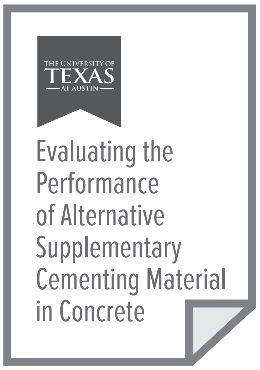
Summary of Research into Supplementary Cementitious Materials (SCM)

Pumice: the Ideal Natural Pozzolan

The University of Texas at Austin research tested and quantified the performance of eight commercially available natural pozzolans. ***This summary focuses on the results delivered by the pumice used in the study****, sourced from Hess Pumice Products of Malad City Idaho and commercially available as Hess Standard Pozz.*

Research *by the* Center for Transportation Research *at the* University of Texas at Austin *on behalf of the* Texas Department of Transportation *and with the cooperation of the* Federal Highway Administration.


THE UNIVERSITY OF TEXAS AT AUSTIN

Evaluating the Performance of Alternative Supplementary Cementing Material in Concrete

Research Motivation

Supplementary Cementitious Materials (SCMs) are recognized and widely used to improve the performance of ordinary Portland cement (OPC) concrete, primarily in terms of strength and durability. SCMs improve the density and quality of the concrete matrix by amplifying the production of calcium silicate hydrate (CSH), the cementitious binder that makes concrete, and by consuming deleterious compounds produced by the cement water hydration reaction and otherwise alter OPC chemistry so as to contribute to the concrete’s ability to resist sulfate, chloride, and alkali- silica attacks, heat-of-hydration cracking, freeze-thaw damage.

SCMs are used as a percentage of cement replacement in the concrete mix design; the true cost of using an SCM factors in the cost savings from the cement it replaces.

Fly ash, a by-product of coal-burning power plants, has been used extensively as a readily-available SCM to improve concrete performance. But fly ash has an uncertain future in terms of necessary quality, availability, and practical cost.[1] This concern motivated the Texas DOT to commission the research summarized here in order to expand its options for sourcing cost-effective and performance-quantified SCMs.

HESS POZZ GRADES

Hess StandardPozz DS-325

PARTICLE SIZE SPECIFICATION

Dx	Micron Size
D50	14 - 16

Hess UltraPozz NCS-3

PARTICLE SIZE SPECIFICATION

Dx	Micron Size
D50	2 - 4

CHEMICAL COMPOSITION

Common Name: **Pumice**
Chemical Name: Amorphous Aluminum Silicate
Silicon Dioxide - 87.4%
Aluminum Oxide - 10.52%
Ferric Oxide - 0.194%
Ferrous Oxide - 0.174%
Sodium - 0.128%
Potassium - 0.099%
Calcium - 0.090%
Titanium Dioxide - 0.0074%
Sulfate - 0.0043%
Magnesium Oxide - 0.126%
Water - 1.11%

> *“Uncertainty in the supply of Class F fly ash due to impending environmental restrictions has made it imperative to find and test alternate sources of supplementary cementitious materials (SCMs) that can provide similar strength and durability benefits to concrete as Class F fly ash.”*
>
> —*from the* Research Abstract

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[1] “In recent years…the future availability of fly ash in the US has become a source of concern because of impending environmental regulations from the US Environment Protection Agency (EPA). Two proposals, one known as a Subtitle C classification of the Resource Conservation and Recovery Act (RCRA), would regulate coal combustion residuals (including fly ash) as a hazardous waste. A second proposal, known as a Subtitle D classification of RCRA, would consider coal combustion residuals as non-hazardous, but would enforce a higher minimum standard for CCR disposal [with] the enforcement of rules under Subtitle D left up to the states. Regardless the IPA has maintained that fly ash can still be used in concrete due to the ‘beneficial use’ exemption, which permits the use of fly ash when completely encapsulated. However, the rising cost of fly ash associated with these environmental rulings will most likely make the use of fly ash in concrete prohibitive.

“Additionally, environmental regulations, like the Clean Air Interstate Rule and Cross State Air Pollution Rule, that aim to reduce air pollution have forced coal-burning power plants to adopt emission reduction techniques that have consequently led to a lower quality of fly ash.

“As these changes in the coal power generation industry are causing considerable uncertainty for the future availability and quality of fly ash, it becomes imperative to identify and test other SCMs that can provide similar strength and durability benefits to concrete as Class F fly ash.”

—from page 1 of “Evaluating the Performance of Alternative Supplementary Cementing Material in Concrete” by Seraj, Cano, Liu et al.

Explanation of this Summary

The following is an abbreviated summary of the research conducted by the University of Texas-Austin (August 2012 to August 2014) to quantify the performance of natural pozzolanic SCMs in concrete and establish the viability of these pozzolans in critical concrete infrastructure.

As Hess Pumice is the company that mines and refines the pumice pozzolan sourced for this study, this abbreviated summary focuses on the test results and research commentary on pumice in particular.[2]

Two rounds of studies were conducted—smaller-scale testing on **pastes and mortars** to identify optimal replacement level for concrete mixtures and for rapid assessment of how natural pozzolans could affect important fresh and hardened state properties of cementitious mixtures. The second round of studies used **concrete prisms**, with some durability testing taking up to two years.

In both studies, samples were also prepared using Class F fly ash so as to compare performance results with the more commonly understood performance results of Class F fly ash.

Material Characterization

Prior to testing, the SCMs were comprehensively characterized to examine the variables that could affect their performance in concrete. The characterization information was used to determine cement replacement dosages and to develop effective reactivity enhancement methods. The table below lists the tests performed.

MATERIAL CHARACTERIZATION TESTS ON PUMICE

ASTM C 618 is the governing specification for coal fly ash (Class C and F) and natural pozzolans (Class N) used in concrete.

SUMMARY OF ASTM C 618 RESULTS

Material Name	SiO_2+ Al_2O_3+ Fe_2O_3	SO_3 %	Moisture Content %	LOI %	Fineness %	SAI 7 day %	SAI 28 day %	Water Requirement	Soundness	Passes ASTM C 618?
PUMICE*	83	.04	1.5	4.4	2	82	93	104	-.02	YES
Passing Criteria in ASTM C 618										
	70%	4%	3%	10%	34%	75%	75%	115%	±0.8%	

OXIDE COMPOSITION RESULTS FROM XRF ANALYSIS

Material Name	SiO_2 %	Al_2O_3 %	Fe_2O_3 %	CaO %	MgO %	SO_3 %	Na_2O %	K_2O %
PUMICE*	69.42	12.42	1.08	0.94	0.44	0.04	3.81	5.16

AVERAGE DENSITY FROM PYCNOMETER

Material Name	Average Density (g/cm^3)
PUMICE*	2.44

*Pumice used throughout tests was Hess Pumice DS325 (standard pozz)

Advanced Characterization Tests

Although the ASTM C 618 tests are useful for a basic characterization of pozzolans, more advanced techniques are needed for a more comprehensive material characterization.

The procedures used were laser particle size analysis (used to determine the entire particle size distribution of a pozzolan, which is useful in predicting some early-stage properties), x-ray diffraction (a compositional characterization test that can differentiate whether oxides are present in amorphous or crystalline phases), thermal gravimetric analysis/differential scanning calorimetry (used to understand the phases present in a material), and methylene blue testing (used to evaluate the relative absorption capacities of the pozzolans).

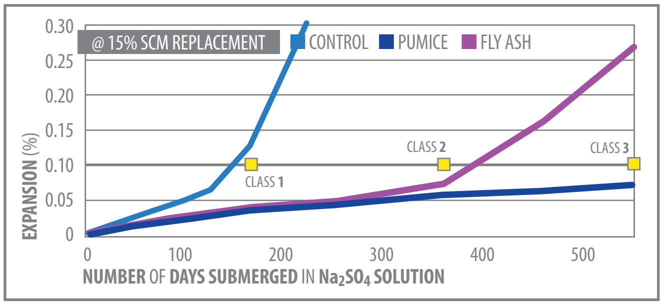
PASTE AND MORTAR STUDIES

The experiments performed in the paste and mortar studies were: isothermal calorimetry, rheological testing, and TGA (paste); compression testing, effect on drying shrinkage, resistance to ASR, and resistance to sulfate attack (mortar).

RESISTANCE TO SULFATE ATTACK

The yellow dots in the graph represent the "ACI 201: Guide to Durability" limits of Class 1, Class 2 and Class 3 sulfate exposure. An SCM qualifies for a Class 1 mild sulfate exposure if it can keep expansions below 0.1% for 6 months, when tested for sulfate attack using ASTM C 1012. Similarly, an SCM qualifies for a Class 2 moderate sulfate exposure at expansions below 0.1% for 12 months. Finally, a Class 3 severe sulfate exposure requires the SCM to keep expansions below 0.1% for 18 months.

RESULTS: The pumice pozzolan concrete qualifies for use in a Class 3 severe sulfate exposure environment at both 15% and 25% replacement levels.



SULFATE EXPOSURE QUALIFICATION AND MORTAR BAR EXPANSION

Mortar Mixture	w/cm	Sulfate Exposure	Expansion (%) of
CONTROL	0.485	Inadequate for sulfate attack	Exceeds 0.1 at 6 months
	0.51	Inadequate for sulfate attack	Exceeds 0.1 at 6 months
PUMICE (15%)	0.50	Qualifies for Class 3	0.068 ± 0.009 at 18 months
FLY ASH (15%)	0.46	Qualifies for Class 2	0.083 ± 0.016 at 12 months
	0.51	Qualifies for Class 1	0.090 ± 0.033 at 6 months
PUMICE (25%)	0.51	Qualifies for Class 3	0.076 ± 0.016 at 18 months
FLY ASH (25%)	0.45	Qualifies for Class 3	0.065 ± 0.009 at 18 months
	0.51	Qualifies for Class 1	0.059 ± 0.008 at 6 months

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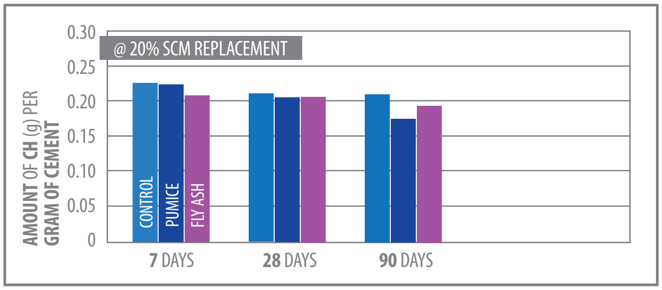
[2] Comparisons with and performance data on the other seven natural pozzolans is available in the original report: "Evaluating the Performance of Alternative Supplementary Cementing Material in Concrete" by Seraj, Cano, Liu et al.

CALCIUM HYDROXIDE CONTENT OF PASTES

The calcium hydroxide contents of the pastes were measured to observe whether the pozzolanic reaction was occurring in the SCM pastes.

RESULTS: Graphing the test results shows that the calcium hydroxide contents of the SCM pastes are generally always lower than that of the control with no SCM, suggesting that the calcium hydroxide in the SCM pastes is being depleted through the pozzolanic reaction. In particular, the 7-day calcium of the pumice paste was similar to that of the control paste with no SCM, however, by 90 days, the pumice paste demonstrated a significant reduction in its calcium hydroxide content (20% or more), indicating that pozzolanic reactions are taking place in the mixture. The decrease of calcium hydroxide content in the TGA results also suggested that pozzolans contributed to long-term strength by converting the calcium hydroxide in the paste to C-S-H.



CONCRETE STUDIES

Concrete Studies were then conducted because it was "imperative to conduct the tests in concrete as well, since the mortar tests are accelerated in different ways and represent a more simplified system than actual concrete mixtures. In addition, some important durability tests do not have well-established mortar tests." The concrete studies were necessary "to establish how well the SCMs would perform in real-world applications."

For the reasons stated above, the remainder of this summary focuses primarily on the research done in round two with concrete prisms.

As for the minimum replacement limit for SCMs, that is dictated by its effect on concrete durability. "In the case of this project, mitigating expansions from ASR was considered to be the most crucial."

TESTS PERFORMED ON CONCRETE MIXTURES

STRENGTH AND DURABILITY TESTS	FRESH STATE TESTS
Compressive Strength (ASTM C 39)	Slump (ASTM C 143)
Drying Shrinkage (ASTM C 157)	Air Content (ASTM C 231)
Resistance to ASR (ASTM C 39)	Unit Weight (ASTM C 29)
CoTE (Tex-428-A)	Setting Time (ASTM C 403)
Resistance to Chloride Ion Penetrability (ASTM C 1202)	

The Concrete Studies included tests for strength and durability and tests quantifying the effects of the SCMs on the fresh state. They were: compressive strength, drying shrinkage, resistance to ASR, resistance to chloride ion penetrability, and CoTE (strength and durability); slump, air content, unit weight, and setting time (fresh state).

FRESH STATE PROPERTIES OF CONCRETE MIXTURES

Concrete slump was measured according to ASTM C 143. The air content of the fresh concrete mixtures was measured according to the pressure method described in ASTM C 231. The unit weight of the mixture was found using the procedures described in ASTM C 29. The setting time of concrete mixtures was found using the procedures of ASTM C 403. In addition to the penetration resistance tests, ultrasonic tests were investigated to continuously monitor the setting process on concrete samples and sieved mortar samples. (This study aims to develop a field-applicable nondestructive testing method for in-situ monitoring of the setting and hardening process of concrete.)

RESULTS: The pumice SCM concrete mixture was able achieve the target slump with the help of a superplasticizer and achieved final set in 3.4 hours, compared to the final set of the control at 4.5 hours.

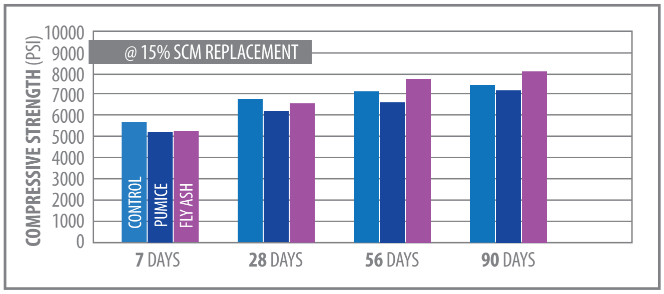
Concrete Mix Description	Admixture Dosage (% of max)	Slump (inches)	Air (%)	Unit Weight (lb/ft^3)	Initial Set (Hrs)	Final Set (Hrs)
CONTROL	12.70	3.25	1.6	150.0	3.4	4.5
PUMICE (15%)	15.48	2.50	1.8	149.6	3.6	5.0
FLY ASH (15%)	2.24	3.75	2.0	148.8	3.5	4.9
PUMICE (25%)	43.73	5.25	2.0	148.8	3.8	5.3
FLY ASH (25%)	0.00	5.50	1.6	148.8	3.9	5.3

COMPRESSIVE STRENGTH

Twelve 4-in. x 8-in. cylinders were cast for compressive strength testing at 7, 28, 56, and 90 days. At the appropriate ages, three cylinders were removed from moist storage and tested in a Forney FX-700 compression machine according to ASTM C 39. End caps set per ASTM C 1231. Average compressive strength was calculated from three cylinders.

RESULTS: The pumice pozzolan concrete mixture gained strength slowly at first, reaching 95% of the control strength at 90 days with a 15% replacement and 99% of the control strength with 25% replacement. This is similar to the trend seen during the mortar studies. It should be noted that although the pumice SCM specimens gained strength slower than the control and the Class F fly ash specimens, at 28 days scored strengths greater than 4500 psi.

	7 DAYS	28 DAYS	56 DAYS	90 DAYS
100C (CONTROL)	5700 (PSI)	6800 (PSI)	7100 (PSI)	7400 (PSI)
SCM @ 15%				
PUMICE	5200 (PSI)	6100 (PSI)	6600 (PSI)	7050 (PSI)
CLASS F FLY ASH	5250 (PSI)	6650 (PSI)	7900 (PSI)	8100 (PSI)
SCM @ 25%				
PUMICE	4500 (PSI)	6200 (PSI)	6800 (PSI)	7400 (PSI)
CLASS F FLY ASH	4600 (PSI)	6300 (PSI)	7300 (PSI)	7700 (PSI)

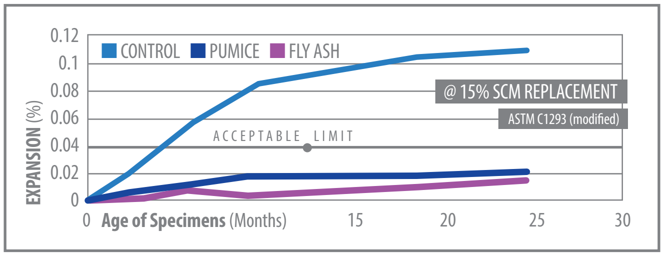


MITIGATING ALKALI SILICA REACTION

Resistance to ASR was measured according to the procedures of ASTM C 1293, except for the concrete mixture design used, which is detailed in the MIXTURE DESIGN table below. The average expansion for each mixture was calculated from three or more bars, and the range was checked to see whether it was within the limits stated in ASTM C 1293.

RESULTS: The pumice SCM concrete mixture performed very well, and kept expansions below the 0.04% limit of ASTM C 1293, validating the results found from the ASTM C 1567 Accelerated Mortar Bar Test for ASR. The table below lists the average expansion of the concrete prisms at 24 months, along with the range of the data.

MIXTURE	**AVERAGE ASR EXPANSION AT 24 MONTHS** (%)
CONTROL	0.109 ± 0.020
PUMICE (15%)	0.022 ± 0.007
FLY ASH (15%)	0.016 ± 0.017
PUMICE (25%)	0.015 ± 0.001
FLY ASH (25%)	0.016 ± 0.005



MIXTURE DESIGN FOR ASTM C 1293 ASR TESTING

Component	Batch Weight (lb/yd^3)	Weight %	Volume %
COARSE AGGREGATE	1937	48.3	43.4
FINE AGGREGATE	1257	31.3	28.9
CEMENTITIOUS MATERIAL	564	14.1	10.6
WATER	254	6.3	15.1
AIR	—	—	2.0

COEFFICIENT OF THERMAL EXPANSION

The CoTE value was measured according to the TxDOT procedures of Tex-428-A. CoTE measurement is another test that was not performed during the paste and mortar phase of the project. However, it is an important durability property to know, especially when considering the performance of concrete pavements, as concrete with a high CoTE can cause early age cracking and joint spalling. In continuously reinforced concrete pavements, a high CoTE value of the concrete may increase the crack spacing and width, affecting the crack load transfer efficiency. Although CoTE is primarily dominated by the aggregate type and source, the SCM type and content could also have smaller effects on the value. As such, these experiments were conducted to ensure that these pozzolans did not have any detrimental effects on the CoTE value of concrete.

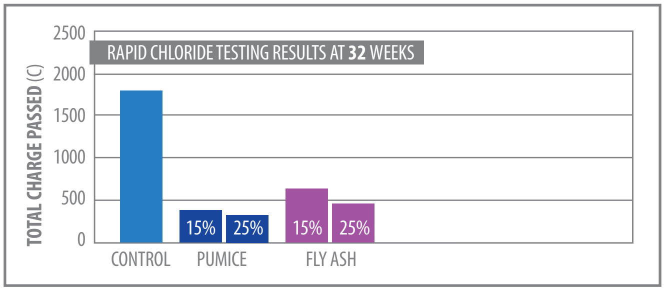
RESULTS: The pumice SCM specimen tested for CoTE showed compliance with Tex-428-A. The difference in CoTE values between the control specimen and the pumice SCM-concrete specimen was small, indicating that the use of pumice as an SCM would not cause any detrimental effects to the CoTE value of concrete.

Concrete Description	Cylinder 1 µ - strain/°F	Cylinder 2 µ - strain/°F	Average µ - strain/°F	Difference from Control µ - strain/°F
CONTROL	3.61	3.56	3.59	—
PUMICE (25%)	4.16	4.15	4.16	0.57
FLY ASH (25%)	4.06	3.56	3.81	0.23

RESISTANCE TO CHLORIDE ION PENETRATION

The chloride penetrability of concrete cylinders that were cured for 32 weeks was measured according to ASTM C 1202. Although the standard does not require repeat testing, three or more cylinders per concrete mixture were tested for rapid chloride penetrability. The range of the data was checked to see whether it was within the limits prescribed by ASTM C 1202.

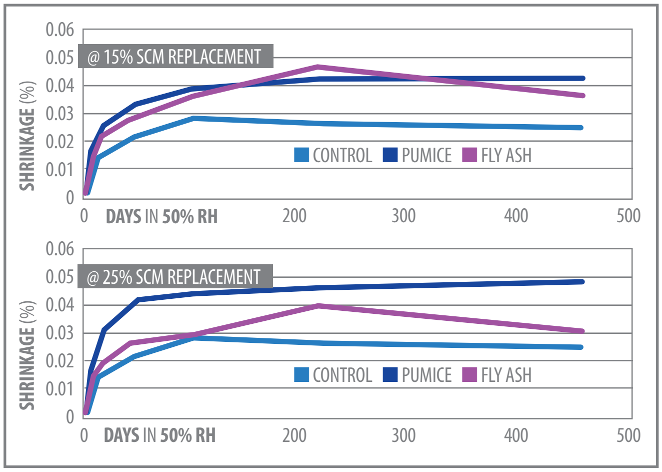
RESULTS: There are no well-established paste and mortar tests for this measurement, but this durability property is crucial, as the ingress of chloride ions can depassivate the steel in concrete and cause corrosion, without needing a drop in the pH content. At 32 weeks, all the SCM-concrete samples had less than 1000 coulombs of total charge passing through them when tested, which indicates very low chloride ion penetrability, according to ASTM C 1202. The overall results indicate that increasing the SCM content also increased the resistance to chloride ion penetrability.



DRYING SHRINKAGE

The drying shrinkage of the concrete bars was measured according to the procedures of ASTM C 157.

RESULTS: The pumice SCM concrete mixture had negligible differences in shrinkage compared to the control when used at a replacement dosage of 15%. However, the amount of shrinkage increased to more than 0.010% of the control as the replacement dosage was increased to 25%.



Conclusions From Concrete Studies

Results from the concrete mixture studies were crucial in understanding how pumice pozzolans might perform in field applications of concrete. One of the most important concrete results was the validation of the accelerated mortar bar test (ASTM C 1567) for ASR using the longer term, more reliable ASTM C 1293 concrete prism test for ASR. It was found that the pumice pozzolan could keep ASR expansions at 2 years below the

0.04% limit of ASTM C 1293 using replacements dosages of 25% or less.

Other important durability results showed that the use of pumice pozzolan increased the resistance of the concrete mixtures to chloride ion penetration. Additionally, the concrete results also showed that drying shrinkage and CoTE would not be a problem if pumice pozzolan was used in concrete mixtures. In terms of strength, the pumice SCM performed very well with strengths similar to or higher than the control at 90 days. Nor did the measurement of the fresh state properties of the concrete mixtures reveal any problems.

Optimum SCM Replacement Dosage

The minimum replacement limit for a given SCM is dictated by its effect on concrete durability—specifically, mitigating expansions from ASR, especially important in regions where ASR is a common source of durability problems. The minimum replacement level for SCMs in this project was determined through the accelerated mortar bar test for ASR (ASTM C 1567). Long-term measurements of concrete specimens using ASTM C 1293 confirmed these minimum replacement dosages to be effective in mitigating ASR. The maximum dosage was determined by the cost of the SCM and its effect on mixture workability. Strength was also an important factor in determining maximum dosage, as the higher the replacement amount, the lower the early age strength of mixtures, due to the dilution effect of replacing hydraulic cement with a slower reacting, pozzolanic material.

PUMICE REPLACEMENT DOSAGES

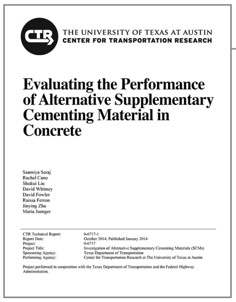
(BY WEIGHT OF CEMENT IN CONCRETE MIXTURES)

	MINIMUM	MAXIMUM
PUMICE	15%	25%

The pumice SCM was able to keep ASR expansion below the limit at a replacement dosage of only 15%. In addition, the pumice-enhanced concrete performed well under sulfate attack, measured according to ASTM C 1012.

At a replacement dosage of 15%, pumice was found to be suitable for a Class 3 severe sulfate exposure level, based on "ACI 201: Guide to Durability."

Pumice-blended cement will perform well to increase the durability of concrete and is recommended in applications where high early strength is not a requirement.



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Evaluating the Performance of Alternative Supplementary Cementing Material in Concrete

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CTR Technical Report: 0-6717-1
Report Date: October 2014; Published January 2014
Project: 0-6717
Project Title: Investigation of Alternative Supplementary Cementing Materials (SCMs)
Sponsoring Agency: Texas Department of Transportation
Performing Agency: Center for Transportation Research at The University of Texas at Austin

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

†This document is also available to the public through the National Technical Information Service: **www.ntis.gov**

A PDF copy of the full University of Texas-Austin research report† "Evaluating the Performance of Alternative Supplementary Cementing Material in Concrete" can be downloaded at: **www.hesspozz.com/downloads**

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Have specific questions?
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