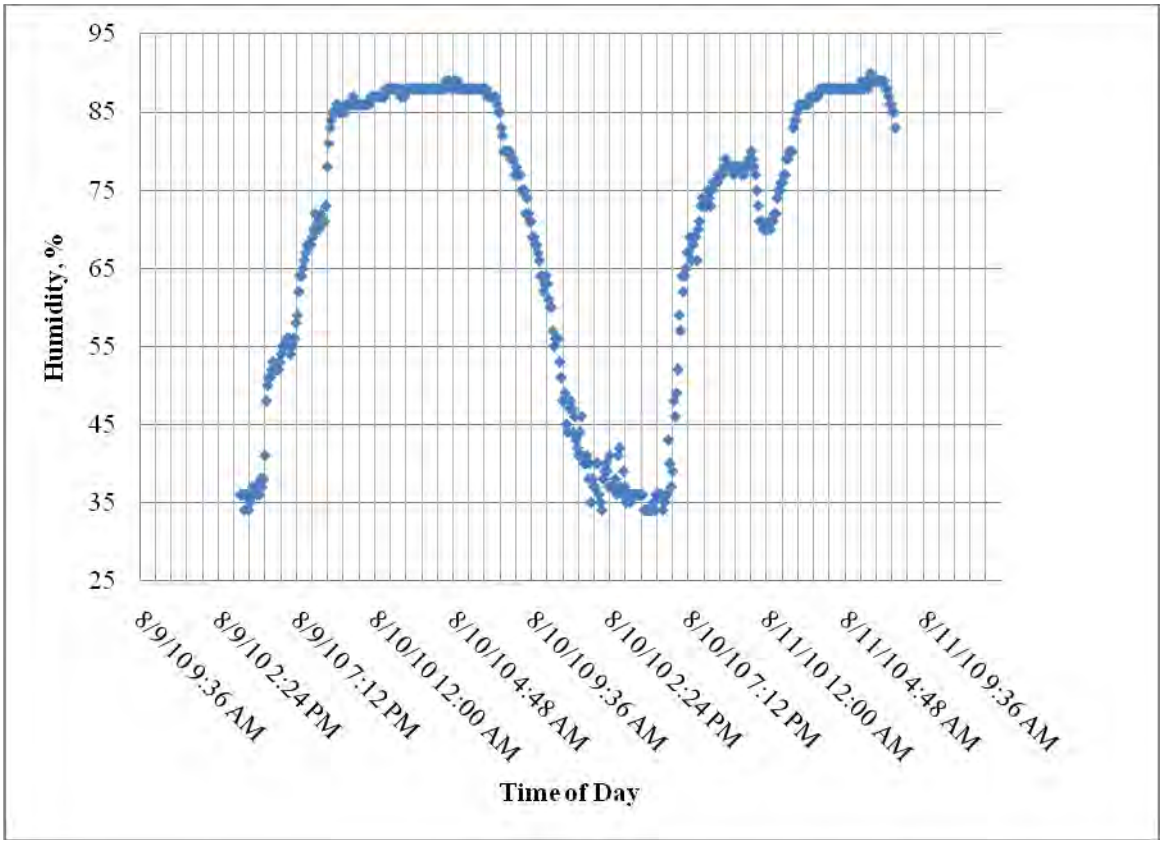


Figure 4. Relative humidity versus time of day

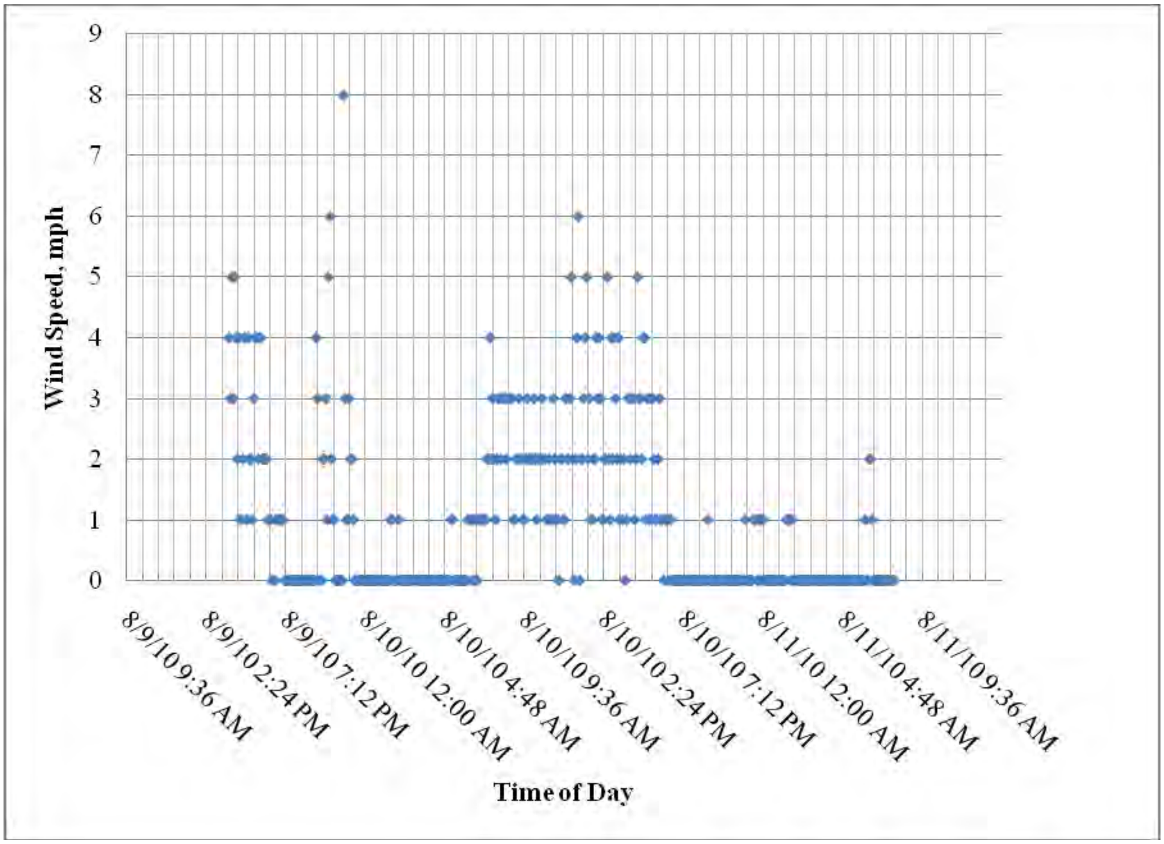


Figure 5. Wind speed versus time of day

- Figures 6 through 13 illustrate some activities during the testing process.

Figure 6. Bridge deck with removable wood form

Figure 7. Bridge deck with concrete being placed

Figure 8. Concrete being vibrated

Figure 9. PCC mobile lab

Figure 10. Two i-buttons being placed

Figure 11. Fresh concrete

Figure 12. Concrete being finished

Figure 13. Concrete being cured with burlap

- The rapid chloride permeability test measures the electrical conductance of a concrete sample as its resistance to chloride ion penetration. The test results shown in Table 2 indicate a classification of "very low" permeability of chloride according to ASTM C1202.
- The strength development 28/7 f_c ratio is reported in Table 2.

Table 2. Properties of hardened concrete

Tests	Results		
7-day compressive strength, psi	3360		
28-day compressive strength, psi	4550		
Rapid chloride permeability, coulombs	Sample 1 1279	Sample 2 732	Average 1006
Strength development 28/7 day fc ratio	1.35		
Shrinkage microstrain @ 28 days, in/in	520		
Average stress rate by restrained ring test, psi/day	50.34		

- Two i-buttons were attached to reinforcing steel before the concrete placement: one was placed on the top layer of the reinforcement steel and the other was placed on the bottom layer of reinforcement steel. The rate of cement hydration is dependent on the temperature and the time. Maturity is used to monitor the cement hydration progress as a function of time and temperature. The temperature of concrete was recorded for up to 28 hours. The concrete temperature over time is plotted in Figure 14(a) and the concrete maturity curve based on the Nurse–Saul method (ASTM C 1074) is generated in Figure 14(b).

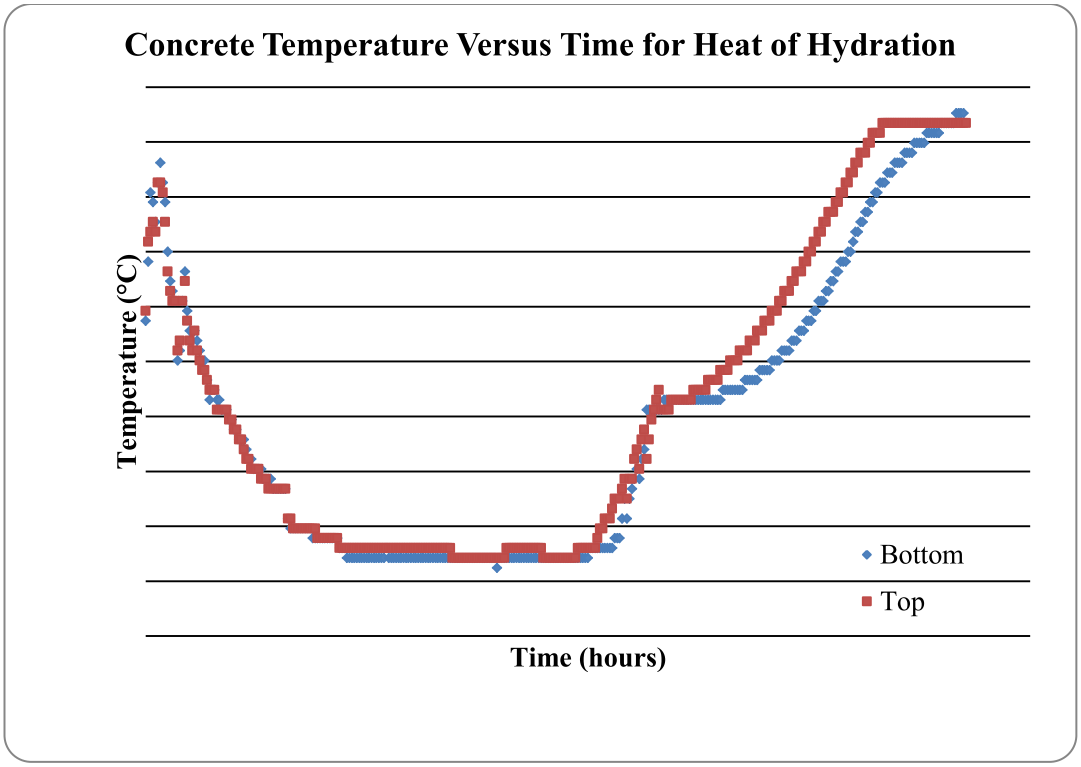


Figure 14(a). Concrete temperatures versus time for heat of hydration

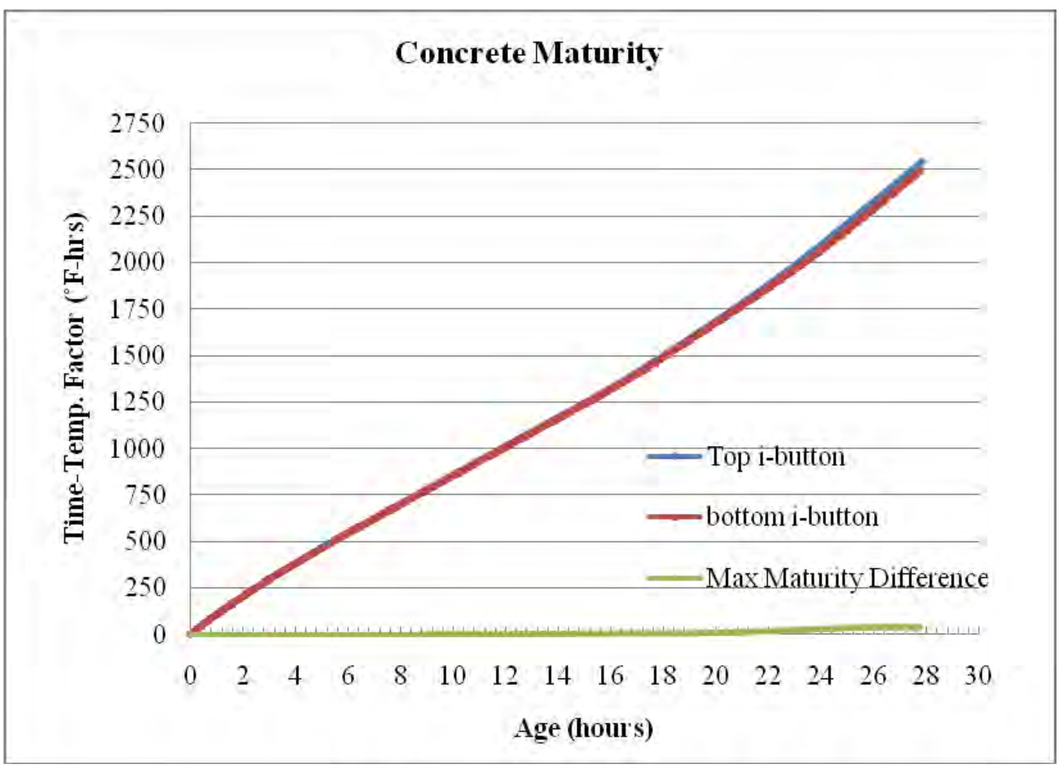


Figure 14(b). Concrete maturity

- Compressive strength, splitting tensile strength, and modulus of elasticity results (ASTM C 39, ASTM C 496, and ASTM C 469) are given in Table 3 and also plotted in Figures 15 through 17.

Table 3. Summation of strength and modulus of elasticity

Location	Age, Days	Compressive Strength, psi	Splitting Tensile Strength, psi	Modulus Of Elasticity, psi
NH	1	620	99	2.90E+06
	3	2,650	278	3.00E+06
	7	3,360	346	3.50E+06
	28	4,550	451	4.05E+06
	56	5,530	489	4.85E+06

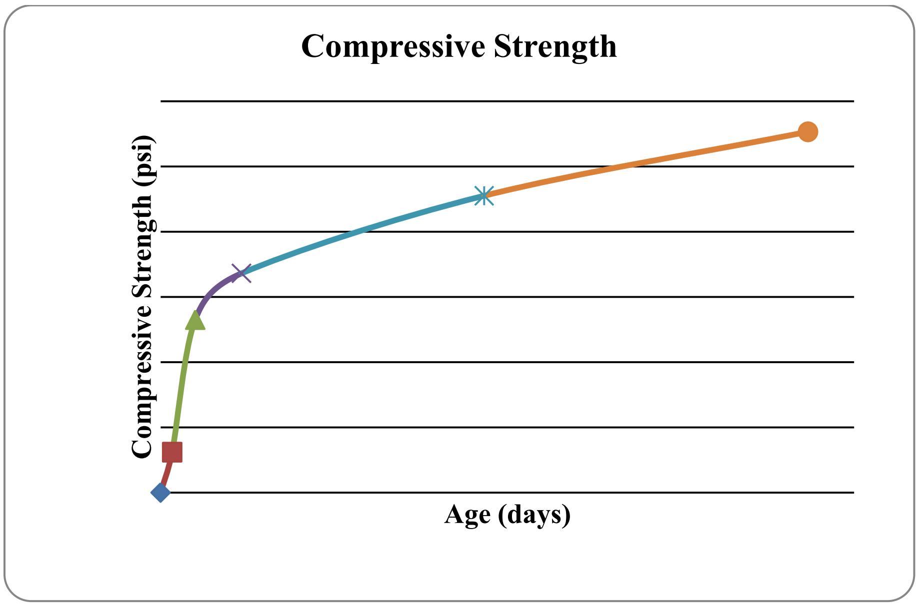


Figure 6. Compressive strength development with time

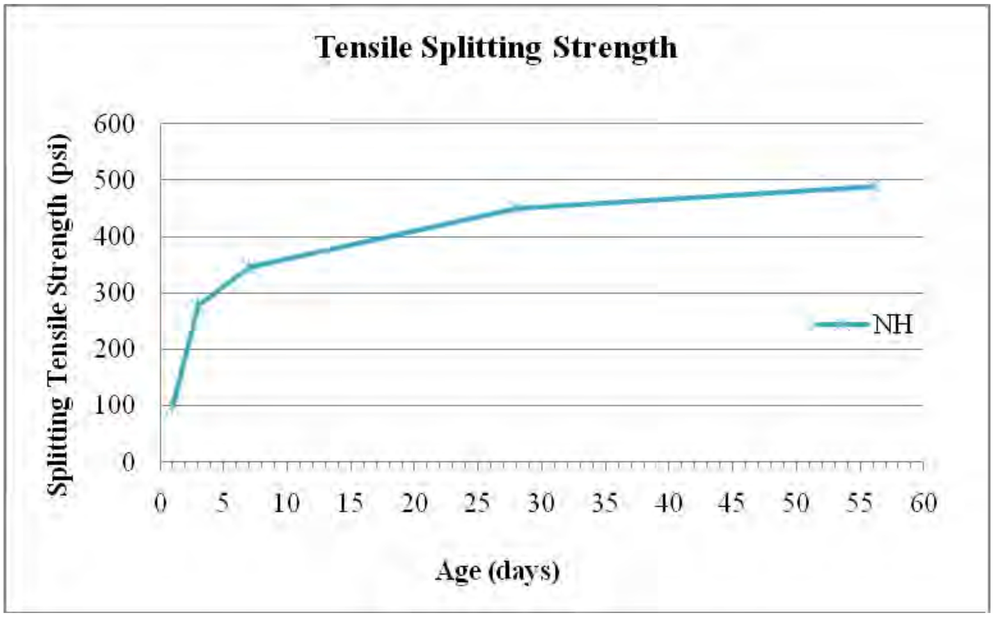


Figure 7. Tensile splitting strength development with time

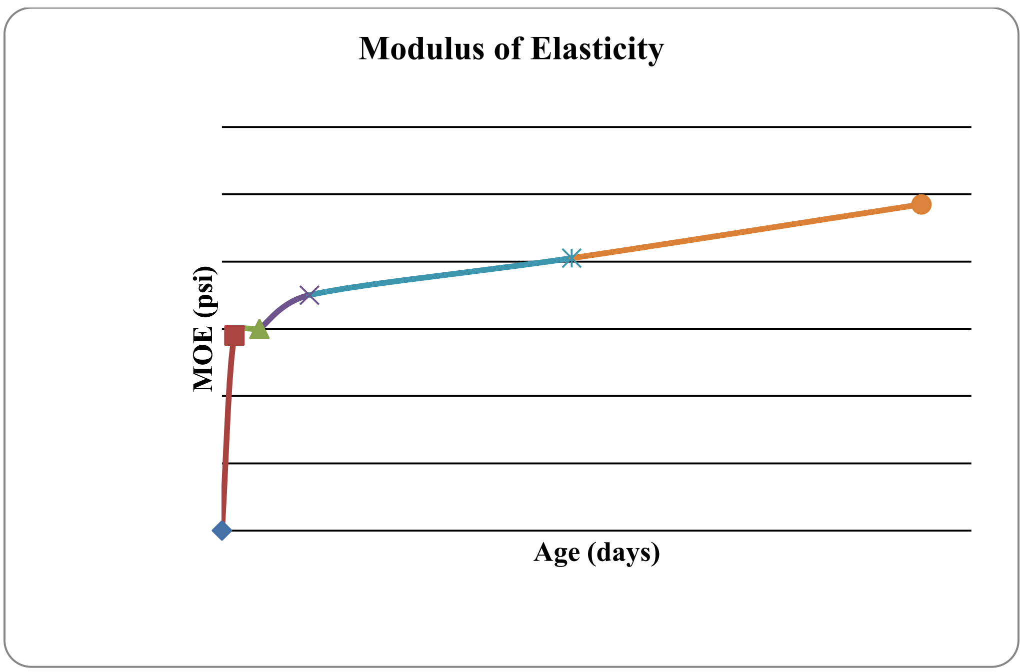


Figure 8. Modulus of elasticity development with time

- A free shrinkage test (ASTM C 157) was conducted in the laboratory. Three concrete beams were wet cured for seven days and then moved to a dry room at 23˚C and 50% relative humidity. The drying shrinkage results are given in Table 4 and are plotted in Figure 18.

Table 4. Free shrinkage test results

New Hampshire Project Free Shrinkage Test (ASTM C 157)					
Dry Time	Beam 1 Change%	Beam 2 Change %	Beam 3 change %	Average	Microstrain
1	-0.024	-0.021	-0.015	-0.020	-200.0
4	-0.015	-0.006	-0.005	-0.009	-86.7
7	-0.024	-0.016	-0.022	-0.021	-206.7
14	-0.029	-0.025	-0.026	-0.027	-266.7
28	-0.055	-0.048	-0.053	-0.052	-520.0
56	-0.064	-0.057	-0.058	-0.060	-596.7

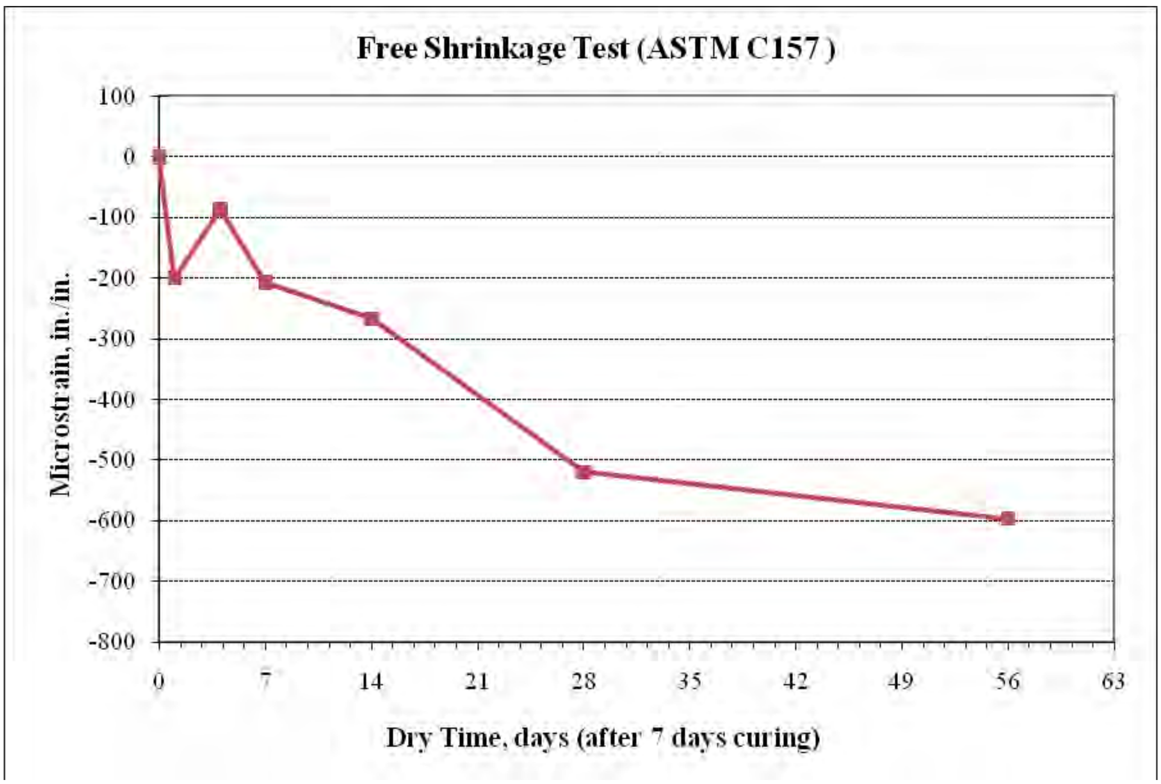


Figure 9. Free shrinkage of prisms (ASTM C 157)

- A restrained shrinkage test was conducted based on ASTM C 1581. Four rings were cast. The rings were demolded and the top surface was covered with paraffin wax 24 hours from casting. The rings were allowed to dry at 23˚C and 50% relative humidity immediately after demolding. Strains in the steel rings were recorded every 10 minutes for up to 28 days, or until the concrete cracked. The configuration of restrained concrete rings is shown in Figure 19. The cracking potential is listed in Table 5 and shown graphically in Figure 20. The cracking potential is classified as “moderate high,” based on the average stress rate.

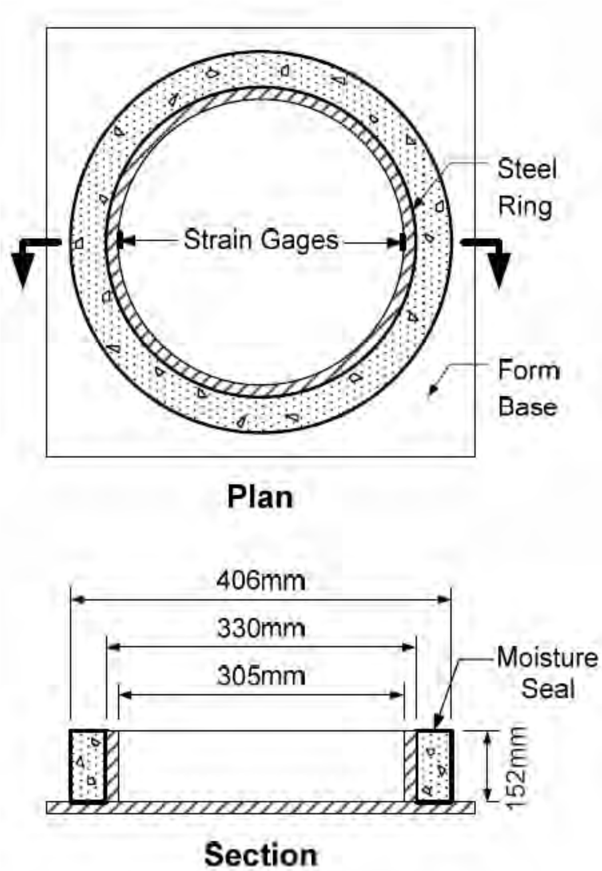


Figure 19. Configuration of restrained concrete ring samples

Table 5. Cracking potential and average stress rate (ASTM C 1581)

Cracking Potential for New Hampshire Project (ASTM C 1581)				
	Ring 1	**Ring 2**	**Ring 3**	**Ring 4**
Strain rate factor (in./in.x10^{-6})/hours$^{1/2}$	-7.06	-6.80	-6.35	-9.00
G (psi)	10.47x10^6	10.47x10^6	10.47x10^6	10.47x10^6
Absolute value of α_{avg} (in./in.10^{-6})/day$^{1/2}$	35.77			
Elapsed time, tr (hours)	294.8	367.1	323.3	350.4
Elapsed time, tr (days)	12.3	15.3	13.5	14.6
Stress rate, q (psi/day) $q=GI\alpha_{avg}I/2\sqrt{t_r}$	53.4	47.9	51.0	49.0
Average stress rate, q (psi/day) $q=GI\alpha_{avg}I/2\sqrt{t_r}$	**50.34**			
Potential for cracking classification (ASTM 1581)	**High (50≤ q)**			

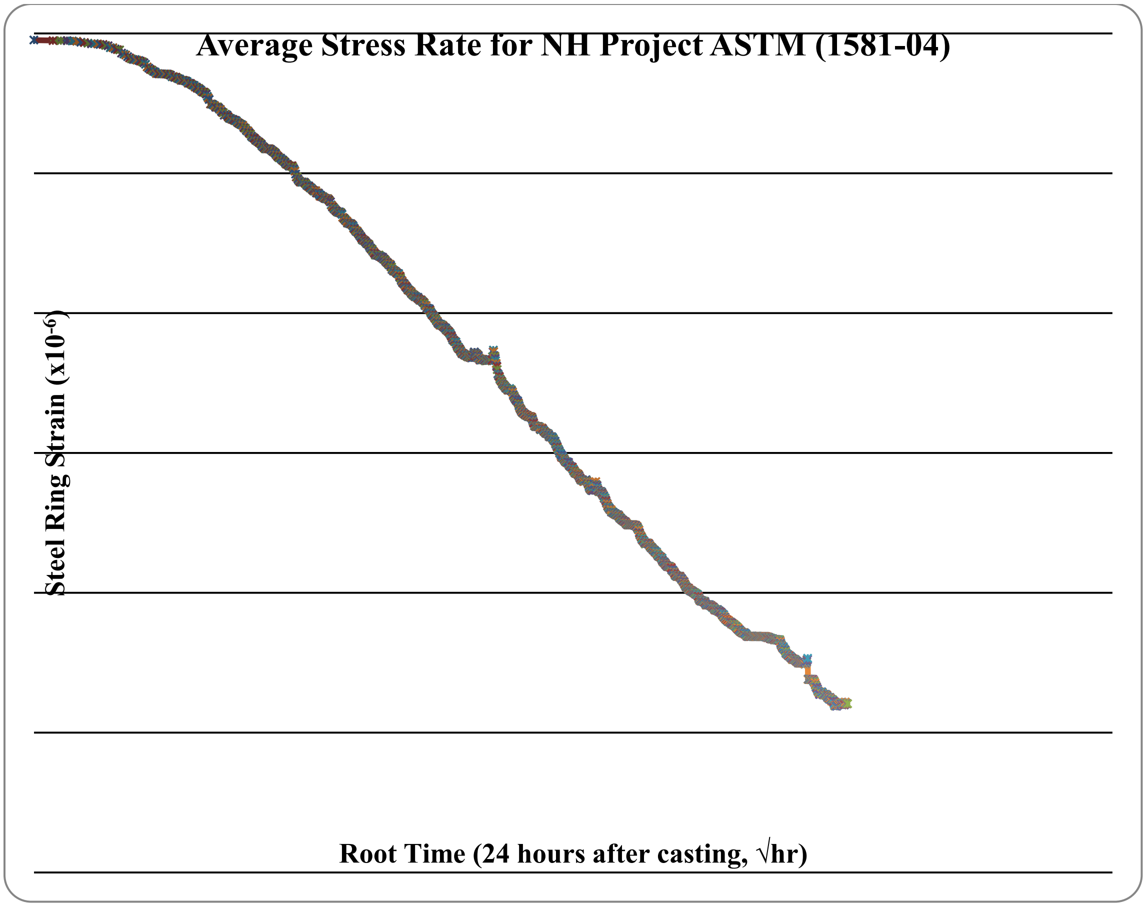


Figure 20. Strains of steel rings resulting from concrete shrinkage

- A salt scaling test (ASTM C 672) was performed: the specimens were subjected to 16 to18 hours freezing and then allowed to thaw at 23 ± 2.0˚C and a relative humidity of 45 to 55% for 6 to 8 hours. A 4% calcium chloride solution was used for conditioning. Visual rating was done every 5 freeze-thaw cycles for up to 50 cycles. The surface was rated on a scale of 0 to 5, with 0 having no scaling, 1 having very slight scaling of 3 mm depth maximum without coarse aggregate visible, 2 having slight to moderate scaling, 3 having moderate scaling with some coarse aggregate visible, 4 having moderate to severe scaling, and 5 having severe scaling with coarse aggregate visible over entire surface. The photograph after the 50th cycle was taken and is shown in Figure 21. The visual ratings assigned to each specimen for cycles 0, 5, 10, 15, 20, 25, and 50 are given in Table 6.

Table 6. Salt scaling test visual condition of specimen

New Hampshire	Condition of Surface					
Salt Scaling Samples	Cycle 5	Cycle 10	Cycle 15	Cycle 20	Cycle 25	Cycle 50
No. 1	1	1	1	1	2	3
No. 2	1	1	1	1	2	3
No. 3	1	1	1	1	2	3

Figure 21. New Hampshire salt scaling sample after 50th freeze-thaw cycle

PROJECT DATA

The following test data are provided for information only; comments and conclusions will be reported in the comprehensive Phase III report of the pooled fund project *Development of Performance Properties of Ternary Mixtures.*

Mix Design & Misc. Info.

General Information

Project:	RT-107, Epsom 15266, NH
Contractor:	Southern NH Poured Concrete Const., Inc.
Mix Description:	611 lb Cementitious
Mix ID:	
Date(s) of Placement:	8/10/2010

Cementitious Materials	Source	Type	Spec. Gravity	lb/yd^3	% Replacement by Mass
Portland Cement:	Ciment Quebec Type II	Type II	3.150	306	
GGBFS:	Lafarge North America	Grade 120	2.910	213	34.86%
Fly Ash:	Headwaters Resources	Class F	2.370	92	15.06%
Silica Fume:					
Other Pozzolan:					
				611	**lb/yd^3**
				6.5	**sacks/yd^3**

Aggregate Information	Source	Type	Spec. Gravity SSD	Absorption (%)	% Passing #4
Coarse Aggregate:	Pike-Hooksett	3/4 Blended Stone	2.670	0.65%	3.6%
Intermediate Aggregate #1:					
Intermediate Aggregate #2:					
Fine Aggregate #1:	Fillmore S&G	Sandstone	2.670	0.78%	99.2%

Coarse Aggregate %:	60.9%
Intermediate Aggregate #1%:	
Intermediate Aggregate #2%:	
Fine Aggregate #1 %:	39.1%

Mix Proportion Calculations

Water/Cementitious Materials Ratio:	0.443
Air Content:	5.00%

	Volume (ft^3)	Batch Weights SSD (lb/yd^3)	Spec. Gravity	Absolute Volume (%)
Portland Cement:	1.557	306	3.150	5.766%
GGBFS:	1.173	213	2.910	4.344%
Fly Ash:	0.622	92	2.370	2.304%
Silica Fume:				
Other Pozzolan:				
Coarse Aggregate:	10.938	1,800	2.670	40.511%
Intermediate Aggregate #1:				
Intermediate Aggregate #2:				
Fine Aggregate #1:	7.023	1,160	2.670	26.009%
Water:	4.338	271	1.000	16.066%
Air:	1.350			5.000%
	27.000	**3,842**		**100.000%**
	Unit Weight (lb/ft^3)	**142.3**	**Paste**	**33.480%**
			Mortar	**60.740%**

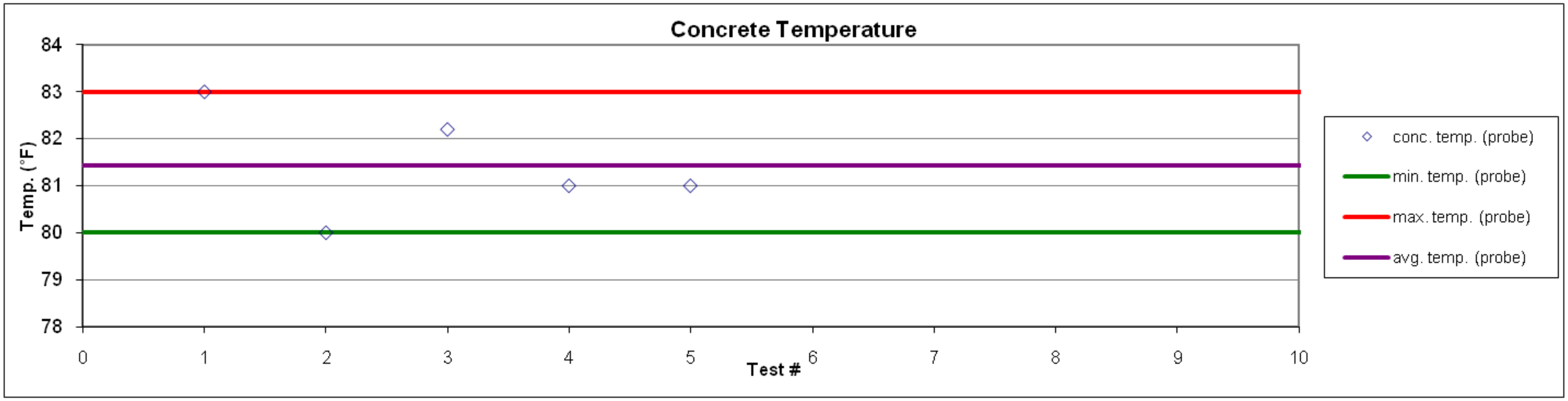
Admixture Information	Source/Description	oz/yd^3	oz/cwt
Air Entraining Admix.:	W.R. Grace Darex II AEA	3.80	0.62
Admix. #1:	Glenium 7500-HRWR (BASF Admixtures)	27.50	4.50
Admix. #2:	Strux 90/40 fibers (7 lb/cubic yard)		
Admix. #3:			

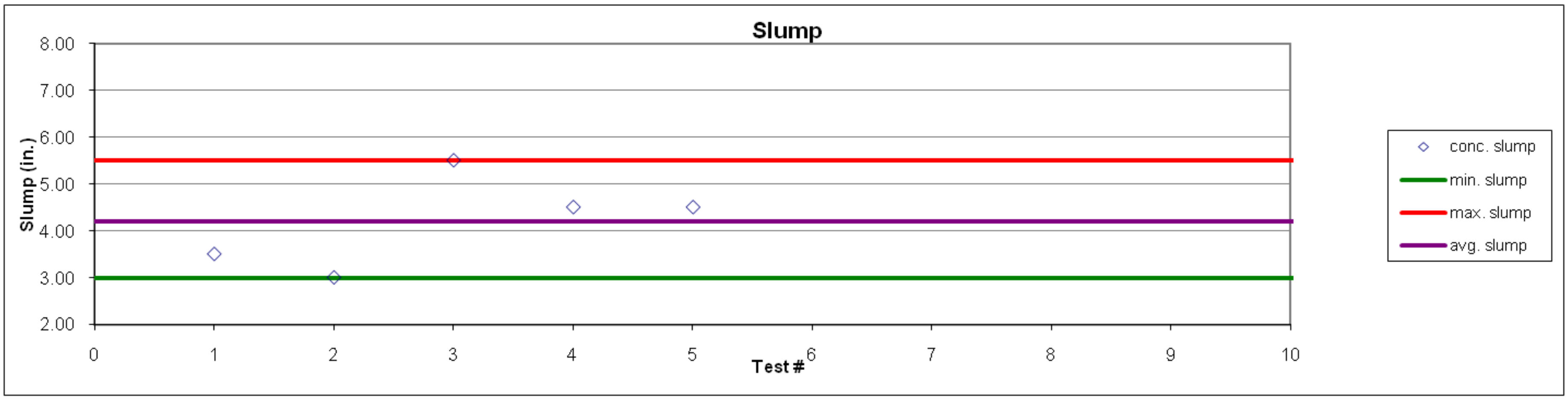
AVA Information	Absolute Volume (%)
Air Free Paste:	28.480%
Air Free Mortar:	55.740%

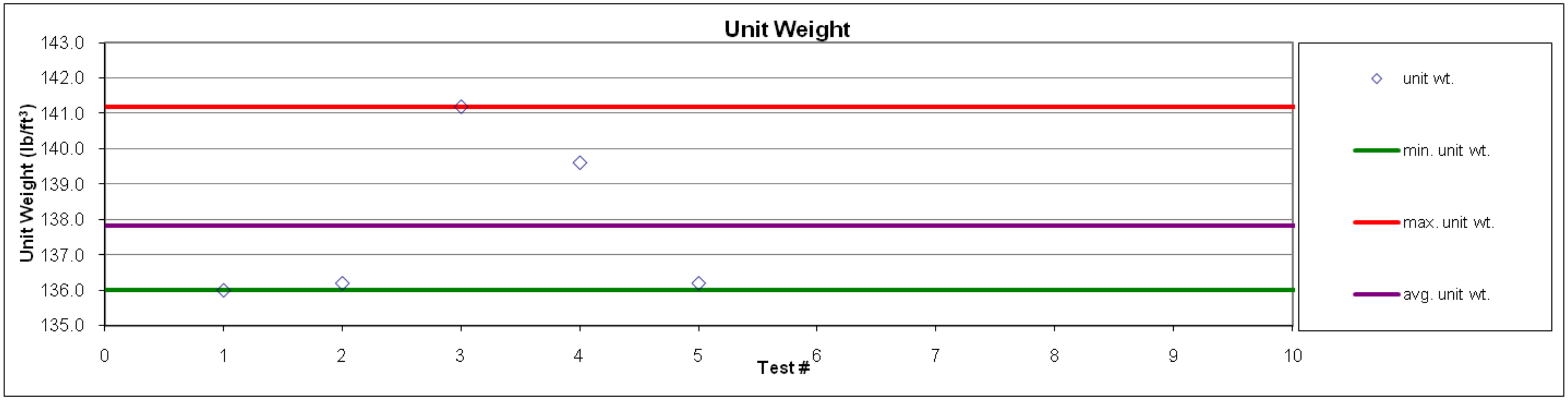
New Hampshire - Ternary Mixtures

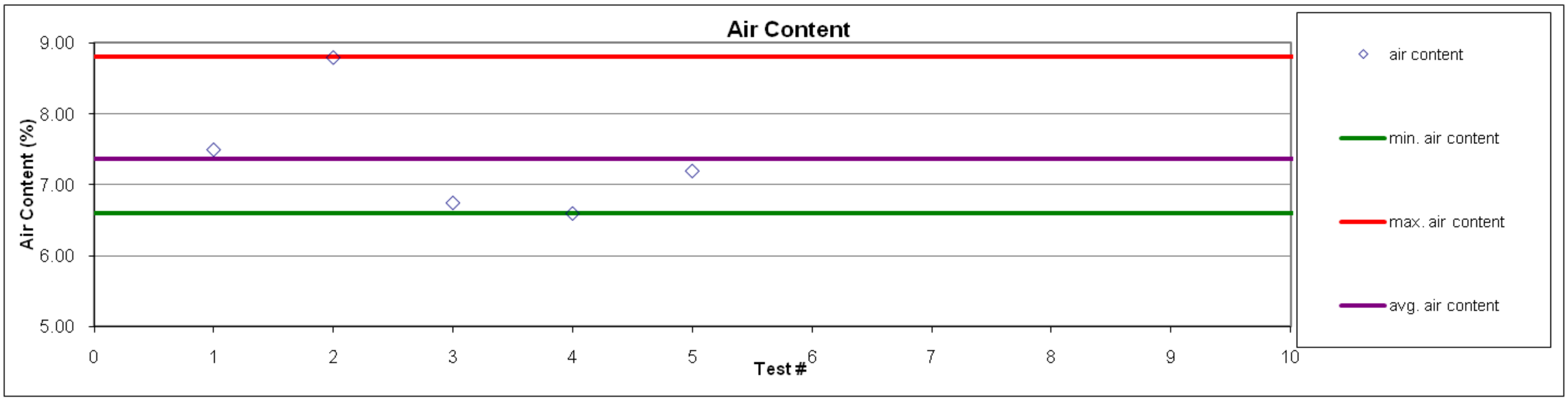
RT-107 Bridge Deck

Sample Information & Identification			Environmental Conditions				Fresh Concrete Workability Properties			Pressure Air
Sample Date	Sample Time	Sample Comments	Relative Humidity (%)	Ambient Temp. (˚F)	Wind Speed (mph)	Conc. Temp. (probe) (˚F)	Slump (in)	Unit Weight (lb/ft^3)	Microwave W/C Ratio (%)	% Air Content
10-Aug-10	8:22 AM	NHDOT sample taken at pump discharge (quality control)	79.0	71.8	3.0	83.0	3.50	136.00	n/a	7.5
10-Aug-10	9:00 AM	NHDOT sample taken at pump discharge (quality control)	75.0	73.1	1.0	80.0	3.00	136.20	n/a	8.8
10-Aug-10	9:15 AM	cp tech center sample taken at truck discharge	72.0	74.0	2.0	82.2	5.50	141.18	0.43	6.8
10-Aug-10	9:17 AM	NHDOT sample taken at pump discharge (quality control)	72.0	74.4	3.0	81.0	4.50	139.60	n/a	6.6
10-Aug-10	9:28 AM	NHDOT sample taken at pump discharge (quality control)	72.0	74.4	1.0	81.0	4.50	136.20	n/a	7.2


Concrete Temperature
Temp. (°F)
84
83
82
81
80
79
78
0
1
2
3
4
5
6
7
8
9
10
Test #
conc. temp. (probe)
min. temp. (probe)
max. temp. (probe)
avg. temp. (probe)


Slump
Slump (in.)
8.00
7.00
6.00
5.00
4.00
3.00
2.00
0
1
2
3
4
5
6
7
8
9
10
Test #
conc. slump
min. slump
max. slump
avg. slump


Unit Weight
Unit Weight (lb/ft³)
143.0
142.0
141.0
140.0
139.0
138.0
137.0
136.0
135.0
0
1
2
3
4
5
6
7
8
9
10
Test #
unit wt.
min. unit wt.
max. unit wt.
avg. unit wt.


Air Content
Air Content (%)
9.00
8.00
7.00
6.00
5.00
0
1
2
3
4
5
6
7
8
9
10
Test #
air content
min. air content
max. air content
avg. air content

NH - Ternary Mixtures

Sample Information:

Project: RT-107, Epsom 15266, NH

Date: 10-Aug-10

Time: 9:15 AM

Type of Paving: Bridge Deck

Direction of Paving: n/a

Sta: n/a

Latitude:

Longitude:

Mix ID:

Truck IDs:

Sample Location Mark & Comments:

Environmental Conditions:

Dew Point: 65.0

Relative Humidity: 72%

Wind Speed: 2.0

Ambient Temp.: 74.0

Concrete Properties:

Base/Soil Temp. (internal)(°F):

Base Temp. (surface)(°F):

Microwave Water Content Samples:

Calorimetry (ADIACAL Cylinders): 4 (9:15 am)

Set-Time (ASTMC403) Mortar Samples:

Cylinder for RCP & Perm. Voids Boil Test: use adiacal

Scaling Blocks: 3

Compressive, Tensile & MOR Cylinders: 30

Shrinkage Beams: 4

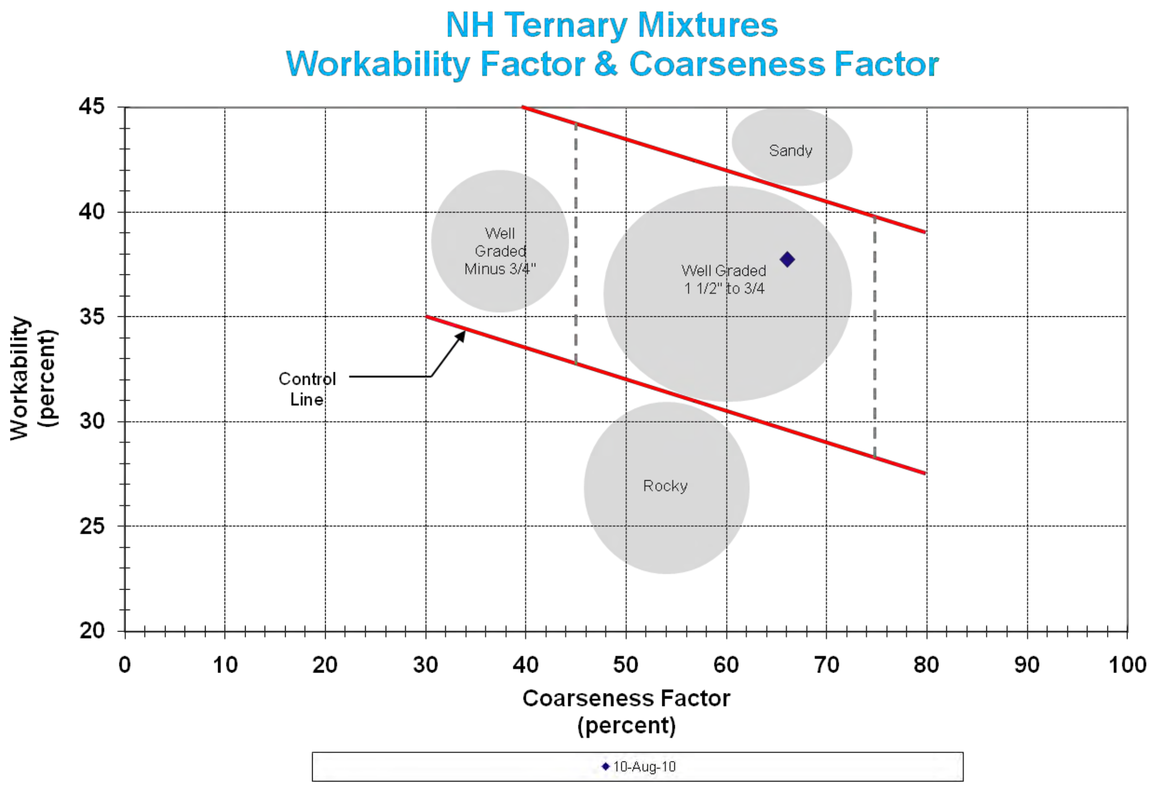
Concrete Temp.(°F):	82.2
Slump (in.):	5.50
Air Content:	6.8%
Unit Weight (lb/ft^3):	141.2

Project: RT-107 Epsom, NH
Mix ID: 13266 Epsom, NH
Sample Comments:
Test Date: 10-Aug-10

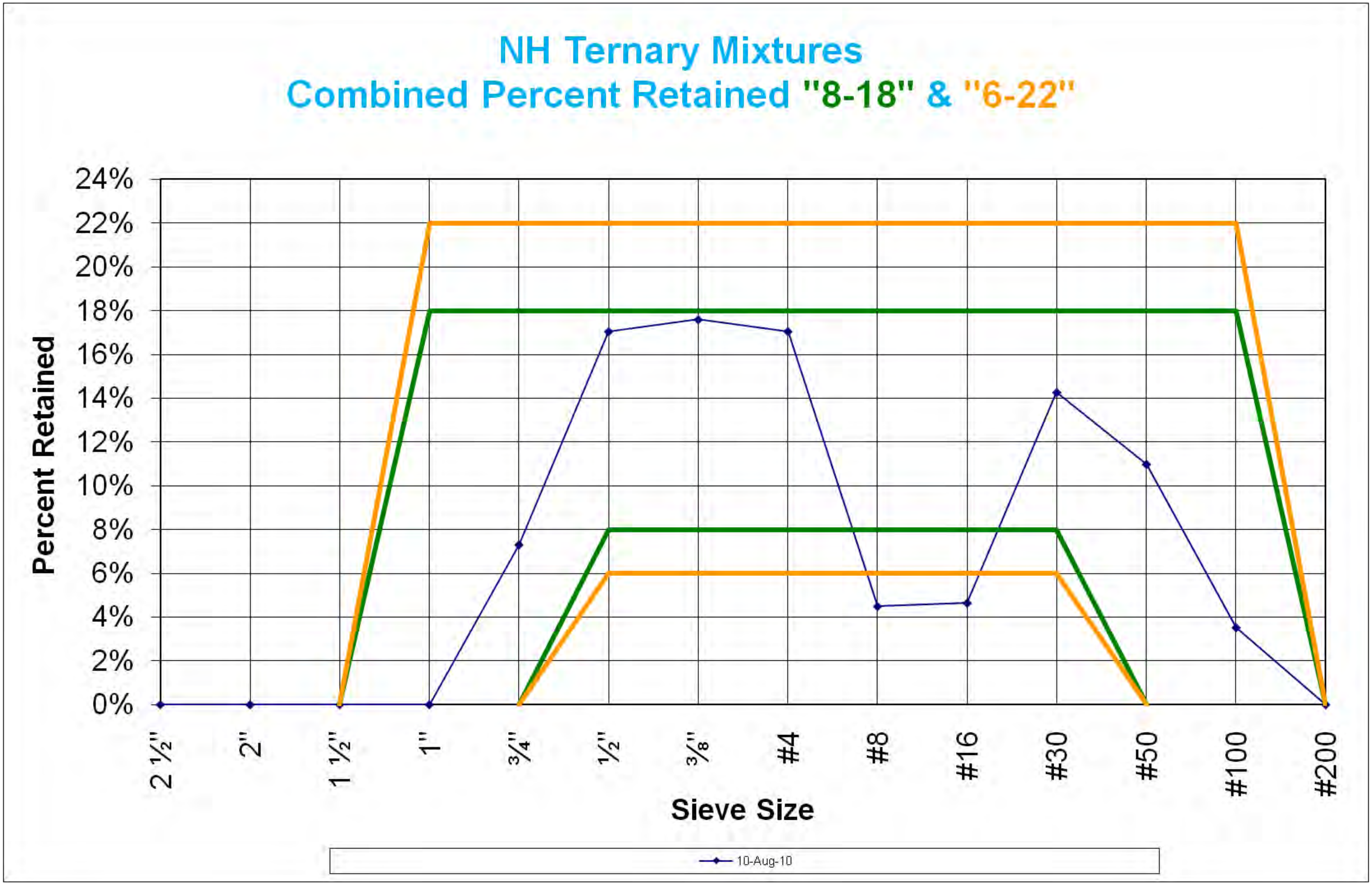
otal Cementitious Material:			611	lb/yd^3
Agg. Ratios:	60.90%	0.00%	39.10%	100.00%

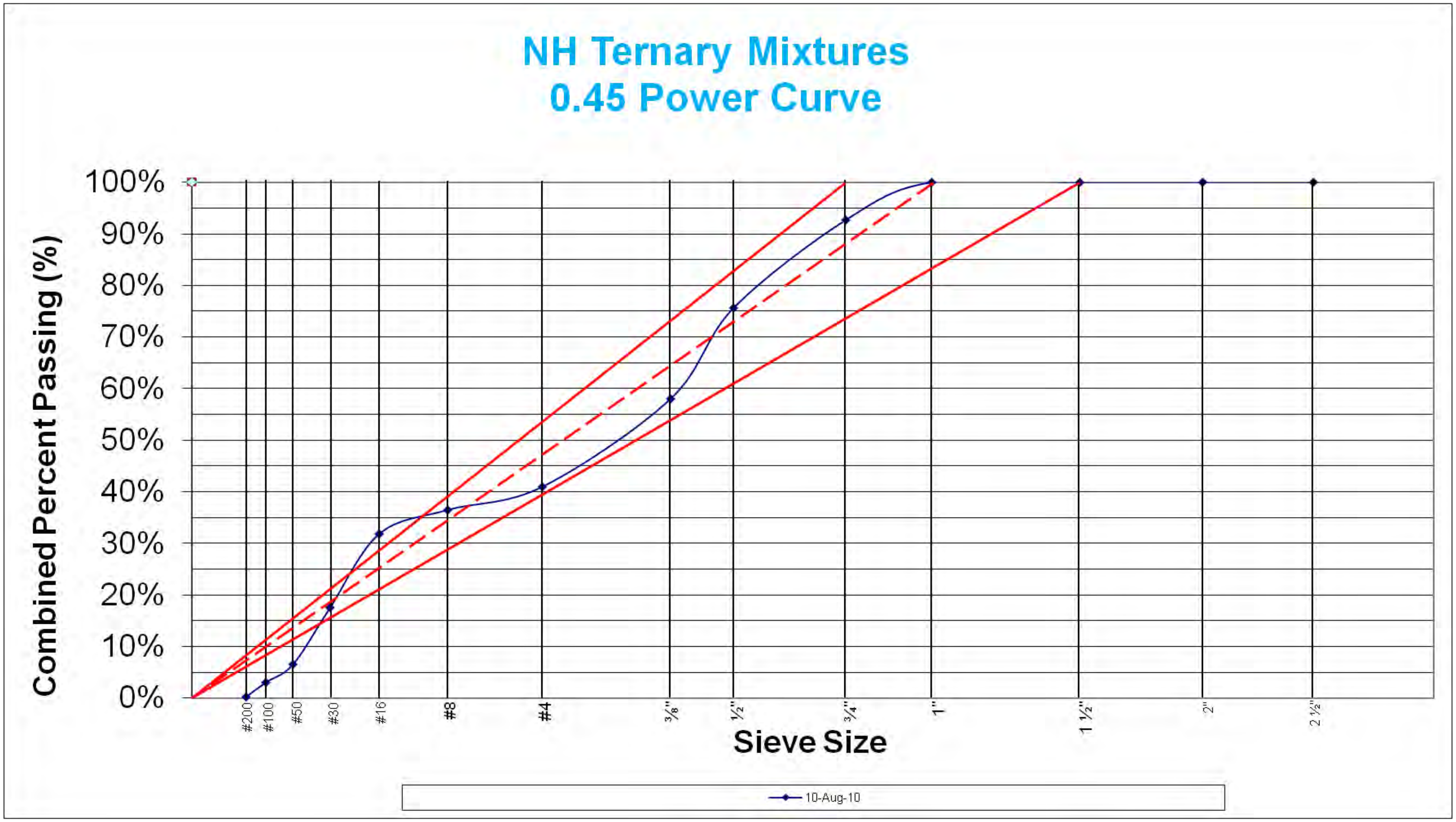
Sieve	Coarse	Intermediate	Fine #1	Fine #2	Combined % Retained	Combined % Retained On Each Sieve	Combined % Passing
2 ½"	100%	0%	100%		0%	0%	100%
2"	100%	0%	100%		0%	0%	100%
1 ½"	100%	0%	100%		0%	0%	100%
1"	100%	0%	100%		0%	0%	100%
¾"	88%	0%	100%		7%	7%	93%
½"	60%	0%	100%		24%	17%	76%
⅜"	31%	0%	100%		42%	18%	58%
#4	4%	0%	99%		59%	17%	41%
#8	1%	0%	91%		64%	4%	36%
#16	1%	0%	80%		68%	5%	32%
#30	1%	0%	43%		82%	14%	18%
#50	1%	0%	15%		93%	11%	7%
#100	1%	0%	6%		97%	4%	3%
#200			0.7%		99.7%		0.3%

Workability Factor: 37.7
Coarseness Factor: 66.1



NH Ternary Mixtures
Workability Factor & Coarseness Factor
Sandy
Well
Graded
Minus 3/4"
Well Graded
1 1/2" to 3/4
Control
Line
Rocky
Workability
(percent)
45
40
35
30
25
20
0
10
20
30
40
50
60
70
80
90
100
Coarseness Factor
(percent)
10-Aug-10


NH Ternary Mixtures
Combined Percent Retained "8-18" & "6-22"
Percent Retained
24%
22%
20%
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
2 ½"
2"
1 ½"
1"
¾"
½"
⅜"
#4
#8
#16
#30
#50
#100
#200
Sieve Size
10-Aug-10


NH Ternary Mixtures
0.45 Power Curve
Combined Percent Passing (%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
#200
#100
#50
#30
#16
#8
#4
3/8"
1/2"
3/4"
1"
1 1/2"
2"
2 1/2"
Sieve Size
10-Aug-10

New Hampshire - Ternary Mixtures

Set Time ASTM C 403

Project RT-107, Epsom 15266, NH

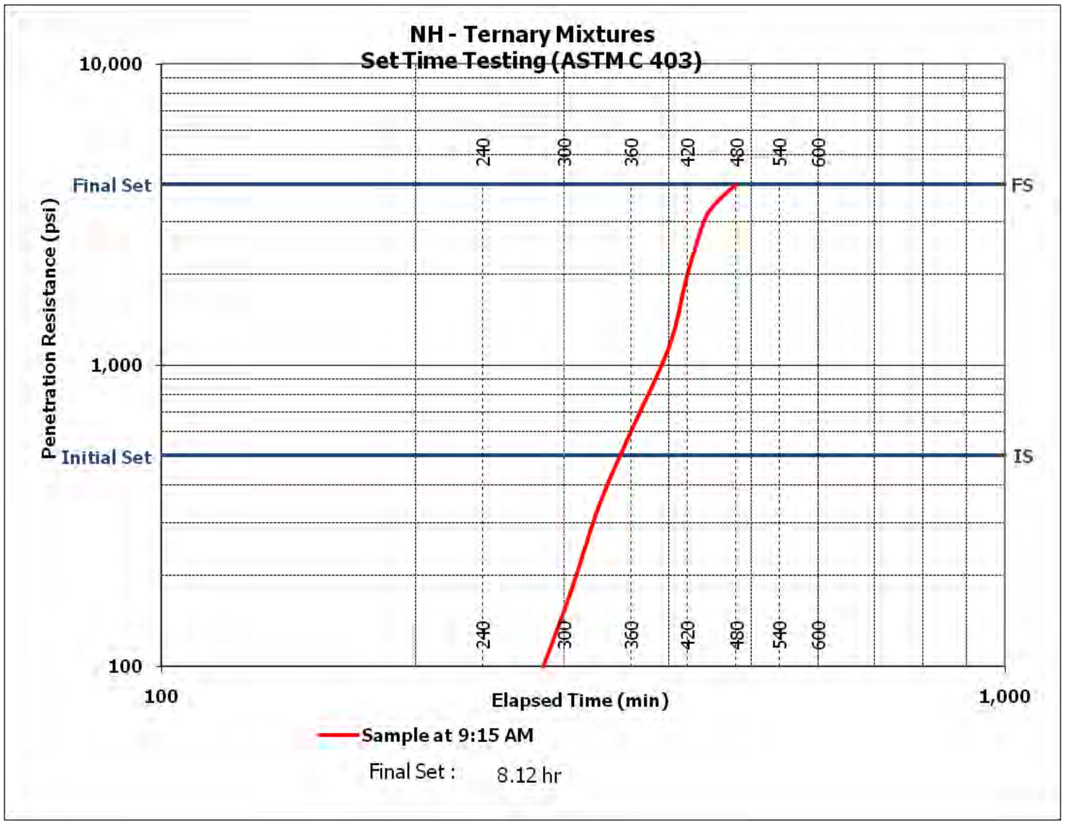
Date: 10-Aug-10 Start Time: 9:15 AM

Sta: n/a

Test Data

Penetration Time (xx:xx-24 hr format)	Time (min)	Needle # (1,2,4,10,20 or 40)	Force (lb)	Penetration Resistance (psi)	Sample Temp. (ºF)
12:50 PM	215.00	1	20	20.00	76.6
1:30 PM	255.00	2	24	48.00	76.6
2:15 PM	300.00	4	38	152.00	77.7
2:45 PM	330.00	10	34	340.00	78.8
3:15 PM	360.00	20	30	600.00	79.9
3:55 PM	400.00	20	58	1160.00	84.2
4:15 PM	420.00	20	100	2000.00	83.3
4:35 PM	440.00	40	76	3040.00	83.1
4:45 PM	450.00	40	84	3360.00	83.1
4:55 PM	460.00	40	90	3600.00	83.1
5:15 PM	480.00	40	100	4000.00	82.9

Initial Set (at 500 psi PR)	estimated times using forecast function	**314**	minutes	**5.24**	hours
Final Set (at 4,000 psi PR)		**487**	minutes	**8.12**	hours


NH - Ternary Mixtures
Set Time Testing (ASTM C 403)
10,000
1,000
100
Final Set
Initial Set
Penetration Resistance (psi)
FS
IS
240
300
360
420
480
540
600
100
1,000
Elapsed Time (min)
Sample at 9:15 AM
Final Set :
8.12 hr

New Hampshire - Ternary Mixtures

Microwave Water Content Worksheet

Project: RT-107, Epsom 15266, NH

Date: 10-Aug-10 Time: 9:15 AM

Sta: n/a

Test Data

Mass of tray+cloth+block+fresh test sample, W_F (g)	3,778.0
Mass of tray+cloth+block, W_S(g)	2,198.5
Mass of tray+cloth+dry sample, W_D (g) (5mins)	3,735.8
Mass of tray+cloth+dry sample, W_D (g) (7 mins)	3,698.4
Mass of tray+cloth+dry sample, W_D (g) (9 mins)*	3,670.2
Mass of tray+cloth+dry sample, W_D (g) (11 mins)*	3,662.1
Mass of tray+cloth+dry sample, W_D (g) (13 mins)*	3,660.1
Mass of tray+cloth+dry sample, W_D (g) (15 mins)*	3,659.8
Mass of tray+cloth+dry sample, W_D (g) (17 mins)*	
Mass of tray+cloth+dry sample, W_D (g) (Final)**	3,659.8
Water content percentage, W_C (%)	**7.5%**
Unit weight of fresh concrete, UW (lb/ft^3)***	141.2
Total water content, W_T, (lb/yd^3)	**285.3**
Total cementitious weight (lb/yd^3)	611
Fine aggregate weight (lb/yd^3)	1160
Coarse Aggregate weight (lb/yd^3)	1800
Intermediate Aggregate weight (lb/yd^3)	0
Fine aggregate absorption (%)	0.78%
Coarse aggregate absorption (%)	0.65%
Intermediate aggregate absorption (%)	0.00%
w/c	**0.433**

* If necessary (stop if the weight loss is less than 1g)

** Mass at test termination

***From unit weight test

PROOVE it

ASTM C 1202-97

TEST CO.

File name = Prooveit user logo.jpg located in application directory.

Test-compagny
Testing street 45
CompagnyCity
Some Country

Your own logo.
size=20x80mm

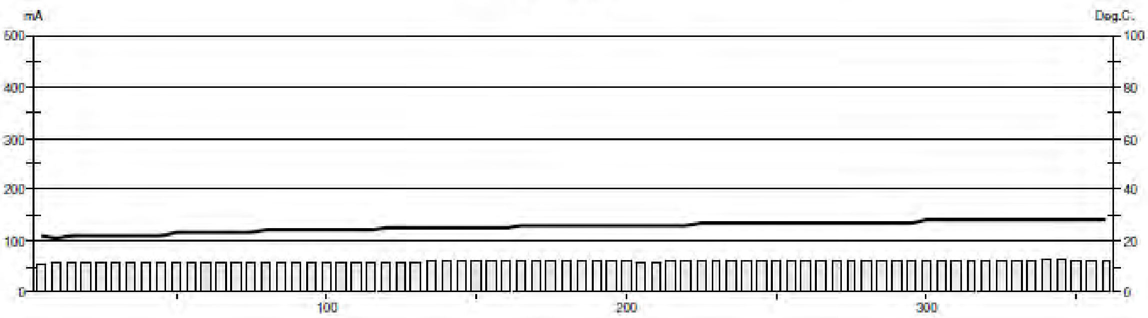
GERMANN INSTRUMENTS

DENMARK

USA

Test report

Voltage Used:	60
Testing time:	06:00 hour
Charge passed:	1279
Adjusted Charge passed:	1109
Permeability class:	Low
Instrument number:	023907
Channel number:	1
Report date:	10/5/2010
Testing by:	pjm
Reference:	NH ternary
Sample diameter:	102
Comment:	---



Time	°C	mA	Time	°C	mA	Time	°C	mA	Time	°C	mA
00:05	22	54.3	01:35	24	58.3	03:05	26	60.1	04:35	27	60.4
00:10	21	55.5	01:40	24	58.5	03:10	26	60.2	04:40	27	59.9
00:15	22	55.1	01:45	24	58.5	03:15	26	60.1	04:45	27	60.6
00:20	22	55.6	01:50	24	57.7	03:20	26	59.4	04:50	27	61.1
00:25	22	56.0	01:55	24	56.6	03:25	26	59.0	04:55	27	61.0
00:30	22	55.9	02:00	25	57.8	03:30	26	58.8	05:00	28	61.3
00:35	22	56.1	02:05	25	57.6	03:35	26	59.6	05:05	28	61.0
00:40	22	57.9	02:10	25	59.1	03:40	26	59.9	05:10	28	60.8
00:45	22	58.0	02:15	25	59.3	03:45	27	60.1	05:15	28	60.8
00:50	23	58.1	02:20	25	59.4	03:50	27	60.1	05:20	28	60.8
00:55	23	58.1	02:25	25	59.5	03:55	27	60.1	05:25	28	60.9
01:00	23	58.1	02:30	25	59.6	04:00	27	60.1	05:30	28	60.9
01:05	23	58.0	02:35	25	59.7	04:05	27	60.1	05:35	28	61.3
01:10	23	58.0	02:40	25	59.7	04:10	27	60.1	05:40	28	61.4
01:15	23	57.8	02:45	26	59.8	04:15	27	60.0	05:45	28	61.4
01:20	24	57.8	02:50	26	60.0	04:20	27	60.2	05:50	28	61.2
01:25	24	58.0	02:55	26	60.0	04:25	27	60.3	05:55	28	61.2
01:30	24	58.2	03:00	26	60.1	04:30	27	60.3	06:00	28	60.5

PROOVE it

ASTM C 1202-97

Test-compagny
Testing street 45
CompagnyCity
Some Country

Your own logo.
size=20x80mm

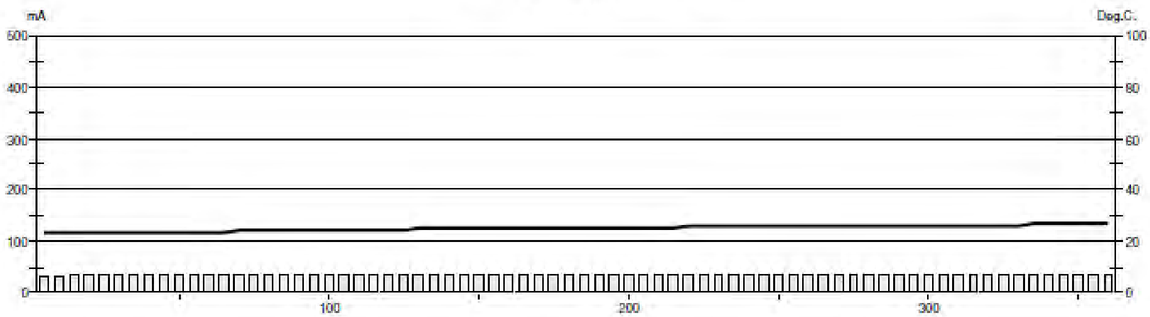
GERMANN INSTRUMENTS

DENMARK

USA

Test report

Voltage Used:	60
Testing time:	06:00 hour
Charge passed:	732
Adjusted Charge passed:	635
Permeability class:	Very Low
Instrument number:	023907
Channel number:	2
Report date:	10/5/2010
Testing by:	PJM
Reference:	NH ternary
Sample diameter:	102
Comment:	---



Time	°C	mA	Time	°C	mA	Time	°C	mA	Time	°C	mA
00:05	23	31.6	01:35	24	33.1	03:05	25	33.9	04:35	26	34.5
00:10	23	32.2	01:40	24	33.2	03:10	25	34.0	04:40	26	34.4
00:15	23	32.7	01:45	24	33.3	03:15	25	34.0	04:45	26	34.4
00:20	23	33.1	01:50	24	33.4	03:20	25	34.1	04:50	26	34.5
00:25	23	33.2	01:55	24	33.4	03:25	25	34.1	04:55	26	34.8
00:30	23	33.3	02:00	24	33.4	03:30	25	34.2	05:00	26	34.7
00:35	23	33.4	02:05	24	33.5	03:35	25	34.2	05:05	26	34.7
00:40	23	33.3	02:10	25	33.6	03:40	26	34.3	05:10	26	34.6
00:45	23	33.3	02:15	25	33.6	03:45	26	34.2	05:15	26	34.7
00:50	23	33.3	02:20	25	33.6	03:50	26	34.1	05:20	26	34.7
00:55	23	33.1	02:25	25	33.6	03:55	26	34.3	05:25	26	34.7
01:00	23	33.1	02:30	25	33.6	04:00	26	34.3	05:30	26	34.8
01:05	23	33.0	02:35	25	33.7	04:05	26	34.4	05:35	27	34.9
01:10	24	32.9	02:40	25	33.8	04:10	26	34.4	05:40	27	34.9
01:15	24	32.9	02:45	25	33.8	04:15	26	34.4	05:45	27	35.1
01:20	24	33.0	02:50	25	33.8	04:20	26	34.4	05:50	27	35.2
01:25	24	33.0	02:55	25	33.9	04:25	26	34.3	05:55	27	35.2
01:30	24	33.1	03:00	25	33.9	04:30	26	34.5	06:00	27	35.2

APPENDIX G. FIELD APPLICATION OF TERNARY MIXTURES: CONSTRUCTION OF A BRIDGE STRUCTURE IN NEW YORK

State Report
August 2011

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ACKNOWLEDGEMENTS

The research team at the National Concrete Pavement Technology Center at Iowa State University sincerely thanks the New York State Department of Transportation for their cooperation, as well as Cold Spring Construction Co., Dalrymple Gravel & Contracting Co., and Headwaters Resources for supplying the equipment and materials.

INTRODUCTION

This document is a report of the activities and observations of a research group that performed on-site testing of a ternary mixture placed on the I-86 bridge structure in Coopers Plains, New York. The cementitious system comprised a binary Type 1P cement (6% silica fume) blended with 20% Class F fly ash. The purpose of this research project is a comprehensive study of how supplementary cementitious materials can be used to improve the performance of concrete mixtures when used in ternary blends.

This is the field demonstration phase of a project that intends to provide consulting to states and contractors on the use and field management of ternary mixtures. A state-of-the-art 44 ft portland cement concrete (PCC) mobile laboratory equipped for on-site cement and concrete testing was provided by the National Concrete Pavement Technology Center (National CP Tech Center) to collect data and field observations.

PROJECT INFORMATION

- HP concrete project on I-86 at exit #42 (D261576, Steuben Co.)
- Contractor: Cold Spring Construction Co.
- Mix ID: C042911015
- I-86, Exit 42 Rehabilitation (Meads Creek Road Reconstruction; pavement, drainage, signs, pavement markings and guiderail, and box culvert replacement) and Bridge Replacement (three composite girders), Town of Campbell.
- Concrete being tested in this demonstration is for bridge abutment stem. The same mix proportion will be used for bridge deck structure, except retarding admixture will be added.

Figure 1. I-86 Coopers Plains bridge abutment stem structure, New York

SITE LOCATION

An area in a central mix plant near the bridge site was prepared by the contractor for the PCC mobile lab. The location of the project (on Interstate 86, Exit 42 in Coopers Plains, New York) is shown in Figure 2 (marked as a red cross).

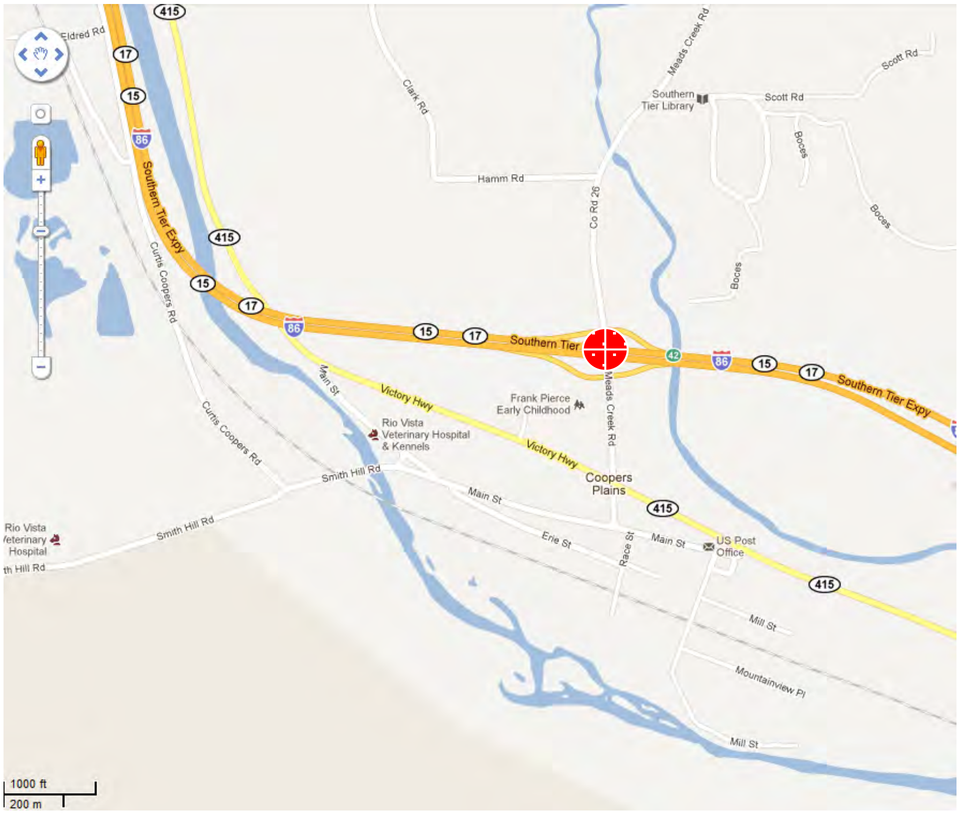


Figure 2. Project location

SAMPLING AND TESTING ACTIVITIES

The mobile lab arrived on site on August 15, 2011. Concrete placement, sampling, and testing took place on August 16, 2011. Hardened concrete samples were transported to Iowa State University on August 18, 2011, for further testing. The following tests were conducted either in the field or in the laboratory:

- Calorimetry test (ASTM C 1679)
- Slump, unit weight, temperature, and air content of fresh concrete : 2 test (ASTM C 143, ASTM C 138, ASTM C 1064, ASTM C 231)
- Microwave w/c ratio: 2 tests (AASHTO T 318)
- Initial set and final set of concrete: 1 test (ASTM C 403)
- Compressive strength, splitting tensile strength, static modulus of elasticity: 4 in. × 8 in. cylinders at 3, 7, 28, and 56 days (ASTM C 39, ASTM C 496, ASTM C 469)
- Rapid chloride permeability: 4 in. × 8 in. cylinders at 56 days (ASTM C 1202)
- Salt scaling: 3 samples (ASTM C 672)
- Free shrinkage best: 3 beams (ASTM C 157)

OBSERVATIONS OF THE RESEARCH TEAM

The following observations were made in the field work:

- Removable wood formwork was used in the bridge abutment stem construction.
- The concrete was mixed at a central mix plant (Cold Spring Construction Co.) and transported to the construction site by ready-mix trucks (Hanson Heidelberg Cement Group).
- Testing concrete from #2 and #12 batches was discharged from ready-mix trucks at 8:05 am and 10:55 am.
- Cold Spring Construction Co. prepared the mix design, which was approved by New York State Department of Transportation (NYSDOT) material bureau. The accepted mix proportions are given in the Project Data section.
- A blend of Type 1P, which contains 6% silica fume by mass (Whitehall, PA), and 20 % Class F fly ash (Headwaters Resources) was used. The coarse and fine aggregates, crushed gravel and rive sand, respectively, were obtained from Dalrymple Gravel & Contracting Co., Erwin, New York.
- Setting time of the mix was determined as a single measurement: initial and final sets occurred at 5.76 hours and 6.72 hours, respectively.
- According to the Workability Factor & Coarseness Factor graph (see Project Data section of this report), combined aggregate gradation for this project fell in the well-graded region. However, from Combined Percent Retained Curve, the aggregate gradation was slightly lacking material retained on the #30 sieve. This did not adversely affect workability or hardened properties of the mixture as observed.
- The fresh concrete tests included slump cone, unit weight, and water-cementitious materials ratio by microwave. Two batches (#2 and #12) were tested by the National CP Tech Center crew at 8:05 am and 10:55 am, respectively. The slump results were 3.75 in. and 4. in.; unit weights of concrete were determined as 138.2 lb/ft^3 and 138.0 lb/ft^3; water-cementitious ratios were found to be 0.46 and 0.47; and the air content were 6.5% and 7.3%, respectively. The design value for water-cementitious material ratio was 0.40 and target air content was 6.5%. The data are provided in the Project Data section.
- Figure 3 through 7 illustrate shots during the site visit.

Figure 3. Concrete central mix plant

Figure 4. National CP Tech Center PCC mobile lab

Figure 5. Concrete being discharged

Figure 6. Concrete being pumped

Figure 7. Concrete being placed in the abutment stem structure

- The weather data recorded by the PCC mobile lab are given in Figures 8 through 10. The relative humidity ranged from 38% to 88%; the ambient temperature ranged from 53.5˚F to 79.2˚F; and the wind speed varied from 0 mph to 9 mph during the recorded period.

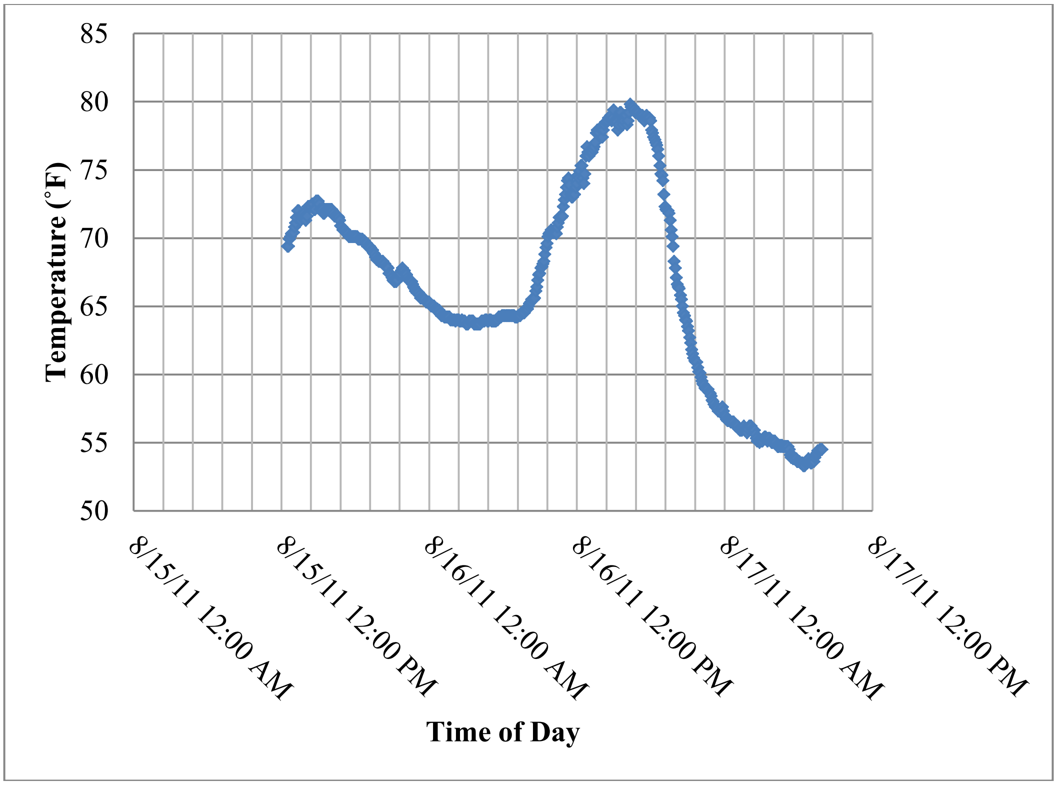


Figure 8. Ambient temperature

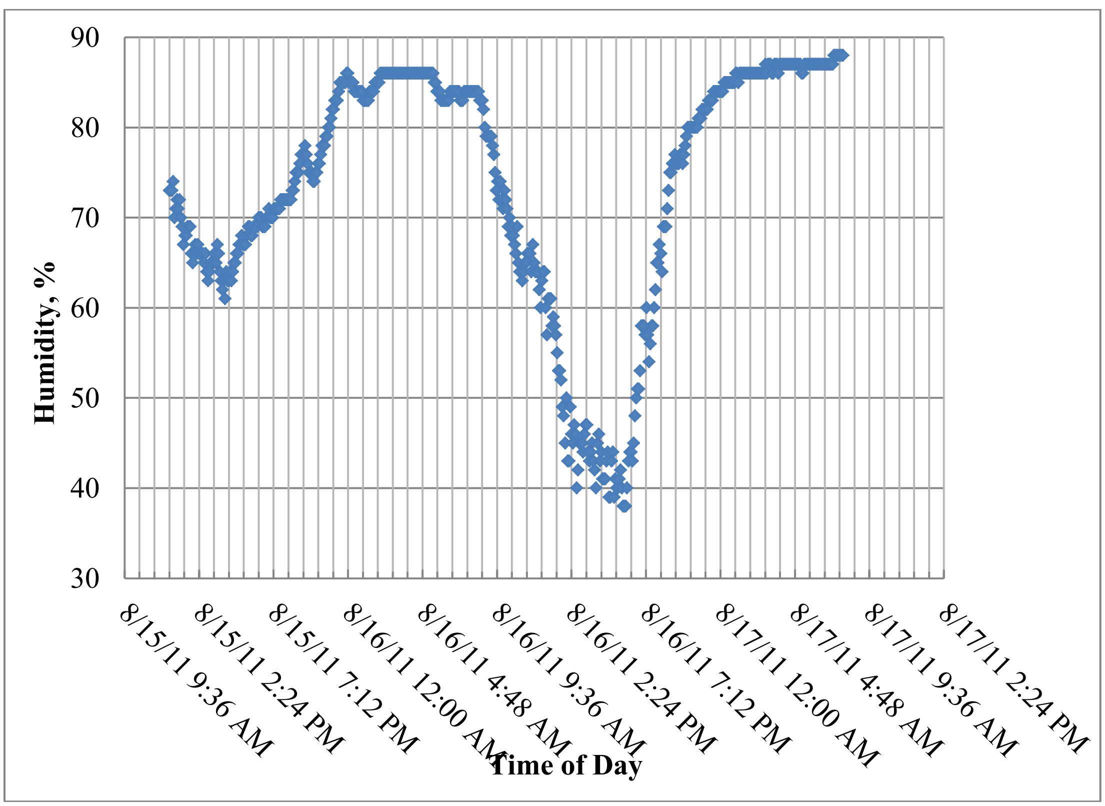


Figure 9. Relative humidity

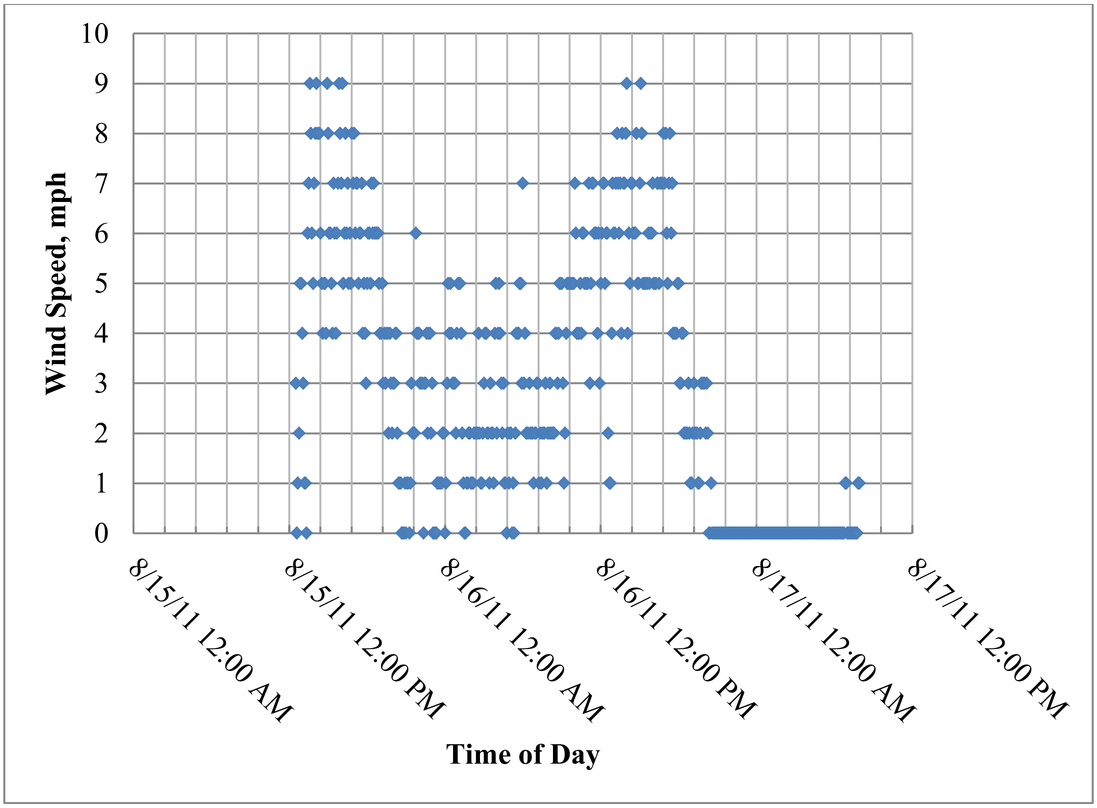


Figure 10. Wind speed

- The rapid chloride permeability test measures the electrical conductance of concrete as its resistance to chloride ion penetration. The test results shown in Table 1 indicate a classification of "low" permeability of chloride in accordance with ASTM C1202.
- The porosity obtained by the boiling test (ASTM C 642) is given in Table 1.
- Compressive strength, splitting tensile strength, and modulus of elasticity results (ASTM C 39, ASTM C 496, and ASTM C 469) are given in Table 2, and also plotted in Figures 11 through 13.

Table 1. Properties of hardened concrete

Tests	Results		
7-day compressive strength, psi	3,160		
28-day compressive strength, psi	3,970		
Rapid chloride permeability, coulombs	Sample 1 1100	Sample 2 1256	Average 1178
Strength development 28/7 day fc ratio	1.26		
Shrinkage μ-strain @ 28 days	693		
Porosity by boil test, %	5.9		

Table 2. Mechanical properties of ternary concrete mix used in the project

Location	Age, days	Compressive Strength, psi	Splitting Tensile Strength, psi	Modulus Of Elasticity, psi
NY	0	0	0	0.00E+00
	3	2,360	303	2.90E+06
	7	3,160	371	3.35E+06
	28	3,970	397	3.75E+06
	56	4,690	403	4.20E+06

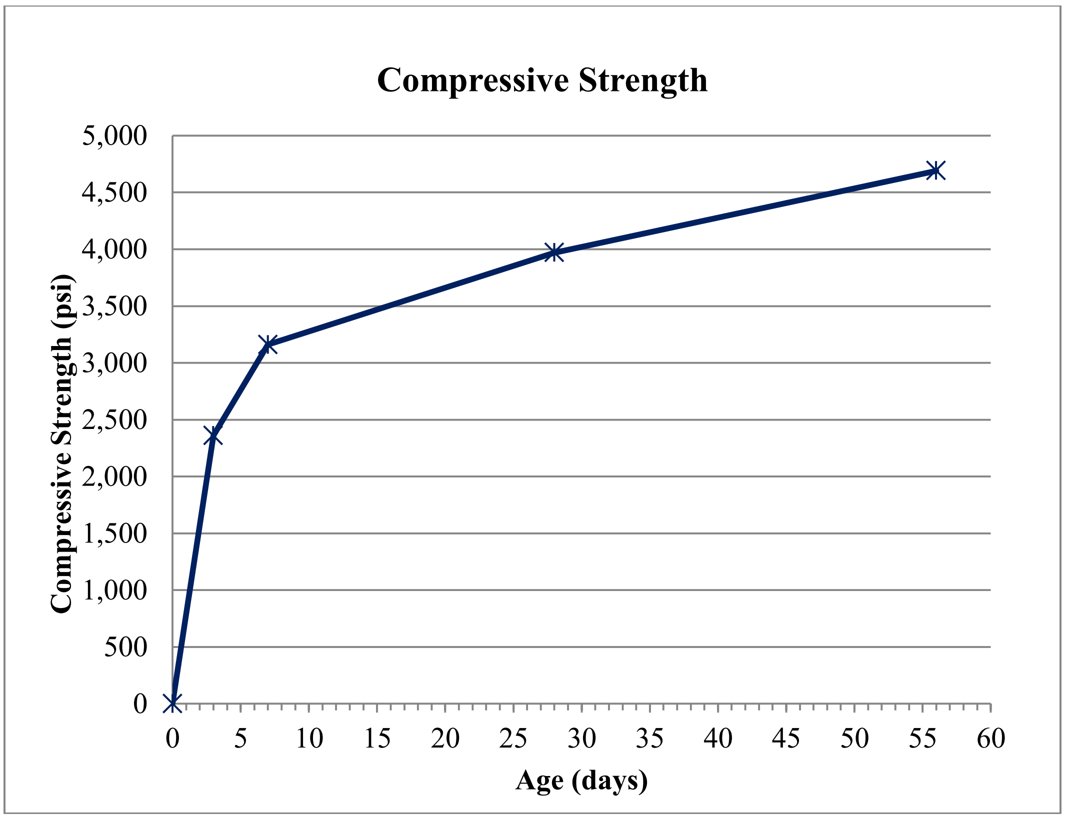


Figure 11. Compressive strength development with time

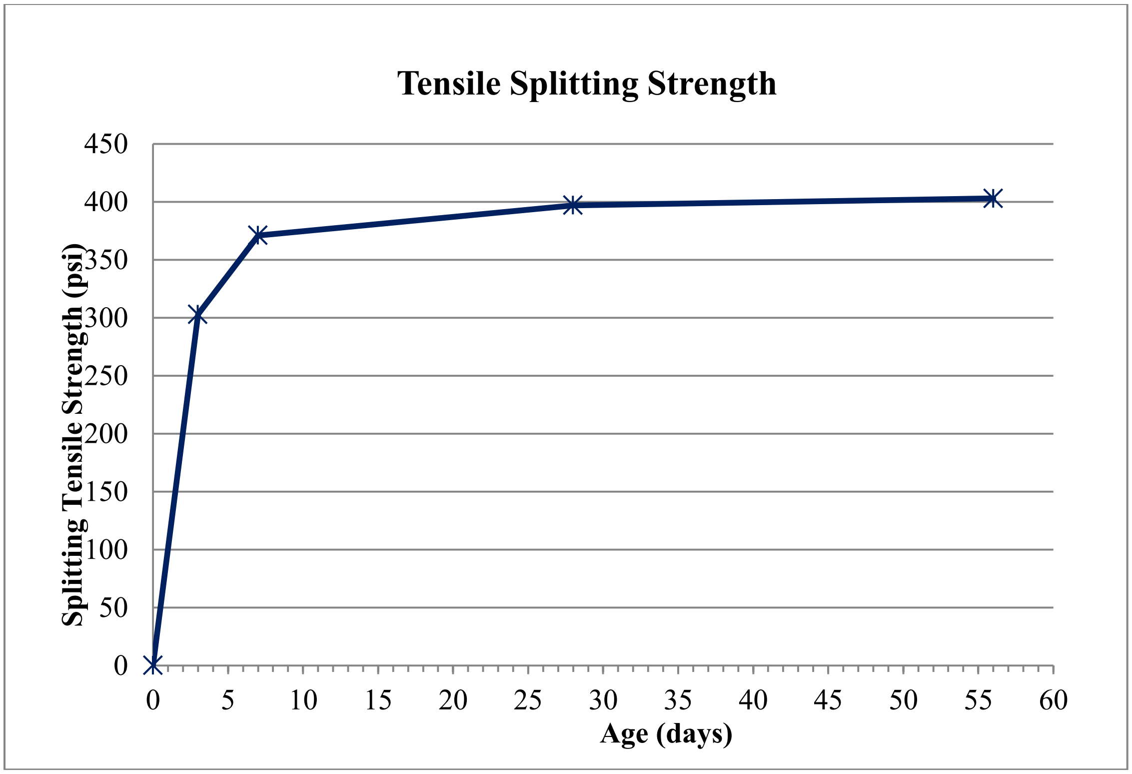


Figure 12. Tensile splitting strength development with time

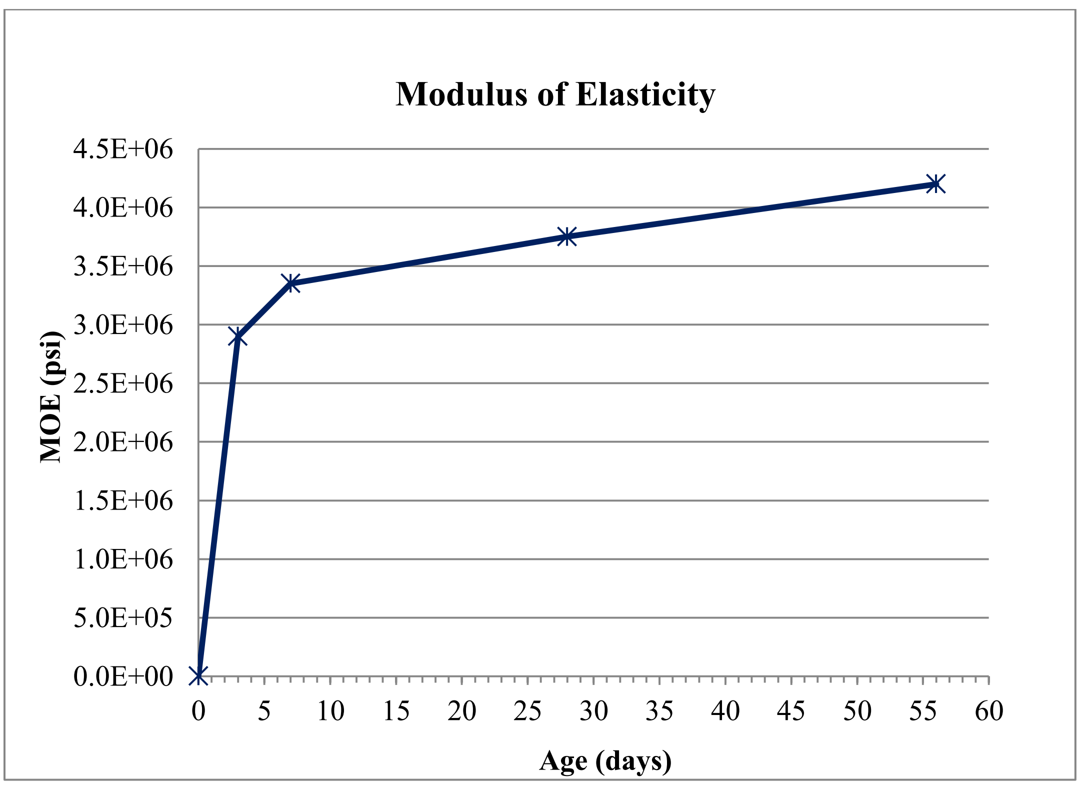


Figure 13. Modulus of elasticity development with time

- The free shrinkage test (ASTM C 157) was conducted in the laboratory. Three beams were cast in the field, moist cured for seven days, and then moved to a dry room at 23˚C and 50% relative humidity. The drying shrinkage results are given in Table 3 and also plotted in Figure 14.

Table 3. Free shrinkage test results

NY Project Free Shrinkage Test (ASTM C 157)					
Dry Time	**Beam 1 change %**	**Beam 2 change %**	**Beam 3 change %**	**Average**	**μ-strain**
1	-0.012	-0.007	-0.013	-0.011	-107
4	-0.034	-0.03	-0.036	-0.033	-333
7	-0.042	-0.038	-0.042	-0.041	-407
14	-0.055	-0.049	-0.059	-0.054	-543
28	-0.068	-0.066	-0.074	-0.069	-693
56	-0.063	-0.062	-0.092	-0.072	-723

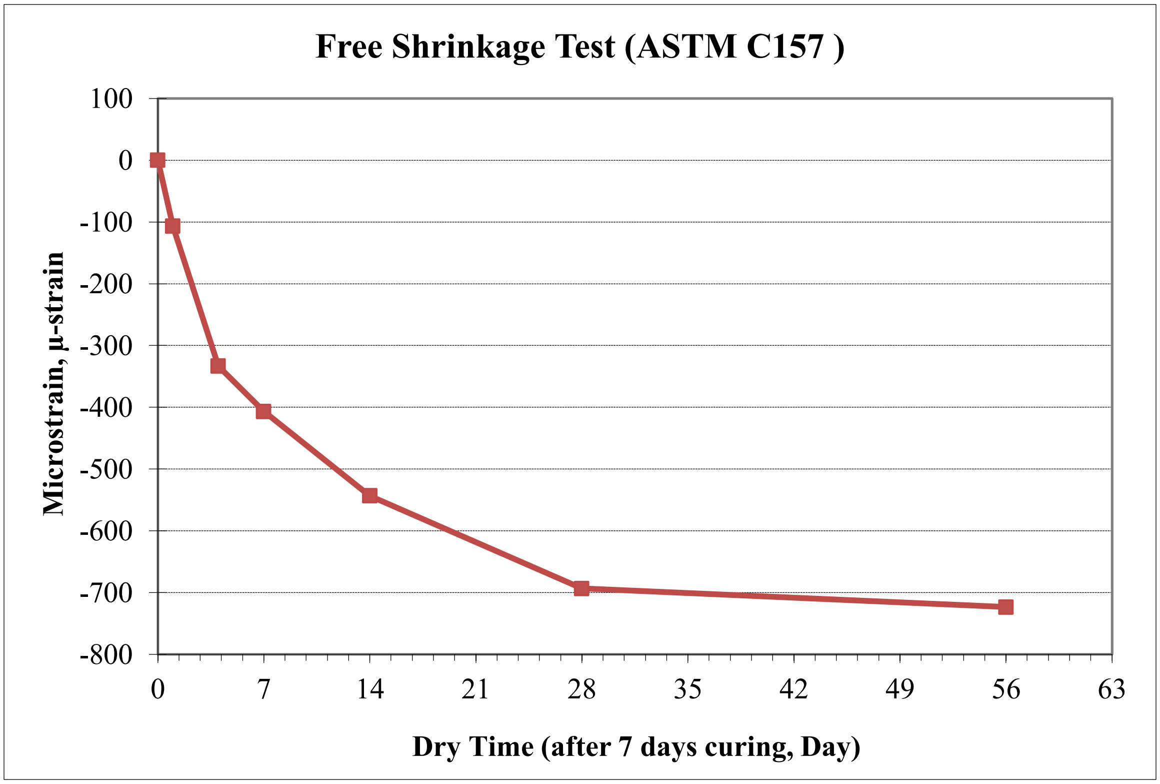


Figure 14. Free shrinkage of prisms (ASTM C 157)

- The air void test (rapid air test) results for four samples are given in Table 4. A spacing factor ≤ 0.20 mm measured using microscopical methods is an indication of a good concrete freeze-thaw resistance. Based on this criterion, the spacing factors were acceptable in all the samples.

Table 4. Air void structure results at the age 28 days

	Air content, %	Specific surface, mm^{-1}	Spacing factor, mm
NY cyl.1 side 1	2.81	41.29	0.155
NY cyl.1 side 2	4.63	47.09	0.109
NY cyl.2 side 1	5.90	51.87	0.088
NY cyl.2 side 2	4.17	52.63	0.102
Ave.	4.38	48.22	0.114

- The calorimetry test was conducted in accordance with ASTM C 1679. The test equipment is shown in Figure 15 and results are given in Figure 16, respectively. The two tests were recorded from 8:05AM and 10:55AM and the peak values reached about 110°F and 115°F, respectively.

Figure 15. Adiacal calorimetry test equipment for heat of hydration of concrete

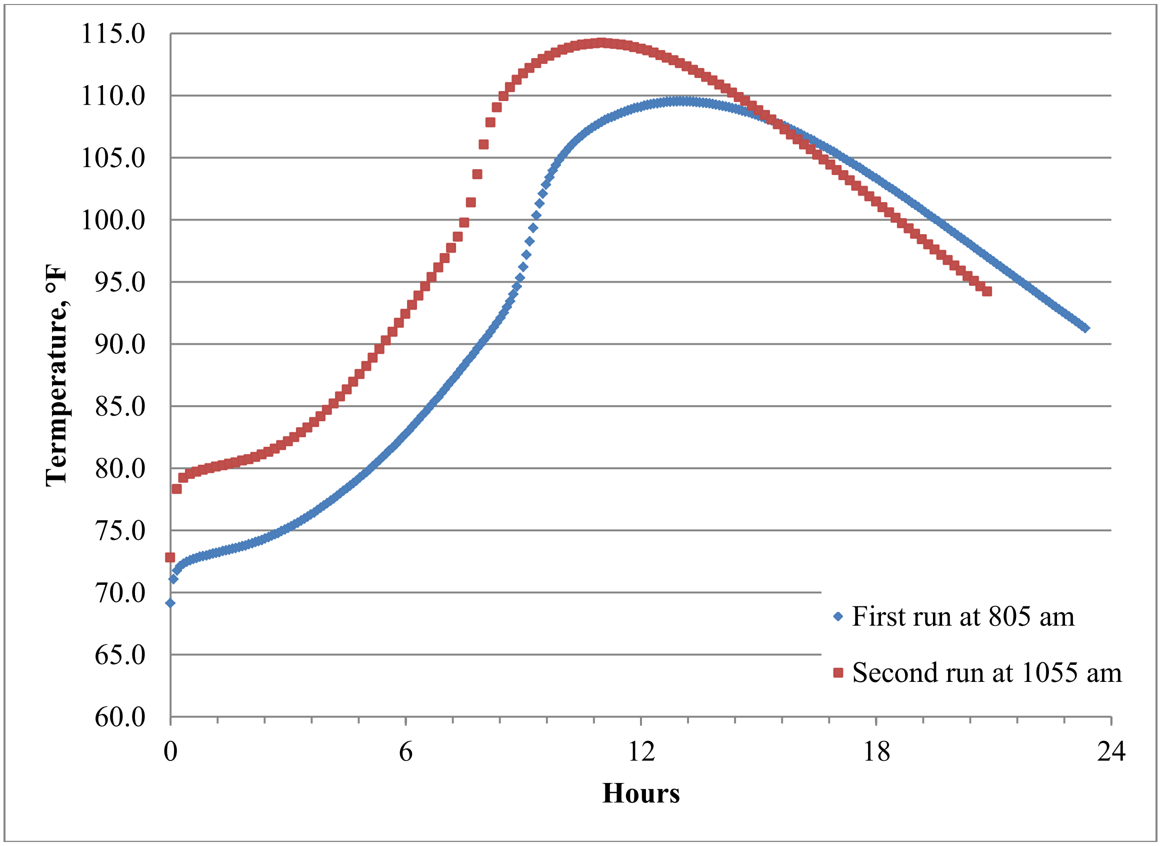


Figure 16. Calorimetry test results

- A salt scaling test (ASTM C 672) was performed in according with ASTM C672. A photograph after the 50th cycle was taken and is shown in Figure 17. The visual ratings assigned to each specimen are given in Table 5.

Table 5. Salt scaling test visual condition of specimens

NY salt scaling specimens	**Condition of surface**					
	Cycle 5	Cycle 10	Cycle 15	Cycle 20	Cycle 25	Cycle 50
No. 1	1	1	1	1	1	1
No. 2	1	1	1	1	1	2
No. 3	1	1	1	1	1	2

Figure 15. New York salt scaling specimens after 50th freeze-thaw cycle

PROJECT DATA

The following test data are provided for information only; comments and conclusions will be reported in the comprehensive Phase III report of the pooled fund project *Development of Performance Properties of Ternary Mixtures.*

Mix Design & Misc. Info.

General Information

Project:	I-86 Coopers Plains Bridge Structure, NY
Contractor:	Cold Spring Construction Co.
Mix Description:	675 lb Cementitious
Mix ID:	C042911015
Date(s) of Placement:	8/16/11

Cementitious Materials	Source	Type	Spec. Gravity	lb/yd^3	% Replacement by Mass
Portland Cement:	Whitehall, PA	Type IP(6)	3.150	540	
GGBFS:					
Fly Ash:	Headwaters Resources	Class F	2.380	135	20.00%
Silica Fume:					
Other Pozzolan:					
				675	**lb/yd^3**
				7.2	**sacks/yd^3**

Aggregate Information	Source	Type	Spec. Gravity SSD	Moisture(%)	% Passing #4
Coarse Aggregate:	Dalrymple Gravel & Contracting Co.	Crushed gravel	2.610	0.50%	2.9%
Intermediate Aggregate #1:					
Intermediate Aggregate #2:					
Fine Aggregate #1:	Dalrymple Gravel & Contracting Co.	Generic FA	2.640	2.97%	100.0%

Coarse Aggregate %:	60.5%
Intermediate Aggregate #1%:	
Intermediate Aggregate #2%:	
Fine Aggregate #1 %:	39.5%

Mix Proportion Calculations

Water/Cementitious Materials Ratio:	0.400
Air Content:	6.50%

	Volume (ft^3)	Batch Weights SSD (lb/yd^3)	Spec. Gravity	Absolute Volume (%)
Portland Cement:	2.747	540	3.150	10.175%
GGBFS:				
Fly Ash:	0.909	135	2.380	3.367%
Silica Fume:				
Other Pozzolan:				
Coarse Aggregate:	10.443	1,710	2.610	38.679%
Intermediate Aggregate #1:				
Intermediate Aggregate #2:				
Fine Aggregate #1:	6.818	1,115	2.640	25.253%
Water:	4.327	270	1.000	16.026%
Air:	1.755			6.500%
	27.000	**3,770**		**100.000%**
	Unit Weight (lb/ft^3)	**139.6**	**Paste**	**36.067%**
			Mortar	**62.442%**

Admixture Information	Source/Description	oz/yd^3	oz/cwt
Air Entraining Admix.:	W.R. Grace Terapave AEA	9.20	1.36
Admix. #1:	W.R. Grace Daracem55 Mid-range plasticiser	12.00	1.78
Admix. #2:			
Admix. #3:			

AVA Information	Absolute Volume (%)
Air Free Paste:	29.567%
Air Free Mortar:	55.942%

NY - Ternary Mixtures

Sample Information:

Project: I-86 Coopers Plains Bridge Structure, NY

Date: 16-Aug-2011

Time: 8:05 AM

Type of Paving: Bridge abutment stem

Placement: Pumped

Sta: n/a

Latitude:

Longitude:

Mix ID: C042911015

Truck IDs: Batch #2

Sample Location Mark & Comments:

Environmental Conditions:

Dew Point: 60.0

Relative Humidity: 84%

Wind Speed: 4.0

Ambient Temp.: 65.0

Concrete Properties:

Base/Soil Temp. (internal)(ºF): n/a

Base Temp. (surface)(ºF): n/a

Microwave Water Content Samples: √

Calorimetry (ADIACAL Cylinders): 4

Set-Time (ASTMC403) Mortar Samples: √

Cylinder for RCP & Perm. Voids Boil Test: use adiacal

Scaling Blocks: 3

Concrete Temp.(ºF):	77.2
Slump (in.):	3.75
Air Content:	6.5%
Unit Weight (lb/ft^3):	138.2

Compressive, Tensile & MOR Cylinders: 30

Shrinkage Beams: 3

NY - Ternary Mixtures

Sample Information:

Project: I-86 Coopers Plains Bridge Structure, NY

Date: 16-Aug-2011

Time: 10:55 AM

Type of Paving: Bridge abutment stem

Placement: Pumped

Sta: n/a

Latitude:

Longitude:

Mix ID: C042911015

Truck IDs: Batch #12

Sample Location Mark & Comments:

Environmental Conditions:

Dew Point: 61.0

Relative Humidity: 69%

Wind Speed: 2.0

Ambient Temp.: 72.0

Concrete Properties:

Base/Soil Temp. (internal)(ºF): n/a

Base Temp. (surface)(ºF): n/a

Microwave Water Content Samples: √

Calorimetry (ADIACAL Cylinders): 4

Set-Time (ASTMC403) Mortar Samples: n/a

Cylinder for RCP & Perm. Voids Boil Test: n/a

Scaling Blocks: n/a

Concrete Temp.(ºF):	78.4
Slump (in.):	4.00
Air Content:	7.3%
Unit Weight (lb/ft^3):	138.0

Compressive, Tensile & MOR Cylinders: n/a

Shrinkage Beams: n/a

New York - Ternary Mixtures

I-86 Coopers Plains Bridge

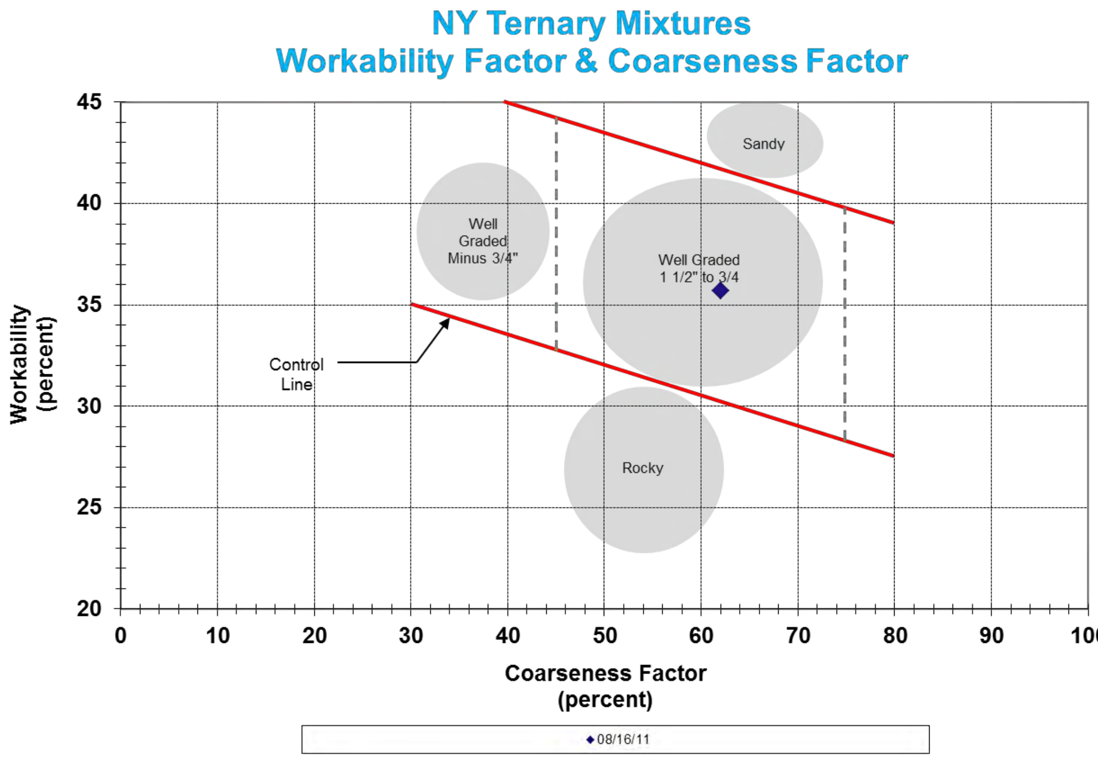
Sample Information & Identification			Environmental Conditions				Fresh Concrete Workability Properties			Pressure Air
Sample Date	Sample Time	Sample Comments	Relative Humidity (%)	Ambient Temp. (˚F)	Wind Speed (mph)	Conc. Temp. (probe) (˚F)	Slump (in)	Unit Weight (lb/ft^3)	Microwave W/C Ratio (%)	% Air Content
16-Aug-11	8:05 AM	cp tech center sample taken at truck discharge	84.0	65.0	4.0	77.2	3.75	138.16	0.46	6.5
16-Aug-11	11:00 AM	cp tech center sample taken at truck discharge	69.0	72.0	2.0	78.4	4.00	138.00	0.47	7.3

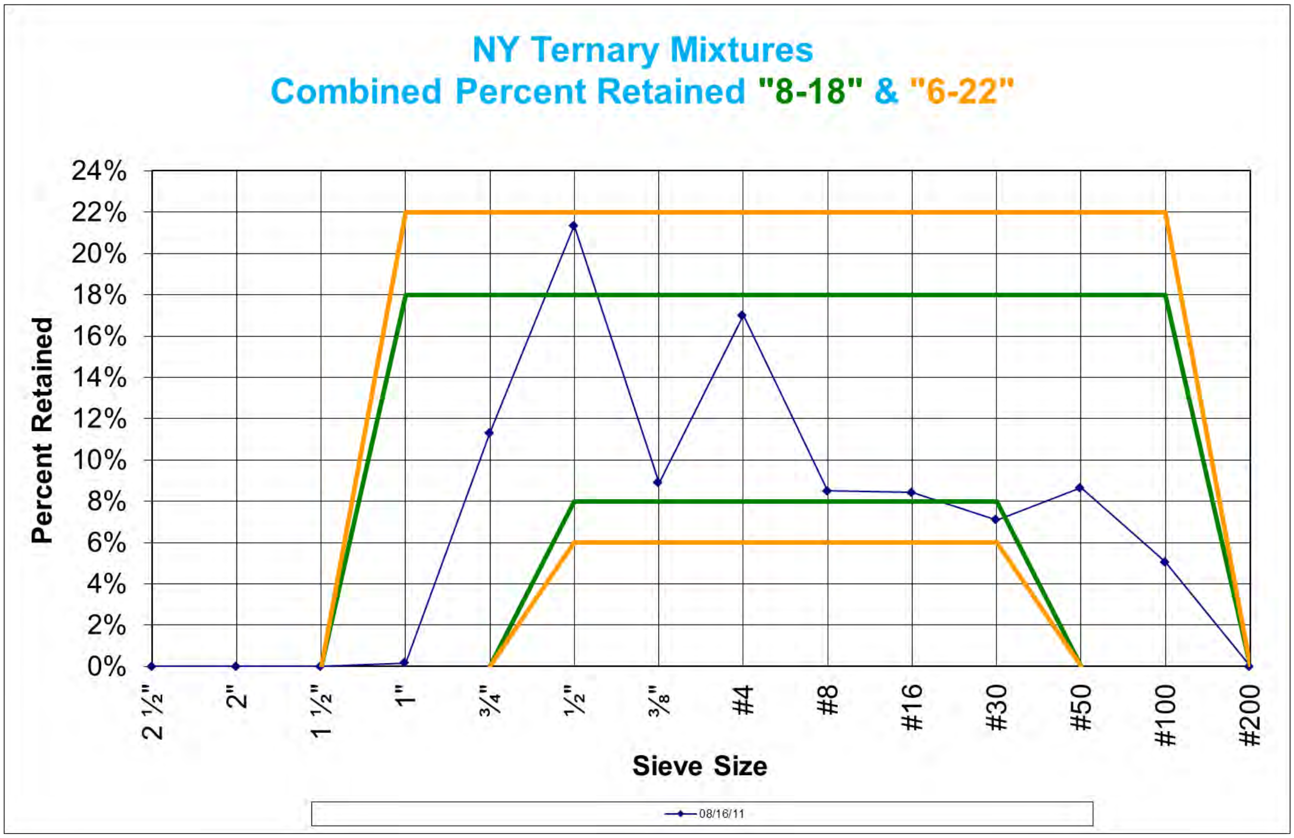
Project: I-86 Coopers Plains Bridge Structure, NY
Mix ID: C042911015
Sample Comments:
Test Date: 08/16/11

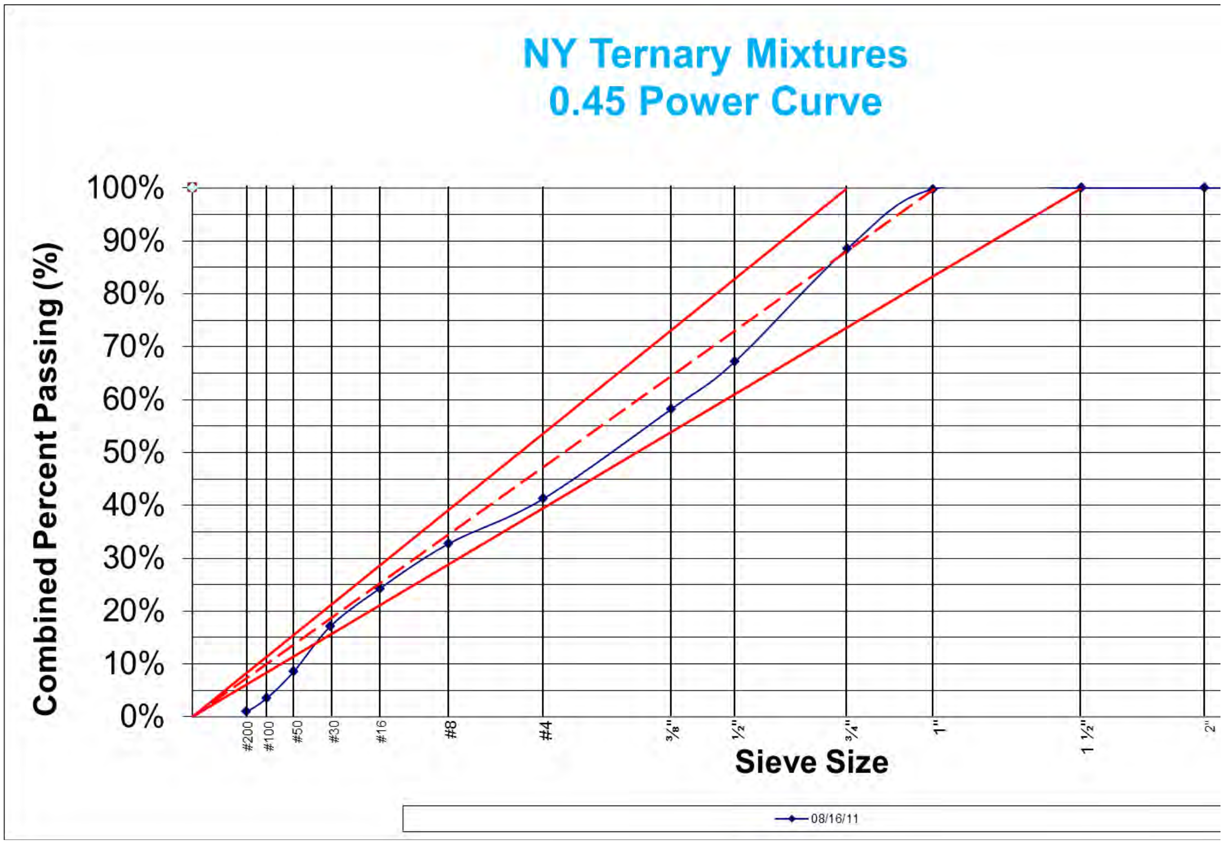
Total Cementitious Material:		675 lb/yd^3		
Agg. Ratios:	60.50%	0.00%	39.50%	100.00%

Sieve	Coarse	Intermediate	Fine #1	Fine #2	Combined % Retained	Combined % Retained On Each Sieve	Combined % Passing
2 ½"	100.0%	0.0%	100.0%		0%	0%	100%
2"	100.0%	0.0%	100.0%		0%	0%	100%
1 ½"	100.0%	0.0%	100.0%		0%	0%	100%
1"	99.7%	0.0%	100.0%		0%	0%	100%
¾"	81.0%	0.0%	100.0%		11%	11%	89%
½"	45.7%	0.0%	100.0%		33%	21%	67%
⅜"	31.0%	0.0%	100.0%		42%	9%	58%
#4	2.9%	0.0%	100.0%		59%	17%	41%
#8	1.3%	0.0%	80.9%		67%	9%	33%
#16	1.0%	0.0%	60.0%		76%	8%	24%
#30	1.0%	0.0%	42.0%		83%	7%	17%
#50	1.0%	0.0%	20.1%		91%	9%	9%
#100	1.0%	0.0%	7.3%		97%	5%	3%
#200			2.4%		99.1%		0.9%

Workability Factor: 35.7
Coarseness Factor: 62.1




NY Ternary Mixtures
Combined Percent Retained "8-18" & "6-22"
24%
22%
20%
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
Percent Retained
2 ½"
2"
1 ½"
1"
¾"
½"
⅜"
#4
#8
#16
#30
#50
#100
#200
Sieve Size
08/16/11


NY Ternary Mixtures
0.45 Power Curve
Combined Percent Passing (%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
#200
#100
#50
#30
#16
#8
#4
⅜"
½"
¾"
1"
1 ½"
2"
Sieve Size
08/16/11

New York - Ternary Mixtures

Set Time ASTM C 403

Project: I-86 Coopers Plains Bridge Structure, NY

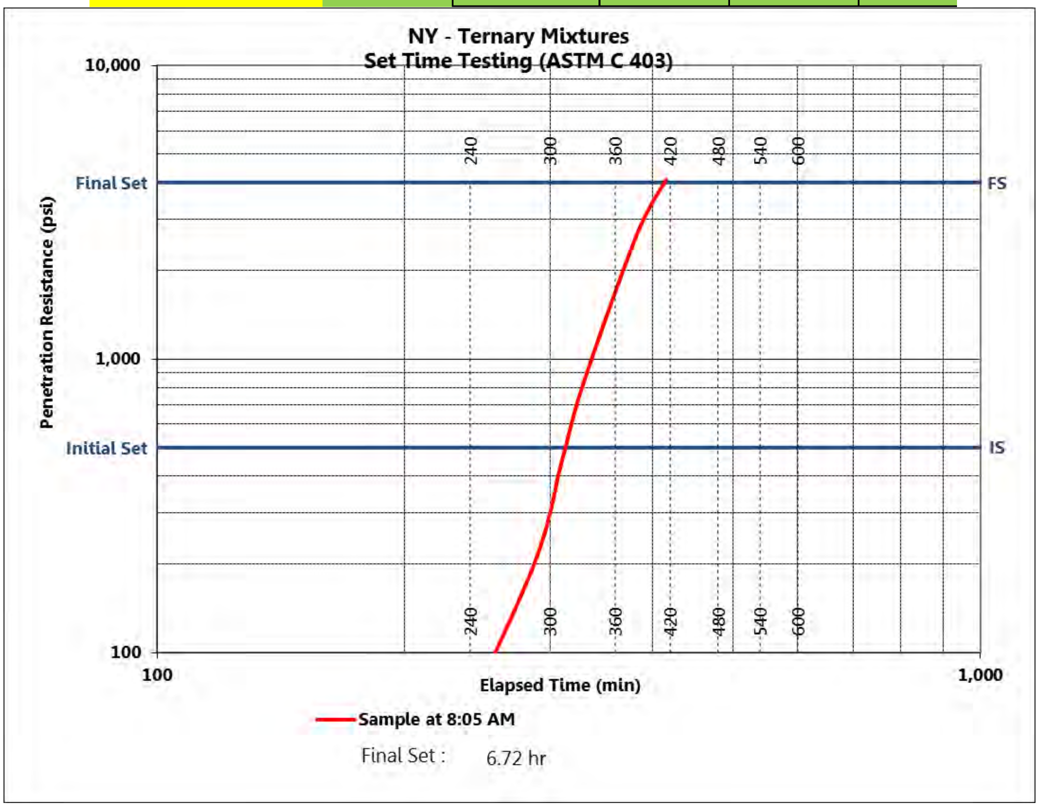
Date: 08-Aug-2011 Start Time: 8:05 AM

Sta: n/a

Test Data

Penetration Time (xx:xx-24 hr format)	Time (min)	Needle # (1,2,4,10,20 or 40)	Force (lb)	Penetration Resistance (psi)	Sample Temp. (ºF)
11:30 AM	205.00	1	26	26.00	75.3
12:49 PM	284.00	2	93	186.00	77.1
1:15 PM	310.00	4	112	448.00	77.7
1:35 PM	330.00	10	84	840.00	78.4
2:28 PM	383.00	40	67	2680.00	81.5
3:00 PM	415.00	40	102	4080.00	82.4

Initial Set (at 500 psi PR)	estimated times using forecast function	**346**	minutes	**5.76**	hours
Final Set (at 4,000 psi PR)		**403**	minutes	**6.72**	hours



New York - Ternary Mixtures

Microwave Water Content Worksheet

Project: I-86 Coopers Plains Bridge Structure, NY
Date: 16-Aug-11 Time: 8:05 AM
Sta: n/a

Test Data

Mass of tray+cloth+block+fresh test sample, W_F (g)	4,480.3
Mass of tray+cloth+block, W_S(g)	2,198.8
Mass of tray+cloth+dry sample, W_D (g) (5mins)	4,454.0
Mass of tray+cloth+dry sample, W_D (g) (7 mins)	4,431.2
Mass of tray+cloth+dry sample, W_D (g) (9 mins)*	4,385.9
Mass of tray+cloth+dry sample, W_D (g) (11 mins)*	4,356.1
Mass of tray+cloth+dry sample, W_D (g) (13 mins)*	4,322.2
Mass of tray+cloth+dry sample, W_D (g) (15 mins)*	4,291.3
Mass of tray+cloth+dry sample, W_D (g) (17 mins)*	4,279.6
Mass of tray+cloth+dry sample, W_D (g) (19 mins)*	4,273.0
Mass of tray+cloth+dry sample, W_D (g) (21 mins)*	4,269.2
Mass of tray+cloth+dry sample, W_D (g) (23 mins)*	4,266.7
Mass of tray+cloth+dry sample, W_D (g) (Final)**	4,266.0
Water content percentage, W_C (%)	**9.4%**
Unit weight of fresh concrete, UW (lb/ft^3)***	138.0
Total water content, W_T, (lb/yd^3)	**350.0**
Total cementitious weight (lb/yd^3)	675
Fine aggregate weight (lb/yd^3)	1115
Coarse Aggregate weight (lb/yd^3)	1710
Intermediate Aggregate weight (lb/yd^3)	0
Fine aggregate absorption (%)	2.97%
Coarse aggregate absorption (%)	0.50%
Intermediate aggregate absorption (%)	0.00%
w/c	**0.457**

* If necessary (stop if the weight loss is less than 1g)
** Mass at test termination
***From unit weight test

New York - Ternary Mixtures

Microwave Water Content Worksheet

Project: I-86 Coopers Plains Bridge Structure, NY
Date: 16-Aug-11 Time: 11:00 AM
Sta: n/a

Test Data

Mass of tray+cloth+block+fresh test sample, W_F (g)	3,769.3
Mass of tray+cloth+block, W_S(g)	2,199.8
Mass of tray+cloth+dry sample, W_D (g) (5mins)	3,721.2
Mass of tray+cloth+dry sample, W_D (g) (7 mins)	3,694.7
Mass of tray+cloth+dry sample, W_D (g) (9 mins)*	3,658.0
Mass of tray+cloth+dry sample, W_D (g) (11 mins)*	3,633.5
Mass of tray+cloth+dry sample, W_D (g) (13 mins)*	3,625.1
Mass of tray+cloth+dry sample, W_D (g) (15 mins)*	3,620.2
Mass of tray+cloth+dry sample, W_D (g) (17 mins)*	3,618.7
Mass of tray+cloth+dry sample, W_D (g) (Final)**	3,617.8
Water content percentage, W_C (%)	**9.7%**
Unit weight of fresh concrete, UW (lb/ft^3)***	138.0
Total water content, W_T, (lb/yd^3)	**359.7**
Total cementitious weight (lb/yd^3)	675
Fine aggregate weight (lb/yd^3)	1115
Coarse Aggregate weight (lb/yd^3)	1710
Intermediate Aggregate weight (lb/yd^3)	0
Fine aggregate absorption (%)	2.97%
Coarse aggregate absorption (%)	0.50%
Intermediate aggregate absorption (%)	0.00%
w/c	**0.471**

* If necessary (stop if the weight loss is less than 1g)
** Mass at test termination
***From unit weight test

Sample ID: ny ternary 1 side 2

Sample Size (mm x mm):	60 x 60	Length Traversed (mm):	2413.1
Paste Content (%):	28.80	Area Traversed (mm x mm):	55 x 55

Chord Length Distribution - Table

Class No.	Chord size (microns)	Number of Chords in Class	Number of Chords in Percent	Air Content in Class	Cumulated Air Content	Chord length frequency	Air content, fraction	
1	0-10	26	1.98	0.010	0.010	0.02	0.010	0.00-0.01
2	10-20	203	15.43	0.130	0.140	0.15	0.130	0.01-0.02
3	20-30	202	15.43	0.210	0.350	0.15	0.210	0.02-0.03
4	30-40	121	9.19	0.170	0.520	0.09	0.170	0.03-0.04
5	40-50	137	10.41	0.250	0.780	0.10	0.250	0.04-0.05
6	50-60	122	9.27	0.280	1.050	0.09	0.280	0.05-0.06
7	60-80	132	10.03	0.380	1.430	0.10	0.380	0.06-0.08
8	80-100	78	5.93	0.290	1.710	0.06	0.290	0.08-0.10
9	100-120	78	5.93	0.360	2.070	0.06	0.360	0.10-0.12
10	120-140	38	2.89	0.200	2.270	0.03	0.200	0.12-0.14
11	140-160	36	2.74	0.220	2.500	0.03	0.220	0.14-0.16
12	160-180	30	2.28	0.210	2.710	0.02	0.210	0.16-0.18
13	180-200	15	1.14	0.120	2.820	0.01	0.120	0.18-0.20
14	200-220	11	0.84	0.100	2.920	0.01	0.100	0.20-0.22
15	220-240	15	1.14	0.140	3.060	0.01	0.140	0.22-0.24
16	240-260	5	0.38	0.050	3.110	0.00	0.050	0.24-0.26
17	260-280	5	0.38	0.060	3.170	0.00	0.060	0.26-0.28
18	280-300	4	0.30	0.050	3.220	0.00	0.050	0.28-0.30
19	300-350	11	0.84	0.150	3.360	0.01	0.150	0.30-0.35
20	350-400	11	0.84	0.170	3.530	0.01	0.170	0.35-0.40
21	400-450	6	0.46	0.100	3.640	0.00	0.100	0.40-0.45
22	450-500	8	0.61	0.160	3.790	0.01	0.160	0.45.0.50
23	500-1000	14	1.06	0.400	3.840	0.01	0.400	0.50-1.00
24	1000-1500	7	0.53	0.370	4.570	0.01	0.370	1.00-1.50
25	1500-2000	1	0.08	0.070	4.630	0.00	0.070	1.50-2.00
26	2000-2500	0	0.00	0.000	4.630	0.00	0.000	2.00-2.50
27	2500-3000	0	0.00	0.000	4.630	0.00	0.000	2.50-3.00
28	3000-4000	0	0.00	0.000	4.630	0.00	0.000	3.00-4.00
						1316		

Air Content (%):	4.63
Specific Surface (mm^{-1}):	47.09
Spacing Factor (mm):	0.109
Void Frequency (mm^{-1}):	0.550
Average Chord Length (mm):	0.085
Paste to Air Ratio:	6.22

Sample ID: ny ternary 1 side 1

Sample Size (mm x mm):	60 x 60	Length Traversed (mm):	2413.1
Paste Content (%):	28.80	Area Traversed (mm x mm):	55 x 55

Chord Length Distribution - Table

Class No.	Chord size (microns)	Number of Chords in Class	Number of Chords in Percent	Air Content in Class	Cumulated Air Content	Chord length frequency	Air content, fraction	
1	0-10	15	2.14	0.010	0.010	0.02	0.010	0.00-0.01
2	10-20	122	17.43	0.070	0.080	0.17	0.070	0.01-0.02
3	20-30	99	17.43	0.100	0.180	0.14	0.100	0.02-0.03
4	30-40	57	8.14	0.080	0.260	0.08	0.080	0.03-0.04
5	40-50	67	9.57	0.120	0.390	0.10	0.120	0.04-0.05
6	50-60	51	7.29	0.120	0.500	0.07	0.120	0.05-0.06
7	60-80	79	11.29	0.230	0.730	0.11	0.230	0.06-0.08
8	80-100	60	8.57	0.220	0.950	0.09	0.220	0.08-0.10
9	100-120	34	4.86	0.160	1.110	0.05	0.160	0.10-0.12
10	120-140	10	1.43	0.050	1.160	0.01	0.050	0.12-0.14
11	140-160	17	2.43	0.100	1.270	0.02	0.100	0.14-0.16
12	160-180	12	1.71	0.080	1.350	0.02	0.080	0.16-0.18
13	180-200	8	1.14	0.060	1.410	0.01	0.060	0.18-0.20
14	200-220	6	0.86	0.050	1.470	0.01	0.050	0.20-0.22
15	220-240	6	0.86	0.060	1.520	0.01	0.060	0.22-0.24
16	240-260	5	0.71	0.050	1.570	0.01	0.050	0.24-0.26
17	260-280	3	0.43	0.030	1.610	0.00	0.030	0.26-0.28
18	280-300	2	0.29	0.020	1.630	0.00	0.020	0.28-0.30
19	300-350	7	1.00	0.090	1.730	0.01	0.090	0.30-0.35
20	350-400	6	0.86	0.090	1.820	0.01	0.090	0.35-0.40
21	400-450	4	0.57	0.070	1.890	0.01	0.070	0.40-0.45
22	450-500	2	0.29	0.040	1.930	0.00	0.040	0.45.0.50
23	500-1000	25	3.57	0.740	2.080	0.04	0.740	0.50-1.00
24	1000-1500	3	0.43	0.150	2.810	0.00	0.150	1.00-1.50
25	1500-2000	0	0.00	0.000	2.810	0.00	0.000	1.50-2.00
26	2000-2500	0	0.00	0.000	2.810	0.00	0.000	2.00-2.50
27	2500-3000	0	0.00	0.000	2.810	0.00	0.000	2.50-3.00
28	3000-4000	0	0.00	0.000	2.810	0.00	0.000	3.00-4.00
						700		

Air Content (%):	2.81
Specific Surface (mm^{-1}):	41.29
Spacing Factor (mm):	0.155
Void Frequency (mm^{-1}):	0.290
Average Chord Length (mm):	0.097
Paste to Air Ratio:	10.25

Sample ID:	ny ternary cyl. 2 side 1

Sample Size (mm x mm):	60 x 60	Length Traversed (mm):	2413.1
Paste Content (%):	28.80	Area Traversed (mm x mm):	55 x 55

Chord Length Distribution - Table

Class No.	Chord size (microns)	Number of Chords in Class	Number of Chords in Percent	Air Content in Class	Cumulated Air Content	Chord length frequency	Air content, fraction	
1	0-10	72	3.90	0.030	0.030	0.04	0.030	0.00-0.01
2	10-20	372	20.15	0.230	0.260	0.20	0.230	0.01-0.02
3	20-30	300	20.15	0.310	0.570	0.16	0.310	0.02-0.03
4	30-40	210	11.38	0.300	0.870	0.11	0.300	0.03-0.04
5	40-50	161	8.72	0.300	1.170	0.09	0.300	0.04-0.05
6	50-60	126	6.83	0.290	1.460	0.07	0.290	0.05-0.06
7	60-80	191	10.35	0.550	2.000	0.10	0.550	0.06-0.08
8	80-100	103	5.58	0.380	2.380	0.06	0.380	0.08-0.10
9	100-120	70	3.79	0.320	2.700	0.04	0.320	0.10-0.12
10	120-140	55	2.98	0.300	2.990	0.03	0.300	0.12-0.14
11	140-160	24	1.30	0.150	3.140	0.01	0.150	0.14-0.16
12	160-180	26	1.41	0.180	3.320	0.01	0.180	0.16-0.18
13	180-200	22	1.19	0.170	3.500	0.01	0.170	0.18-0.20
14	200-220	16	0.87	0.140	3.640	0.01	0.140	0.20-0.22
15	220-240	9	0.49	0.090	3.730	0.00	0.090	0.22-0.24
16	240-260	8	0.43	0.080	3.810	0.00	0.080	0.24-0.26
17	260-280	7	0.38	0.080	3.890	0.00	0.080	0.26-0.28
18	280-300	7	0.38	0.080	3.970	0.00	0.080	0.28-0.30
19	300-350	11	0.60	0.150	4.120	0.01	0.150	0.30-0.35
20	350-400	10	0.54	0.160	4.270	0.01	0.160	0.35-0.40
21	400-450	6	0.33	0.100	4.380	0.00	0.100	0.40-0.45
22	450-500	4	0.22	0.080	4.460	0.00	0.080	0.45.0.50
23	500-1000	27	1.46	0.800	4.520	0.01	0.800	0.50-1.00
24	1000-1500	5	0.27	0.250	5.510	0.00	0.250	1.00-1.50
25	1500-2000	2	0.11	0.140	5.640	0.00	0.140	1.50-2.00
26	2000-2500	0	0.00	0.000	5.640	0.00	0.000	2.00-2.50
27	2500-3000	0	0.00	0.000	5.640	0.00	0.000	2.50-3.00
28	3000-4000	2	0.11	0.260	5.900	0.00	0.260	3.00-4.00
						1846		

Air Content (%):	5.90
Specific Surface (mm^{-1}):	51.87
Spacing Factor (mm):	0.088
Void Frequency (mm^{-1}):	0.760
Average Chord Length (mm):	0.077
Paste to Air Ratio:	4.88

Sample ID: ny ternary 1 cyl. 2 side 2

Sample Size (mm x mm):	60 x 60	Length Traversed (mm):	2413.1
Paste Content (%):	28.80	Area Traversed (mm x mm):	55 x 55

Chord Length Distribution - Table

Class No.	Chord size (microns)	Number of Chords in Class	Number of Chords in Percent	Air Content in Class	Cumulated Air Content	Chord length frequency	Air content, fraction	
1	0-10	45	3.40	0.020	0.020	0.03	0.020	0.00-0.01
2	10-20	249	18.79	0.150	0.170	0.19	0.150	0.01-0.02
3	20-30	184	18.79	0.190	0.360	0.14	0.190	0.02-0.03
4	30-40	123	9.28	0.180	0.540	0.09	0.180	0.03-0.04
5	40-50	154	11.62	0.280	0.820	0.12	0.280	0.04-0.05
6	50-60	101	7.62	0.230	1.050	0.08	0.230	0.05-0.06
7	60-80	132	9.96	0.380	1.430	0.10	0.380	0.06-0.08
8	80-100	104	7.85	0.380	1.810	0.08	0.380	0.08-0.10
9	100-120	56	4.23	0.250	2.070	0.04	0.250	0.10-0.12
10	120-140	45	3.40	0.240	2.310	0.03	0.240	0.12-0.14
11	140-160	28	2.11	0.170	2.480	0.02	0.170	0.14-0.16
12	160-180	18	1.36	0.130	2.610	0.01	0.130	0.16-0.18
13	180-200	16	1.21	0.130	2.730	0.01	0.130	0.18-0.20
14	200-220	11	0.83	0.100	2.830	0.01	0.100	0.20-0.22
15	220-240	6	0.45	0.060	2.890	0.00	0.060	0.22-0.24
16	240-260	3	0.23	0.030	2.920	0.00	0.030	0.24-0.26
17	260-280	4	0.30	0.050	2.960	0.00	0.050	0.26-0.28
18	280-300	1	0.08	0.010	2.980	0.00	0.010	0.28-0.30
19	300-350	11	0.83	0.140	3.120	0.01	0.140	0.30-0.35
20	350-400	4	0.30	0.060	3.180	0.00	0.060	0.35-0.40
21	400-450	5	0.38	0.090	3.270	0.00	0.090	0.40-0.45
22	450-500	5	0.38	0.100	3.370	0.00	0.100	0.45.0.50
23	500-1000	13	0.98	0.400	3.390	0.01	0.400	0.50-1.00
24	1000-1500	5	0.38	0.270	4.040	0.00	0.270	1.00-1.50
25	1500-2000	2	0.15	0.140	4.170	0.00	0.140	1.50-2.00
26	2000-2500	0	0.00	0.000	4.170	0.00	0.000	2.00-2.50
27	2500-3000	0	0.00	0.000	4.170	0.00	0.000	2.50-3.00
28	3000-4000	0	0.00	0.000	4.170	0.00	0.000	3.00-4.00
						1325		

Air Content (%):	4.17
Specific Surface (mm^{-1}):	52.63
Spacing Factor (mm):	0.102
Void Frequency (mm^{-1}):	0.550
Average Chord Length (mm):	0.076
Paste to Air Ratio:	6.91

PROOVE it

ASTM C 1202-97

TEST CO.

File name = Prooveit user logo.jpg located in application directory.

Test-compagny
Testing street 45
CompagnyCity
Some Country

Your own logo.
size=20x80mm

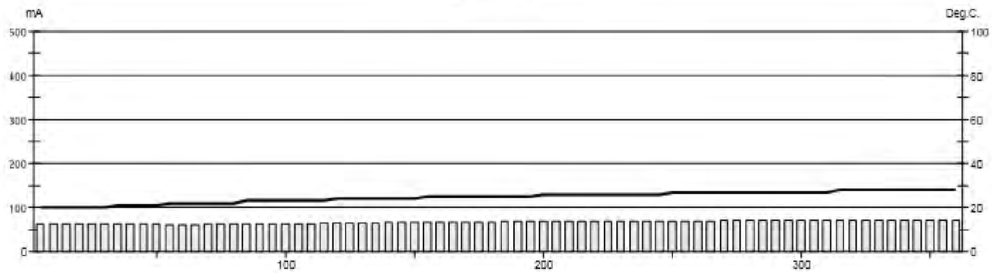
GERMANN INSTRUMENTS

DENMARK
Phone: +45 3967 7117
Fax: +45 3967 3167

USA
Phone: (847)329-9999
Fax: (847)329-8888

Test report

Voltage Used:	60
Testing time:	06:00 hour
Charge passed:	1448
Adjusted Charge passed:	1256
Permeability class:	Low
Instrument number:	023907
Channel number:	1
Report date:	10/13/2011
Testing by:	---
Reference:	NY T MIX
Sample diameter:	102
Comment:	---



Time	°C	mA	Time	°C	mA	Time	°C	mA	Time	°C	mA
00:05	20	62.1	01:35	23	62.4	03:05	25	68.2	04:35	27	70.6
00:10	20	62.9	01:40	23	62.5	03:10	25	68.2	04:40	27	70.7
00:15	20	62.2	01:45	23	62.8	03:15	25	68.7	04:45	27	70.8
00:20	20	62.3	01:50	23	63.5	03:20	26	68.7	04:50	27	70.9
00:25	20	62.6	01:55	23	64.3	03:25	26	68.7	04:55	27	71.0
00:30	20	63.3	02:00	24	64.8	03:30	26	69.0	05:00	27	71.1
00:35	21	63.1	02:05	24	65.2	03:35	26	69.1	05:05	27	71.1
00:40	21	62.3	02:10	24	65.5	03:40	26	69.2	05:10	27	71.3
00:45	21	61.9	02:15	24	65.6	03:45	26	69.4	05:15	28	71.3
00:50	21	61.5	02:20	24	66.2	03:50	26	69.6	05:20	28	71.4
00:55	22	61.0	02:25	24	66.3	03:55	26	69.6	05:25	28	71.4
01:00	22	61.3	02:30	24	66.5	04:00	26	69.7	05:30	28	71.5
01:05	22	61.3	02:35	25	66.9	04:05	26	69.9	05:35	28	71.6
01:10	22	61.4	02:40	25	66.9	04:10	27	70.0	05:40	28	71.7
01:15	22	61.7	02:45	25	67.3	04:15	27	70.0	05:45	28	71.6
01:20	22	61.6	02:50	25	67.5	04:20	27	70.1	05:50	28	71.7
01:25	23	61.6	02:55	25	67.7	04:25	27	70.3	05:55	28	71.7
01:30	23	62.1	03:00	25	67.8	04:30	27	70.5	06:00	28	71.8

PROOVE it

ASTM C 1202-97

Test-compagny
Testing street 45
CompagnyCity
Some Country

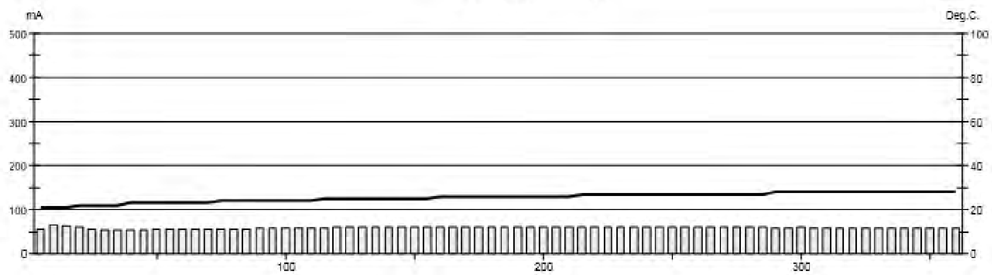
GERMANN INSTRUMENTS

DENMARK

USA

Test report

Voltage Used:	60
Testing time:	06:00 hour
Charge passed:	1268
Adjusted Charge passed:	1100
Permeability class:	Low
Instrument number:	023907
Channel number:	2
Report date:	10/13/2011
Testing by:	---
Reference:	NY TMIX
Sample diameter:	102
Comment:	---



Time	°C	mA	Time	°C	mA	Time	°C	mA	Time	°C	mA
00:05	21	55.3	01:35	24	57.8	03:05	26	60.1	04:35	27	59.5
00:10	21	64.1	01:40	24	58.0	03:10	26	59.9	04:40	27	59.8
00:15	21	62.4	01:45	24	58.2	03:15	26	59.8	04:45	27	59.3
00:20	22	60.2	01:50	24	58.3	03:20	26	60.2	04:50	28	58.9
00:25	22	55.8	01:55	25	58.7	03:25	26	60.2	04:55	28	58.8
00:30	22	54.4	02:00	25	59.2	03:30	26	60.1	05:00	28	59.2
00:35	22	53.8	02:05	25	59.4	03:35	27	60.3	05:05	28	59.1
00:40	23	54.0	02:10	25	59.3	03:40	27	60.5	05:10	28	59.1
00:45	23	54.4	02:15	25	59.4	03:45	27	60.4	05:15	28	58.9
00:50	23	55.2	02:20	25	59.8	03:50	27	60.2	05:20	28	58.9
00:55	23	55.6	02:25	25	59.6	03:55	27	60.1	05:25	28	58.5
01:00	23	55.4	02:30	25	59.8	04:00	27	59.9	05:30	28	58.3
01:05	23	55.8	02:35	25	60.1	04:05	27	59.6	05:35	28	58.4
01:10	23	56.2	02:40	26	60.1	04:10	27	59.5	05:40	28	58.5
01:15	24	56.6	02:45	26	60.4	04:15	27	59.7	05:45	28	58.8
01:20	24	56.8	02:50	26	60.2	04:20	27	59.6	05:50	28	58.8
01:25	24	56.9	02:55	26	60.0	04:25	27	59.6	05:55	28	58.7
01:30	24	57.5	03:00	26	60.3	04:30	27	59.4	06:00	28	58.7

APPENDIX H. FIELD APPLICATION OF TERNARY MIXTURES: CONSTRUCTION OF A BRIDGE DECK IN PENNSYLVANIA

State Report
July 2010

Research Team
Peter Taylor
Paul Tikalsky
Kejin Wang
Gary Fick
Xuhao Wang

Sponsored through
Federal Highway Administration DTFH61-06-H-00011 Work Plan 19
FHWA Pooled Fund Study TPF-5(117): California, Illinois, Iowa (lead state), Kansas, Mississippi, New Hampshire, Oklahoma, Pennsylvania, Utah, Wisconsin; American Coal Ash Association, American Concrete Pavement Association, Headwaters Resources, Portland Cement Association, Slag Cement Association

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(InTrans Project 09-361)

A report from
National Concrete Pavement Technology Center
Iowa State University
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ACKNOWLEDGMENTS

The research team at the National Concrete Pavement Technology Center at Iowa State University sincerely thanks the Pennsylvania Department of Transportation for their cooperation, as well as Plum Contracting Company and New Enterprise Stone & Lime Co., Inc, for supplying the equipment and materials.

INTRODUCTION

This document is a report of the activities and observations of a research team that performed on-site testing of a ternary mixture placed on a State Road 36, section 20, bridge deck in Pennsylvania. The cementitious system comprised a Type I/II cement, Grade 100 slag cement, and Class F fly ash. The purpose of this research project is a comprehensive study of how supplementary cementitious materials can be used to improve the performance of concrete mixtures when used in ternary blends.

This is the third phase of a project that intends to provide consulting to states and contractors on the use and field management of ternary mixtures. A state-of-the-art 44 ft portland cement concrete (PCC) mobile laboratory equipped for on-site cement and concrete testing was provided by the National Concrete Pavement Technology Center (National CP Tech Center) to collect data and field observations.

PROJECT INFORMATION

- Project No. ECMS#21899
- Roaring Spring, Blair County, New07A42&07B42
- Contractor: Plum Contracting
- State Route 36, section 20
- Bridge deck placement (1 span: structural steel girders with concrete deck) (Figure 1)

Figure 1. State Route 36 Section 20 bridge deck

SITE LOCATION

An area at the bridge site was prepared by the contractor for the PCC mobile lab. The location of the project and mobile lab is shown in Figure 2.

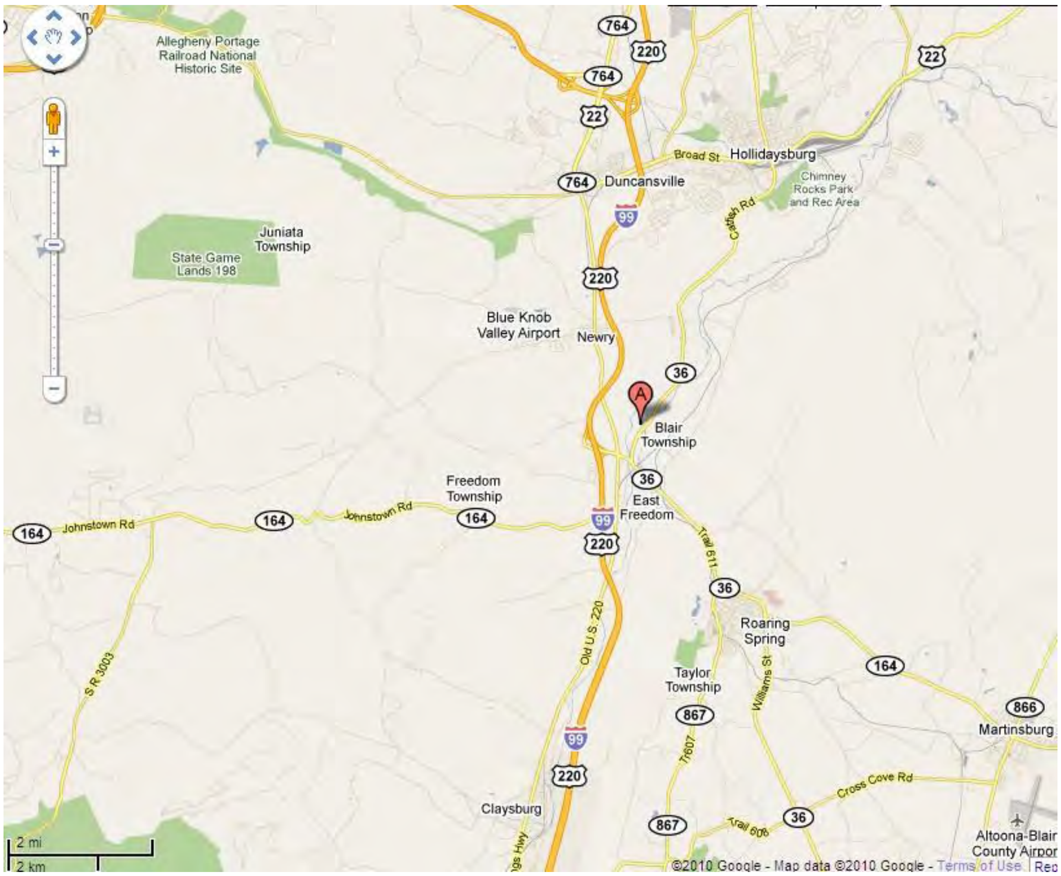


Figure 2. Project and mobile lab location

SAMPLING AND TESTING ACTIVITIES

The mobile lab arrived on site on July 13, 2010. Concrete placement, sampling, and testing took place on July 14, 2010. Hardened samples were transported to Iowa State University on July 16, 2010, for further testing. The following tests were conducted either in the field or in the laboratory:

- Calorimetry test (ASTM C 1679)
- Slump, unit weight, temperature, and air content of fresh concrete: 2 tests (ASTM C 143, ASTM C 138, ASTM C 231)
- Microwave w/c ratio: 2 tests
- Initial set and final set: 1 test (ASTM C 403)
- Compressive strength, splitting tensile strength, static modulus of elasticity: 4 in. x 8 in. cylinders at 1 day, 3 days, 7 days, 28 days, and 56 days (ASTM C 39, ASTM C

496, ASTM C 469)
- Rapid chloride permeability: 4 in. x 8 in. cylinders at 56 days (ASTM C 1202)
- Porosity analysis (boil test) of hardened concrete: 4 in. x 8 in. cylinders (ASTM C 642)
- Salt scaling: 3 samples (ASTM C 672)
- Free shrinkage test: 4 beams (ASTM C 157)
- Restrained rings: 4 samples (ASTM C 1581)
- Two i-buttons are buried on the top and bottom layers of reinforcement to investigate maturity of concrete (ASTM C 1074)

OBSERVATIONS OF THE RESEARCH TEAM

The following observations were made in the field work:

- Concrete paving: Contractors were using Bid-Well 3600 typical form riding bridge deck paver for a rural bridge deck. The bridge deck was 8 in. deep with a 2.5 in. cover on the top layer of reinforcement and a 1 in. cover on the bottom layer of reinforcement.
- All concrete came from a fixed batch plant and was delivered to the job site in transit mix trucks or front-ready-mix trucks. A front-ready-mix truck was used to transfer material from a central mixed concrete to a rear-ready-mix truck. The concrete was placed using a conveyor belt.
- The mix design was from New Enterprise Stone & Lime Co., Inc, and approved by the Pennsylvania Department of Transportation (PennDOT). The mix proportions are given in the project data section.
- Cementitious materials include Type I/II portland cement (Holcim-Hagerstown, Maryland), Grade 100 slag cement (GranCem-Camden, New Jersey), and Class F fly ash (Headwaters-Sammis Plant). Dolomitic limestone coarse aggregate (Class A57) was used, and the fine aggregate was sandstone. An MBVR air entraining agent, Glenium 3030 water reducer, and 100XR retarder were used as chemical admixtures.
- According to the workability factor and coarseness factor graph (see Project Data section of this report), the combined aggregate gradation for this project fell in the well-graded region. Similarly, the aggregate gradation indicated a well-graded system.
- The weather conditions at the job site recorded by the PCC mobile lab are given in Table 1 below and graphically in Figures 3 through 5. The relative humidity ranged from 70% to 82%; the ambient temperature ranged from 69˚F to 77.4˚F; the wind speed varied from 0 mph to 7 mph; and the concrete temperature ranged from 73˚F to 80.4˚F during the recorded period.
- The fresh concrete tests included slump cone, unit weight, and water/cementitious materials ratio by microwave. The National CP Tech Center crew carried out tests for two sets of specimens; the PennDOT crew ran tests for six. Slump result varied from 3.0 in. to 6.5 in. (performed by the PennDOT). The National CP Tech Center crew performed unit weight tests in duplicate: the values were 147.3 lb/ft^3 and 147.1 lb/ft^3. The water-cementitious materials ratios obtained from microwave water-cementitious ratio tests were 0.50 and 0.46. The design value was 0.41. The data are provided in

the Project Data section.

- The air content varied from 5.0% to 7.1%, with an average value of 6.0% based on eight sets of testing. The specified minimum was 6%.
- Setting time of the mix was determined as a single measurement: initial set occurred at 3.63 hours and the final set was achieved at 10.96 hours (see Project Data section).

Table 1. Ambient conditions of S.R. 36 Section 20 bridge deck project

PA - Ternary Mixtures

S.R. 36 Section 20 Bridge Deck

Sample Information & Identification			Environmental Conditions			
Sample Date	Sample Time	Sample Comments	Relative Humidity (%)	Ambient Temp. (˚F)	Wind Speed (mph)	Conc. Temp. (probe) (˚F)
14-Jul-10	7:20 AM	cp tech center sample taken at truck discharge	82.0	69.0	3.0	80.4
14-Jul-10	8:05 AM	PennDOT sample taken at pump discharge (quality control)	70.0	77.4	0.0	73.0
14-Jul-10	8:50 AM	PennDOT sample taken at pump discharge (acceptance test/quality control test)	75.0	75.4	0.0	74.0
14-Jul-10	8:50 AM	PennDOT sample taken at pump discharge (acceptance test/quality control test)	75.0	75.4	0.0	80.0
14-Jul-10	9:27 AM	PennDOT sample taken at pump discharge (quality assurance test)	77.0	74.6	0.0	75.0
14-Jul-10	9:30 AM	cp tech center sample taken at truck discharge	78.0	72.0	7.0	78.8
14-Jul-10	10:01 AM	PennDOT sample taken at pump discharge (quality control)	79.0	73.9	0.0	79.0
14-Jul-10	10:38 AM	PennDOT sample taken at pump discharge (quality control)	79.0	73.2	0.0	79.0

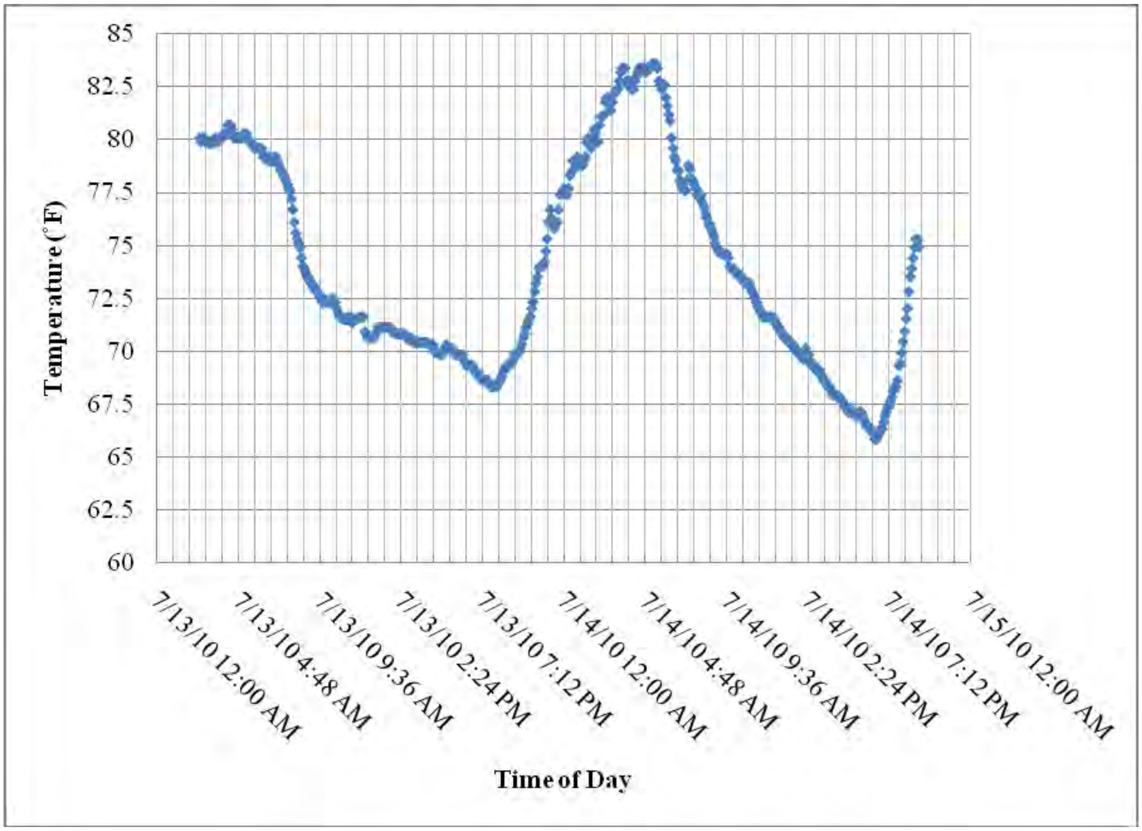


Figure 3. Ambient temperature versus time of day

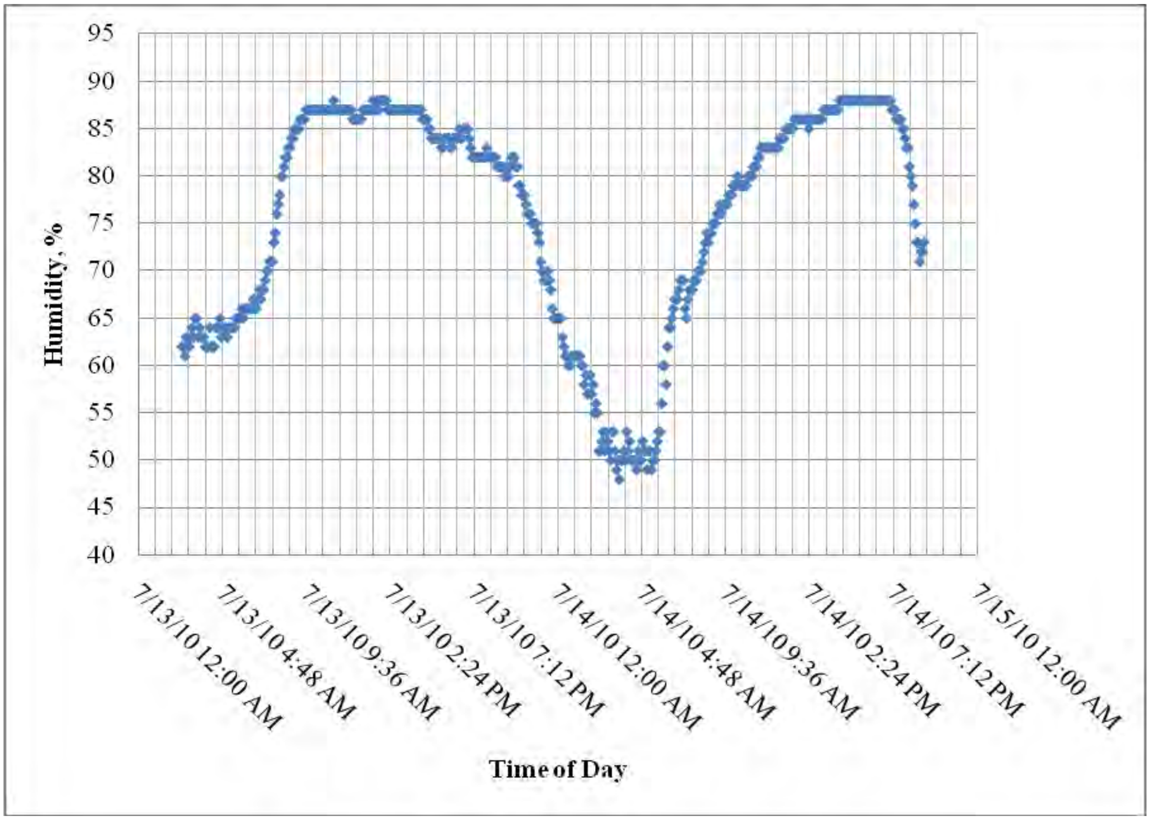


Figure 4. Relative humidity versus time of day

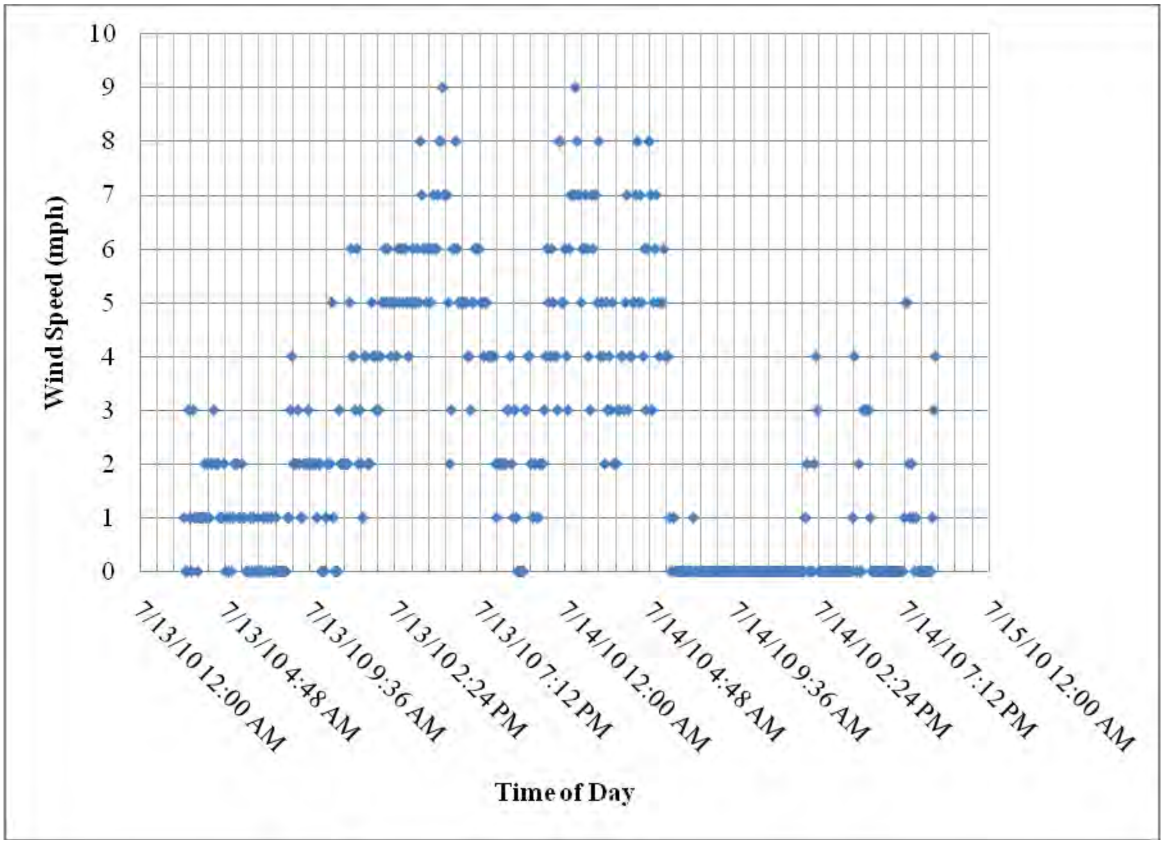


Figure 5. Wind speed versus time of day

- Figures 6 through 13 illustrate some activities during the testing process.

Figure 6. Concrete being tested by PennDOT technicians

Figure 7. Concrete being spread by construction crews

Figure 8. Concrete being tested by National CP Tech technician

Figure 9. Concrete being tested by PCC mobile lab

Figure 10. Concrete being finished

Figure 11. Two i-buttons being embeded on site

Figure 12. Concrete being vibrated

Figure 13. Concrete temperature being tested by sensor

- The feedback from PennDOT on workability and durability was positive—nly some minor cracking over the pier at four months after bridge deck being constructed (Figures 14 and 15).

Figure 14. Bridge deck surface four months after construction

Figure 15. Bridge deck surface four months after construction

- The rapid chloride permeability test measures the electrical conductance of a concrete sample as its resistance to chloride ion penetration. The test results shown in Table 2 indicate a classification of "very low" chloride permeability according to ASTM C1202.

- The compressive strengths at 7 and 28 days and the 28/7-day strength development ratio is reported in Table 2.

Table 2. Properties of hardened concrete

Tests	Results		
7-day compressive strength, psi	4240		
28-day compressive strength, psi	4700		
Rapid chloride permeability, coulombs	Sample 1 1860	Sample 2 1731	Average 1796
Strength development 28/7-day fc ratio	1.11		
Shrinkage microstrain @ 28 days, in/in	612.5		
Average stress rate by restrained ring test, psi/day	55.35		

- Two i-buttons were attached to reinforcing steel before the concrete placement: one was placed on the top layer of reinforcement steel and the other was placed on the bottom layer of reinforcement steel. The rate of cement hydration is dependent on the temperature and the time. Maturity is used to monitor the cement hydration progress as a function of time and temperature. The temperature of concrete was recorded for up to 28 hours. The concrete temperature over time is plotted in Figure 16(a) and concrete maturity curve based on the Nurse–Saul method (ASTM C 1074) is generated in Figure 16(b).

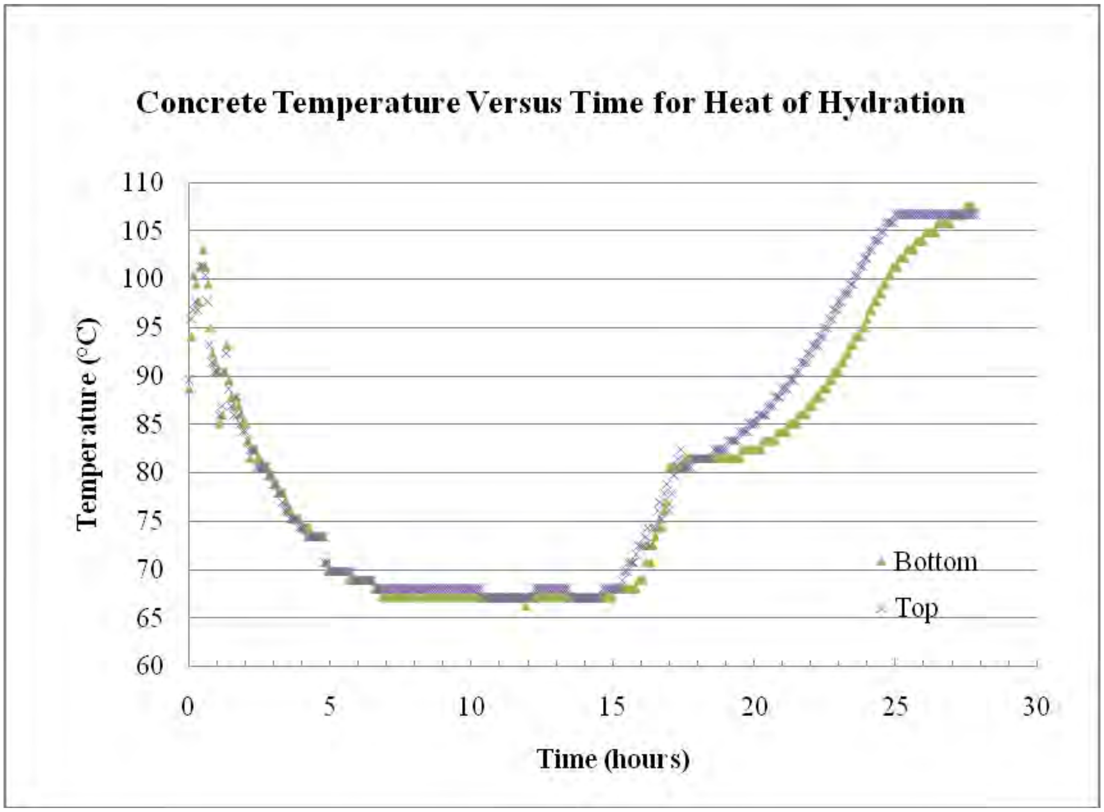


Figure 16(a). Concrete temperatures versus time for heat of hydration

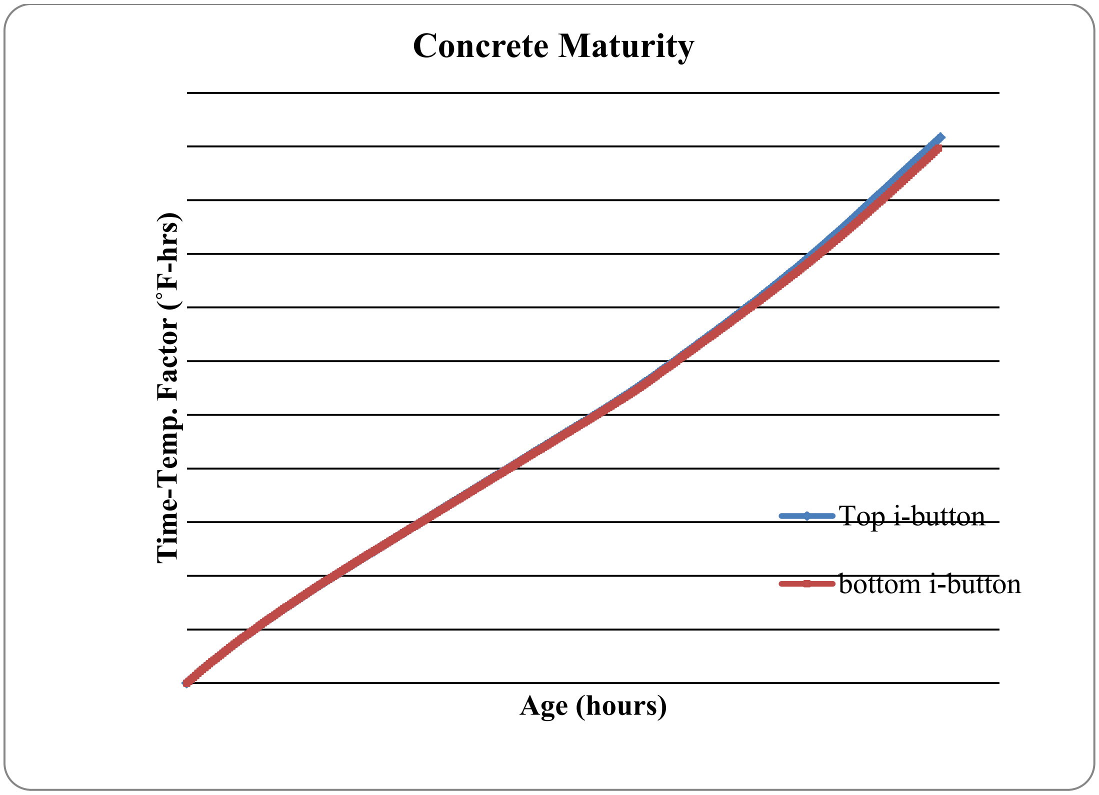


Figure 16(b). Concrete maturity

- Compressive strength, splitting tensile strength, and modulus of elasticity results (ASTM C 39, ASTM C 496, and ASTM C 469) are given in Table 3 and also plotted in Figures 17 through 19.

Table 3. Summation of strength and modulus of elasticity

Location	Age, Days	Compressive Strength, psi	Splitting Tensile Strength, psi	Modulus Of Elasticity, psi
PA	1	2,010	291	3.95E+06
	3	3,430	281	4.45E+06
	7	4,240	375	4.60E+06
	28	4,700	488	5.25E+06
	56	5,620	497	5.60E+06

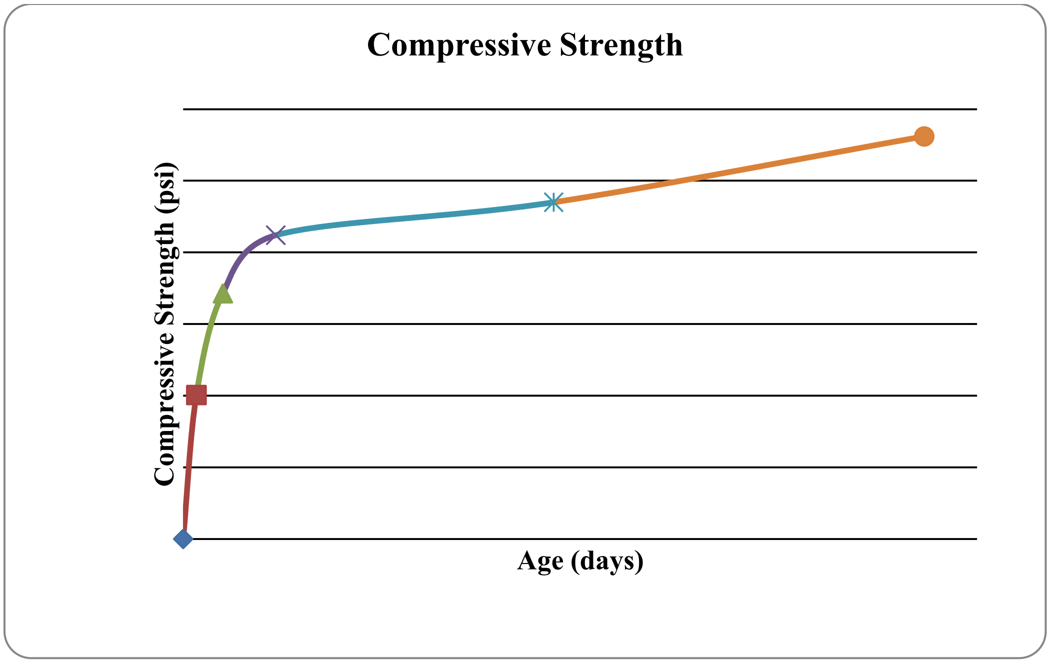


Figure 16. Compressive strength development with time

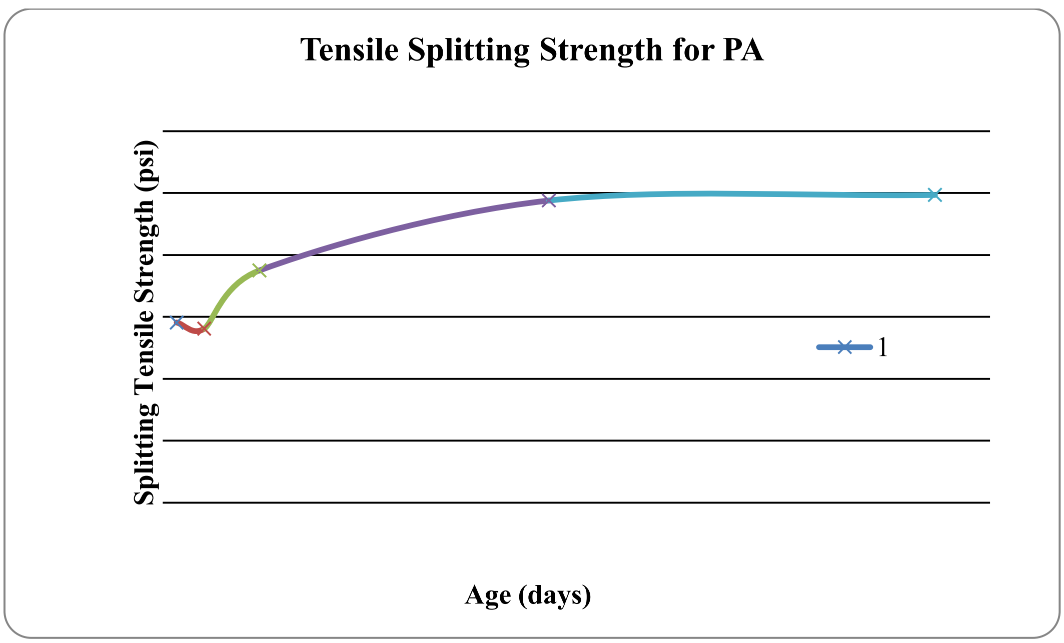


Figure 17. Tensile splitting strength development with time

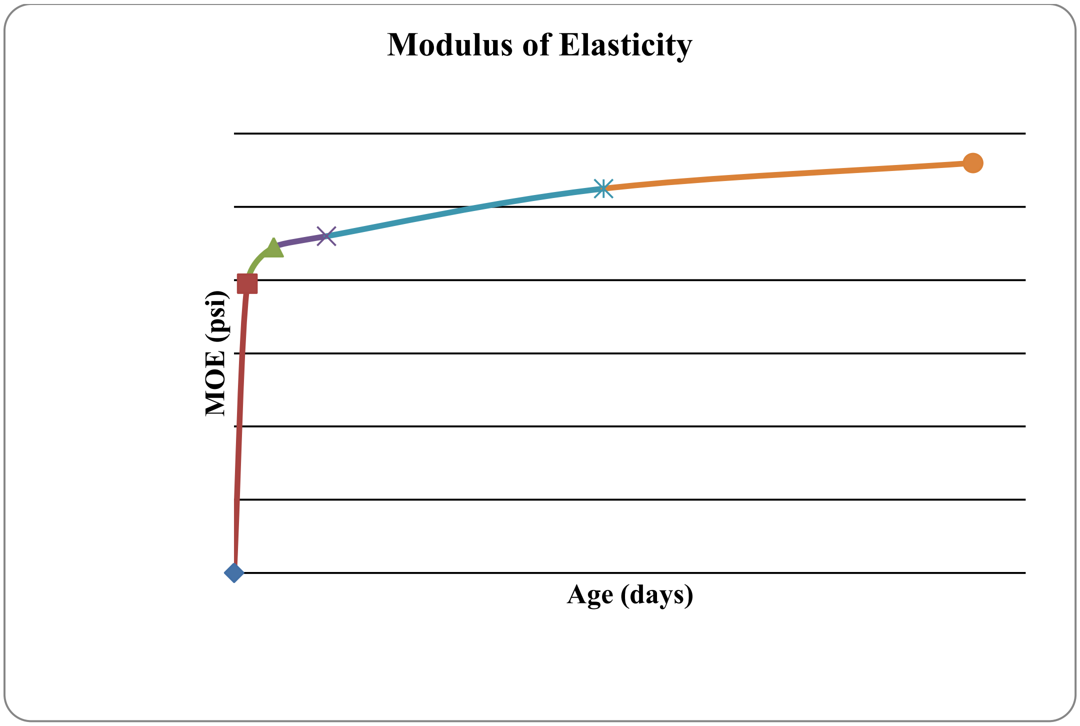


Figure 19. Modulus of elasticity development with time

- A free shrinkage test (ASTM C 157) was conducted in the laboratory. Three beams were wet cured for seven days and then moved to a dry room at 23˚C and 50% relative humidity. The drying shrinkage results are given in Table 4 and also plotted in Figure 20.

Table 4. Free shrinkage test results

PA Project Free Shrinkage Test (ASTM C 157)						
Dry Time	**Beam 1 Change%**	**Beam 2 Change %**	**Beam 3 Change %**	**Beam 4 Change %**	**Average**	**Microstrain**
1	-0.002	-0.005	-0.004	-0.003	-0.003	-35
4	-0.010	-0.012	-0.010	-0.013	-0.011	-112.5
7	-0.019	-0.020	-0.019	-0.021	-0.020	-197.5
14	-0.026	-0.025	-0.031	-0.029	-0.028	-277.5
28	-0.061	-0.062	-0.064	-0.058	-0.061	-612.5
56	-0.070	-0.068	-0.065	-0.070	-0.068	-682.5

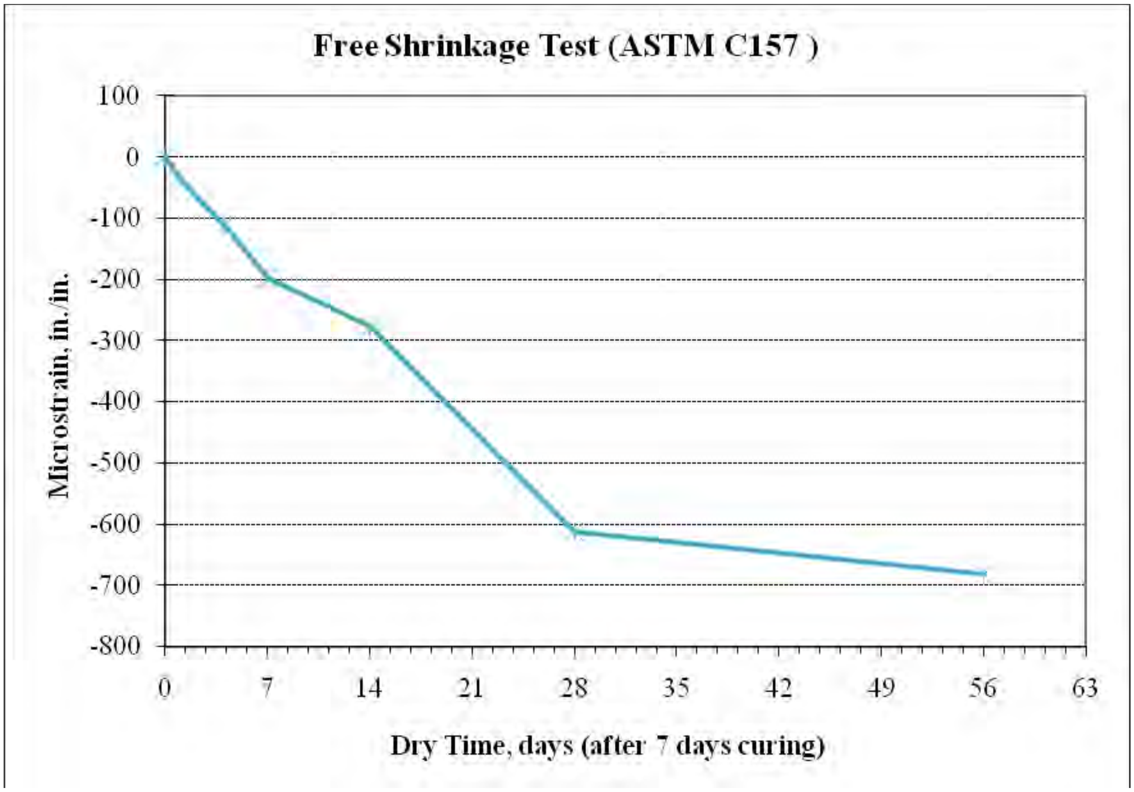


Figure 20. Free shrinkage of prisms (ASTM C 157)

- A restrained shrinkage test was conducted based on ASTM C 1581. Four rings were cast. The rings were demolded and the top surface was covered with paraffin wax 24 hours from casting. The rings were allowed to dry at 23˚C and 50% relative humidity immediately after demolding. Strains in the steel rings were recorded every 10 minutes for up to 28 days, or until the concrete cracked. The configuration of restrained concrete rings is shown in Figure 21. The cracking potential is listed in Table 5 and shown graphically in Figure 22. The cracking potential is classified as “moderate high,” based on the average stress rate.

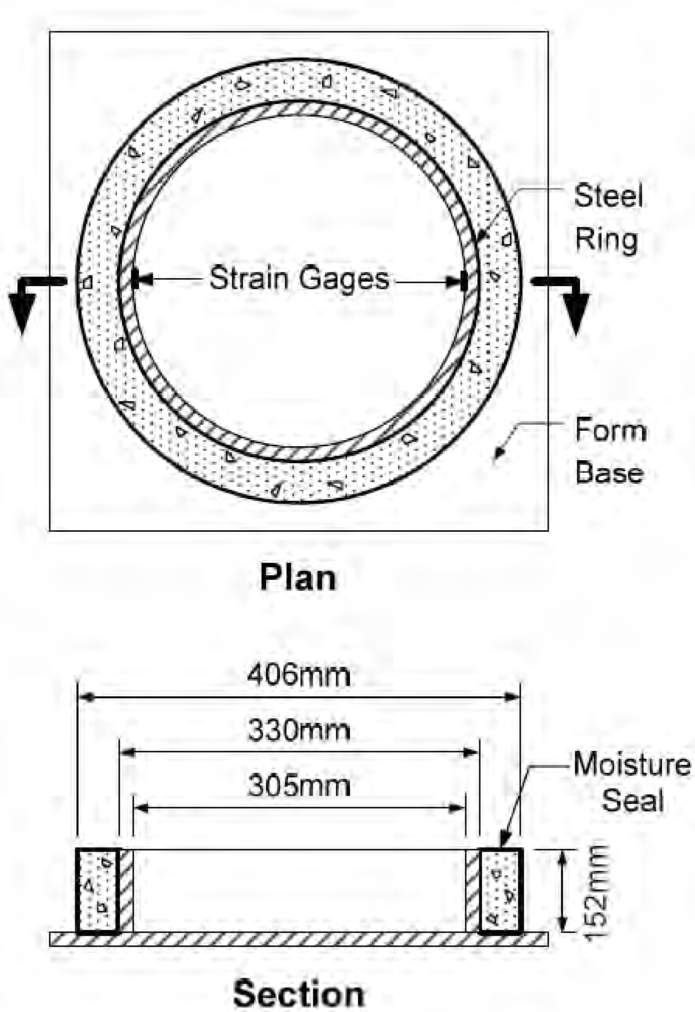


Figure 21. Configuration of restrained concrete ring samples

Table 5. Cracking potential and average stress rate (ASTM C 1581)

Cracking Potential for PA Project (ASTM C 1581)			
	Ring 1	Ring 2	Ring 3
Strain rate factor (in./in.x10^{-6})/hours$^{1/2}$	-7.86	-5.56	-7.37
G (psi)	10.47x106	10.47x106	10.47x106
Absolute value of α_{avg} (in./in.10^{-6})/day$^{1/2}$		33.95	
Elapsed time, tr (hours)	270.0	270.0	210.0
Elapsed time, tr (days)	11.3	11.3	8.8
Stress rate, q (psi/day) $q=GI\alpha_{avg}I/2\sqrt{t_r}$	53.0	53.0	60.1
Average stress rate, q (psi/day) $q=GI\alpha_{avg}I/2\sqrt{t_r}$		**55.35**	
Potential for cracking classification (ASTM 1581)		**High (50≤ q)**	

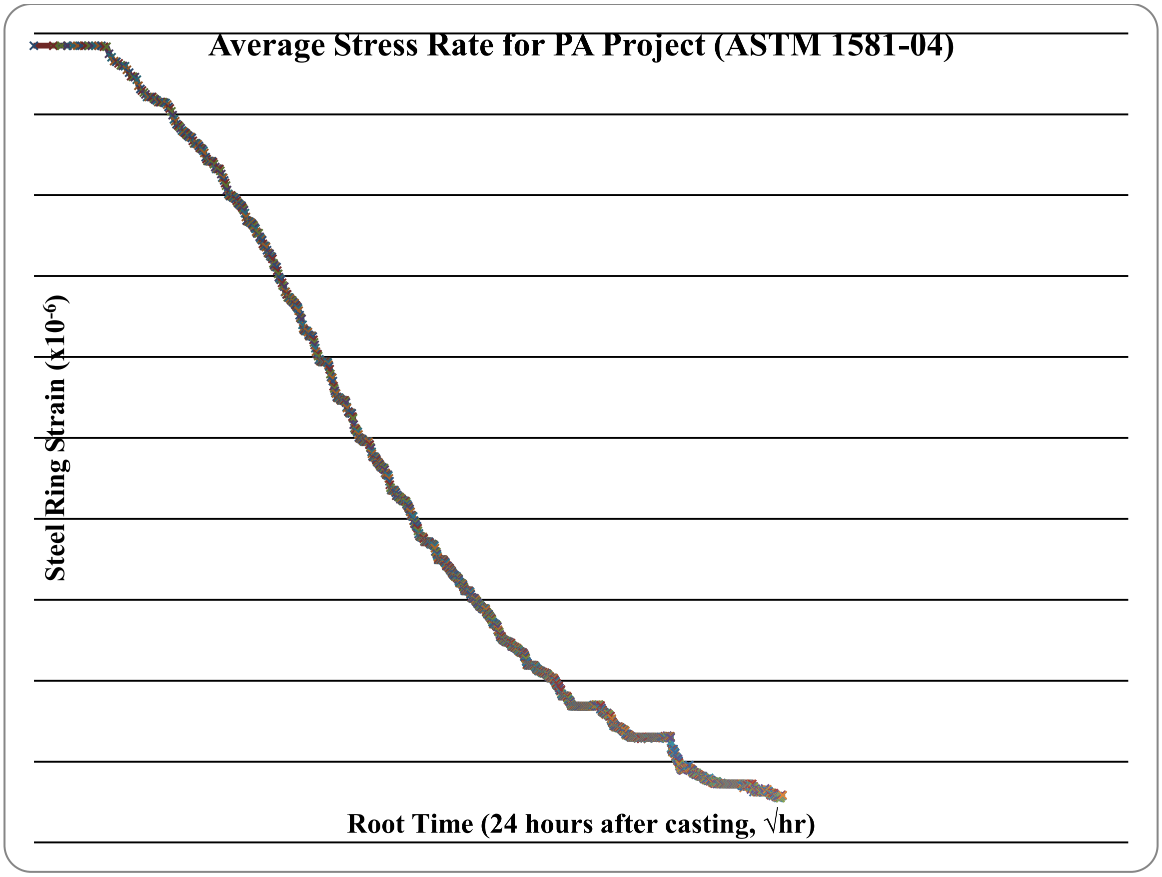


Figure 22. Strains of steel rings resulting from concrete shrinkage

- A salt scaling test (ASTM C 672) was performed: the specimens were subjected to 16 to18 hours of freezing and then allowed to thaw at 23 ± 2.0˚C and a relative humidity of 45 to 55% for 6 to 8 hours. A 4 % calcium chloride solution was used for conditioning. A visual rating was done every 5 freeze-thaw cycles for up to 50 cycles. The surface was rated on a scale of 0 to 5, with 0 having no scaling, 1 having very slight scaling of 3 mm depth maximum without coarse aggregate visible, 2 having slight to moderate scaling, 3 having moderate scaling with some coarse aggregate visible, 4 having moderate to severe scaling, and 5 having severe scaling with coarse aggregate visible over entire surface. A photograph after the 50th cycle was taken and is shown in Figure 23. The visual ratings assigned to each specimen for cycles 0, 5, 10, 15, 20, 25, and 50 are given in Table 6.

Table 6. Salt scaling test visual condition of specimen

PA Salt Scaling Samples	Condition of Surface					
	Cycle 5	**Cycle 10**	**Cycle 15**	**Cycle 20**	**Cycle 25**	**Cycle 50**
No. 1	1	1	1	2	2	2
No. 2	1	1	1	2	2	2

No. 3	1	1	1	2	2	2

Figure 23. PA salt scaling sample after 50th freeze-thaw cycle

PROJECT DATA

The following test data are provided for information only; comments and conclusions will be reported in the comprehensive Phase III report of the pooled fund project *Development of Performance Properties of Ternary Mixtures.*

Mix Design & Misc. Info.

General Information

Project:	State Road 36 Section 20, Bridge Deck in Roaring Spring, Blair County, PA
Contractor:	Plum Contracting
Mix Description:	587 lb Cementitious
Mix ID:	ECMS#21899
Date(s) of Placement:	7/14/2010

Cementitious Materials	Source	Type	Spec. Gravity	lb/yd^3	% Replacement by Mass
Portland Cement:	Holcim-Hagerstown, MD.	Tpye I/II	3.150	323	
GGBFS:	GranCem-Camden, NJ (gr-100)	Grade 100	2.900	176	
Fly Ash:	Headwaters-Sammis Plant	Class F	2.400	88	14.99%
Silica Fume:					
Other Pozzolan:					
				587	**lb/yd^3**
				6.2	**sacks/yd^3**

Aggregate Information	Source	Type	Spec. Gravity SSD	Absorption (%)	% Passing #4
Coarse Aggregate:	NESL Roaring Spring	Dolomitic L.S.	2.840	0.32%	2.0%
Intermediate Aggregate #1:					
Intermediate Aggregate #2:					
Fine Aggregate #1:	NESL- Ishman	Sandstone	2.610	0.94%	99.0%

Coarse Aggregate %:	59.4%
Intermediate Aggregate #1%:	
Intermediate Aggregate #2%:	
Fine Aggregate #1 %:	40.6%

Mix Proportion Calculations

Water/Cementitious Materials Ratio:	0.410
Air Content:	6.00%

	Volume (ft^3)	Batch Weights SSD (lb/yd^3)	Spec. Gravity	Absolute Volume (%)
Portland Cement:	1.643	323	3.150	6.088%
GGBFS:	0.973	176	2.900	3.603%
Fly Ash:	0.588	88	2.400	2.177%
Silica Fume:				
Other Pozzolan:				
Coarse Aggregate:	10.882	1,928	2.840	40.314%
Intermediate Aggregate #1:				
Intermediate Aggregate #2:				
Fine Aggregate #1:	7.430	1,210	2.610	27.528%
Water:	3.857	241	1.000	14.289%
Air:	1.620			6.002%
	26.993	**3,966**		**100.000%**
	Unit Weight (lb/ft^3)	**146.9**	**Paste**	**32.158%**
			Mortar	**60.217%**

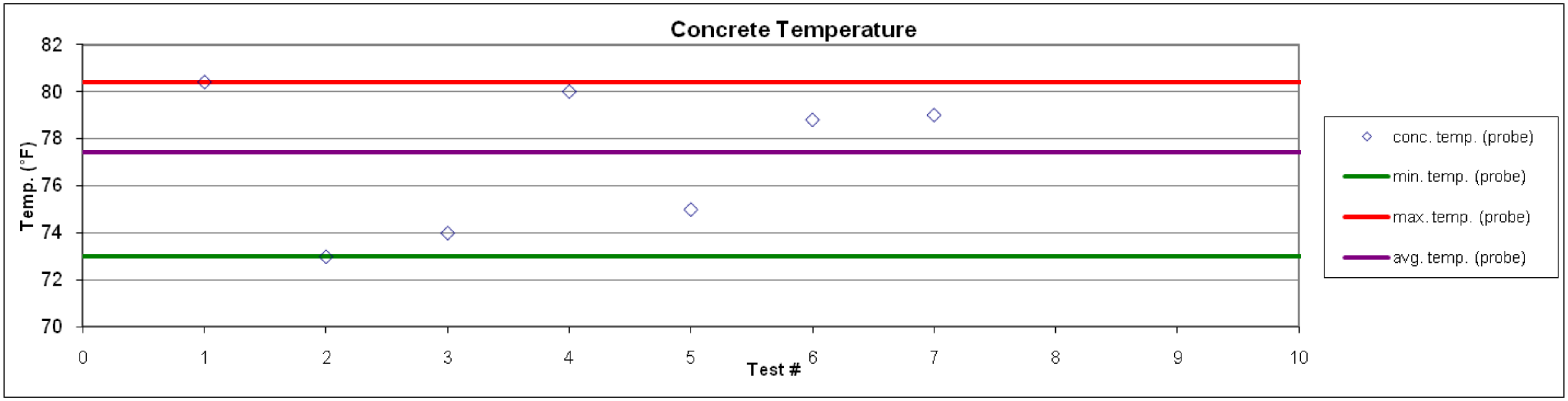
Admixture Information	Source/Description	oz/yd^3	oz/cwt
Air Entraining Admix.:	MBVR AEA	7.04	1.20
Admix. #1:	Glenium 3030 WR	35.22	6.00
Admix. #2:	100XR RE	11.74	2.00
Admix. #3:			

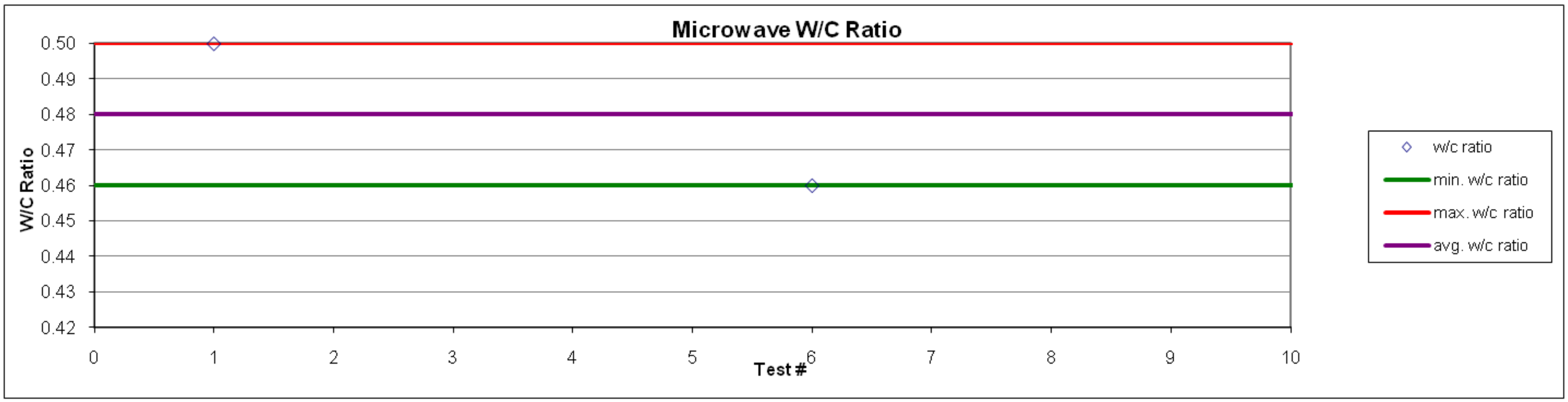
AVA Information	Absolute Volume (%)
Air Free Paste:	26.157%
Air Free Mortar:	54.215%

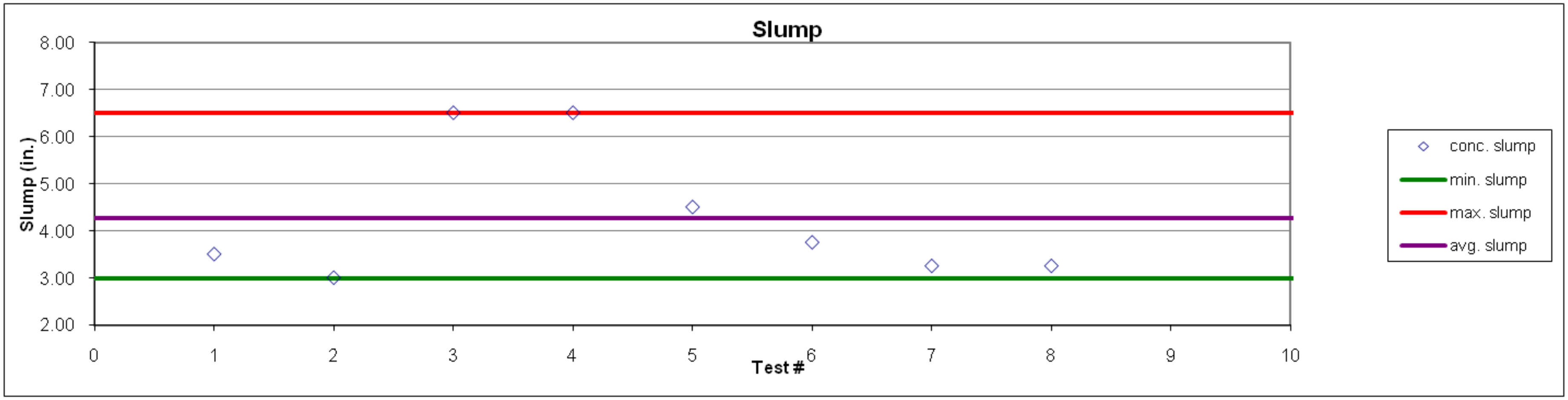
PA - Ternary Mixtures

S.R. 36 Section 20 Bridge Deck

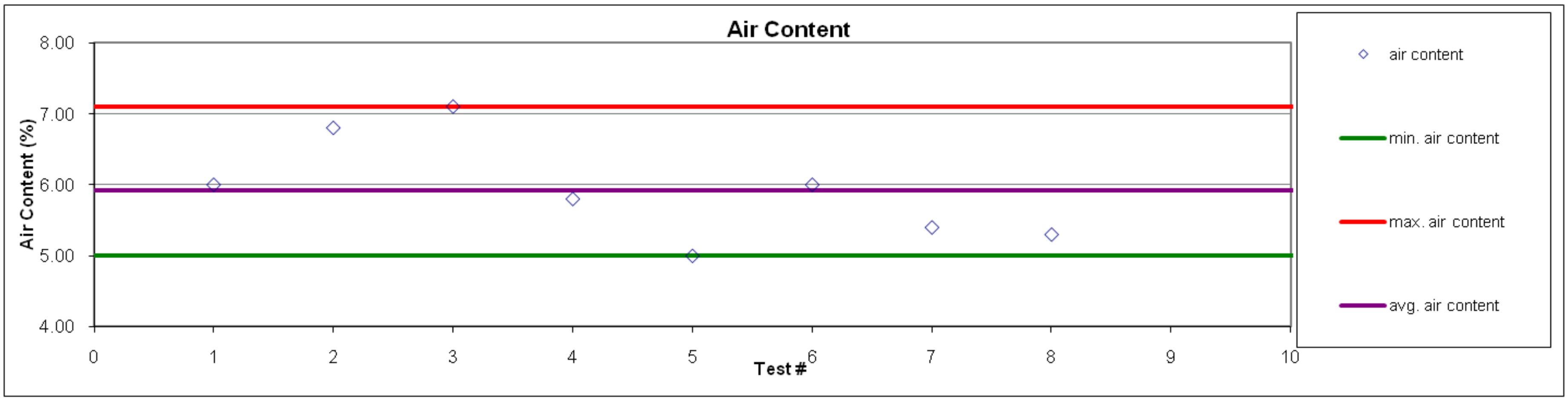
Sample Information & Identification			Environmental Conditions				Fresh Concrete Workability Properties			Pressure Air
Sample Date	Sample Time	Sample Comments	Relative Humidity (%)	Ambient Temp. (˚F)	Wind Speed (mph)	Conc. Temp. (probe) (˚F)	Slump (in)	Unit Weight (lb/ft^3)	Microwave W/C Ratio (%)	% Air Content
14-Jul-10	7:20 AM	cp tech center sample taken at truck discharge	82.0	69.0	3.0	80.4	3.50	147.32	0.50	6.0
14-Jul-10	8:05 AM	PennDOT sample taken at pump discharge (quality control)	70.0	77.4	0.0	73.0	3.00	n/a	n/a	6.8
14-Jul-10	8:50 AM	PennDOT sample taken at pump discharge (acceptance test/quality control test)	75.0	75.4	0.0	74.0	6.50	n/a	n/a	7.1
14-Jul-10	8:50 AM	PennDOT sample taken at pump discharge (acceptance test/quality control test)	75.0	75.4	0.0	80.0	6.50	n/a	n/a	5.8
14-Jul-10	9:27 AM	PennDOT sample taken at pump discharge (quality assurance test)	77.0	74.6	0.0	75.0	4.50	n/a	n/a	5.0
14-Jul-10	9:30 AM	cp tech center sample taken at truck discharge	78.0	72.0	7.0	78.8	3.75	147.08	0.46	6.0
14-Jul-10	10:01 AM	PennDOT sample taken at pump discharge (quality control)	79.0	73.9	0.0	79.0	3.25	n/a	n/a	5.4
14-Jul-10	10:38 AM	PennDOT sample taken at pump discharge (quality control)	79.0	73.2	0.0	79.0	3.25	n/a	n/a	5.3


Concrete Temperature
Temp. (°F)
82
80
78
76
74
72
70
0
1
2
3
4
5
6
7
8
9
10
Test #
conc. temp. (probe)
min. temp. (probe)
max. temp. (probe)
avg. temp. (probe)


Microwave W/C Ratio
W/C Ratio
0.50
0.49
0.48
0.47
0.46
0.45
0.44
0.43
0.42
0
1
2
3
4
5
6
7
8
9
10
Test #
w/c ratio
min. w/c ratio
max. w/c ratio
avg. w/c ratio



Slump
Slump (in.)
8.00
7.00
6.00
5.00
4.00
3.00
2.00
0
1
2
3
4
5
6
7
8
9
10
Test #
conc. slump
min. slump
max. slump
avg. slump



Air Content
Air Content (%)
8.00
7.00
6.00
5.00
4.00
0
1
2
3
4
5
6
7
8
9
10
Test #
air content
min. air content
max. air content
avg. air content

PA - Ternary Mixtures

Sample Information:

Project: SR 36 Section 20, Bridge Deck in Roaring Spring, Blair County, PA

Date: 14-Jul-10

Time: 7:20 AM

Type of Paving: Bridge Deck

Direction of Paving: n/a

Sta: n/a

Latitude:

Longitude:

Mix ID:

Truck IDs:

Sample Location Mark & Comments:

Environmental Conditions:

Dew Point: 63.0

Relative Humidity: 82%

Wind Speed: 3.0

Ambient Temp.: 69.0

Concrete Properties:

Base/Soil Temp. (internal)(ºF):

Base Temp. (surface)(ºF):

Microwave Water Content Samples:

Calorimetry (ADIACAL Cylinders): 4 (7:53 am)

Set-Time (ASTMC403) Mortar Samples:

Cylinder for RCP & Perm. Voids Boil Test: use adiacal

Scaling Blocks: 3

Concrete Temp.(ºF):	80.4
Slump (in.):	3.50
Air Content:	6.0%
Unit Weight (lb/ft^3):	44.6

Compressive, Tensile & MOR Cylinders: 30

Shrinkage Beams: 4

PA - Ternary Mixtures

Sample Information:

Project: SR 36 Section 20, Bridge Deck in Roaring Spring, Blair County, PA

Date: 14-Jul-10

Time: 9:30 AM

Type of Paving: Bridge Deck

Direction of Paving: n/a

Sta: n/a

Latitude:

Longitude:

Mix ID:

Truck IDs:

Sample Location Mark & Comments:

Environmental Conditions:

Dew Point: 64.0

Relative Humidity: 78%

Wind Speed: 7.0

Ambient Temp.: 72.0

Concrete Properties:

Base/Soil Temp. (internal)(ºF):

Base Temp. (surface)(ºF):

Microwave Water Content Samples:

Calorimetry (ADIACAL Cylinders): 4 (10:00am)

Set-Time (ASTMC403) Mortar Samples:

Cylinder for RCP & Perm. Voids Boil Test: use adiacal

Scaling Blocks: n/a

Compressive, Tensile & MOR Cylinders: n/a

Shrinkage Beams: n/a

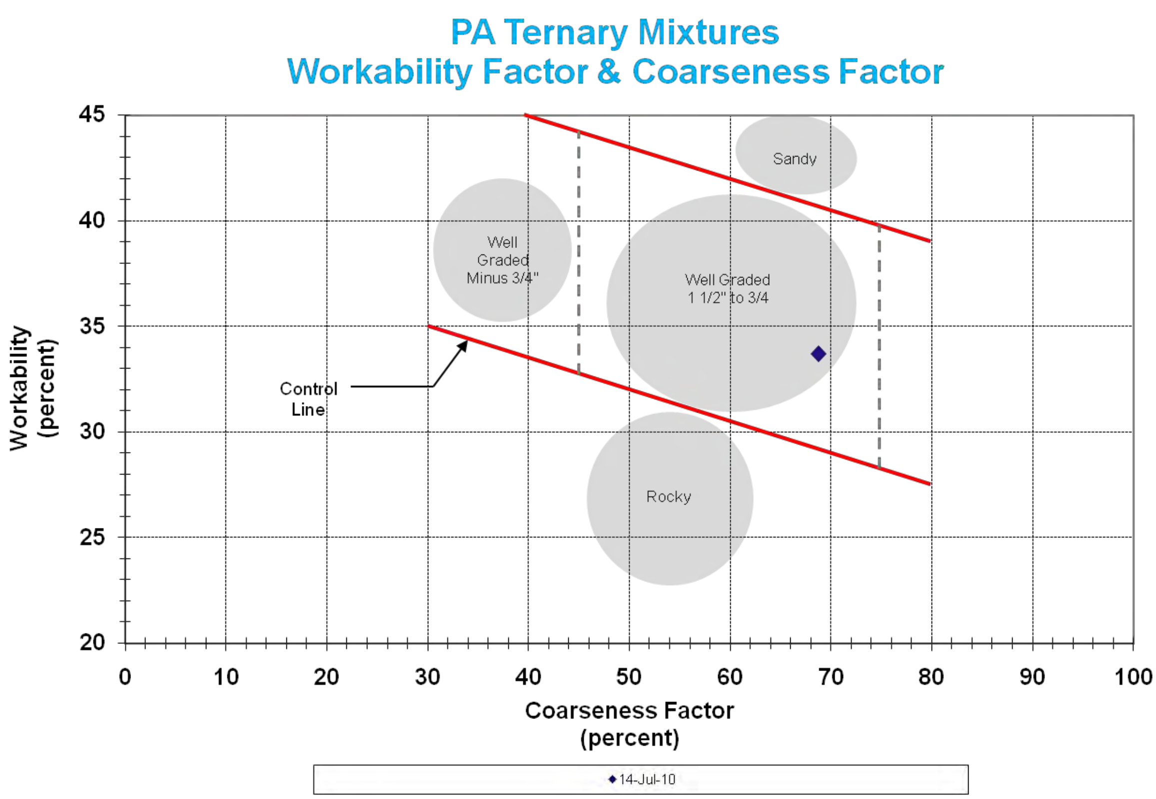
Concrete Temp.(ºF):	78.8
Slump (in.):	3.75
Air Content:	6.0%
Unit Weight (lb/ft^3):	44.6

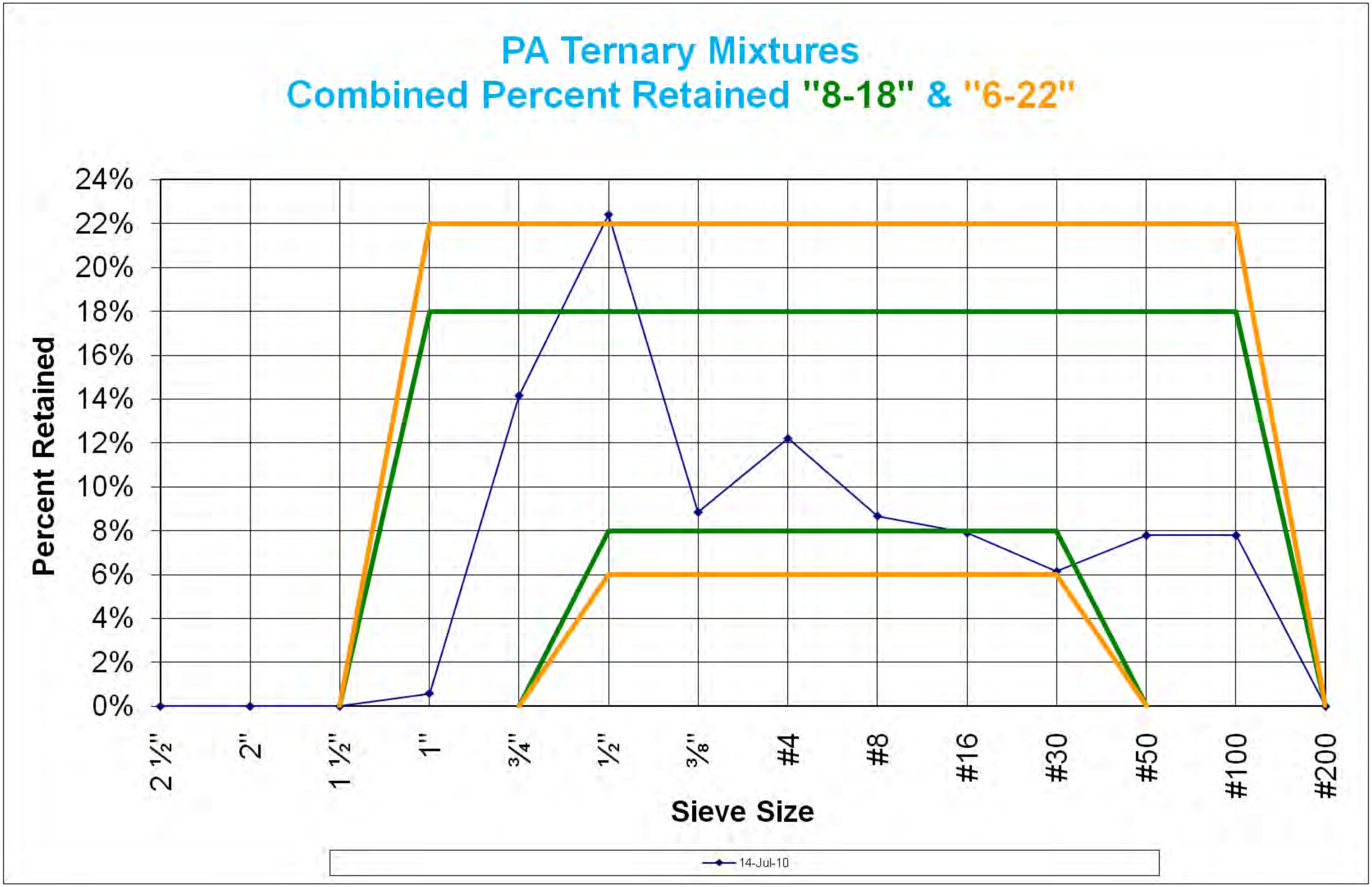
Project: Bridge Deck Paving in Roaring Spring, PA
Mix ID: ECMS#21899
Sample Comments:
Test Date: 14-Jul-10

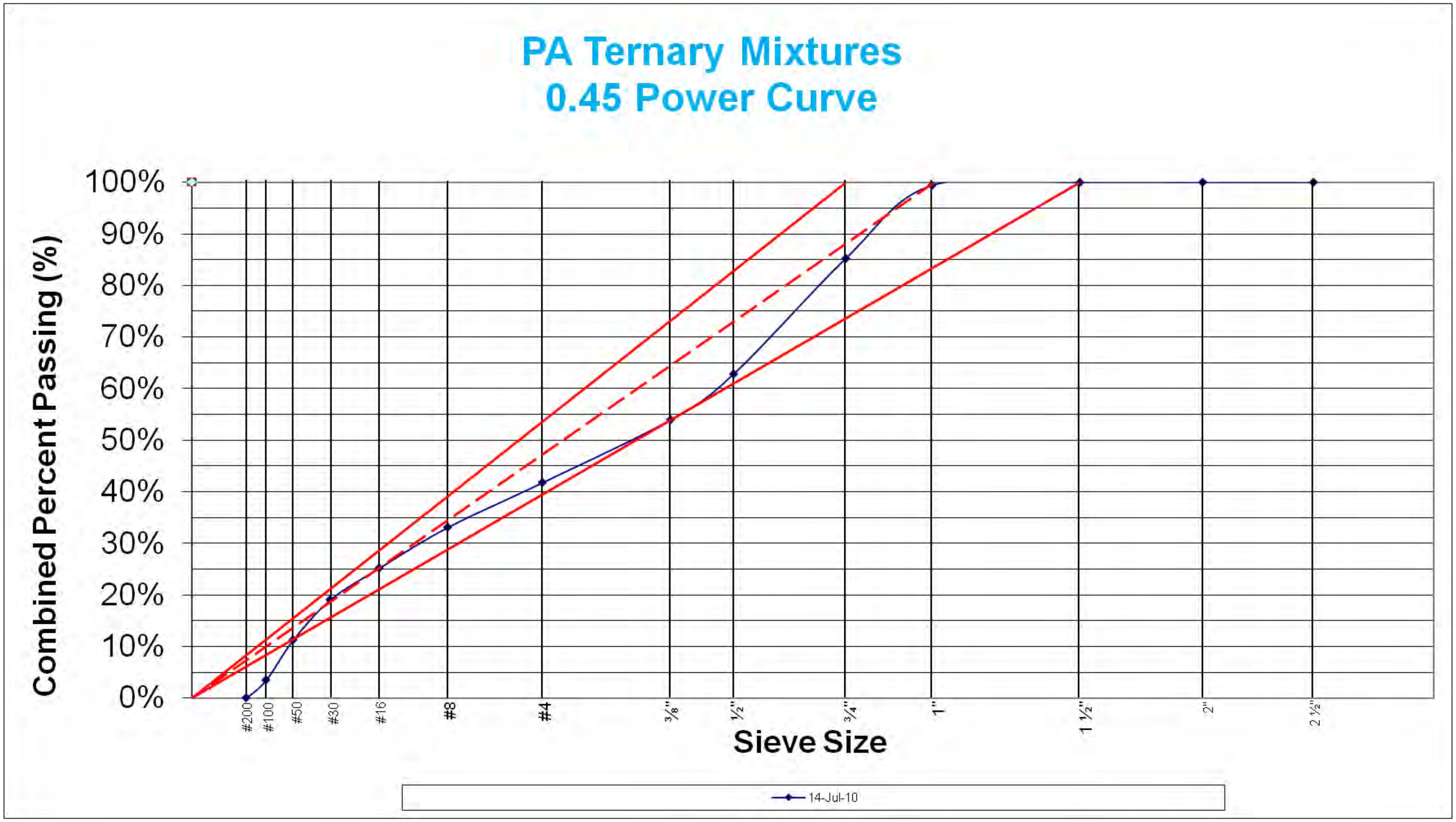
otal Cementitious Material:	587 lb/yd^3			
Agg. Ratios:	59.00%	0.00%	41.00%	100.00%

Sieve	Coarse	Intermediate	Fine #1	Fine #2	Combined % Retained	Combined % Retained On Each Sieve	Combined % Passing
2 ½"	100%	0%	100%		0%	0%	100%
2"	100%	0%	100%		0%	0%	100%
1 ½"	100%	0%	100%		0%	0%	100%
1"	99%	0%	100%		1%	1%	99%
¾"	75%	0%	100%		15%	14%	85%
½"	37%	0%	100%		37%	22%	63%
⅜"	22%	0%	100%		46%	9%	54%
#4	2%	0%	99%		58%	12%	42%
#8	1%	0%	80%		67%	9%	33%
#16	1%	0%	60%		75%	8%	25%
#30	1%	0%	45%		81%	6%	19%
#50	1%	0%	26%		89%	8%	11%
#100	1%	0%	7%		97%	8%	3%
#200					100.0%		0.0%

Workability Factor: **33.7**
Coarseness Factor: **68.8**




PA Ternary Mixtures
Combined Percent Retained "8-18" & "6-22"
Percent Retained
24%
22%
20%
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
2 ½"
2"
1 ½"
1"
¾"
½"
⅜"
#4
#8
#16
#30
#50
#100
#200
Sieve Size
14-Jul-10



PA Ternary Mixtures
0.45 Power Curve
Combined Percent Passing (%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
#200
#100
#50
#30
#16
#8
#4
3/8"
1/2"
3/4"
1"
1 1/2"
2"
2 1/2"
Sieve Size
14-Jul-10

Pennsylvania - Ternary Mixtures

Set Time ASTM C 403

Project: SR 36 Section 20, Bridge Deck in Roaring Spring, Blair County, PA

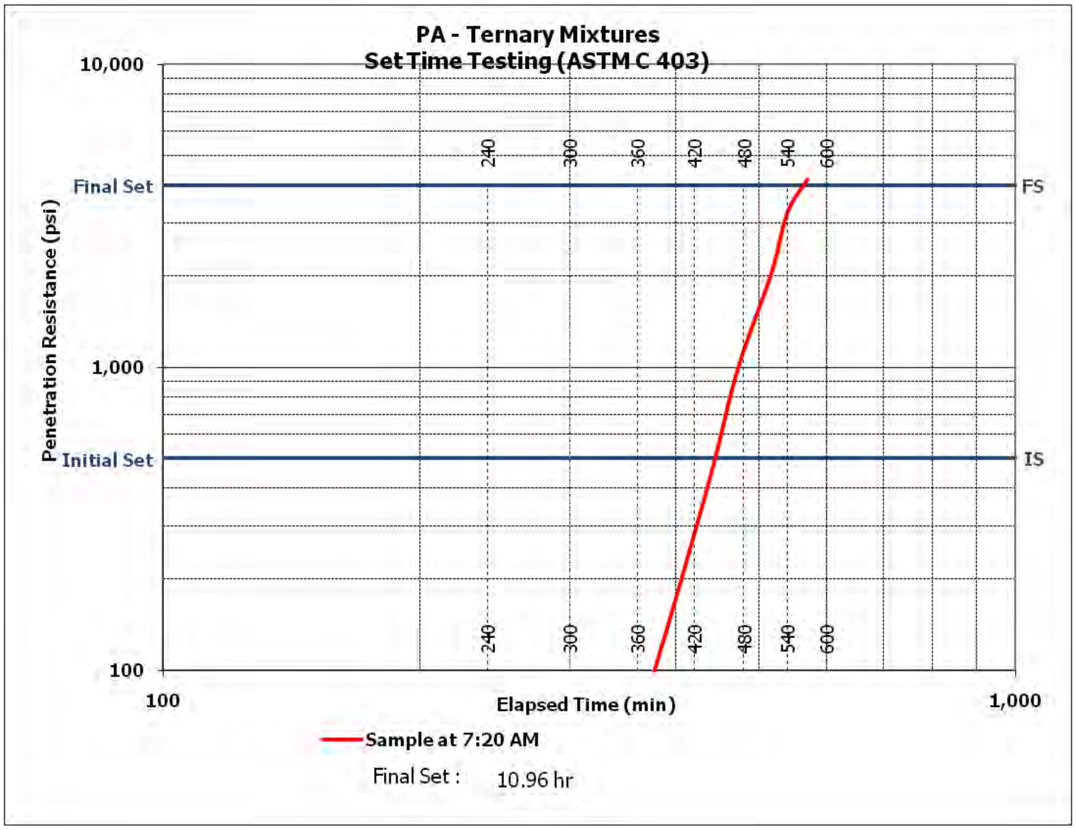
Date: 14-Jul-10 Start Time: 7:20 AM

Sta: n/a

Test Data

Penetration Time (xx:xx-24 hr format)	Time (min)	Needle # (1,2,4,10,20 or 40)	Force (lb)	Penetration Resistance (psi)	Sample Temp. (ºF)
12:50 PM	330.00	1	36	36.00	73.2
1:30 PM	370.00	2	42	84.00	74.7
2:35 PM	435.00	4	100	400.00	76.3
3:12 PM	472.00	10	98	980.00	78.1
3:57 PM	517.00	20	102	2040.00	77.9
4:20 PM	540.00	40	81	3240.00	77.9
4:50 PM	570.00	40	104	4160.00	77.4

Initial Set (at 500 psi PR)	estimated times using forecast function	**218**	minutes	**3.63**	hours
Final Set (at 4,000 psi PR)		**658**	minutes	**10.96**	hours



PA - Ternary Mixtures
Set Time Testing (ASTM C 403)
Penetration Resistance (psi)
10,000
Final Set
1,000
Initial Set
100
FS
IS
240
300
360
420
480
540
600
100
Elapsed Time (min)
1,000
Sample at 7:20 AM
Final Set : 10.96 hr

PA - Ternary Mixtures

Microwave Water Content Worksheet

Project: SR 36 Section 20, Bridge Deck in Roaring Spring, Blair County, PA
Date: 14-Jul-10 Time: 7:20 AM
Sta: n/a

Test Data

Mass of tray+cloth+block+fresh test sample, W_F (g)	3,722.3
Mass of tray+cloth+block, W_S(g)	2,198.3
Mass of tray+cloth+dry sample, W_D (g) (5mins)	3,686.7
Mass of tray+cloth+dry sample, W_D (g) (7 mins)	3,645.6
Mass of tray+cloth+dry sample, W_D (g) (9 mins)*	3,620.8
Mass of tray+cloth+dry sample, W_D (g) (11 mins)*	3,606.9
Mass of tray+cloth+dry sample, W_D (g) (13 mins)*	3,603.6
Mass of tray+cloth+dry sample, W_D (g) (15 mins)*	3,602.3
Mass of tray+cloth+dry sample, W_D (g) (17 mins)*	3,601.6
Mass of tray+cloth+dry sample, W_D (g) (Final)**	3,601.6
Water content percentage, W_C (%)	**7.9%**
Unit weight of fresh concrete, UW (lb/ft^3)***	146.6
Total water content, W_T, (lb/yd^3)	**313.5**
Total cementitious weight (lb/yd^3)	587
Fine aggregate weight (lb/yd^3)	1210
Coarse Aggregate weight (lb/yd^3)	1928
Intermediate Aggregate weight (lb/yd^3)	0
Fine aggregate absorption (%)	0.94%
Coarse aggregate absorption (%)	0.32%
Intermediate aggregate absorption (%)	0.00%
w/c	**0.504**

* If necessary (stop if the weight loss is less than 1g)
** Mass at test termination
***From unit weight test

Pennsylvania - Ternary Mixtures

Microwave Water Content Worksheet

Project: SR 36 Section 20, Bridge Deck in Roaring Spring, Blair County, PA
Date: 14-Jul-10 Time: 9:30 AM
Sta: n/a

Test Data

Mass of tray+cloth+block+fresh test sample, W_F (g)	3,786.1
Mass of tray+cloth+block, W_S(g)	2,198.0
Mass of tray+cloth+dry sample, W_D (g) (5mins)	3,753.3
Mass of tray+cloth+dry sample, W_D (g) (7 mins)	3,715.5
Mass of tray+cloth+dry sample, W_D (g) (9 mins)*	3,685.4
Mass of tray+cloth+dry sample, W_D (g) (11 mins)*	3,674.6
Mass of tray+cloth+dry sample, W_D (g) (13 mins)*	3,672.2
Mass of tray+cloth+dry sample, W_D (g) (15 mins)*	3,671.1
Mass of tray+cloth+dry sample, W_D (g) (17 mins)*	3,670.6
Mass of tray+cloth+dry sample, W_D (g) (Final)**	3,670.6
Water content percentage, W_C (%)	**7.3%**
Unit weight of fresh concrete, UW (lb/ft^3)***	146.6
Total water content, W_T, (lb/yd^3)	**287.9**
Total cementitious weight (lb/yd^3)	587
Fine aggregate weight (lb/yd^3)	1210
Coarse Aggregate weight (lb/yd^3)	1928
Intermediate Aggregate weight (lb/yd^3)	0
Fine aggregate absorption (%)	0.94%
Coarse aggregate absorption (%)	0.32%
Intermediate aggregate absorption (%)	0.00%
w/c	**0.461**

* If necessary (stop if the weight loss is less than 1g)
** Mass at test termination
***From unit weight test

PROOVE it

ASTM C 1202-97

TEST CO.

File name = Prooveit user logo.jpg located in application directory.

Test-compagny
Testing street 45
CompagnyCity
Some Country

Your own logo, size=20x80mm

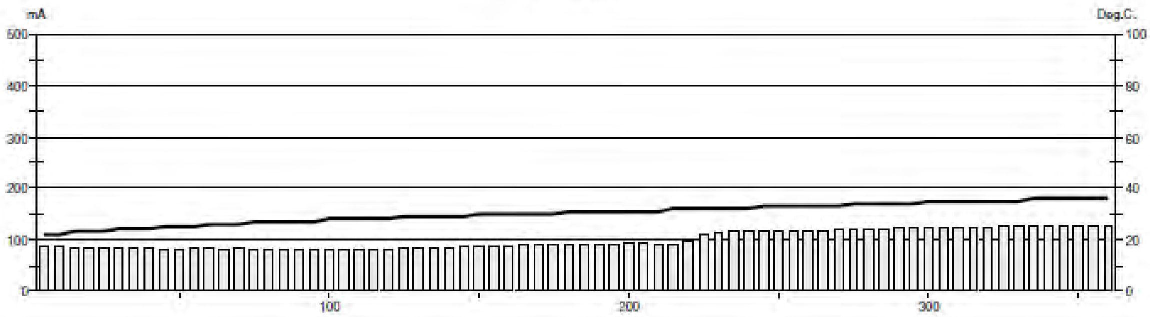
GERMANN INSTRUMENTS

DENMARK
Phone: +45 3967 7117
Fax: +45 3967 3167

USA
Phone: (847)329-9999
Fax: (847)329-8888

Test report

Voltage Used:	60
Testing time:	06:00 hour
Charge passed:	2144
Adjusted Charge passed:	1860
Permeability class:	Low
Instrument number:	023907
Channel number:	1
Report date:	8/27/2010
Testing by:	
Reference:	PA TERN #1
Sample diameter:	102
Comment:	---



Time	°C	mA	Time	°C	mA	Time	°C	mA	Time	°C	mA
00:05	22	86.6	01:35	27	80.5	03:05	31	90.3	04:35	34	120.0
00:10	22	86.5	01:40	28	80.3	03:10	31	91.3	04:40	34	120.7
00:15	23	85.4	01:45	28	79.7	03:15	31	91.2	04:45	34	121.1
00:20	23	84.3	01:50	28	80.6	03:20	31	93.2	04:50	34	122.0
00:25	23	84.6	01:55	28	79.7	03:25	31	94.1	04:55	34	122.1
00:30	24	84.4	02:00	28	79.6	03:30	31	91.7	05:00	35	123.0
00:35	24	84.5	02:05	29	81.5	03:35	32	92.4	05:05	35	123.1
00:40	24	85.2	02:10	29	84.3	03:40	32	97.8	05:10	35	123.3
00:45	25	81.0	02:15	29	84.9	03:45	32	112.2	05:15	35	123.8
00:50	25	80.8	02:20	29	85.8	03:50	32	114.3	05:20	35	123.7
00:55	25	81.5	02:25	29	87.2	03:55	32	115.4	05:25	35	123.9
01:00	26	81.5	02:30	30	86.6	04:00	32	115.9	05:30	35	124.8
01:05	26	80.7	02:35	30	87.5	04:05	33	117.0	05:35	36	125.4
01:10	26	81.5	02:40	30	87.7	04:10	33	117.4	05:40	36	125.9
01:15	27	80.3	02:45	30	89.8	04:15	33	118.0	05:45	36	125.4
01:20	27	80.5	02:50	30	89.1	04:20	33	118.8	05:50	36	125.1
01:25	27	80.7	02:55	30	89.6	04:25	33	119.0	05:55	36	125.4
01:30	27	79.6	03:00	31	88.8	04:30	33	119.5	06:00	36	126.9

PROOVE it

ASTM C 1202-97

TEST CO.

Test-compagny
Testing street 45
CompagnyCity
Some Country

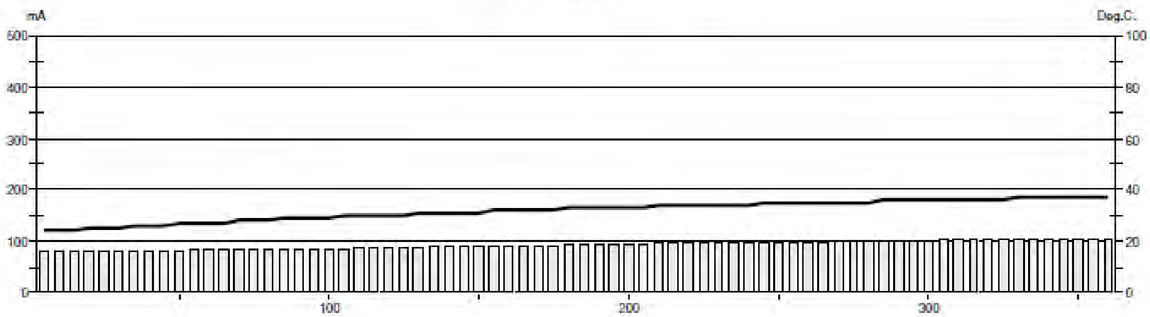
GERMANN INSTRUMENTS

DENMARK

USA

Test report

Voltage Used:	60
Testing time:	06:00 hour
Charge passed:	1995
Adjusted Charge passed:	1731
Permeability class:	Low
Instrument number:	023907
Channel number:	2
Report date:	8/27/2010
Testing by:	
Reference:	PA TERN #2
Sample diameter:	102
Comment:	---



Time	°C	mA	Time	°C	mA	Time	°C	mA	Time	°C	mA
00:05	24	80.0	01:35	29	85.2	03:05	33	93.4	04:35	35	100.0
00:10	24	80.3	01:40	29	85.7	03:10	33	94.0	04:40	35	100.2
00:15	24	79.7	01:45	30	85.9	03:15	33	94.4	04:45	36	100.4
00:20	25	79.4	01:50	30	86.3	03:20	33	94.4	04:50	36	100.8
00:25	25	80.0	01:55	30	86.7	03:25	33	94.7	04:55	36	101.2
00:30	25	80.3	02:00	30	87.2	03:30	34	95.1	05:00	36	101.5
00:35	26	80.3	02:05	30	87.5	03:35	34	95.4	05:05	36	101.6
00:40	26	80.2	02:10	31	88.0	03:40	34	95.9	05:10	36	102.0
00:45	26	80.1	02:15	31	88.5	03:45	34	96.8	05:15	36	102.4
00:50	27	81.0	02:20	31	89.0	03:50	34	97.2	05:20	36	102.5
00:55	27	81.7	02:25	31	89.8	03:55	34	97.3	05:25	36	102.9
01:00	27	82.4	02:30	31	90.0	04:00	34	97.3	05:30	37	103.0
01:05	27	82.9	02:35	32	90.3	04:05	35	97.5	05:35	37	103.3
01:10	28	83.4	02:40	32	90.8	04:10	35	97.8	05:40	37	103.8
01:15	28	83.8	02:45	32	91.2	04:15	35	98.3	05:45	37	104.0
01:20	28	84.3	02:50	32	91.6	04:20	35	98.9	05:50	37	104.2
01:25	29	84.6	02:55	32	92.3	04:25	35	99.1	05:55	37	104.5
01:30	29	85.0	03:00	33	92.9	04:30	35	99.7	06:00	37	104.4

APPENDIX I.
FIELD APPLICATION OF TERNARY MIXTURES: CONSTRUCTION OF A RIGID PAVEMENT IN UTAH

State Report
August 2011

Research Team
Paul Tikalsky
Peter Taylor
Kejin Wang
Amanda Gilliland
Xuhao Wang

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American Coal Ash Association, American Concrete Pavement Association, Headwaters Resources, Portland Cement Association, Slag Cement Association

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www.cptechcenter.org

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ACKNOWLEDGMENTS

The research team at the National Concrete Pavement Technology Center at Iowa State University sincerely thanks the research team at the Utah Department of Transportation for providing the cooperation and test bed. All of the contributions from the job site personnel and Geneva Rock Co. are also gratefully acknowledged.

INTRODUCTION

This document is a report of the activities and observations of a research team that performed on-site testing of a ternary mixture placed on a portion of pavement in Utah. A portion of the pavement was a binary blended cement concrete mixture and a portion was a ternary blended cement concrete mixture. This allowed for comparisons to be made between the two. The binary blended cement concrete pavement will be referred to as the control section of the pavement. Portion of control mixture pavement comprised a Type II/V cement with 25% Class F (Navajo) fly ash and portion of ternary blended pavement comprised ASTM 1157 limestone blended cement: 10% limestone crushed with control clinker and 25% Class F(Navajo) fly ash.

The purpose of this research project is a comprehensive study of how supplementary cementitious materials can be used to improve the performance of concrete mixtures when used in ternary blends. This is the third phase of a project that intends to provide consultation to states and contractors with the use and field management of ternary mixtures. Specimens were collected in the field and tested by CMT Engineering Laboratory.

PROJECT INFORMATION

- Project: 10400 South – Bangerter Highway to Redwood Road
- Type of project: Concrete pavement
- Location of project: Salt Lake County, Utah
- Date specimens were collected: Control Mixture: May 18, 2009; Ternary Mixture: July 28, 2009
- Design details: Portion of control mixture pavement (Type II/V cement with 25% class F (Navajo) fly ash) and portion of ternary blended pavement (Holcim EnvirocoreTM cement- 10% limestone crushed with control clinker and 25% class F (Navajo) fly ash)
- Parties involved on project:
    - Owner: Utah Department of Transportation (UDOT)
    - Contractor: WW Clyde Company
    - Cement Producer: Holcim
    - Mix Design: Geneva Rock
    - Testing: CMT Engineering Laboratory

SITE LOCATION

Concrete pavement was placed along 10400 South between Bangerter Highway (3630 West) and Redwood Road (1700 West) (Figure 1). The control mixture was placed from Bangerter Highway to 3200 West, and From 3350 West to Redwood Road. The ternary mixture was placed in the two west bound travel lanes between 3200 West and 3350 West (Figure 2).

Figure 1. Location of project

Figure 2. Location of ternary blended concrete

SPECIFICATION AND MIXTURE DESIGN

Utah requires a minimum cementitious material content of 470 lbs/yd^3 for pavements and 564 lbs/yd^3 for bridge decks (UDOT 2008). They also limit the amount of Class F fly ash replacement to a minimum of 20%. Maximum limits for Class F fly ash are specified at 30% if the fly ash is replacing a blended hydraulic cement. Class C fly ash is not permitted in Utah. Other pozzolans are permitted as long as they expand less than 0.1% in ASR testing according to ASTM C 1567. The mixture designs used for the Utah pavement met the state requirements.

Table 1. Mixture design for control and ternary portion of Salt Lake City, Utah pavement

Mixture Design **W/C 0.37**		**Control (75TII-V/25FA)**	**Ternary (75E/25FA)**
Total cementitious materials	(lb/yd^3)	657.5	657.5
Type II/V cement	(lb/yd^3)	493.0	0.0
ASTM 1157 limestone blended cement	(lb/yd^3)	0.0	493.0
Fly ash	(lb/yd^3)	164.5	164.5
Water	(lb/yd^3)	245.0	245.0
Fine aggregate	(lb/yd^3)	1373.0	1373.0
Coarse aggregate #67	(lb/yd^3)	1022.0	1022.0
Coarse aggregate #467	(lb/yd^3)	498.0	498.0
Air entraining agent	(oz/yd^3)	5.9	5.9
Midrange water reducer	(oz/yd^3)	30.2	30.2

SAMPLING AND TESTING ACTIVITIES

Specimens were collected on site for the control mixture (May 18, 2009) and for the ternary mixture (July 28, 2009) according to ASTM C31 for further testing. Samples were taken from multiple outbound concrete trucks. The control mixture followed the standard curing method, while the ternary blend mixture was cured in both standard and field conditions. Data collected from laboratory-cured specimens will be presented in this summary. The following tests were conducted in the field or in the laboratory:

Field test: slump, temperature, and air content of fresh concrete—1 test (ASTM C 143, ASTM C 231)

Tests were performed according to the following standards:

- Salt scaling specimens were cured for 14 days in wet conditions and 14 days in dry conditions.
- Compressive Strength specimens were measured at 1, 3, 14, 28, 56, and 91 days.
- Shrinkage was measured at 1, 3, 14, 28, 56, and 91 days.
- Electrical resistivity was measured using a four probe array on specimens at 1, 3, 7, 14, 28, and 56 days according to the Florida Method of Test for Concrete Resistivity. The

electrical resistivity testing is proposed to evaluate resistance to chloride ion penetration faster than the procedure in ASTM C 1202.

Table 2. Lab testing specimens for control mixture

Test	Type of Specimen	Number	ASTM Specification
Salt Scaling	9”×9”×4” bricks	4	ASTM C 672
Rapid Chloride Permeability	4” Φ cylinder	4	ASTM C 1202
Electrical Resistivity	4” Φ cylinder	4	Florida Method of Test
Compressive Strength	6” Φ cylinder	21	ASTM C 39

Table 3. Lab testing specimens for ternary mixture

Test	Type of Specimen	Number	ASTM Specification
Salt Scaling	9”×9”×4” bricks	4	ASTM C 672
Rapid Chloride Permeability	4” Φ cylinder	4	ASTM C 1202
Compressive Strength	6” Φ cylinder	21	ASTM C 39
Shrinkage	6” Φ cylinder	4	ASTM C 157

OBSERVATIONS OF THE RESEARCH TEAM

The following observations were made in this field testing:

- Mixture design: The control pavement used a 7-sack mixture with a Type II/V blend from Devil Slide, Utah, with 25% Class F fly ash as a portion of the cementitious material. The fly ash was supplied from the Navajo Generating Station in Page, Arizona. The ternary blend used a performance based cement meeting ASTM C 1157 containing 10% ground limestone flour. The ASTM C 1157 cement used the same clinker as the control cement and blended it with 10% limestone flour. 25% of the C 1157 cement (E) was replaced with the Class F fly ash.
- State specifications for cement content and SCM replacement: Utah requires a minimum cementitious material content of 470 lbs/yd^3 for pavements and 564 lbs/yd^3 for bridge decks (UDOT 2008). They also limit the amount of Class F fly ash replacement to a minimum of 20%. Maximum limits for Class F fly ash are specified at 30% if the fly ash is replacing a blended hydraulic cement. Class C fly ash is not permitted in Utah. Other pozzolans are permitted as long as they expand less than 0.1% in ASR testing according to ASTM C 1567. The mixture designs used for the Utah pavement met the state requirements.
- Slump, air content, and temperature were taken for every new sample obtained from an outgoing concrete truck. The average values for slump, air content, and temperature is shown in Table 3.
- The times for sampling and ambient weather conditions are summarized in Table 4 and 5.
- Figures 3 illustrates the paving operation at 10400 South using the ternary blended

cementitious concrete mixture. Conventional equipment and practices were maintained without modifications.

- Figure 4 shows the ease of finishing the pavement and the tight clean edges that were maintained throughout the paving operation with the ternary mixture.

Table 4. Average slump, air content, and temperature for control and ternary blend

Test	Control Mixture	Ternary Blend Mixture
Slump (in.)	1 1/4	1 1/8
Air Content (%)	5.6	5.4
Temperature (°F)	69	77

Table 5. Conditions of sample collection of control mixture specimens

Sample Date	Sample Time	Comments	Outside Temperature
May 18, 2009	10:00 AM	Sunny, warm. Sample taken from outbound truck at ready mix plant	78°F
May 18, 2009	10:45 AM	Sunny, warm. Sample taken from outbound truck at ready mix plant	78°F

Table 6. Conditions of sample collection of ternary mixture specimens

Sample Date	Sample Time	Comments	Outside Temperature
July 28, 2009	5:49 AM	Warm. Sample taken from outbound truck at ready mix plant	60°F
July 28, 2009	6:12 AM	Warm. Sample taken from outbound truck at ready mix plant	60°F
July 28, 2009	6:41 AM	Warm. Sample taken from outbound truck at ready mix plant	60°F
July 28, 2009	7:15 AM	Warm. Sample taken from outbound truck at ready mix plant	60°F

Figure 3. Paving operation at 10400 South, Salt Lake City, Utah

Figure 4. Ternary mixture maintained edges and finished well

Table 7. Average compressive strength of field samples for control and ternary blend (ASTM C 39)

	Compressive Strength (psi) 7 Days	Compressive Strength (psi) 28 Days	28/7 Day Ratio
Control Mixture	3495	4454	1.27
Ternary Blend Mixture	3303	5396	1.63

Table 8. Average shrinkage of field samples for control and ternary blend (ASTM C 157 Cylinders)

	Shrinkage (με) 14 Days	Shrinkage (με) 28 Days	Specification (με) at 28 Days
Control Mixture	10	280	500
Ternary Blend Mixture	0	210	500

Table 9. Average RCPT results of field samples for control and ternary blend (ASTM C 1202)

	Chloride Ion Penetrability Coulombs 28 Days	Chloride Ion Penetrability Coulombs 180 Days	Specification (Coulombs) at 28 Days
Control Mixture	493	---	>2000
Ternary Blend Mixture	1800	463	>2000

The concrete mixture met each of the performance specification measures, and its RCPT test results showed very low chloride penetration results at 180 days. The concrete control, a binary mixture with Type II cement and fly ash, and the ternary mixture with the limestone blended cement and fly ash both had low shrinkage and excellent strength development. This correlates well with laboratory testing conducted with the same material combination, which showed that the strength development was excellent at 14 and 28 days, and the chloride ion penetrability drops substantially within a few months of placement.

The feedback from the contractor on workability and finishing properties was excellent. Interviews with the placing crews after the control and ternary cast indicate the ternary cast with excellent rheological properties for the paving machine. In addition, the crew comments indicate it needed a minimal amount of finishing and the edges help as well or better than other mixtures made by the same crew at other locations. The primary comment from the crew was that it was a smooth day of paving with no problems.

At 100 days after casting, the pavement was inspected for cracking. No cracking was found outside of pavement joints. The joints appear to be well formed and functional. After the first two winters there was no scaling or freeze-thaw damage.