TTI: 0-6656-01

Texas A&M Transportation Institute

Further Validation of ASR Testing and Approach for Formulating ASR-Resistant Concrete Mix: Technical Report

Technical Report 0-6656-01-R1

Cooperative Research Program

TEXAS A&M TRANSPORTATION INSTITUTE
COLLEGE STATION, TEXAS

in cooperation with the
Federal Highway Administration and the
Texas Department of Transportation
http://tti.tamu.edu/documents/0-6656-01-R1.pdf

Technical Report Documentation Page

1. Report No. FHWA/TX-18/0-6656-01-R1	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle FURTHER VALIDATION OF ASR TESTING AND APPROACH FOR FORMULATING ASR-RESISTANT CONCRETE MIX: TECHNICAL REPORT	5. Report Date Published September 2018 6. Performing Organization Code
7. Author(s) Anol Mukhopadhyay, Kai-Wei Liu, and Mostafa Jalal	8. Performing Organization Report No. Report 0-6656-01-R1
9. Performing Organization Name and Address Texas A&M Transportation Institute The Texas A&M University System College Station, Texas 77843-3135	10. Work Unit No. (TRAIS) 11. Contract or Grant No. Project 0-6656-01
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office 125 E. 11th Street Austin, Texas 78701-2483	13. Type of Report and Period Covered Technical Report: March 2015–February 2018 14. Sponsoring Agency Code

15. Supplementary Notes

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.
Project Title: Further Validation of ASR Testing and Approach for Formulating ASR-Resistant Concrete Mix
URL: http://tti.tamu.edu/documents/0-6656-01-R1.pdf

16. Abstract

The main objective of this study was to further validate the developed rapid aggregate and concrete test methods and a combined innovative approach for formulating performance-based alkali-silica reaction (ASR)–resistant concrete mixes. An innovative step-by-step approach has been developed to formulate ASR-resistant concrete mixes based on four recommended steps. In Step 1, determination of aggregate ASR composite activation parameter (CAP) and threshold alkalinity (THA) using a rapid aggregate chemical test called the volumetric change measuring device (VCMD) is performed. The lower the CAP, the higher the reactivity. Based on the measured CAP and THA, mix design formulation is conducted in Step 2 by applying mix design controls. In Step 3, verification and adjustment of the mix developed in Step 2 is performed based on the THA and pore solution alkalinity (PSA) relationship—PSA needs to be below THA in order to prevent/minimize ASR. Mix design validation using a recently developed accelerated concrete cylinder test (ACCT) is part of Step 4. Concrete mixes made of aggregates with different levels of alkali-silica reactivity were tested using the above approach. The mixes after Steps 2–3 are actually job concrete mixes. The CAP-based method showed better correlation with ASTM C1293 than ASTM C1260 and was found to be effective for consistently identifying the aggregates belonging to false positive and false negative categories. The VCMD method was found to be effective for identifying alkali loading as a function of aggregate reactivity. A low level of alkali loading (e.g., ≤ 3 lb/cy) is needed for an aggregate with very high reactivity and vice versa. Therefore, the current practice of assigning 3.5 lb/cy for all concrete mixes irrespective of aggregate reactivity and type of application may not provide adequate protection. All four steps are recommended for developing case-specific ASR-resistant mixes with high reliability. If a strong agreement between mixes developed through Steps 1–3 and validated in Step 4 is observed based on extensive testing, then concrete validation testing (part of Step 4) can be considered optional. If the PSA measurement technique is not available, a combined use of the NIST model (estimating PSA contribution from cement portion) and ASTM C311 (determining available alkalis from supplementary cementitious material [SCM] used) was found to be effective to estimate PSA of the cement-SCM combination with acceptable accuracy. For the aggregates whose reactivity prediction based on the current test methods (e.g., C1260 and/or C1293) or field performance is satisfactory, the user can develop mixes based on guidelines in Step 2. However, mix design validation through concrete testing (Step 4) will be very useful and is highly recommended to ensure placement of safe and durable concrete mixes. The combined approach based on rapid and reliable test methods will facilitate formulating (a) case-specific ASR-resistant mixes (tailoring mix design depending on the level of protection needed) using locally available materials to ensure long-lasting durable concrete and save on repair costs, and (b) an effective and safe way to use locally available fly ashes (the ACCT method has the capability to perform fly ash optimization effectively) and meet future challenges when good-quality fly ashes are no longer available.

17. Key Words Alkali-Silica Reaction, ASR-Resistant Concrete Mixture, Concrete Durability	18. Distribution Statement No restrictions. This document is available to the public through NTIS: National Technical Information Service Alexandria, Virginia http://www.ntis.gov

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 60	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

FURTHER VALIDATION OF ASR TESTING AND APPROACH FOR FORMULATING ASR-RESISTANT CONCRETE MIX: TECHNICAL REPORT

by

Anol Mukhopadhyay
Research Scientist
Texas A&M Transportation Institute

Kai-Wei Liu
Assistant Transportation Researcher
Texas A&M Transportation Institute

and

Mostafa Jalal
Graduate Assistant—Research
Texas A&M Transportation Institute

Report 0-6656-01-R1
Project 0-6656-01
Project Title: Further Validation of ASR Testing and Approach for Formulating ASR-Resistant Concrete Mix

Performed in cooperation with the
Texas Department of Transportation
and the
Federal Highway Administration

Published September 2018

TEXAS A&M TRANSPORTATION INSTITUTE
College Station, Texas 77843-3135

DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of FHWA or TxDOT. This report does not constitute a standard, specification, or regulation. The research scientist in charge of the project was Dr. Anol K. Mukhopadhyay.

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

ACKNOWLEDGMENTS

This project was completed in cooperation with TxDOT and FHWA. The authors wish to express their appreciation to TxDOT and FHWA personnel for their support throughout this study. Special thanks are extended to Darrin Jensen for serving as project coordinator. The research team highly appreciates the technical feedback provided by Andy Naranjo and Rachel Cano during the course of this project. Acknowledgment is also given to the staff at the Texas A&M Transportation Institute.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND AND SIGNIFICANCE OF WORK

Alkali-silica reaction (ASR) is a chemical reaction between some siliceous constituents of concrete aggregates and hydroxyl ions (Diamond 1983). The concentration of hydroxyl ions in concrete pore solution is predominantly controlled by the concentration of sodium and potassium (Diamond 1989). The product of this reaction is a gel known as ASR gel. In the presence of sufficient moisture (> 80% relative humidity [RH]), the gel absorbs moisture due to its hygroscopic nature and swells, which leads to creation of tensile stress in concrete. Crack formation initiates when tensile stress exceeds tensile strength of concrete (Ponce and Batic 2006). ASR in concrete is recognized as a major concern for the Texas Department of Transportation (TxDOT). New cases of ASR are continuously being reported despite the advancements in ASR test methods and mitigation strategies of the last decades. However, current ASR test methods are empirical in nature and have little relevance to field conditions. The main purpose of an ASR test method is to measure aggregate reactivity prior to use in concrete structures and develop ASR-resistant mixes. The current approach of testing and mitigating damaging ASR depends heavily on the accelerated mortar-bar test (AMBT) (ASTM C1260 [ASTM 2014]) and concrete prism test (CPT) (ASTM C1293 [ASTM 2015]). The American Association of State Highway and Transportation Officials (AASHTO) R80-17 and ASTM C1778 provides a procedure for evaluating aggregate reactivity by C1260/1567 and C1293 and determining measures to prevent ASR on the basis of performance testing or prescriptive selection from a list of different options (AASHTO 2017a). Although these approaches have resulted in significant advances in the avoidance of ASR damage in concrete structures, there are limitations and drawbacks. ASTM C1260 (mortar bar) is a rapid test (severe test conditions to make it accelerated, 14 days), but the test results are sometimes unrelated to field performance. CPT has been considered the best index for field performance, but the test duration (minimum 1 year) imposes a major limitation (Swamy 1992; Marks 1996; Bauer et al. 2006).

Researchers have noticed that an increasing trend of aggregates belong to false positive and false negative categories (FHWA n.d.). Current ASR tests are not capable of determining threshold alkalinity and testing the effects of alkalis from cement as well as supplementary cementitious materials (SCMs) on ASR. The concrete mixtures that were identified as safe mixtures based on 2 years of ASTM C1293 data were found to be reactive based on 15 years of block data.[1] It was observed that optimum fly ash level to control ASR varies with the tests (e.g., C1567 or C1293) that are used to determine the optimum content. Optimum fly ash content actually depends on fly ash characteristics (e.g., CaO%, soluble alkalis, glass composition and content), aggregate reactivity, and aggregate threshold alkalinity (THA). Therefore, assigning a common fly ash replacement level irrespective of these factors (i.e., one size fits all) may not be adequate. It would be beneficial to accurately, fairly, and rapidly assess the ASR potential of each aggregate at various alkali loadings. Thus, there is a strong need for developing a rapid and reliable ASR test method and a procedure to create an ASR-resistant concrete mix. An effective way of tailoring mix design depending on the level of protection needed is warranted to help

---

[1] ACI meeting (personal communication, March 28, 2017).

transportation officials ensure valuable resource conservation and avoid paying for premium ASR protection when only minor protection is needed.

In a previous project, Research Project 0-6656 (Mukhopadhyay and Liu 2014), a volumetric change measuring device (VCMD)–based aggregate-solution method was established as a rapid (within 5 days) and reliable method to determine aggregate reactivity in terms of measuring composite activation parameter (CAP) through extensive aggregate testing and testing for pure phase (e.g., glass) material. A new accelerated concrete cylinder testing (ACCT) procedure was also developed in this research project as a relatively rapid ASR concrete test method. However, that method needs extensive further work in order to validate the ACCT as a rapid and reliable concrete ASR testing method.

A procedure to design an ASR-resistant concrete mix based on CAP, THA, pore solution alkalinity (PSA), and concrete validation testing using ACCT was also developed in Research Project 0-6656. The procedure to formulate ASR-resistant concrete mixes involves four steps:

- Step 1: Determination of CAP and THA from VCMD-based aggregate-solution test.
- Step 2: Formulation of an ASR-resistant mix by applying mix design controls depending on CAP-based reactivity prediction, THA, and some consideration of the severity of ambient conditions.
- Step 3: Mix design adjustment/verification based on the THA-PSA relationship—PSA needs to be below THA in order to prevent/minimize ASR.
- Step 4: Mix design validation through concrete testing—use of ACCT method to measure expansion of concrete cylinder in a short time.

However, this procedure needs further verification to formulate ASR-resistant concrete mixes using both the VCMD and ACCT methods.

1.1.1 Volumetric Change Measuring Device Test

In research project 0-6656 (Mukhopadhyay and Liu 2014), a VCMD-based rapid (within 5 days) and reliable ASR test method was used to test aggregates and validate measurement of aggregate alkali-silica reactivity in terms of measuring CAP (Liu and Mukhopadhyay 2014a). A representative CAP can be determined by testing as-received aggregates (i.e., field aggregates) with 0.5 N NaOH (NH) + $Ca(OH)_2$ (CH) solution (similar to concrete pore solution) and with permissible-within-the-lab repeatability. The lower the CAP, the higher the reactivity. In research project 0-6656, the CAP-based method was found to be effective for consistently identifying the aggregates belonging to false positive and false negative categories, which is the main benefit of the VCMD-based aggregate-solution method. The aggregate-solution testing was also used to determine aggregate THA of ASR based on the CAP versus alkalinity relationship. In general, the higher the aggregate reactivity (i.e., the lower the CAP), the lower the THA. THA could be very useful in determining alkali loading for different aggregate sources. A reactive aggregate can practically behave as nonreactive or very slow reactive if concrete PSA can be maintained below THA. The CAP-based aggregate reactivity parameter can be effectively used to detect aggregate source variability in terms of ASR as a part of an aggregate quality control program. The VCMD method has merit as an alternative to the current AMBT method (i.e., ASTM C1260).

1.1.2 Accelerated Concrete Cylinder Test

In research project 0-6656 (Mukhopadhyay and Liu 2014), the ACCT method was developed to determine the length change of a concrete cylinder (3 × 6 inches) due to ASR at a temperature of 60°C (Liu and Mukhopadhyay 2015). The length change of cylindrical specimens is measured through a linear variable differential transformer (LVDT) data acquisition system. Making the soak solution chemistry equal to the pore solution chemistry ensures a no-leaching test condition. The ACCT takes around 28–45 days to identify a reactive aggregate with alkali loading of 4.5 lb/cubic yard [cy]. However, the time needed to test a slowly reactive straight cement mix with lower alkali loadings (e.g., 3.0–4.0 lb/cy) is relatively high and yet to be established (e.g., 2–3 months for aggregate with slow reactivity). Because the data collection in the ACCT is automatic through LVDT (no human error) under constant temperature (no error due to temperature difference), the reliability of the ACCT was expected to be high. Creating a leach-proof situation in the ACCT is another advantage that enhances the reliability of this test. The ACCT, with relatively low alkali loadings (4.5 lb/cy with a straight cement mix as opposed to high alkali loadings [i.e., 8.9 lb/cy] through alkali boosting in the current ASTM C1293 test) and at 60°C, can effectively be used to pass/fail an aggregate in a relatively short time (≤ 45 days). It is interesting to point out that the effective alkali loading range for commonly used precast mixes is close to 4.5 lb/cy.

1.2 RESEARCH OBJECTIVES

The main objectives of this study were to further validate the aggregate-solution method and the ACCT and validate the approach developed in Research Project 0-6656 for formulating an ASR-resistant concrete mix. The combined use of aggregate-solution testing measuring CAP and THA and concrete testing was the main basis to formulate the ASR-resistant concrete mix. The specific objectives were as follows:

- Validate the usefulness of THA in determining alkali loading for different aggregate sources that could potentially be used to modify TxDOT mix design Option 7. In Option 7 of TxDOT Item 421, it is recommended that the total alkali contribution from cement in the concrete should not exceed 3.5 lb/cy of concrete when using hydraulic cement alone. Because of the gradual change of fly ash composition (e.g., more availability of blended ash/Class C ash than Class F fly ash), the department needs to investigate other methods to determine potential reactivity of aggregates in terms of alkali threshold (current test methods are not suitable to determine alkali threshold) in order to be prepared in the event Class F fly ash is no longer readily available.
- Further validate the ACCT (testing period, expansion limits, level of alkali loadings, appropriate level of soak solution chemistry, suitable specimen dimension, etc.) method.
- Validate suitability of the ACCT to test job concrete mix (e.g., a field concrete mix with application of suitable ASR-preventive mix design measures).
- Validate the procedure/approach to formulate an ASR-resistant concrete mix based on CAP, THA, PSA, and concrete validation testing using the ACCT.
- Assign optimum replacement levels of fly ash to control ASR by using the proposed concrete testing—the replacement levels need to reduce the expansion at the recommended testing period below the recommended limits.

1.3 ORGANIZATION OF THE REPORT

The work that was performed under different tasks (according to the original proposal) is presented in this report as chapters:

- Chapter 1 is an introduction describing the research background and objectives, as well as the report organization.
- Chapter 2 presents the basis of aggregate material selection and collection, mainly focusing on aggregates belonging to false positive and false negative categories.
- Chapter 3 presents validation of the usefulness of THA in determining alkali loading for different aggregate sources.
- Chapter 4 discusses further validation of the ACCT, focusing on assigning a suitable testing period, verifying the expansion limit, assigning a practical alkali loading for concrete mix, assigning an appropriate level of soak solution chemistry, and investigating the effect of specimen dimension.
- Chapter 5 presents validation of the four-step procedure/approach that was developed to formulate an ASR-resistant concrete mix in the previous project along with verification of the different options (different combination of four steps depending on the need for rapidity [shorter testing period] and reliability). Assigning the optimum level of fly ash depending on the type and quality of fly ash using the ACCT is also an important aspect that is covered in this chapter.
- Chapter 6 provides a summary and conclusions based on the research findings from this study and recommendations for further work.

CHAPTER 2: MATERIALS

This chapter presents the basis for aggregate selection for ASR testing, followed by a discussion of aggregate material collection and relevant aggregate characterization.

2.1 MATERIAL SELECTION

The researchers proposed testing at least 10 aggregates (both coarse and fine aggregates) with full factorial experimental design (described in Chapter 3). Aggregate sources, including both coarse and fine aggregates, were selected based on the following considerations.

- Aggregates having ASR records based on the current methods, including but not limited to ASTM C1260 and ASTM C1293, with additional information pertaining to mineralogy, including but not limited to type and distribution of reactive constituents and chemistry.
- Aggregates belonging to false positive and false negative categories.
- The receiving agency's recommendation on important aggregate sources that need determination of alkali loading based on THA.
- Aggregates, both coarse and fine, used to make TxDOT exposure blocks. Previously, TxDOT initiated constructing concrete blocks using mixes of varying levels of alkalinity and aggregate reactivity and monitoring expansion due to ASR over time under ambient conditions.

The potential aggregate sources were identified after critically analyzing the existing ASR data covering the above criteria and obtaining feedback from the TxDOT project manager and technical committee members. Detailed information on the selected aggregate sources is provided in Table 2.1. The coarse aggregates (CA1 to CA7) passed the C1260 (AMBT) but failed the C1293 (CPT) tests.

2.2 MATERIAL COLLECTION

For each source, the required amount of material (determined based on the full factorial experimental design discussed in Chapter 3) was collected. One 55-gal drum of aggregate material for each source was found to be adequate.

2.3 MATERIAL CHARACTERIZATION

For comparison purposes, both coarse aggregate (CA) and fine aggregate (FA) gradations were specified (dashed lines in Figure 2.1) and met ASTM C33 specifications. Grading requirements for coarse aggregates are based on a nominal size from 1 inch to No. 4. In addition, all aggregate-related properties (e.g., dry unit weight, specific gravity, and absorption capacity) were also determined and are presented in Table 2.1. The dry unit weight (DRUW), absorption capacity (AC), and specific gravity (SG_{od}), as well as the types of reactive constituents, were measured according to ASTM C127, C128, C138, and C295, respectively. These aggregate properties were used in the VCMD test to determine aggregate quantity and other parameters.

Table 2.1. List of Selected Aggregates.

Aggregate	Type	C1260 %	C1293 %	DRUW lb/ft^3	AC %	SG_{od}
FA1	Fine	0.269	0.054	104.04	0.31	2.61
FA2	Fine	0.241	0.110	106.41	0.51	2.61
FA3	Fine	0.003	N/A	110.6	8.2	2.04
FA4	Fine	0.182	0.100	105.16	0.83	2.43
CA1	Coarse	0.031	0.155	92.64	0.71	2.61
CA2	Coarse	0.024	0.129	94.19	0.92	2.57
CA3	Coarse	0.062	0.092	97.67	0.92	2.57
CA4	Coarse	0.025	0.098	98.30	1.39	2.55
CA5	Coarse	0.025	0.099	97.23	1.05	2.64
CA6	Coarse	0.040	0.082	102.30	0.98	2.57
CA7	Coarse	0.046	0.091	101.73	0.91	2.61

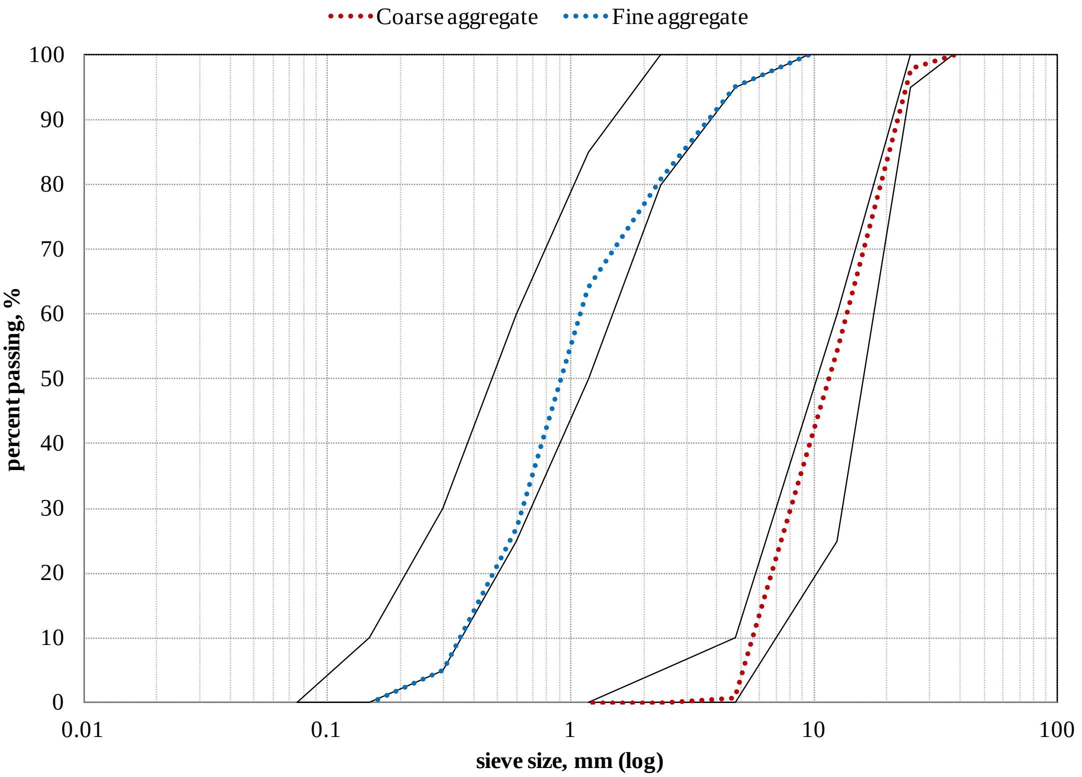

Figure 2.1. Gradation Curves of Aggregates.

CHAPTER 3: VALIDATION OF THE USEFULNESS OF THRESHOLD ALKALINITY IN DETERMINING ALKALI LOADING FOR DIFFERENT AGGREGATE SOURCES

The current practice is to assign a common alkali loading applicable for all concrete mixes in different applications (i.e., one size fits all). However, the effective approach of designing an ASR-resistant mix relies on determining the alkali loading of individual aggregates. Current ASR test methods are not capable of determining THA and/or alkali loading of an aggregate. The objective of the work described in this chapter was to validate the usefulness of THA to determine the alkali loading of an aggregate. The THA of the selected aggregates presented in Chapter 2 was determined using the following steps and methodology:

- Testing the aggregates (described in Chapter 2) at multiple temperatures (e.g., 60, 70, and 80°C) and alkalinities (e.g., 1 N NH + CH and 0.5 N NH + CH).
- Determining CAP at the selected alkalinities (e.g., 1 N NH + CH and 0.5 N NH + CH) for each tested aggregate.
- Developing a trend between CAP and alkalinity and assigning a THA value through modeling for each tested aggregate.

Researchers developed a calibration curve between measured PSA and assigned alkali loading of the tested cement paste samples. A method based on the extraction of pore solution followed by analysis using X-ray fluorescence (XRF) was used to determine PSA. The calibration curve of PSA versus alkali loading was used to convert the measured THA values into alkali loading (lb/cy). This procedure was applied to determine alkali loading for all the tested aggregates. Determining alkali loading for individual aggregates facilitated the design of a case-specific durable ASR-resistant mix, the validation of which is presented in Chapters 4 and 5.

3.1 EXPERIMENTS AND MODELING TO DETERMINE COMPOSITE ACTIVATION ENERGY

Table 3.1 presents the design of the experiments. In general, for each aggregate, a total of 18 test runs (3 × 2 × 3; i.e., three levels of temperatures, two levels of alkalinities, and three replicas) were conducted.

Table 3.1. Factors and Levels in the Design of Experiments.

Factors	No. of Levels	Level Description
Material Type	10 Aggregates	FA1, 2, 4 and CA1 to 7 in Table 2.1
Temperature	3	60, 70, and 80°C
Solution Normality	2	0.5 N and 1 N NH with CH—CH is added until above saturation

The selected aggregates were tested using the VCMD (AASHTO T364-17) according to the experimental design described in Table 3.1, and ASR free volume change over time was measured at multiple temperatures and alkalinities. In the VCMD test, an as-received aggregate is immersed in a soak solution, and solution volume change is measured through a float-LVDT data acquisition system over time at three temperatures (e.g., 60, 70, and 80°C inside an oven) followed by calculation of rate constants at the three tested temperatures (T) and determination of CAP based on Arrhenius rate theory (Liu and Mukhopadhyay 2014a; Mukhopadhyay and Liu 2014; AASHTO 2017b). In the previous report (0-6656), the reactivity term was presented as compound activation energy (CAE). Based on earlier experiments with borosilicate glass, the measured CAE values at different alkali levels remain almost unchanged. However, CAE values showed an apparent relationship with alkalinity (CAE decreases with increasing alkalinity) for all the tested aggregates. Since solution volume change measurement in the VCMD represents a net solution volume change primarily due to ASR (a combined effect of all four steps [Liu and Mukhopadhyay 2014b] of ASR reaction mechanisms) with some secondary hidden effects (little) related to aggregate proprieties (e.g., heterogeneity, degree of resistance of solution migration/diffusion through the aggregate), it is advisable to name the reactivity parameter as CAP. Although CAP is a good way to measure aggregate reactivity, it should not be confused with the classical activation energy of a specific reaction in a pure phase system. Extensive aggregate testing has shown that a representative CAP can be determined within 5 days and with permissible repeatability (Mukhopadhyay and Liu 2014). Using an automatic data acquisition system, testing inside an oven to maintain the testing temperature in a closed environment, and using a fundamental engineering property (i.e., CAP) as a measure of aggregate reactivity increases the reliability of the VCMD test. The CAP for all the tested aggregates, along with ASTM C1260 and ASTM C1293 expansion (percent), is listed in Table 3.2. Table 3.3 provides the CAP-based aggregate classification system. A comparative assessment between CAP and ASTM C1260 14-day and ASTM C1293 1-year expansion data of the tested aggregates is presented in Figures 3.1 and 3.2.

Table 3.2. The CAP Values for the Tested Aggregates at Two Levels of Alkalinities along with C1260- and C1293-Based Reactivity Values.

Project	Aggregate	C1260 Value	C1293 Value	CAP, KJ/Mol	
				0.5 N NH + CH	1 N NH + CH
0-6656-01	FA1	0.269	0.054	46.34	22.91
	FA2	0.241	0.110	41.01	21.68
	FA4	0.182	0.100	40.57	27.29
	CA1*	0.031	0.155	34.07	23.16
	CA2*	0.024	0.129	44.23	24.36
	CA3*	0.062	0.092	38.39	25.78
	CA4*	0.025	0.098	40.50	12.51
	CA5*	0.025	0.099	39.07	20.91
	CA6*	0.040	0.082	38.83	10.88
	CA7*	0.046	0.091	48.66	25.90
0-6656	FA1-old	0.554	0.590	26.00	15.98
	FA2-old	0.334	0.171	34.98	23.25
	FA3-old	0.317	0.058	32.64	22.55
	FA4-old	0.242	0.043	36.39	26.82
	FA5-old	0.079	0.035	60.36	52.78
	FA6-old	0.381	0.391	26.96	19.95
	CA4-old	0.179	0.149	39.18	30.33
	CA1-old	0.417	0.078	29.73	22.15
	CA2-old	0.250	0.047	35.98	29.68
	CA3-old	0.227	0.071	41.78	21.29
	CA5-old**	0.140	0.020	57.03	45.35
	CA6-old*	0.100	0.097	36.74	29.65
	CA7-old*	0.040	0.129	35.72	27.24
	CA8-old	0.012	0.027	61.70	46.77

* Passed by ASTM C1260 but failed by ASTM C1293.

** Passed by ASTM C1293 but failed by ASTM C1260.

Table 3.3. CAP-Based Aggregate Classification System.

Aggregate Reactivity Class	Description of Aggregate Reactivity	CAP Ranges, KJ/mole	
		0.5 N NH + CH	1 N NH + CH
R0	Nonreactive	≥ 60	≥ 46
R1	Moderately reactive	45–60	35–46
R2	Highly reactive	30–45	20–35
R3	Very highly reactive	≤ 30	≤ 20

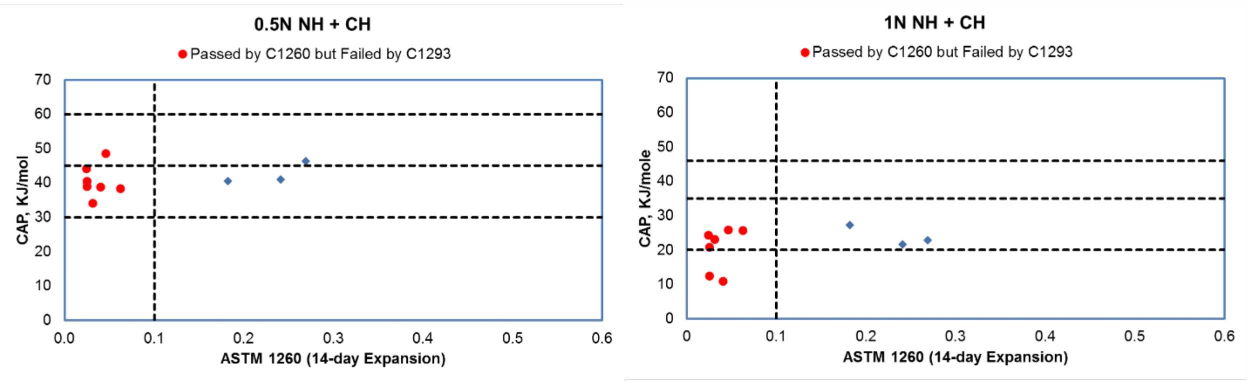

Figure 3.1. Correlation between CAP of Aggregate and ASTM C1260.

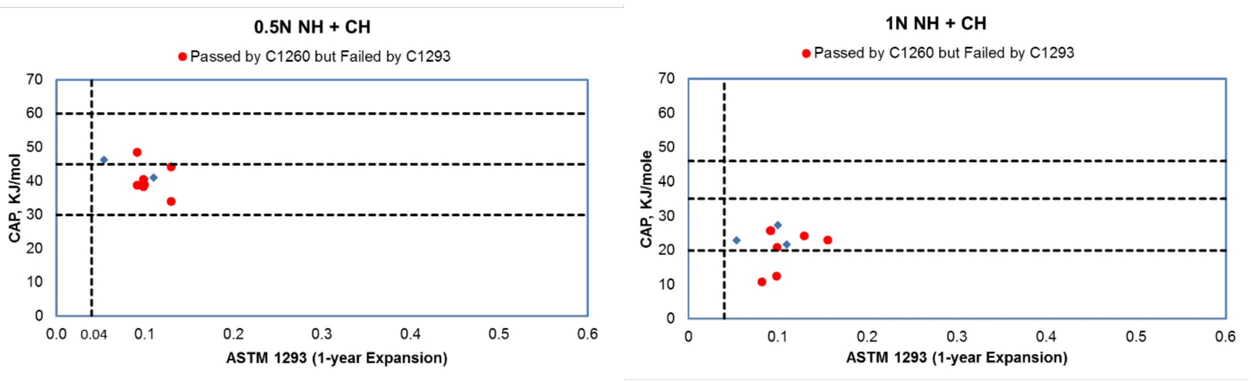

Figure 3.2. Correlation between CAP of Aggregate and ASTM C1293.

Table 3.2 and Figures 3.1 to 3.2 indicate:

- A representative CAP can be determined by testing an aggregate with 0.5 N NH + CH solution. Testing an aggregate with a solution chemistry (0.5 N NH + CH) similar to a concrete pore solution represents testing at the field level of alkalinity.
- The results in Figures 3.1 and 3.2 show that the aggregates passed by ASTM C1260 but failed by ASTM C1293 (false positive aggregates marked by red dots) have a relatively low CAP. Based on the CAP-based reactivity prediction shown in Table 3.3 (i.e., the lower the CAP, the higher the reactivity), these aggregates (marked as red dots) are reactive aggregates (reactivity varies a little from medium to slowly reactive). This finding indicates that the VCMD-based reactivity prediction does not agree with ASTM C1260 but matches well with the reactivity prediction based on the ASTM C1293 method (Figure 3.2). This result implies that measurement of CAP using the VCMD method can consistently identify the aggregates belonging to false positive category in a short period of time. This consistent identification is the main benefit of the VCMD method, and therefore the VCMD method can be used as an alternative to the ASTM C1260 method.

3.2 DETERMINATION OF THRESHOLD ALKALI LOADING (TAL) FOR EACH AGGREGATE

An apparent relationship between CAP and alkali concentration (e.g., alkalinity) is evident from the results of the studied aggregates (see Table 3.2). The higher the alkalinity, the lower the CAP. This possibly suggests that the energy barrier to initiate ASR becomes low at high alkalinity and high at low alkalinity. An attempt was made to establish a mathematical relationship between CAP and alkalinity. The following model (Equation 2.1) was used to establish a relationship between CAP and alkalinity:

$$CAP = \mathrm{E}_{\mathrm{a}_0} + \frac{C_1}{C^n} \qquad \text{(Equation 2.1)}$$

Where CAP is the composite activation parameter (KJ/mol), E_{ao} is the activation parameter-threshold (KJ/mol), C_1 is the activation parameter curvature coefficient (KJ/(mol)$^{1-n}$), n is the activation parameter curvature exponent, and C is alkalinity (mol).

Figure 3.3 shows the results for FA1 as an example. As shown in the plot, when alkalinity increases, CAP decreases. The measured CAP values at the tested alkali levels (i.e., 1 N and 0.5 N NH + CH) are aptly described by the predicted curve (green curve in Figure 3.3) between alkalinity and CAP. This result demonstrates the applicability of the proposed model. The existence of a characteristic THA for each aggregate manifested from the plots as well. A THA for each aggregate was mathematically calculated from the CAP versus alkalinity plot and is summarized in Table 3.4. In general, the higher the reactivity, the lower the THA. If an aggregate with low THA (i.e., low level of alkali tolerance) is used in concrete, the PSA of that concrete needs to be maintained at a low level too. The common approaches to maintain a low level of PSA are (a) use of low alkali cement, (b) use of good-quality fly ash with low alkali content, and (c) assurance of minimum contribution of additional alkalis from an external source(s). A reactive aggregate can practically behave as nonreactive or very slowly reactive provided the alkalinity (PSA) can be maintained below the THA. This factor is addressed in detail in Chapters 4 and 5.

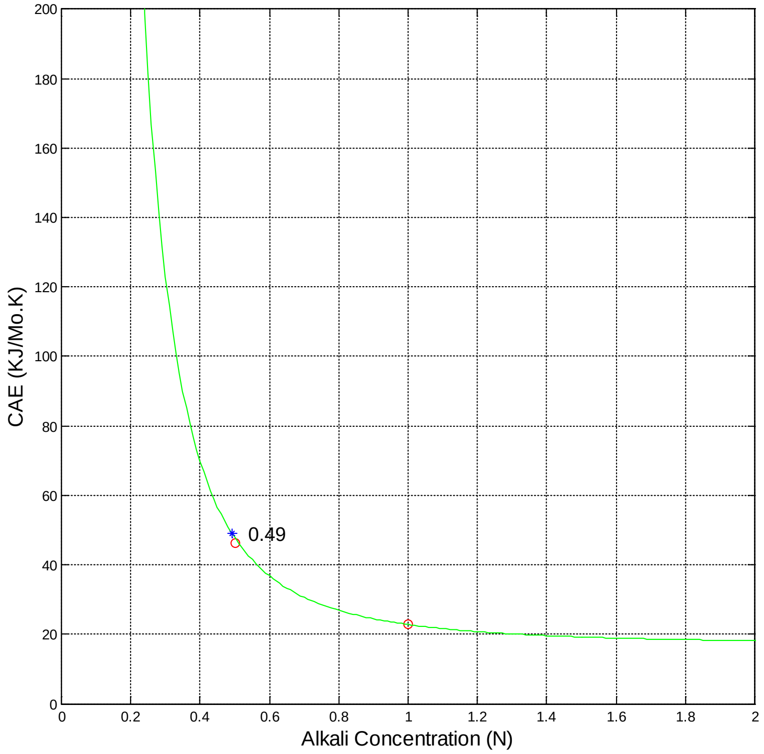

Figure 3.3. Effect of Alkalinity on the CAP of FA1.

Table 3.4. Summary of THA.

Project	Aggregate	CAP, KJ/Mol		THA, N
		0.5 N NH + CH	1 N NH + CH	
0-6656-01	FA1	46.34	22.91	0.49
	FA2	41.01	21.68	0.46
	FA4	40.57	27.29	0.45
	CA1*	34.07	23.16	0.40
	CA2*	44.23	24.36	0.47
	CA3*	38.39	25.78	0.44
	CA4*	40.50	12.51	0.47
	CA5*	39.07	20.91	0.45
	CA6*	38.83	10.88	0.45
	CA7*	48.66	25.90	0.50
0-6656	FA1-old	26.00	15.98	0.27
	FA2-old	34.98	23.25	0.46
	FA3-old	32.64	22.55	0.47
	FA4-old	36.39	26.82	0.46
	CA4-old	39.18	30.33	0.46
	CA1-old	29.73	22.15	0.30
	CA2-old	35.98	29.68	0.39
	CA3-old	41.78	21.29	0.42
	CA5-old**	57.03	45.35	0.49
	CA6-old*	36.74	29.65	0.46
	CA7-old*	35.72	27.24	0.39

* Passed by ASTM C1260 but failed by ASTM C1293.
** Passed by ASTM C1293 but failed by ASTM C1260.

The cement paste cylinders (2 × 4 inches) using nine levels of alkali loadings (see Table 3.5) were cast. The use of a high-alkali (Na_2O_e = 0.82 percent) Portland cement with varying fly ash replacement and extra NaOH pallets (whenever needed) was adequate to achieve the different levels of alkali loadings. The cement paste cylinders were covered with a plastic lid and then stored under 98±2 percent RH at 23±2°C for 7 days. After the 7-day curing, the specimens were de-molded, and pore solutions (Barneyback and Diamond 1981) were extracted from each paste specimen. The extracted pore solution was analyzed using XRF to determine Na^+ and K^+ ion concentration. Table 3.5 presents the composition (Na^+ and K^+) of pore solutions extracted from the studied cement pastes. A minimum of three cement paste specimens for each mix listed in Table 3.4 were squeezed to extract the pore solution, and then the extracted solutions were mixed to get a representative pore solution. The Na equivalent (Na^+_e) represents the total alkali levels for each mix in this study. Figure 3.4 shows the correlation between PSA and alkali loading. The measured THA values (Table 3.4) were then converted using the calibration curve of PSA versus alkali loading (Figure 3.4) into alkali loading. The alkali loading of all the tested aggregates was determined by applying this procedure, and results are shown in Table 3.6. A comparative assessment between the TAL values (Table 3.6) and PSA of different concrete mixes using these aggregates at different levels of alkali loading was the basis to predict the concrete expansion behavior before conducting the ACCT-based concrete validation testing, which is described in Chapters 4 and 5.

Table 3.5. Cement Mix Design along with Corresponding Pore Solution Chemistry Data.

Alkali (lb/cy)	Cement (sack/cy)	Fly Ash Replacement %	Add. NH (lb/cy)	PSA				
				Na^+ (ppm)	K^+ (ppm)	Na^+ (N)	K^+ (N)	Na^+_e (N)
2.47	5.83	45	—	1110	13410	0.048	0.343	0.251
2.92	5.83	35	—	1790	16700	0.078	0.427	0.327
3.15	5.83	30	—	1800	16600	0.078	0.425	0.330
3.37	5.83	25	—	2260	21800	0.098	0.558	0.427
3.60	5.83	20	—	2310	22500	0.100	0.575	0.440
4.05	5.83	10	—	2775	23825	0.121	0.609	0.480
4.27	5.83	5	—	3882	28860	0.169	0.738	0.604
4.50	5.83	—	—	4153	31562	0.181	0.807	0.657
4.99	5.83	—	0.49	5800	27420	0.252	0.701	0.666

Note: — represents not adding item.

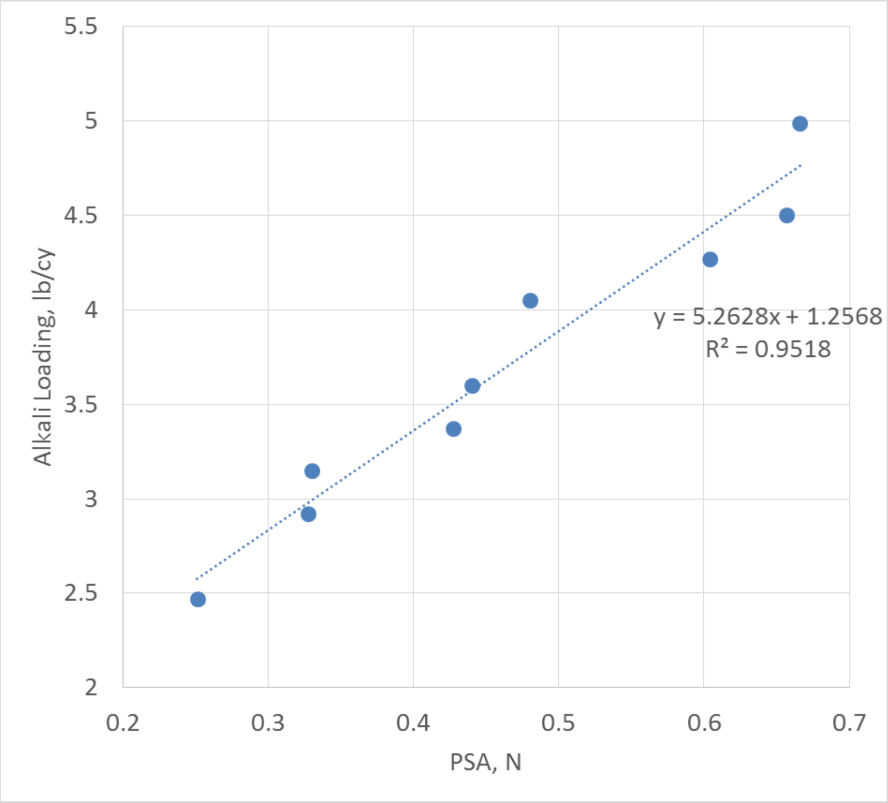

Figure 3.4. Correlation between Alkali Loading and PSA.

Table 3.6. Summary of Threshold Alkali Loading.

Project	Aggregate	THA, N	TAL, lb/cy
0-6656-01	FA1	0.49	3.8
	FA2	0.46	3.7
	FA4	0.45	3.6
	CA1*	0.40	3.4
	CA2*	0.47	3.7
	CA3*	0.44	3.6
	CA4*	0.47	3.7
	CA5*	0.45	3.6
	CA6*	0.45	3.6
	CA7*	0.50	3.9
0-6656	FA1-old	0.27	2.7
	FA2-old	0.46	3.7
	FA3-old	0.47	3.7
	FA4-old	0.46	3.7
	CA4-old	0.46	3.7
	CA1-old	0.30	2.8
	CA2-old	0.39	3.3
	CA3-old	0.42	3.5
	CA5-old**	0.49	3.8
	CA6-old*	0.46	3.7
	CA7-old*	0.39	3.3

* Passed by ASTM C1260 but Failed by ASTM C1293.

** Passed by ASTM C1293 but Failed by ASTM C1260.

3.3 SUMMARY

A general classification system based on previous (from Project 0-6656) and new (from current Project 0-6656-01) data covering aggregate reactivity based on CAP and alkali loading is proposed (see Table 3.7).

Table 3.7. General Guidelines to Select Concrete Alkali Loading.

Aggregate Reactivity Class	Description of Aggregate Reactivity	CAP Ranges, KJ/mole (0.5 N NH + CH)	Alkali loading, lb/cy
R0	Nonreactive	≥ 60	4.0 to 4.5
R1	Moderately reactive	45–60	3.5 to 4.0
R2	Highly reactive	30–45	3.0 to 3.5
R3	Very highly reactive	≤ 30	≤ 3.0

The researchers recommend that the alkali loading for the tested aggregates in this project (Table 3.6) be maintained ≤ 3.5 lb/cy (i.e., 3.0–3.5) in order to ensure the ASR-resistant property of the concrete mixtures made of these tested aggregates, with the exception of two aggregates (FA1-old and CA1-old). Although most of these tested aggregates should perform well with alkali loading slightly higher than 3.5 lb/cy (i.e., 3.6–3.9, Table 3.6), it is better to maintain the alkali loading at 3.5 lb/cy (according to the current TxDOT practice) to ensure a safe durable mix in terms of ASR. However, some aggregates (e.g., CA1, CA2-old, and CA7-old) need slightly lower than 3.5 lb/cy alkali loading. For a highly reactive aggregate (FA1-old and CA1-old, as shown in Table 3.6), the concrete alkali loading needs to be maintained below 3 lb/cy (corresponding to R3, Table 3.7). A higher level (e.g., 35–45 percent) of Class F fly ash replacement with negligible soluble alkali contribution or effective use of ternary blends (i.e., use of another suitable SCM, such as slag, silica fume, and metakaolin, along with cement and fly ash) is needed to attain a low level of concrete alkali loading (i.e., below 3.0 lb/cy). If a higher content of fly ash/ternary blend is not allowed, application of different mix design controls (e.g., application of Li-compounds or other suitable chemicals [Liu et al. 2018]) in conjunction with conventional use of fly ash is recommended. Verification of the applicability of the above guidelines is described in Chapters 4 and 5.

CHAPTER 4: FURTHER VALIDATION OF ACCELERATED CONCRETE CYLINDER TEST

The objective of the task described in this chapter was to further validate the ACCT method by (a) assigning a suitable testing period, (b) verifying the expansion limit, (c) assigning a practical alkali loading for testing a concrete mix, (d) assigning a suitable and representative level of a soak solution chemistry, (e) investigating the effect of specimen dimension, and (f) investigating the suitability of the ACCT method to test job concrete mix. Chapter 5 describes the mix design validation using the ACCT method.

The CPT (ASTM C1293) has been considered the best index for field performance, but the test duration is a major drawback. Ranc and Debray (1992) first introduced the accelerated concrete prism test (ACPT) in the early 1990s. The concrete prisms were stored over water at 60°C instead of 38°C. The results showed good correlation between the 38°C and 60°C tests after the testing period of 56 days. Other researchers (Grosbois and Fontaine 2000; Touma et al. 2001) also found a reasonably good correlation between 1-year concrete prism expansions at 38°C and 2- to 4-month prism expansion at 60°C. Although the test duration was shortened by simply increasing the test temperature, a significant reduction in expansion associated with high-alkali leaching was noticed in the ACPT compared to the CPT (Fournier et al. 2004). When alkali leaches out of the specimens, the sulfate ions replace the leached alkali hydroxides and decrease the pH of the pore solution. This eventually causes a reduction in expansion.

The developed ACCT overcomes some of the above limitations and offers a reliable ASR concrete test method. The unique features of this concrete ASR test method are:

- Automated LVDT-based length change measurement system that eliminates human error during length measurement.
- Measurements to avoid alkali leaching—sample tested by immersing in alkaline soak solution condition.
- Testing inside an oven at a relatively high temperature (60°C), thus reducing testing time due to faster reaction.
- Testing at varying levels of alkali loadings (alkali-boosted concrete to reduce testing period as well as alkali levels similar to job concrete mix).
- Avoiding reduction of pore solution pH due to alkali leaching followed by replacement with sulfate ions (as described above for the ACPT).

4.1 DESIGN OF EXPERIMENTS

As described in Chapter 2, some of the tested aggregates came from a previous project, and the remaining were collected in the current project. The reactivity information of the tested aggregates is summarized in Table 4.1. The factors and levels that were selected for the ACCT based experimental program are summarized in Table 4.2.

Table 4.1. List of Tested Aggregates.

Aggregate	Type	CAP-Based Reactivity (Chapter 3)	C1260 Value	C1293 Value
FA6-old	Fine	R3	0.381	0.391
FA4	Fine	R2	0.182	0.100
FA5-old	Fine	R0	0.079	0.035
CA4-old	Coarse	R2	0.179	0.149
FA3	Fine	R0	0.003	N/A
CA8-old	Coarse	R0	0.012	0.027
CA1-old	Coarse	R3	0.417	0.078
CA3-old	Coarse	R2	0.227	0.071
CA5-old	Coarse	R1	0.140	0.020
New Mexico Rhyolite (NMR)	Coarse	R3	1.300	N/A

Table 4.2. Factors and Levels in the Design of Experiments.

Factors	No. of Levels	Level Description
Material Type	10 Aggregates	The 10 aggregates in Table 4.1
Temperature	1	60°C
Alkali Loading	1	4.5 lb/cy using high-alkali cement (Na_2O_e = 0.82%) without using alkali boosting (i.e., no addition of external alkalis)
Soak Solution Chemistry	3	Soak solution = pore solution for all mixes Soak solution = 1/2, 1/3, or 1/4 of pore solution for selected mixes

4.2 USEFULNESS OF ACCT METHOD WITH LOW ALKALI LOADINGS (4.5 LB/CY)

Based on the data generated in the previous project, the ACCT with relatively low alkali loadings, including but not limited to 4.5 lb/cy and 60°C, can effectively be used to determine aggregate reactivity in a relatively short time. All the concrete mixes made of the selected aggregates listed in Table 4.1 were tested at the alkali level of 4.5 lb/cy with soak solution volume to concrete volume (s/c) = 3. A comparative assessment between ACCT results and ASTM C1293 data was used to verify whether relatively low alkali loading around 4.5 lb/cy could be effective to pass/fail an aggregate in a relatively short time.

All the tested ACCT mixtures were without alkali boosting. Table 4.3 presents a detailed description of the mix designs. For the mix designs shown in Table 4.3, the concretes were mixed by hand following ASTM C192 procedures. The cement and fine aggregates were thoroughly dry blended in a clean stainless steel bowl. The coarse aggregates were then added into the bowl, and dry mixing continued until a homogeneous mix of cement, coarse aggregate, and fine aggregate was achieved. Deionized water was then added, and mixing continued for an additional 5 minutes until a homogeneous concrete mix was achieved. Concrete cylinders using each mix (see Table 4.3) were cast for the ACCT. Testing a concrete mix with a low alkali loading, including but not limited to 4.5 lb/cy, without any alkali boosting allowed researchers to make the alkali conditions less severe and close to alkali loading of some of the high cement content field concrete mixes (e.g., precast concrete mixes). Note that ASTM C1293 tests a standard mix with a high level of alkali loading including but not limited to 8.9 lb/cy.

Table 4.3. Concrete Mix Design (4.5 lb/cy) for Conducting the ACCT.

	Coarse Aggregate	Fine Aggregate	Alkali (lb/cy)	Water to Cement Ratio (w/c)	Coarse Aggregate Factor	Cement Factor (CF) (sacks/cy)
Mix 1	CA8-old	FA6-old	4.5	0.45	0.76	5.83
Mix 2	CA1-old	FA6-old				
Mix 3	CA1-old	FA5-old				
Mix 4	CA4-old	FA3				
Mix 5	CA8-old	FA4				
Mix 6	CA3-old	FA4				
Mix 7	NMR	FA3				
Mix 8	CA8-old	FA5-old				
Mix 9	CA5-old*	FA5-old				

* Passed by C1293 but failed by C1260.

Mix 1 with alkali loading 4.5 lb/cy was used to verify the repeatability (within the lab) of the ACCT method. The expansions corresponding to the three replicas were used to calculate the coefficient of variation (COV), and the expansion results are presented in Figure 4.1. The COV based on expansion data after 14 days of the tested mixes was mostly within 10 percent, which supports permissible repeatability (within the lab) of the ACCT method.

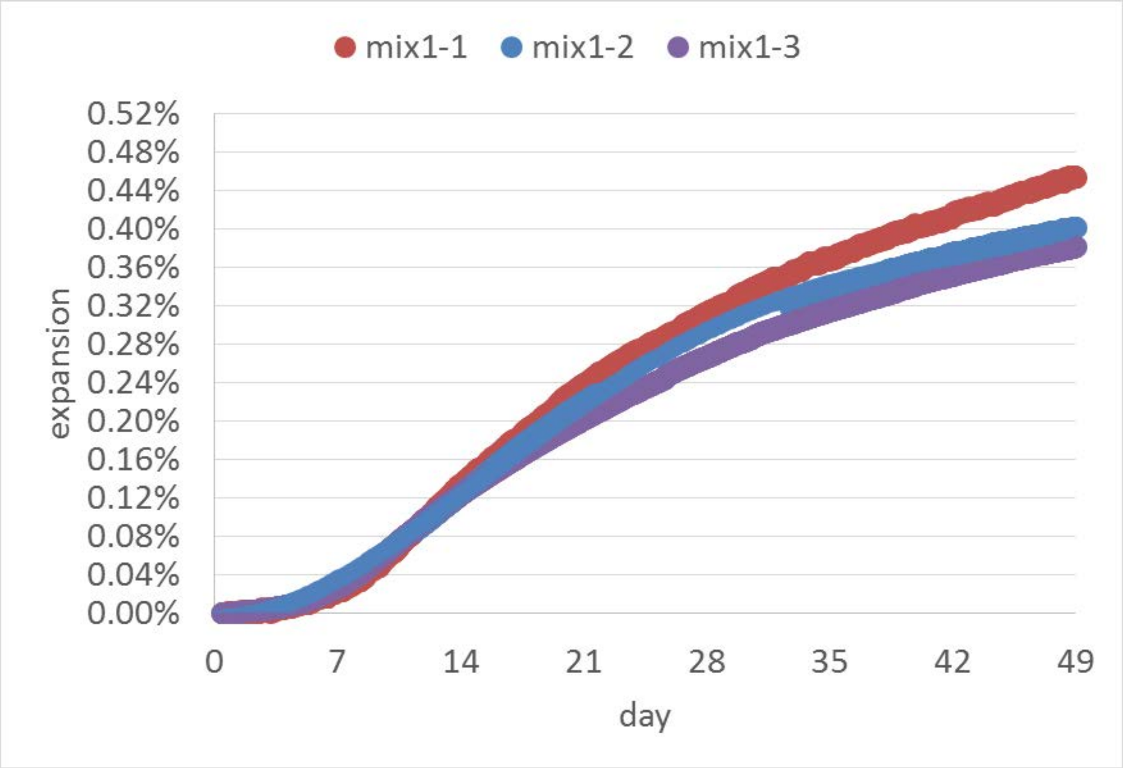

Figure 4.1. Expansion of Mix 1 with Alkali Level of 4.5 lb/cy.

Selected concrete mixes (Mixes 1 to 9, Table 4.3) were tested using the ACCT at 60°C with an alkali level of 4.5 lb/cy and compared with the ASTM C1293 for validation purposes. For each test corresponding to each mix, the soak solution chemistry was equal to the pore solution chemistry. For specimens containing SCMs, it is recommended to determine pore solution chemistry based on extraction techniques since some SCMs (especially some fly ashes) may contribute soluble alkalis to the pore solution. If the pore solution extraction method is not available, a combined use of the National Institute of Standards and Technology (NIST) model and ASTM C311 (measure available alkalis of SCMs) is recommended to estimate PSA of the fly ash mixes with acceptable accuracy. For any fly ash mix, PSA of the cement portion can be determined using the NIST model, and ASTM C311 can be used to determine available alkalis for fly ash separately. The final estimated PSA is then calculated by adding Na+ and K+ concentrations of pore solutions determined by the NIST model and ASTM C311 (fly ash). For example, with 30 percent fly ash replacement level, the model can be used to estimate the PSA corresponding to 70 percent cement and ASTM C311 for the fly ash. If C311 testing detects soluble alkalis contribution from the used SCMs, then adding PSA estimated using the model with the measured available alkalis by the C311 shall provide the effective final PSA of the tested concrete. The soak solution chemistry will be equal to this final PSA (measured by the extraction technique or estimated), and an additional 1 g (0.0022 lb) of $Ca(OH)_2$ per liter should be added in order to saturate the solution. Figures 4.2 to 4.10 show the ACCT-based expansion curves over time for the nine mixes. For all mixes, the higher the ASR aggregate reactivity (i.e., lower CAP/higher ASTM C1293 expansion value), the higher the measured ACCT expansion. Table 4.4 presents a comparison of the ACCT expansion data with the 1-year CPT (ASTM C1293) expansion data. For all the reactive mixes (Mixes 1–7), the expansion percentages equivalent to ASTM C1293 expansion values were achieved by the ACCT method within 56 days.

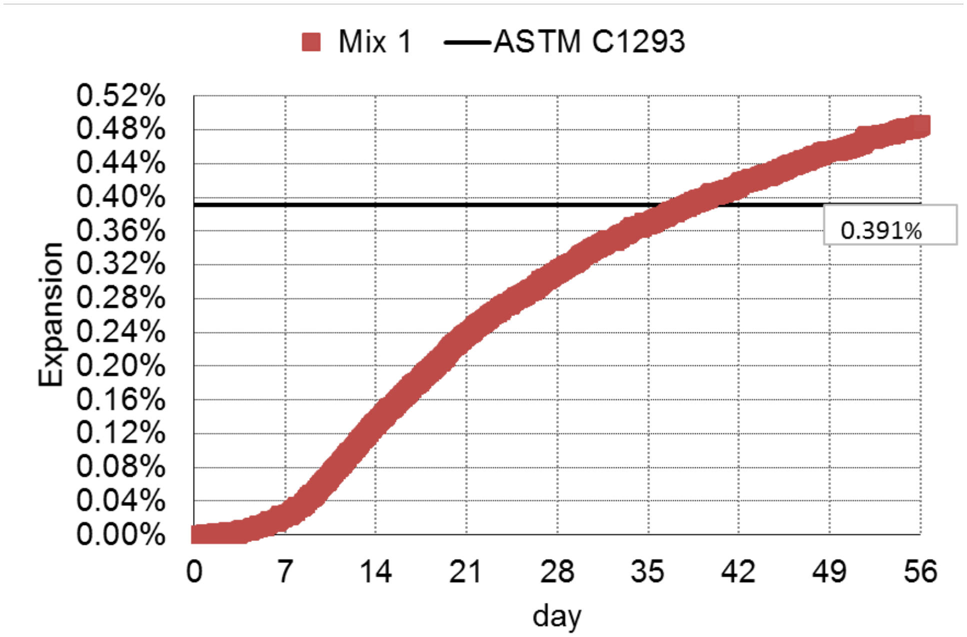

Figure 4.2. Expansion Curve of ACCT (Mix 1) over Time at Alkali Level of 4.5 lb/cy.

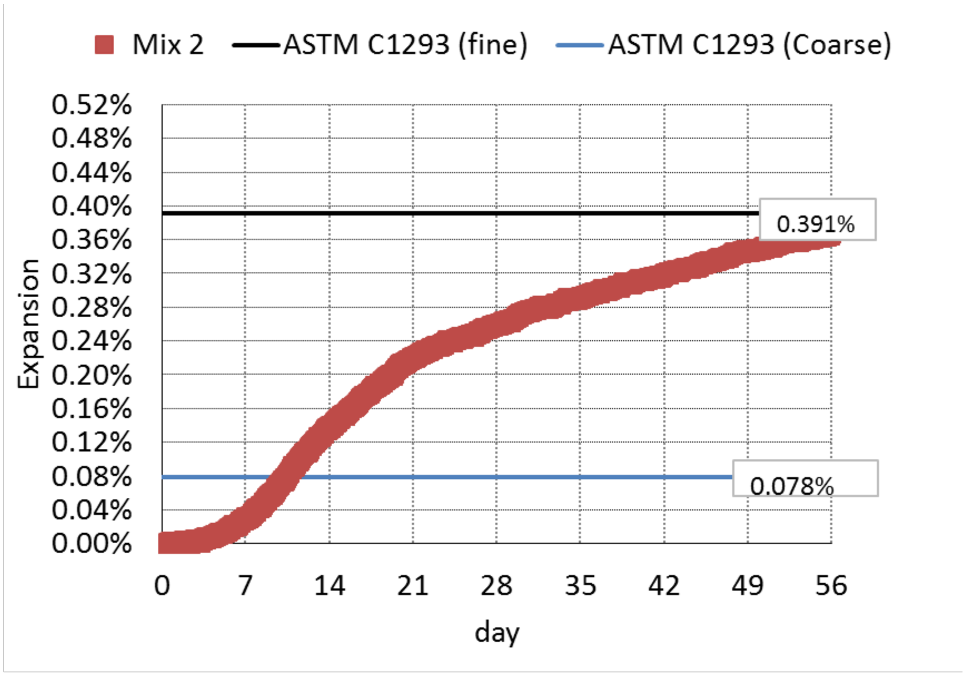

Figure 4.3. Expansion Curve of ACCT (Mix 2) over Time at Alkali Level of 4.5 lb/cy.

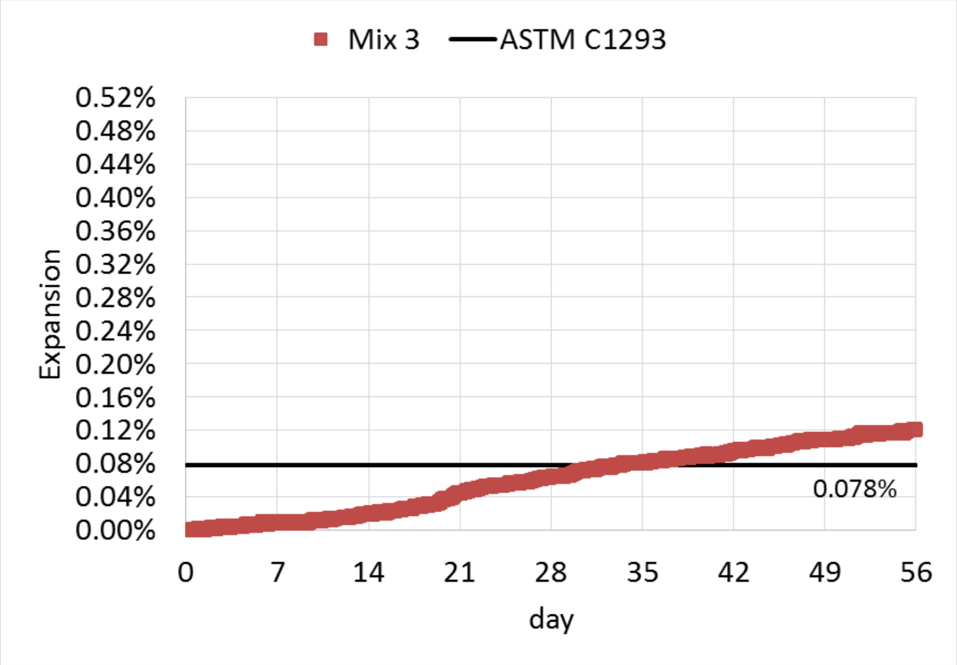

Figure 4.4. Expansion Curve of ACCT (Mix 3) over Time at Alkali Level of 4.5 lb/cy.

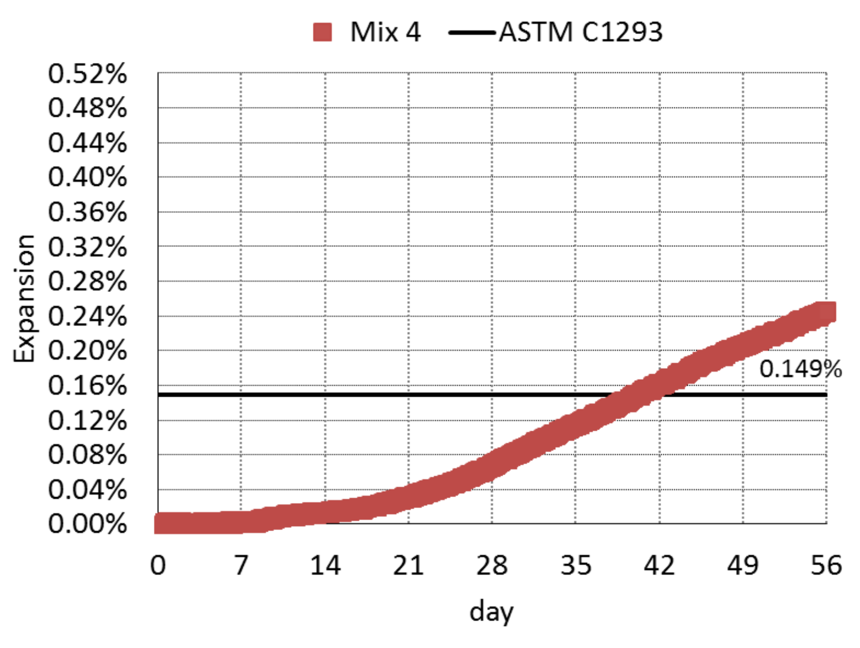

Figure 4.5. Expansion Curve of ACCT (Mix 4) over Time at Alkali Level of 4.5 lb/cy.

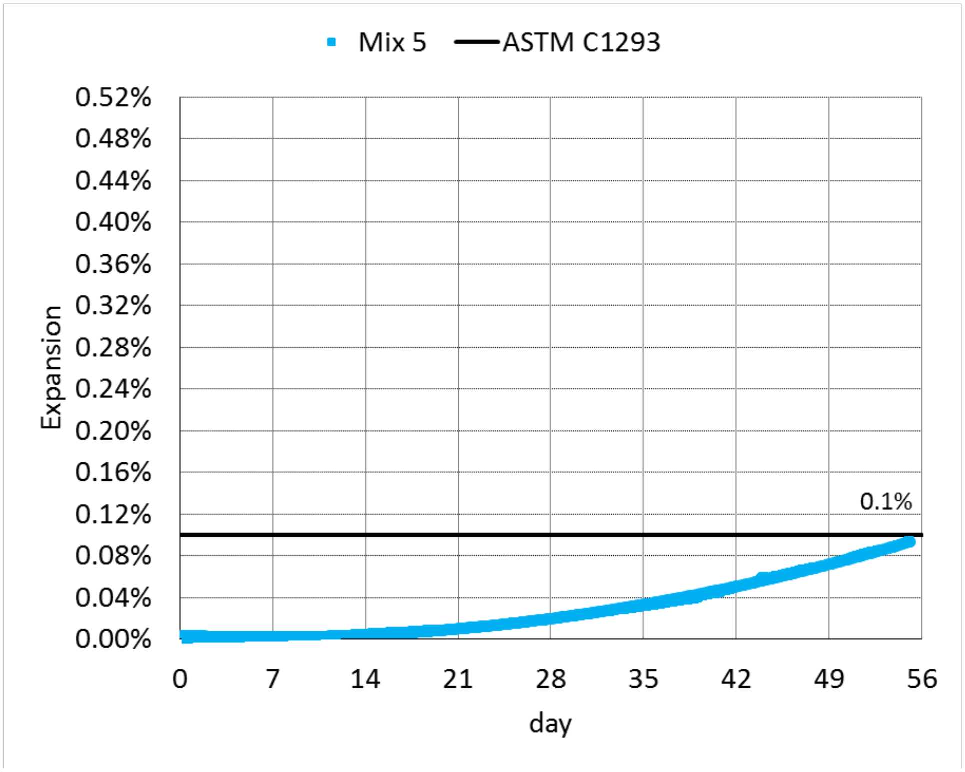

Figure 4.6. Expansion Curve of ACCT (Mix 5) over Time at Alkali Level of 4.5 lb/cy.

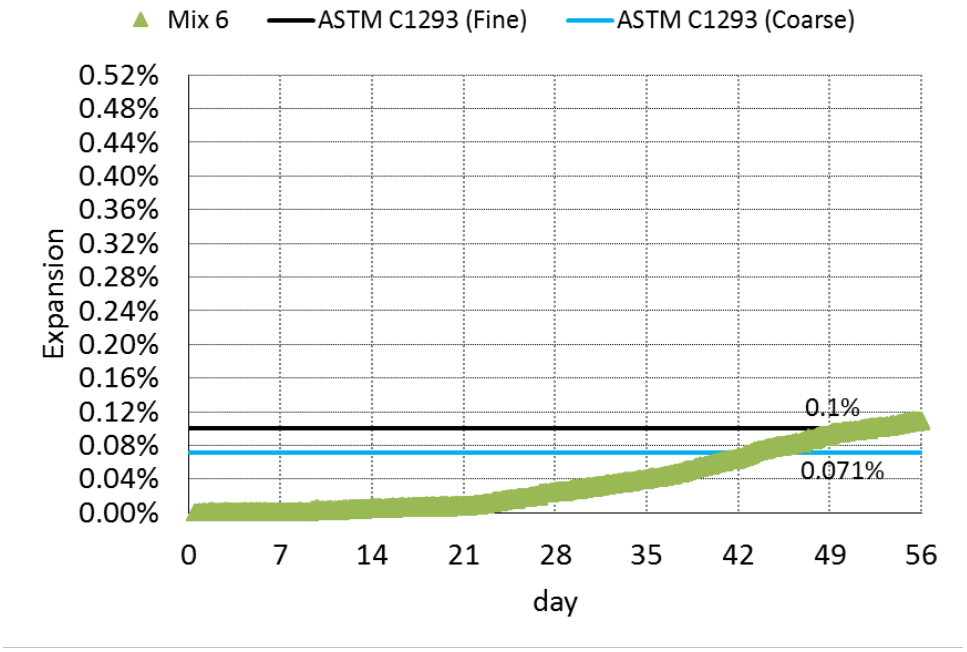

Figure 4.7. Expansion Curve of ACCT (Mix 6) over Time at Alkali Level of 4.5 lb/cy.

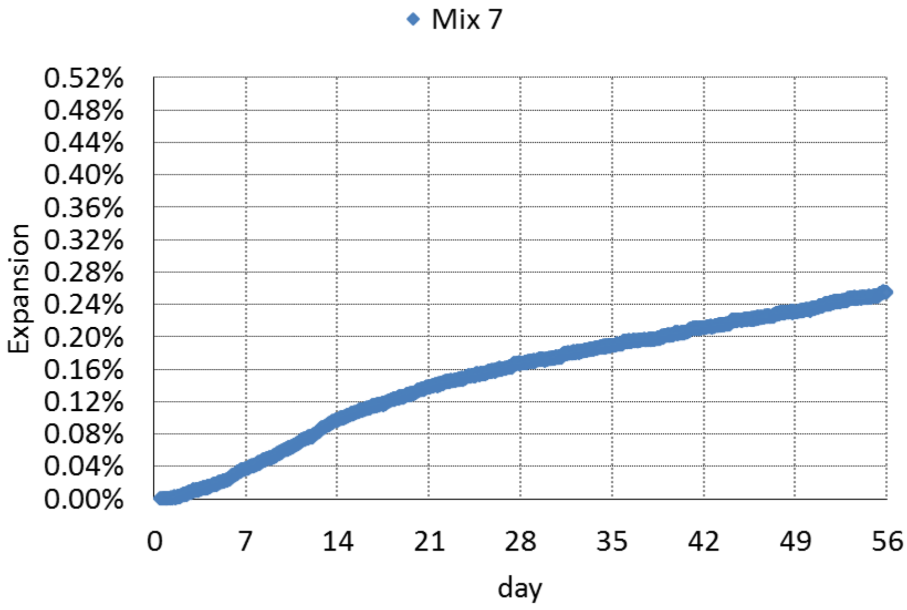

Figure 4.8. Expansion Curve of ACCT (Mix 7) over Time at Alkali Level of 4.5 lb/cy.

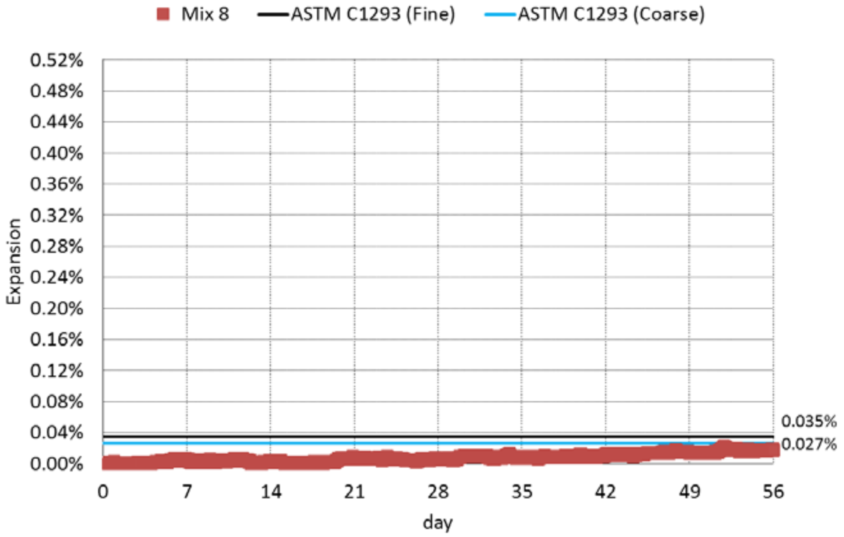

Figure 4.9. Expansion Curve of ACCT (Mix 8) over Time at Alkali Level of 4.5 lb/cy.

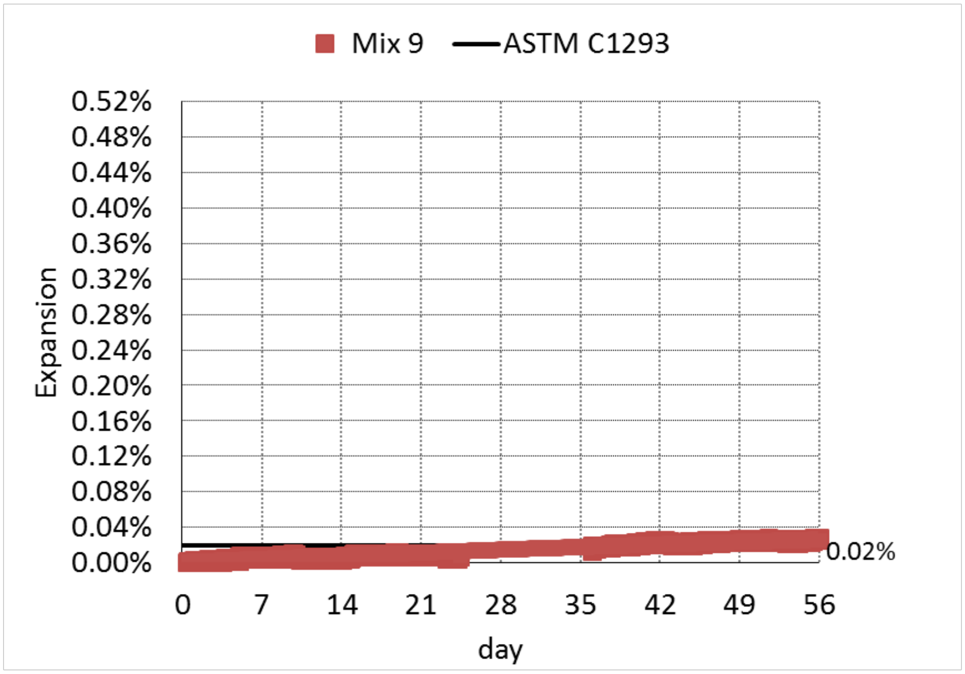

Figure 4.10. Expansion Curve of ACCT (Mix 9) over Time at Alkali Level of 4.5 lb/cy.

Table 4.4. Aggregate Reactivity Based on ACCT Expansion (4.5 lb/cy).

Mix	**Time to Reach ASTM C1293 1-year Expansion (Days)**	**Time (Days) to Cross 0.04% Expansion Limit**	**ASTM C1293 1-year Expansion (%)**	**CAP Classification (Chapter 3)**
1	36	9	0.391	R0 coarse + R3 fine aggregate
2	10/56	8	0.078/0.391	R3 coarse + R3 fine aggregate
3	33	20	0.078	R2 coarse + R0 fine aggregate
4	27	22	0.149	R2 coarse + R0 fine aggregate
5	56	37	0.100	R0 coarse + R2 fine aggregate
6	43/50	35	0.071/0.100	R2 coarse + R2 fine aggregate
7	Not Applicable	7	NA	R3 coarse + R0 fine aggregate
8	None	None	0.027/0.035	R0 coarse + R0 fine aggregate
9*	35	None	0.020	R0 coarse + R0 fine aggregate

* Passed by C1293 but failed by C1260. NA – Not available

Based on the results shown in Table 4.4, the ACCT with relatively low alkali loading (i.e., 4.5 lb/cy without alkali boosting) can achieve the 1-year ASTM C1293 value within 2 months. A concrete mix with a conventional cement content (e.g., ~ 6.0–6.5 sack/cy) will be sufficient to achieve 4.5 lb/cy alkali loadings if the Na_2O_e of the cement is relatively high (e.g., $0.6 < Na_2O_e \leq 0.82$). However, if the Na_2O_e of the cement is low (e.g., ~ 0.55), a high cement content (~ 6.5–7.5 sack/cy) with and without adding extra alkali may be needed in order to achieve 4.5 lb/cy alkali loading. It can be concluded that (a) the magnitude of measured ACCT expansion depends on the reactivity of the aggregate and whether the coarse or fine aggregate is reactive, and (b) the ACCT method with relatively low alkali loadings, including but not limited to 4.5 lb/cy can effectively be used to pass/fail an aggregate in a relatively short time (i.e., achieve the 0.04 percent expansion limit within 45 days).

4.3 VERIFICATION OF THE EXPANSION LIMIT

The expansion limit of 0.04 percent has been reported as a pass/fail criterion for ASTM C1293 as well as for the exposure block (Hooton 2012). The expansion limit of 0.04 percent was assigned for the results in the present study, as shown in Figures 4.2 to 4.10. The expansion data from all the selected concrete mixes listed in Table 4.3 were compared with the expansion data from ASTM C1293 and are summarized in Table 4.4.

For all the mixes studied (covering a range of aggregate reactivity and combinations), the expansion limit of 0.04 percent was achieved within 38 days. The higher the aggregate reactivity, the shorter the duration to achieve the 0.04 percent limit. For example, the expansion limit of 0.04 percent was reached within 10 days for the highly reactive mixes (e.g., Mixes 1, 2, and 7) and within 38 days for the less reactive mixes (i.e., Mixes 3 to 6). This finding indicates that using the expansion limit of 0.04 percent with the alkali loading of 4.5 lb/cy was sufficient for the ACCT method to identify the studied mixes within 38 days. The 38-day ACCT expansions were 0.398, 0.091, 0.152, 0.046, 0.065, 0.022, and 0.019 percent for Mixes 1, 3, 4, 5, 6, 8, and 9, respectively, which match well with the diagnostic 1-year ASTM C1293 expansion percentages (i.e., 0.391, 0.078, 0.149, 0.100, 0.071, 0.027/0.035, and 0.02, respectively).

Mix 8 was a reference nonreactive mix (both coarse and fine aggregate). The coarse aggregate in Mix 9 was a false negative aggregate (i.e., failed by C1260 but passed by C1293). Note that this coarse aggregate was identified as nonreactive by CAP-based classification (in Chapter 3, Table 3.4) and nonreactive based on ACCT expansion until 56 days (Figure 4.10, Table 4.4). This finding is an indication of the reliability of the ACCT method. Therefore, the expansion limit of 0.04% for the ACCT method with relatively low alkali loadings (~ 4.5 lb/cy) can effectively be applied to identify the concrete mixes with varying reactivity in a relatively short period of time.

4.4 DETERMINATION OF AN EFFECTIVE TESTING PERIOD

Based on the results presented in Sections 4.2 and 4.3, the ACCT with an alkali loading of 4.5 lb/cy is an effective method to pass/fail a concrete mix with the expansion limits of 0.04 percent from 7 to 37 days, depending on the aggregate reactivity. Figure 4.11 shows plots of 1-year expansions in ASTM C1293 versus the 28-, 35-, 42-, 49-, and 56-day ACCT expansions at the alkali level of 4.5 lb/cy (0.82 percent Na_2O_e). The figure presents how and where 1-year expansions in ASTM C1293 correlate well with ACCT expansion at each testing time. Based on the results with the testing periods of 28 and 35 days (Figure 4.11a), the ACCT-based reactivity prediction does not correlate well with the prediction by the ASTM C1293 (i.e., some aggregates are identified as reactive by the C1293 but nonreactive by the ACCT and vice versa). However, a good correlation between C 1293 and ACCT is evident (Figure 4.11b) at testing periods of 42, 49, and 56 days. Therefore, 45 days (a standardized period near 42 days) was assigned as an effective testing period for the ACCT to evaluate alkali-silica reactivity at an alkali level of 4.5 lb/cy.

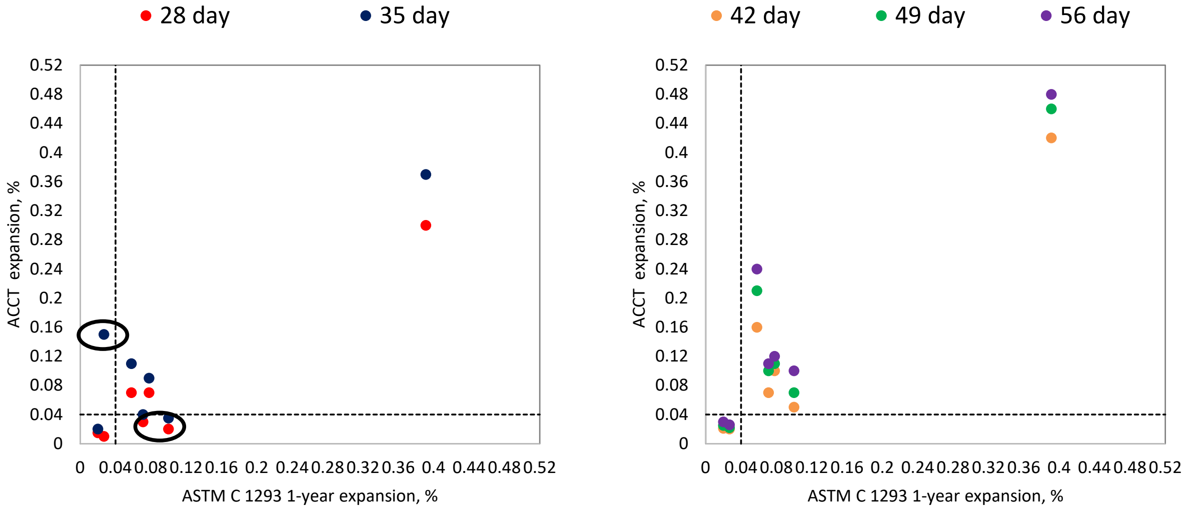

Figure 4.11. Comparison of Expansion at 1 Year in ASTM C1293 Test versus Expansion at (a) 28 and 35 Days, and (b) 42, 49, and 56 Days in the ACCT Test with Alkali Level of 4.5 lb/cy.

4.5 EFFECT OF SPECIMEN DIMENSION

Concrete specimens of different dimensions, including but not limited to a cylinder of 3 x 6 inches, a cylinder of 4 x 6 inches, and a cylinder of 4 x 3.375 inches were cast using Mix 1, and expansion over time was measured by the ACCT method at different temperatures, including but not limited to 38°C and 60°C, under alkali leach-proof conditions. Figures 4.12 and 4.13 show the effect of specimen sizes and temperatures on the concrete expansion behavior in the ACCT with an alkali loading of 4.5 lb/cy. Figure 4.12 indicates that the expansion difference between 3- and 4-inch-diameter (regardless of height) specimens was small. A similar finding was obtained in earlier research (Pour-Ghaz et al. 2012), where the effect of specimen dimension was studied in a similar setup (i.e., use of LVDT to measure length change of mortar cylinder in 1 N NaOH solution), and expansion difference between 3- and 4-inch-diameter specimens was found to be small. Therefore, a cylinder of 3 x 6-inch dimension was accepted as a representative specimen dimension for the ACCT method. Figure 4.13 shows that the higher the temperature (60 versus 38°C), the higher the concrete cylinder expansion.

The CPT method using a testing temperature of 38°C has been considered the best index for field performance, but the test duration imposes a major limitation. Efforts have been made by different researchers in the past to accelerate CPT (accelerated CPT—ACPT) by increasing the testing temperature (Ideker et al. 2010). Although the test duration was shortened by simply increasing the testing temperature, a significant reduction in expansion associated with higher alkali leaching in the ACPT than the CPT was noticed (Ideker et al. 2010). The ACCT eliminates alkali leaching from the concrete specimen during testing by matching the pore solution to the soak solution. By doing this, the ACCT at 38 and 60°C can achieve the 1-year ASTM C1293 value within 6 and 1.5 months, respectively. Therefore, the reliability of the ACCT method is high, and the ACCT can be considered an alternative method to the current ASTM C1293.

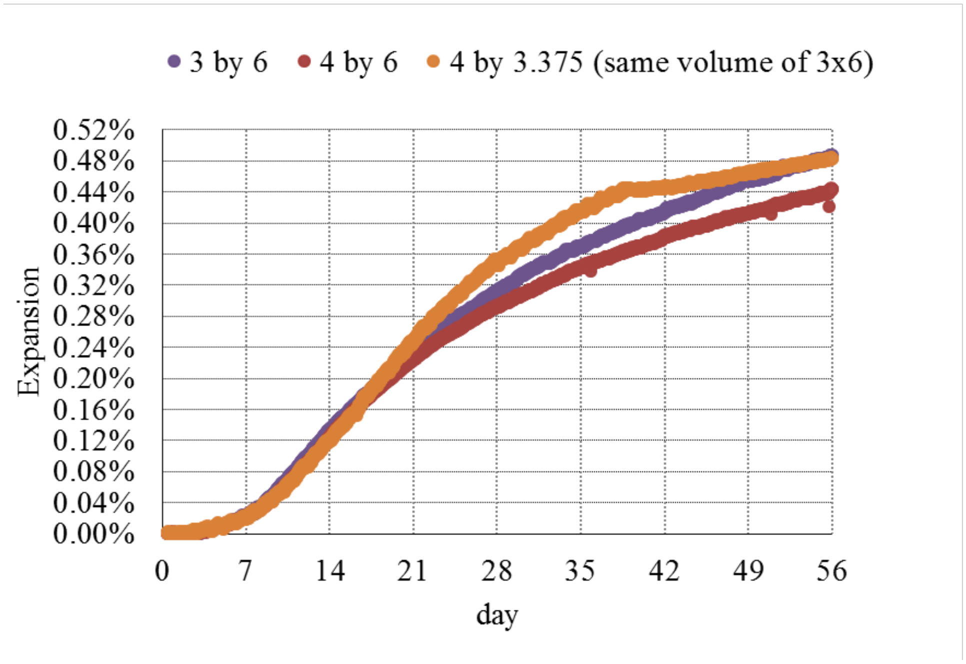

Figure 4.12. Effect of Specimen Dimension on ACCT (Mix 1) Expansion at 60ºC.

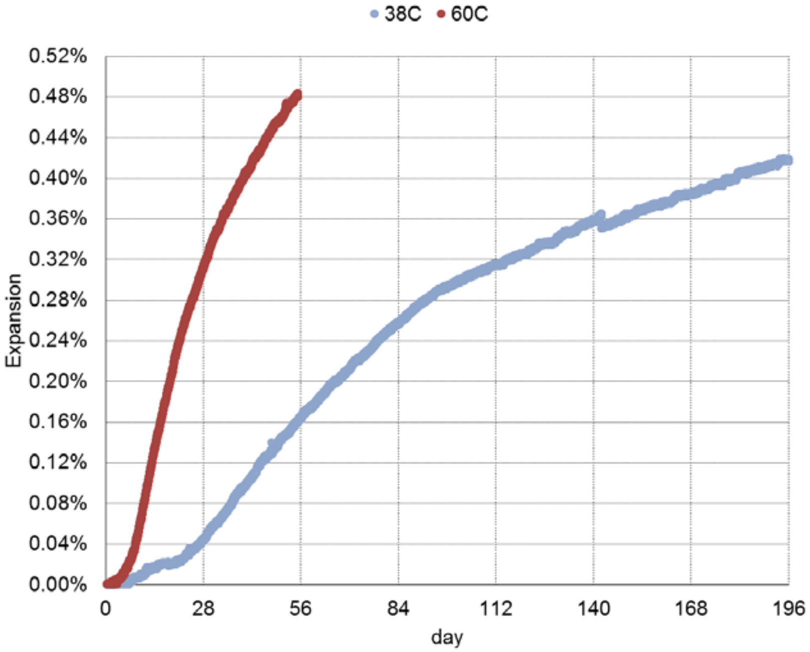

Figure 4.13. Effect of Temperature on ACCT (Mix 1) Expansion.

4.6 EFFECTS OF SOAK SOLUTION CHEMISTRY AND SOAK SOLUTION QUANTITY

The results from Research Project 0-6656 (Mukhopadhyay and Liu 2014) indicated that (a) the soak solution should be equal to the pore solution of the tested specimen; and (b) use of a large quantity (e.g., s/c = 3.0) of soak solution might cause an accelerating effect (i.e., sustaining

ASR with high rate) by maintaining an adequate source of external alkalis (i.e., reservoir of alkali ions) similar to ASTM C1260. It was important to conduct a study on the effect of modifying the soak solution chemistry, including but not limited to soak solutions equal to 1/2, 1/3, or 1/4 of pore solution alkalinity and soak solution quantity on concrete expansion, in order to decide which soak solution chemistry/quantity provides data with high reliability. One selected concrete mix (Mix 1) with an alkali loading of 4.5 lb/cy was tested in a soak solution of varying concentrations, including soak solution equal to pore solution, soak solution equal to 1/2 of pore solution, and soak solution equal to 1/3 or 1/4 of pore solution, with different soak solution quantities (s/c = 3 and 0.27), as shown in Figures 4.14, 4.15, and 4.16. Figures 4.15 and 4.16 show that a reduction in soak solution concentration and quantity causes a reduction in expansion. Although the accelerating effect is minimized by simply reducing the soak solution concentration and quantity, a longer testing duration is needed to achieve the expansion limit of 0.04 percent or the ASTM C1293 value (i.e., 0.391 percent). The ACCT method, with the soak solution equal to the pore solution, best represents the field condition—that is, the visualization of a continuous supply of alkalis and moisture from the pore solution in the surrounding areas of a hypothetical concrete cylinder inside a field concrete structure matches well with the ACCT testing conditions. Although s/c = 0.27 and 3 both satisfy a continuous supply of moisture, the reservoir effect (greater supply of alkali ions) should be more with s/c = 3 than with s/c = 0.27. A continuous long-term supply of alkalis from an unlimited pore solution in the surrounding areas of a hypothetical concrete cylinder is best represented by s/c = 3. Based on this analogy, the ACCT method with a soak solution equal to a pore solution concentration and s/c = 3 was recommended for all future testing. This eliminates leaching and at the same time creates an alkali condition like field concrete.

Figure 4.14. Two ACCT Setups Corresponding to Two Solution-to-Concrete Ratios: s/c = 3 (left) and s/c = 0.27 (right).

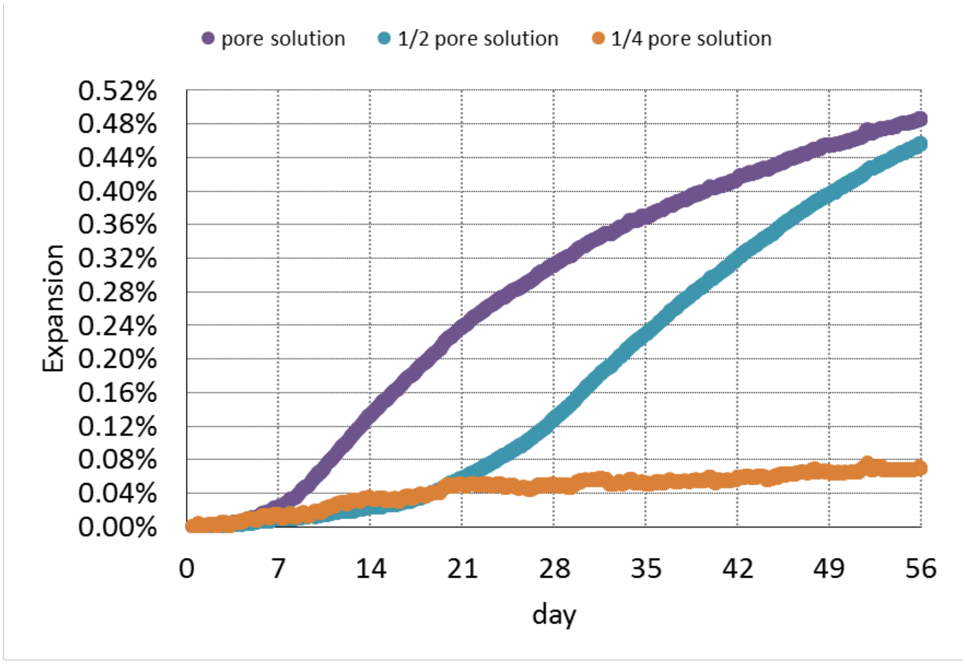

Figure 4.15. ACCT (s/c = 3) Using Mix 1 with Soak Solution Equal to Pore Solution, Soak Solution Equal to 1/2 of Pore Solution, and Soak Solution Equal to 1/4 of Pore Solution.

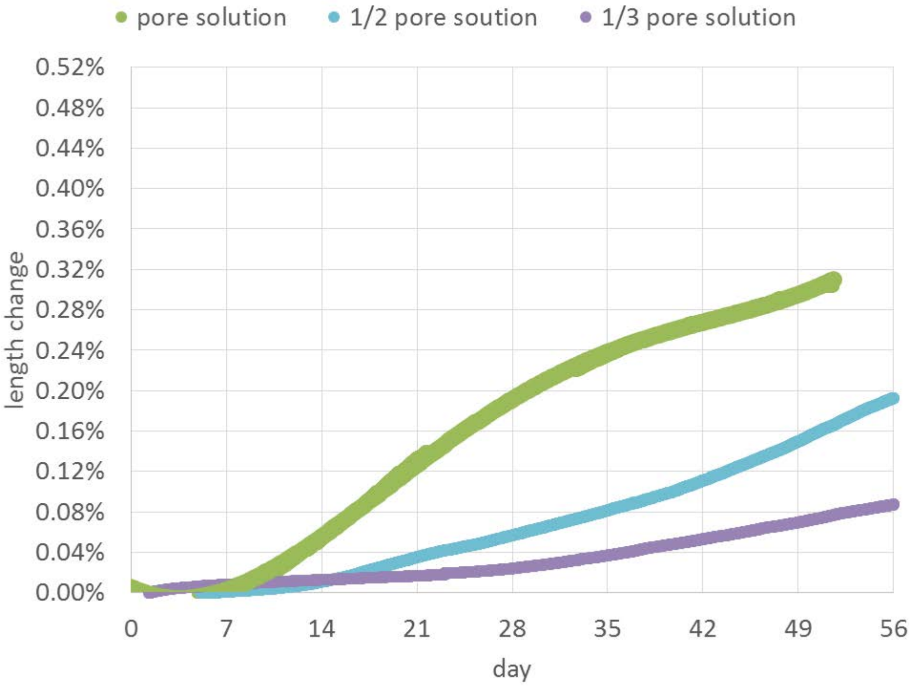

Figure 4.16. ACCT (s/c = 0.27) Using Mix 1 with Soak Solution Equal to Pore Solution, Soak Solution Equal to 1/2 of Pore Solution, and Soak Solution Equal to 1/3 of Pore Solution.

Selected mixes (Mixes 1 and 3) from Table 4.3 were tested with an alkali loading of 4.5 lb/cy in the soak solution equal to the pore solution with s/c = 0.27. A comparison between s/c = 3 and 0.27 is shown in Figures 4.17 and 4.18. For the studied mixes, the expansion limit of 0.04 percent was achieved relatively quickly for a large quantity of soak solution (s/c = 3). For Mix 1, it reached the expansion limit of 0.04 percent within 10 days with s/c = 3 and within 14 days with s/c = 0.27. For Mix 3, the time to reach the expansion of 0.04 percent increased from 21 days to 42 days when the s/c decreased from 3 to 0.27. Although the testing data using s/c = 0.27 are limited at this time, it seems that an effective testing period of 45 days is still valid to evaluate the ASR reactivity in the ACCT with the expansion limit of 0.04 percent at an alkali level of 4.5 lb/cy and s/c of 0.27. Testing with s/c = 0.27 might represent the field situation where the external source of alkali is limited or nonexistent, whereas testing with s/c = 3 might represent the field situation where chances of penetration of the external source of alkali (e.g., deicing chemicals or direct penetration of sea water) to the concrete are high. Thus, simulation of field conditions in the lab may be possible and make the test more effective.

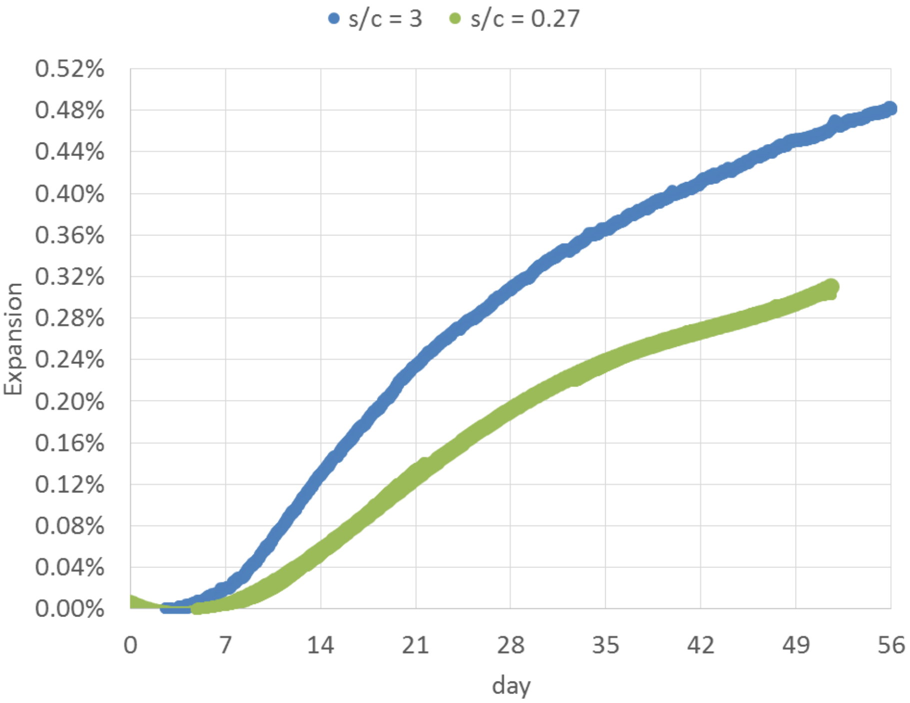

Figure 4.17. ACCT Using Mix 1 in Soak Solution Equal to Pore Solution with s/c = 3 and 0.27.

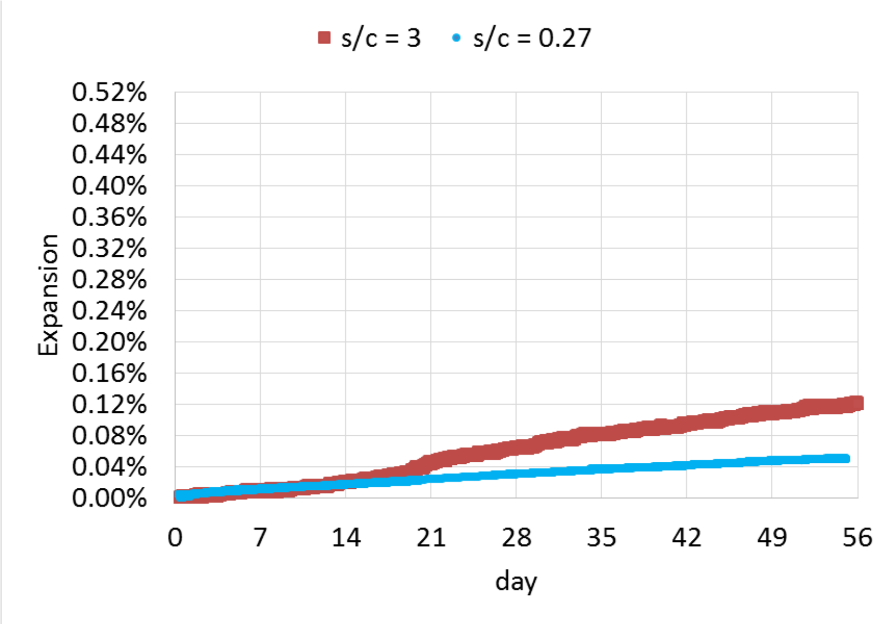

Figure 4.18. ACCT Using Mix 3 in Soak Solution Equal to Pore Solution with s/c = 3 and 0.27.

4.7 SUMMARY

Based on the results, the following conclusions can be drawn:

- The ACCT (s/c = 3) with relatively low alkali levels (4.5 lb/cy, soak solution equal to pore solution) as opposed to high alkali levels (8.9 lb/cy) in the current CPT test can effectively be used to pass/fail an aggregate in a relatively short time (≤ 45 days) with an expansion limit of 0.04 percent.
- The expansion difference between 3- and 4-inch-diameter specimens was found to be smaller in the ACCT. Therefore, a 3 x 6-inch cylinder is recommended as an acceptable specimen dimension for the ACCT.
- The continuous steady state supply of alkalis and moistures (conditions similar to field concrete) is satisfied using the ACCT method with S/C = 3. The continuous long-term supply of alkalis may not be satisfied in the ACCT method with S/C = 0.27. As a result, time needed to identify a reactive aggregate by the ACCT method with S/C = 0.27 was found to be more than that with S/C = 3. Because a mismatch situation—aggregate passed by S/C = 0.27 but failed by S/C = 3—was not observed based on limited testing in this project, the use of S/C = 3 for the ACCT method is recommended as a standard practice.
- Researchers recommend that the alkali loading for the tested aggregates in this study should be maintained at ≤ 3.5 lb/cy (i.e., 3.0–3.5) in order to ensure ASR-resistant property of the concrete mixtures made of these aggregates. However, for a highly reactive aggregate (e.g., Mixes 1 and 7, see Tables 4.3 and 4.4), the concrete alkali loading needs to be maintained below 3 lb/cy. A higher level (e.g., 35–45 percent) of good-quality fly ash (e.g., conventional Class F ash) is needed to attain a low level of concrete alkali loading (i.e., below 3.0 lb/cy). The applicability of the above guidelines is verified in Chapter 5.

CHAPTER 5: VALIDATION OF THE APPROACH FOR FORMULATING AN ASR-RESISTANT MIX

The objective of the task described in this chapter was to (a) validate the approach developed in Research Project 0-6656 and (b) optimize fly ash content. An approach to design an ASR-resistant concrete mix based on CAP, THA, PSA, and concrete validation testing was developed in the previous Research Project 0-6656. The steps involved in developing an ASR-resistant mix are listed below:

- Step 1: Determination of CAP-based aggregate reactivity (AASHTO T364-17) and THA by the VCMD-based aggregate chemical test method. A linear equation was developed and presented in Chapter 3 to convert the measured THA (normality, N) to TAL (lb/cy).
- Step 2: Development of an ASR-resistant mix by selecting suitable mix design controls depending on CAP-based reactivity prediction, THA/TAL, and by applying some consideration to the severity of exposure conditions. Guidelines (through examples) for formulation of ASR-resistant concrete mixes are provided in Table 5.1.
- Step 3: Mix design adjustment/verification based on THA-PSA relationship. This step provides an additional control (optional). PSA needs to be below THA in order to prevent or minimize ASR. The mixes after Step 2 should satisfy this requirement. However, some SCMs (e.g., some Class C fly ashes) may contribute alkalis to the pore solution, and alkali loading assignment based on cement alkali alone may not provide adequate control. Therefore, researchers recommend (though optionally) determining PSA of the concrete mix by extracting the pore solution from equivalent cement paste samples after 7 days, followed by measuring elemental concentrations by XRF or another suitable analyzer.
- Step 4: Mix design validation through concrete testing—use of ACCT method to measure expansion of concrete cylinder in a short time. Validation of the mixes after Step 2 or 3 using the ACCT method is the best way to ensure safe and durable mixes.

Table 5.1. Explanation of Guidelines to Formulate ASR Resistant Concrete Mixes Based on CAP, TAL, and Some Consideration on the Severity of Exposure Conditions.

CAP-Based Aggregate Reactivity (Step 1)	Threshold Alkali Loading—(TAL) – Step 1	Severity of Exposure Conditions	Mix Design Controls	
			Step 2	AASHTO R80-17/ ASTM C1778
High (R3)	3.0 ± 0.20 lb/cy	High Example: High rainfall (high RH) ± high T ± seawater-contaminated aggregates ± use of deicers	- If alkali loading ≥ 3.0 lb/cy, use relatively lower cement factor with higher amount of Class F ash replacement (e.g., up to 35%, TxDOT Option 1) - If alkali loading ≤ 3.0 lb/cy, use ternary/quaternary blends (e.g., TxDOT Options 2 or 3)	Use of AASHTO R80-17 preventive measures for level of prevention Y, Z, or ZZ
		Low <u>Example</u>: Low rainfall (low RH) ± low temperature ± no source of external alkalis	- Same as above with the approval of using TxDOT Option 5 (Class C ash) as an additional option	Use of AASHTO R80-17 preventive measures for level of prevention W, X, Y, or Z
Medium (R2)	3.2–3.5 lb/cy	High	- Use of TxDOT Option 1 with relatively higher level (e.g., 30–35%) of fly ash replacement (FAR) for TAL close to 3.2 lb/cy but relatively lower level of FAR (e.g., 25–30%) for TAL close to 3.5 lb/cy is recommended - TxDOT Options 2 or 3 or 5 can also be used depending on the availability of SCMs, especially if TAL is close to 3.2 lb/cy	Use of AASHTO R80-17 preventive measures for level of prevention W, X, Y, Z, or ZZ
		Low	Same as above	Use of AASHTO R80-17 preventive measures for level of prevention W, X, Y, or Z
Low (R1)	3.5–4.0 lb/cy	High	- TxDOT Option 1 with conventional practice of Class F fly ash replacement (e.g., 20–25%)	Use of AASHTO R80-17 preventive measures for level of prevention W, X, Y, or Z
		Low	Same as above	Same as above
None reactive (R0)	N/A	N/A	Conventional mix design	N/A

5.1 VERIFICATION OF THE APPROACH DEVELOPED IN RESEARCH PROJECT 0-6656

Formulation of ASR-resistant concrete mixes using aggregates with varying levels of ASR reactivity and different types of fly ash with varying replacement levels was conducted using the proposed approach. The results are presented in Table 5.2.

Table 5.2. Results Supporting the Feasibility of the Proposed Approach.

Mix	**Step 1: Aggregate Reactivity Prediction (Table 4.1)**	**Step 1: THA (N) TAL (lb/cy)**	**Step 2: Alkali Loading (lb/cy)**	**Step 3: PSA (N)**	**Exp. Prediction Based on THA (N) and PSA (N) Relationship**
1 (Table 4.3) s/c = 3	R3 Fine aggregate (FA6-old) AASHTO T364-17: CAP = 26.96 KJ/mol • ASTM C1260: 0.381% • ASTM C1293: 0.391%	0.35 (3.1)*	2.9 (35% F ash)	0.33	Exp. < 0.04% = safe
			3.2 (30% F ash)	0.35	Exp. ≥ 0.04% = borderline (may or may not be safe)
			3.4 (25% F ash)	0.43	Exp. >> 0.04% = not safe
			3.6 (20% F ash)	0.44	Exp. >>> 0.04% = not safe
			4.5 (0% ash)	0.66	Exp. >>>>> 0.04% = not safe
7 (Table 4.3) s/c = 3	R3 Coarse aggregate (NMR) AASHTO T364-17: CAP = 17.56 KJ/mol • ASTM C1260: 1.3%	0.29 (2.8)*	3.2 (30% F ash)	0.35	Exp. >> 0.04% = not safe
			3.6 (20% F ash)	0.44	Exp. >>>> 0.04% = not safe
			4.5 (0% ash)	0.66	Exp. >>>>> 0.04% = not safe
6 (Table 4.3) s/c = 3	R2 Fine + R2 Coarse aggregates (FA4+CA3-old) AASHTO T364-17: CAP = 40.57/39.86 KJ/mol • ASTM C1260: 0.182/0.227% • ASTM C1293: 0.100/0.071%	0.45 (FA4) 0.46 (CA3-old) (3.6/3.7)*	3.2 (30% F ash)	0.35	Exp. < 0.04% = safe
			3.6 (20% F ash)	0.44	Exp. ≤ 0.04% = should be safe
			4.5 (0% ash)	0.66	Exp. >> 0.04% = not safe
4 (Table 4.3) s/c = 3	R2 Coarse aggregate (CA4-old) AASHTO T364-17: CAP = 39.18 KJ/mol • ASTM C1260: 0.179% • ASTM C1293: 0.149%	0.52 (4.0)*	3.0 (0% ash)	0.38	Exp. < 0.04% = safe
			4.5 (0% ash)	0.66	Exp. >> 0.04% = not safe
			8.9 (0% ash)	1.00	Exp. >>>> 0.04% = not safe
5 (Table 4.3) s/c = 3	R2 Fine Aggregate (FA4) AASHTO T364-17: CAP = 40.57 KJ/mol • ASTM C1260: 0.182% • ASTM C1293: 0.100%	0.45 (3.6)*	3.4 (25% F ash)	0.43	Exp. ≤ 0.04% = should be safe
			4.5 (0% ash)	0.66	Exp. >> 0.04% = not safe
10 s/c = 0.27	R2 Fine aggregate (FA2) AASHTO T364-17: CAP = 41.01 KJ/mol • ASTM C1260: 0.241% • ASTM C1293: 0.110%	0.46 (3.7)*	3.6 (20% F ash)	0.44	Exp. ≤ 0.04% = should be safe
			4.5 (0% ash)	0.66	Exp. >> 0.04% = not safe

Note: Exp.: Expansion; N: Normality.
* TAL was based on PSA vs. alkali loading calibration curve.

A brief description/analysis for the results obtained by applying the recommended steps is provided below.

In Step 1, four fine aggregates and three coarse aggregates were tested using the VCMD method (AASHTO T364-17) as well as conventional methods. VCMD-based CAP values along with 14-day expansion of ASTM C1260 and 1-year expansion of C1293 values are listed in Table 5.2 (second column). The reactivity prediction based on CAP is in good agreement with the prediction based on C1260 and C1293 tests. The THA (normality)/TAL (lb/cy) values for each aggregate were determined based on the procedure developed in this approach and are presented in the third column as part of Step 1.

In Step 2, as part of conventional mix design practice to control ASR, three Class F fly ashes were used with varying replacement levels. The reduction of alkali loading with increasing fly ash replacement levels is displayed in the fourth column in Table 5.2. For example, the alkali loading for Mix 1 without any fly ash was 4.5 lb/cy. The alkali loading was reduced to 3.6, 3.4, 3.2, and 2.9 lb/cy, with corresponding fly ash replacement levels of 20, 25, 30, and 35 percent, respectively.

In Step 3, the pore solution was extracted from the representative paste specimens (2 x 4 inches) for each mix, and chemical composition was determined by XRF to determine the PSA. The measured PSA values for all the studied mixtures are listed in Column 5 in Table 5.2. A comparative assessment between the THA values in the third column (Step 1) and PSA values in the fifth column (Step 3) allowed for predicting the expansion behavior (sixth column) of the different mixes. For example, no measurable ASR expansion or expansion below the limit (0.04 percent) is predicted for the mixes with PSA < THA (e.g., Mix 1 with 35 percent fly ash [PSA = 0.33 < THA = 0.35], Mix 6 with 30 percent fly ash, Mix 4 with 3.0 lb/cy, Mix 5 with 25 percent fly ash replacement, and Mix 10 with 20 percent fly ash replacement), and these combinations are safe mixes. Similarly, when the THA is very close to the PSA (e.g., borderline cases—Mix 1 with 30 percent and Mix 6 with 20 percent fly ash replacements), the expansion can be equal to or slightly greater or slightly lower than the expansion limit (0.04 percent), depending on the aggregate reactivity. Researchers recommend increasing the fly ash content (> 30 percent for Mix 1 and > 20 percent for Mix 6) in order to make these mixes safe. However, when the PSA is greater than the THA, the expansion will be higher than the limit at a specified testing duration, and those mixes (e.g., Mix 1 with 0–25 percent fly ash, Mix 7 with 0–30 percent fly ash, Mixes 5, 6, and 10 with 0 percent fly ash, and Mix 4 with alkali loading 4.5–8.9 lb/cy) are not safe.

In Step 4, the predicted expansion (sixth column in Table 5.2) was validated by testing those mixes using the ACCT method. The results (expansion versus time curves) for the studied mixtures are provided in Figures 5.1 to 5.8. Testing with different types of Class F fly ash with varying replacement levels will facilitate verifying the effectiveness of the ACCT method to determine optimum fly ash content for controlling ASR.

The pore solution alkalinity (Na^+_e) was reduced from 0.66 N (reference sample without fly ash) to 0.44–0.43 N with 20–25 percent fly ash and 0.33 N with 30–35 percent fly ash replacement. Figures 5.1 to 5.6 show the expansion curves of Mixes 1, 4, 5, 6, and 7 with and without different levels and types of fly ash replacement using s/c = 3.

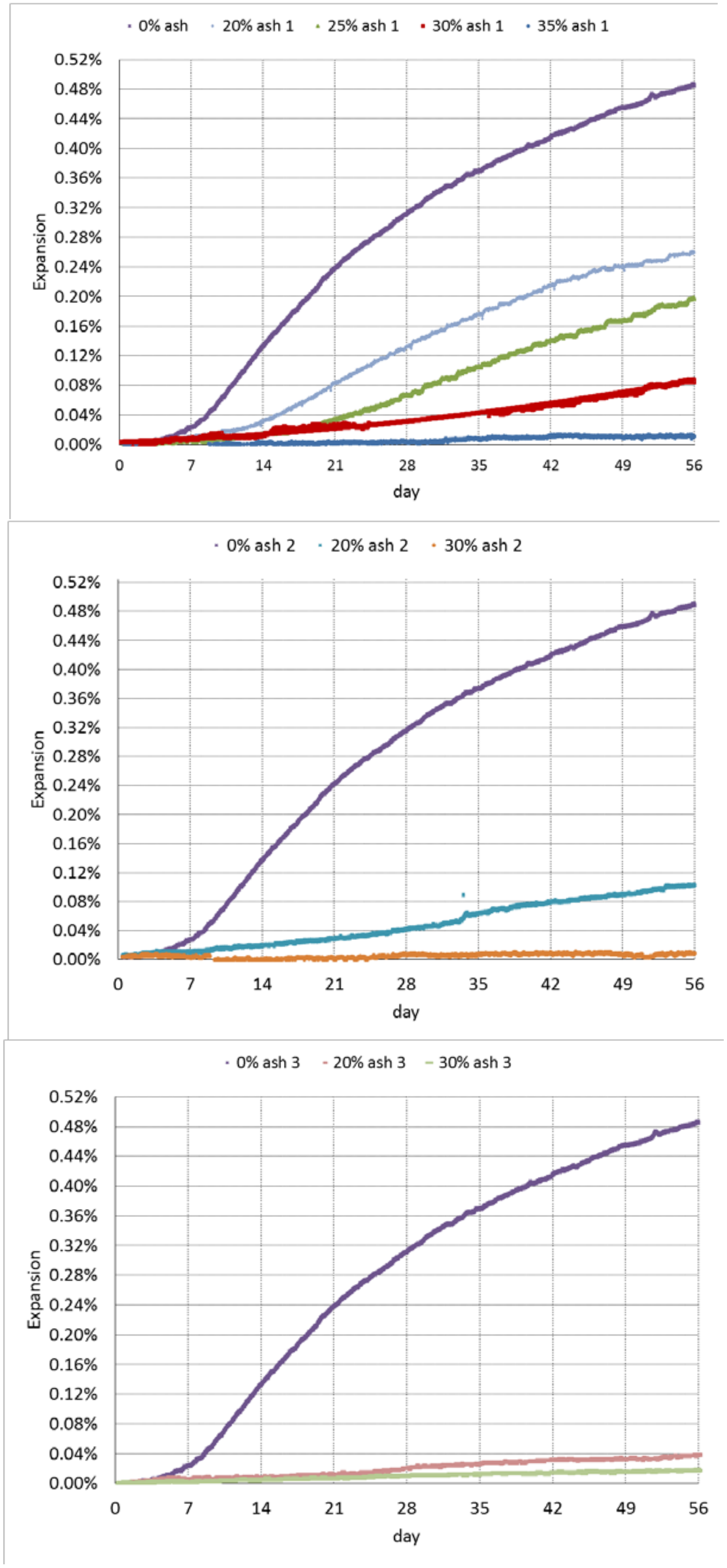

Figure 5.1. Expansion of Mix 1 with and without Fly Ash Replacement (s/c = 3).

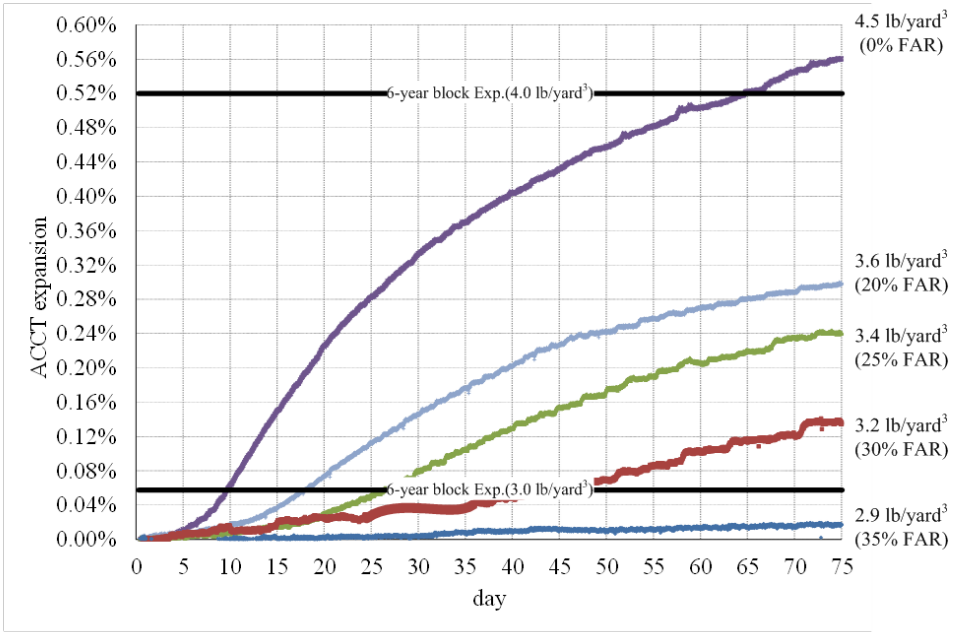

Figure 5.2. Expansion of Mix 1 with Fly Ash 1 Replacement for a Long Period of Time (s/c = 3).

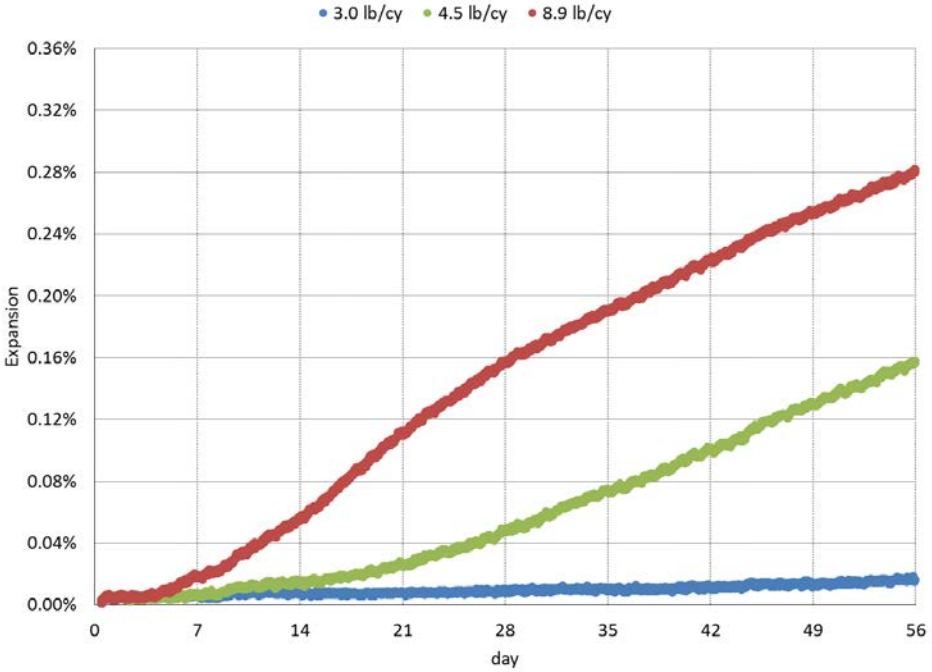

Figure 5.3. Expansion over Time for Mix 4 (s/c = 3).

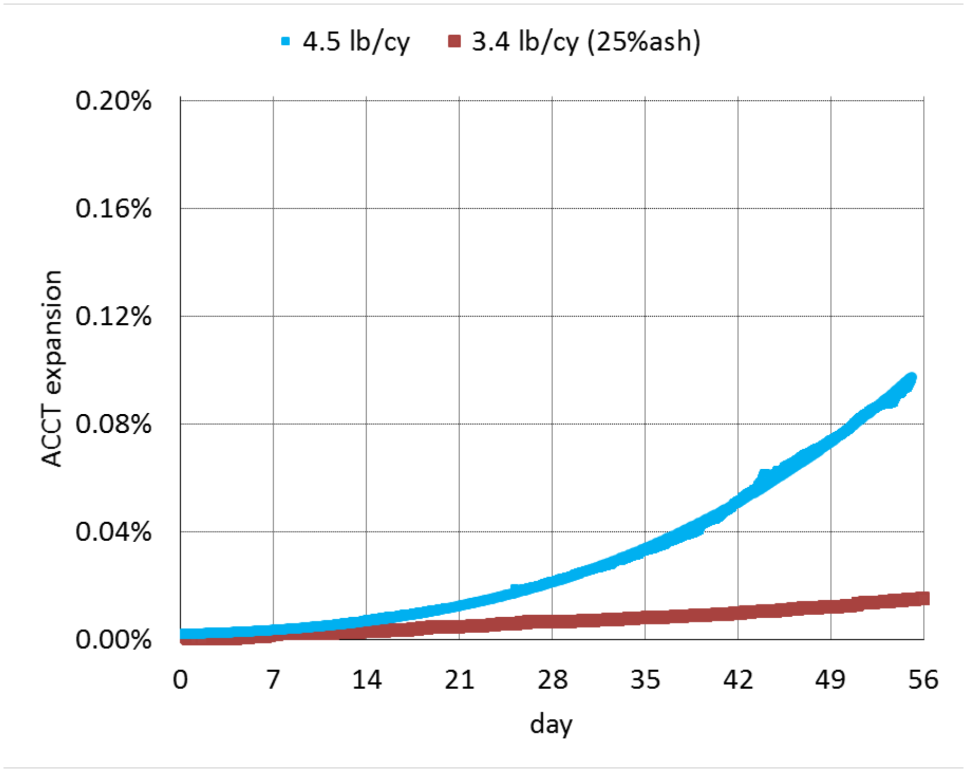

Figure 5.4. Expansion over Time for Mix 5 (s/c = 3).

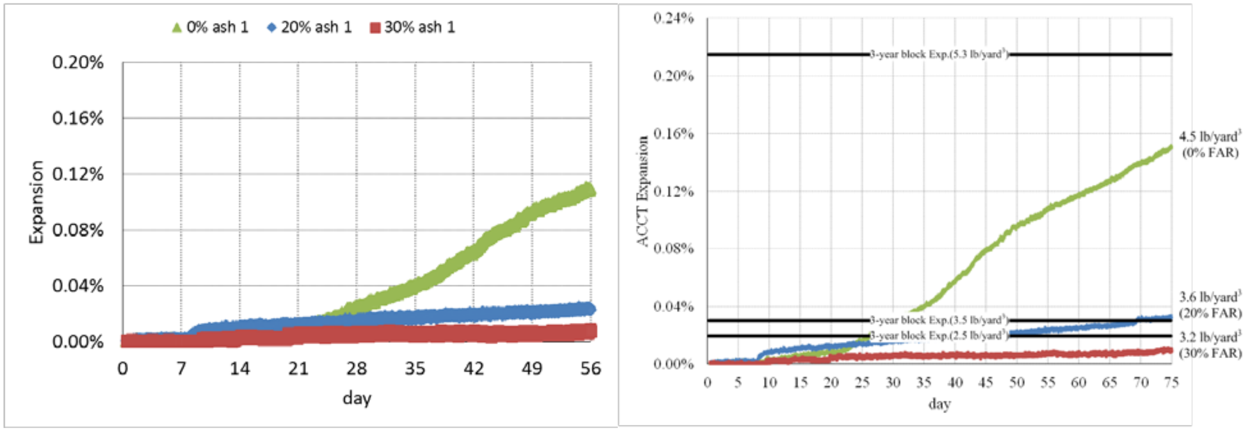

Figure 5.5. Expansion of Mix 6 with and without Fly Ash Replacement (left) and Tested with Fly Ash 1 for a Long Period of Time (right) (s/c = 3).

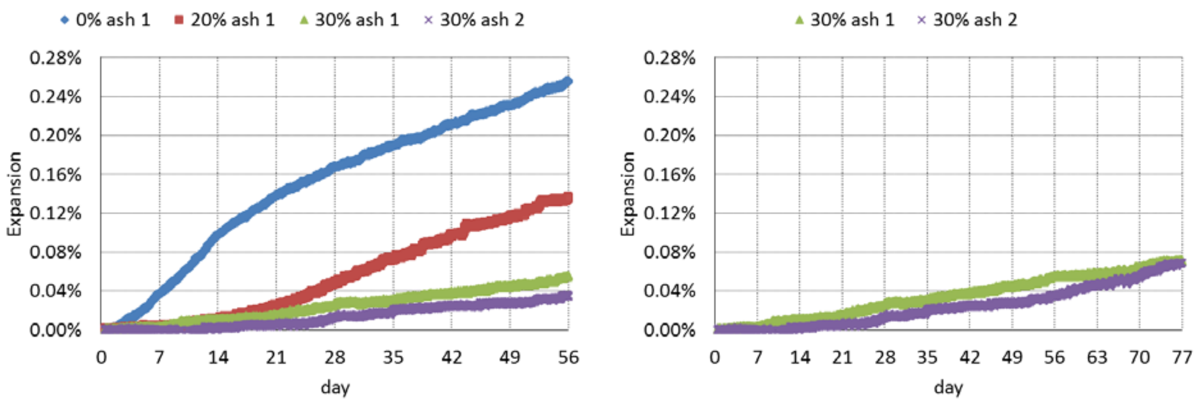

Figure 5.6. Expansion of Mix 7 with and without Fly Ash Replacement (left) and Tested with Fly Ash for a Long Period of Time (right) (s/c = 3).

At 42 days, as shown in Figure 5.1, the expansion reduced from 0.41 percent (control sample without fly ash) to 0.21 percent, 0.14 percent, 0.06 percent, and 0.011 percent for the mixes with 20 percent, 25 percent, 30 percent, and 35 percent Fly Ash 1 replacement, respectively. The expansion reduced from 0.41 percent (control sample without fly ash) to 0.08 percent and 0.01 percent for the mixes with 20 percent and 30 percent Fly Ash 2 replacement, respectively. The expansion reduced from 0.41 percent (control sample without fly ash) to 0.03 percent and 0.02 percent for the mixes with 20 percent and 30 percent Fly Ash 3 replacement, respectively. For all fly ash replacement mixes (Figures 5.1 to 5.4), the higher the level of fly ash replacement, the higher the level of alkalinity reduction in the pore solution, which correlates to a higher level of expansion reduction. It was clearly observed that 20–25 percent fly ash replacement (conventional practice) was not sufficient to reduce the expansion below 0.04 percent for Mix 1, which is made of a highly reactive fine aggregate. However, 35% FAR (2.9 lb/cy) is adequate, which is also validated by the 6-year exposure block expansion data shown in Figure 5.2. Although 45 days was found to be adequate for most of the mixes with fly ash, waiting 75 days should be considered as a safe practice.

Researchers observed that the expansion of Mix 1 with 20 percent Fly Ash 3 crossed the expansion limit of 0.04 percent at 56 days, and the expansion of 35 percent Fly Ash 1, 30 percent Fly Ash 2, and 30 percent Fly Ash 3 remained below the expansion limit after 56 days. The expansion of Mix 4 with an alkaline loading of 3 lb/cy remained below the expansion limit after 56 days. The expansion of Mix 5 with 25 percent Fly Ash 1 remained below the expansion limit after 56 days. The expansion of Mix 6 with 20–30 percent Fly Ash 1 (3.6–3.2 lb/cy) remained below the expansion limit after 56 days, and the 3-year exposure block data (Figure 5.5) show that limiting the total alkali loading in plain concrete to 3.5 lb/cy is effective to control ASR. The expansion of Mix 7 with 20–30 percent Fly Ash 1 and 2 replacements (conventional practice) was not sufficient to reduce the expansion below 0.04 percent for Mix 7, which is made of a highly reactive coarse aggregate. This finding indicates that a job mix tested using the ACCT can be considered an ASR-resistant mix if the expansion remains below the limit (0.04 percent) up to 75 days of testing.

Figures 5.7 to 5.9 show the expansion curves of Mixes 1, 5, and 10 with and without fly ash replacement using s/c = 3 and/or 0.27. The expansion limit of 0.04 percent was achieved quickly for mixes with a large quantity of soak solution (s/c = 3). Although the expansion data of fly ash replacement using s/c = 0.27 are limited at this time, it seems that an effective testing period of 75 days is still valid for evaluating ASR-resistant mixes using the ACCT with the expansion limit of 0.04 percent at an alkali level of 4.5 lb/cy. Testing more mixes covering different types of fly ashes (especially Class C and blended ashes) using a small quantity of soak solution (s/c = 0.27) is needed to verify the robustness of the ACCT method with s/c = 0.27 to optimize fly ash.

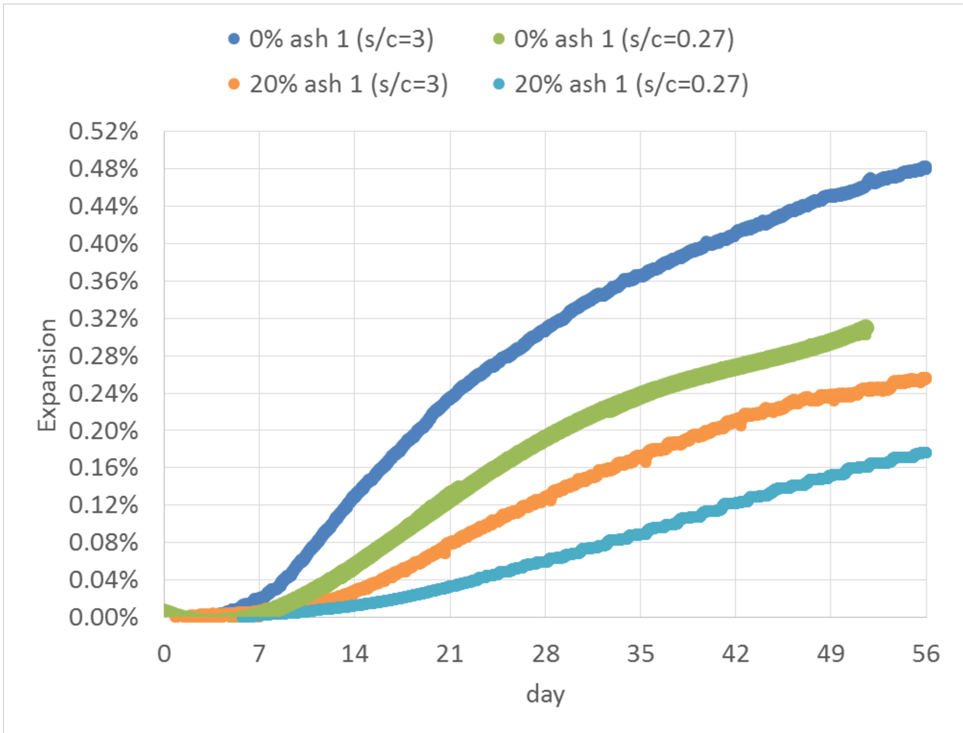

Figure 5.7. ACCT Using Mix 1 with and without Fly Ash Replacement (s/c = 3 and 0.27).

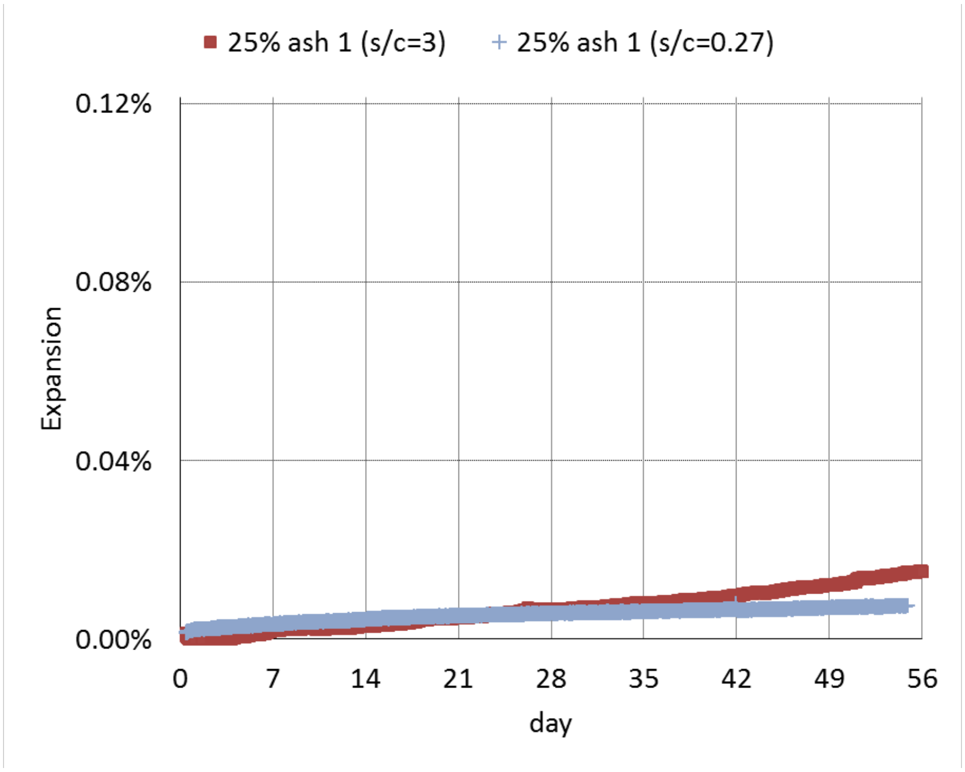

Figure 5.8. ACCT Using Mix 5 with Fly Ash Replacement (s/c = 3 and 0.27).

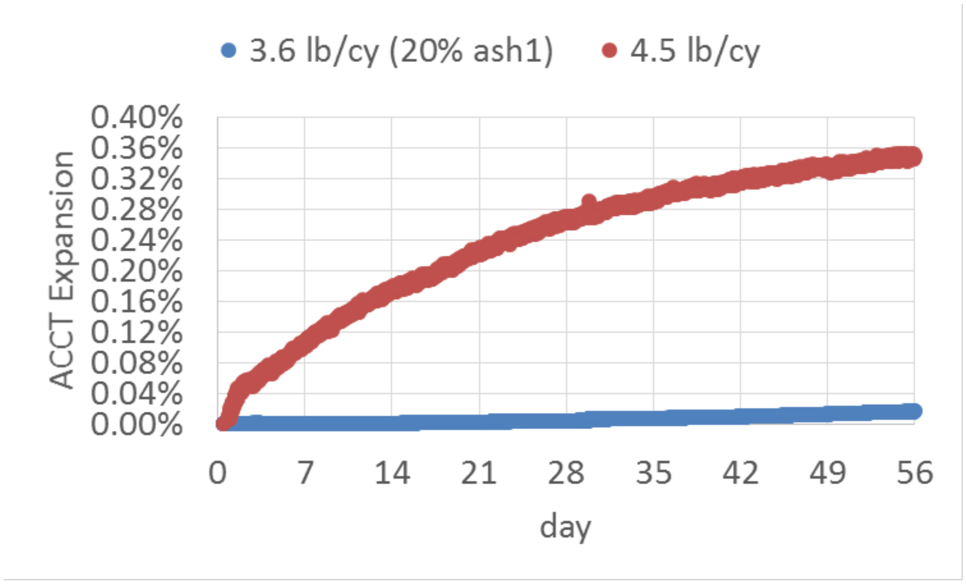

Figure 5.9. Expansion over Time for Mix 10 (s/c = 0.27).

5.2 FLY ASH OPTIMIZATION

The ACCT method was found to be effective for assigning an optimum level of fly ash content in order to reduce ASR expansion below the prescribed limit. As Figures 5.1 to 5.6 illustrated, Mixes 1 and 7 indicated that 25 percent fly ash was not enough to reduce the expansion below the limit, but 35 percent was sufficient to reduce the expansion below the limit.

In this work on fly ash optimization, mixes (see Table 5.1) were tested at varying levels of replacement of different types of fly ash that are commonly used by TxDOT with the ACCT, and optimum replacement levels to control ASR were assigned. Table 5.3 shows the optimum fly ash content of tested mixes.

Table 5.3. Optimum Fly Ash Content of Different Mixes.

Mix	**Aggregate Reactivity Prediction (Table 5.2)**	**Optimum Fly Ash Replacement, %**
1 s/c = 3	R3 Fine Aggregate (FA6-old) AASHTO T364-17: CAP = 26.96 KJ/mol • ASTM C1260: 0.381% • ASTM C1293: 0.391%	35% F Ash 1 30% F Ash 2 or 3
7 s/c = 3	R3 Coarse Aggregate (NMR) AASHTO T364-17: CAP = 17.56 KJ/mol • ASTM C1260: 1.3%	> 30% F Ash 1 or 2
6 s/c = 3	R2 Fine + R2 Coarse Aggregates (FA4 + CA3-old) AASHTO T364-17: CAP = 40.57/39.86 KJ/mol • ASTM C1260: 0.182/0.227% • ASTM C1293: 0.100/0.071%	20% F Ash 1
5 s/c = 3	R2 Fine Aggregate (FA4) AASHTO T364-17: CAP = 40.57 KJ/mol • ASTM C1260: 0.182% • ASTM C1293: 0.100%	25% F Ash 1
10 s/c = 0.27	R2 Fine Aggregate (FA2) AASHTO T364-17: CAP = 41.01 KJ/mol • ASTM C1260: 0.241% • ASTM C1293: 0.110%	20% F Ash 1

Some departments of transportation allow only 25 percent fly ash in their mixes (a standard replacement level irrespective of fly ash type or quality), and the results in Table 5.3 indicate that for some mixes, 25 percent replacement level (Mixes 1 and 7) is not adequate to control ASR. For the aggregate used for Mix 1, 35 percent fly ash replacement is adequate. For the aggregate used in Mix 7, 35–40 percent replacement may be adequate. Therefore, this innovative approach has great potential to optimize fly ash and other SCM replacement levels depending on aggregate reactivity and PSA.

5.3 SUMMARY

Based on the results obtained on validation of the developed performance-based approach for formulating an ASR-resistant mix, the main findings are summarized below:

- The developed procedure to design an ASR-resistant concrete mix based on CAP, THA/TAL, PSA, and ACCT was verified by testing six mixes. All of the proposed steps are recommended in order to develop case-specific, performance-based ASR-resistant mixes with high reliability. If the pore solution extraction method (needed in Step 3) is not available, dependency on concrete validation testing will be high in order to develop a safe ASR-resistant mix with high reliability. However, an expert can design an ASR-resistant mix based on CAP-based reactivity prediction and THA/TAL without conducting concrete validation testing. The practice of formulating an ASR-resistant mix based on CAP and THA may be acceptable (since it saves time), but some amount of risk may be involved.

- In terms of the aggregates for which reactivity prediction based on the current rapid (e.g., ASTM C1260) test methods is satisfactory, CAP measurement through aggregate-solution testing may not be mandatory. However, mix design verification/validation through direct concrete testing (i.e., the ACCT) is useful and highly recommended. An aggregate identified as medium to highly reactive by the current methods may not necessarily show a high expansive stress in concrete. Mix design verification through direct rapid and reliable concrete testing provides high reliability.
- The ACCT can be used to determine optimum content of fly ash in order to develop safe ASR-resistant mixes in a relatively short time (i.e., 45–75 days). It has the ability to emerge as a potential method to test job concrete mix (e.g., a field concrete mix with typical ASR mitigation measures) in the laboratory and serve as an alternative method to validate an ASR-resistant mix.
- The developed approach has great potential to optimize fly ash and other SCMs' replacement levels depending on aggregate reactivity and PSA.
- The proposed approach can be easily merged with the flow chart recommended by AASHTO R80-17 (ASTM C1778) to formulate ASR-resistant mixes. The VCMD and ACCT can be used wherever R80-17 recommends using test methods in the flow chart and in formulating ASR-resistant mixes using the proposed four steps, depending on aggregate reactivity (R0–R3) and exposure conditions (S1–S4), and using the guidelines on use of SCMs.

CHAPTER 6: CONCLUSIONS AND FURTHER WORK

This chapter summarizes the main findings of this study and provides recommendations on further work. Some gap-filling lab tests, along with the use of exposure block data to calibrate the ACCT method, are proposed as further work that can be accommodated in future implementation efforts.

6.1 CONCLUSIONS

Based on the results obtained in this study, the following conclusions are drawn:

- CAP-based aggregate reactivity prediction using the VCMD method for aggregates belonging to false positive and false negative categories does not agree with the C1260-based prediction but aligns well with the C1293-based prediction. The VCMD method can be used as an alternative to C1260.
- The VCMD method was found to be effective for determining that alkali loading is a function of aggregate reactivity. A low level of alkali loading (e.g., ≤ 3 lb/cy) is needed for an aggregate with very high reactivity (e.g., R3) and vice versa. Therefore, the current practice of assigning a common fixed alkali loading (e.g., 3.5 lb/cy) for all concrete mixes irrespective of aggregate reactivity and types of application may not provide adequate protection.
- The ACCT with relatively low alkali levels (4.5 lb/cy), as opposed to the high alkali levels (8.9 lb/cy) specified in the current ASTM C1293 test, can effectively be used to pass/fail an aggregate in a relatively short time (i.e., 28–45 days) with soak solution alkalinity equal to PSA and an expansion limit of 0.04 percent. The expansion difference between 3- and 4-inch-diameter specimens was found to be smaller in the ACCT. Therefore, a 3 x 6-inch cylinder is recommended as an acceptable specimen dimension in the ACCT.
- The ACCT method also has the ability to test job concrete mix (e.g., a mix with typical ASR mitigation measures) in the laboratory within 75 days and to serve as an alternative method to validate an ASR-resistant mix.
- A general guideline to select concrete alkali loading according to VCMD-based measured reactivity and alkali loading is proposed. A higher level (30–35 percent) of good-quality fly ash (e.g., Class F ash, TxDOT Option 1) or use of TxDOT Option 2 or 3 with or without Option 6 is needed in order to achieve a low level of concrete alkali loading (i.e., ≤ 3 lb/cy) required for a very highly reactive aggregate. The use of TxDOT Option 3 is safe if an aggregate with 3.0–3.5 lb/cy alkali loading is used to make concrete. However, the use of TxDOT Option 5 with Class C ash can also be recommended in this case. The current TxDOT practice of using Option 1 with 20–25 percent Class F ash can be allowed for aggregates with 3.5–4.0 lb/cy recommended alkali loading. The use of straight cement concrete mix (Option 7) with permissible cement alkalis and CF may be allowed if the aggregate alkali loading requirement is ≥ 4 lb/cy.
- A procedure to design an ASR-resistant concrete mix based on CAP, THA, PSA, and ACCT has been developed. The steps involved in developing an ASR-resistant mix are:
  - Step 1: Determination of CAP and THA from aggregate-solution testing using the VCMD.

  - Step 2: Development of an ASR-resistant mix by applying mix design controls depending on CAP-based reactivity prediction, THA, and some consideration of the severity of exposure conditions.
  - Step 3: Mix design adjustment/verification based on THA-PSA relationship. Determination of PSA of the mixes in Step 2 using the pore solution extraction method or any other suitable method (e.g., adding PSA of cement portion estimated by the NIST model with the available alkali of SCMs measured by the ASTM C311) —PSA needs to be below THA in order to prevent/minimize ASR—is optional but recommended.
  - Step 4: Mix design validation through concrete testing—use of the ACCT method to measure concrete ASR expansion in a short time.
- Use of all four mix design steps is recommended in order to develop case-specific ASR-resistant mixes (performance based) with high reliability. If a strong agreement between mixes developed through Steps 1–3 and validated in Step 4 is observed, then concrete validation testing (Step 4) can be considered optional. However, the user needs to make this decision based on proper judgment. If the PSA measurement technique is not available, a combined use of the NIST model (estimating PSA contribution from cement portion) and ASTM C311 (determining available alkalis from supplementary cementitious material [SCM] used) was found to be effective to estimate PSA of the cement-SCM combination with acceptable accuracy. For the aggregates whose reactivity prediction is based on the current test methods (e.g., C1260 and/or C1293) or whose field performance is satisfactory, the user can develop mixes based on guidelines in Step 2 (similar to TxDOT Options 1–6 and/or AASHTO R80-17/ASTM C1778 guidelines). However, mix design validation through direct concrete validation using the ACCT (Step 4) will be very useful and is highly recommended to ensure placement of safe and durable concrete mixes.
- The proposed approach can be merged with the flow chart recommended by AASHTO R80-17 to formulate ASR-resistant mixes. For example, the VCMD (Step 1) and ACCT (Step 4) can be used wherever R80-17 recommends using test methods (i.e., AMBT or CPT) to determine aggregate reactivity class (R0 to R3 in Table 1 of R80-17). Based on the aggregate reactivity class determined in Step 1, the level of ASR risk, level of prevention, and preventive measures can be selected according to Tables 2, 3, 5, and 8 in R80-17 to formulate ASR-resistant mixes. However, verification and validation of the ASR-resistant mixes using the proposed Step 4 (i.e., the ACCT) is an effective way to test job concrete mixes and ensure placement of safe and durable concrete mixes.
- The ACCT method was found to be effective in determining optimum fly ash content in order to develop safe ASR-resistant mixes in a relatively short time (i.e., 75 days). Optimum fly ash content is a function of aggregate reactivity, TAL, and fly ash characteristics, and assigning a fixed value for all possible concrete mixes may not provide adequate protection. Since the ACCT method was found to be effective to perform fly ash optimization, it has the ability to emerge as a potential method to test a job mix (e.g., a mix with typical ASR mitigation measures) in the laboratory and serve as an alternative method to validate an ASR-resistant mix.
- The combined approach based on rapid and reliable test methods will facilitate formulating (a) case-specific ASR-resistant mixes (tailoring mix design depending on the level of protection needed) using locally available materials to ensure long-lasting

durable concrete and save on repair costs, and (b) an effective and safe way to use locally available fly ashes and meet future challenges when good-quality fly ashes (especially F ashes) are no longer available.

6.2 SUGGESTED GAP-FILLING TESTS AND USE OF EXPOSURE BLOCK DATA

The recommendations on further validation of the ACCT method using exposure block data followed by use of the ACCT method to do SCM optimization as well as testing job concrete mixes are listed below:

- Limited use of TxDOT exposure block data was found to be effective to validate the ACCT method (e.g., Fig. 5.2, Mix 1 and Fig. 5.5, Mix 6). Further validation using all available TxDOT exposure block data will be very useful for benchmarking the ACCT method with the field performance. For some cases where ASR might have started inside the exposure block but not yet manifested outside and/or expansion is still under 0.04 percent, petrographic examination can provide useful information (e.g., gel formation, crack propagation, etc.) and help to establish a good coloration between the ACCT and the exposure block.
- The ACCT was found to be effective in this study for determining optimum content of Class F fly ash in order to develop safe ASR-resistant mixes in a relatively short time (i.e., 45–75 days). However, further research using the ACCT method is needed to test several job concrete mixes containing Class C fly ashes, blended ashes, or other SCMs (e.g., slag) in order to validate the robustness of the ACCT to perform SCM optimization. Application of the quantitative x-ray diffraction method to determine glass content and crystalline phases that contribute soluble alkalis and sulfates for different types of fly ashes (e.g., Class C ashes, off-spec blended ashes, and ashes from blended coal), along with pore solution measurement/estimation followed by the ACCT testing, will be very useful in understanding the effectiveness of all available fly ashes and in meeting future challenges due to scarcity of Class F ashes.
- Concrete mixes that were passed by ASTM C1293 but failed by a 15-year exposure block (might be performing well in the field) can be reproduced in the lab (if possible) and tested by the ACCT to validate both mixture performance and ACCT method effectiveness.

REFERENCES

AASHTO (2017a). R80-17 Determining the reactivity of concrete aggregates and selecting appropriate measures for preventing deleterious expansion in new concrete construction. American Association of State Highway and Transportation Officials.

AASHTO (2017b). T364-17 Determination of composite activation energy of aggregates due to alkali-silica reaction (chemical method). American Association of State Highway and Transportation Officials.

ASTM (2014). C1260 Standard test method for potential alkali reactivity of aggregates (mortar-bar method). West Conshohocken, PA, ASTM International.

ASTM (2015). C1293 Standard test method for determination of length change of concrete due to alkali-silica reaction. West Conshohocken, PA, ASTM International.

Barneyback, R. and S. Diamond (1981). “Expression and analysis of pore fluids from hardened cement pastes and mortars.” Cement and Concrete Research 11(2): 279–285.

Bauer, S., B. Cornell, D. Figurski, T. Ley, J. Miralles, and K. Folliard(2006). Alkali-silica reaction and delayed ettringite formation in concrete: A literature review. FHWA/TX-06/0-4085-1, Texas. Department of Transportation, Research and Technology Implementation Office.

Diamond, S. (1983). Alkali reaction in concrete-pore solution effect. In Proceedings of the 6th International Conference on Alkali-Aggregate Reaction in Concrete, Copenhagen, pp. 155–166.

Diamond, S. (1989). ASR-another look at mechanisms. In Proceedings of the 8th International Conference on Alkali-Aggregate Reaction, Kyoto, Japan, pp. 83–94.

FHWA (n.d.). AAR Webinar Session 4—AAR test methods. https://www.fhwa.dot.gov/pavement/concrete/asr/slides/session04.pdf. Accessed February 30, 2018.

Fournier, B., R. Chevrier, M. de Grosbois, R. Lisella, K. Folliard, J. Ideker, M. Shehate, M. Thomas, and S. Baxter (2004). The accelerated concrete prism test (60 C): variability of the test method and proposed expansion limits. In Proceedings of the 12th International Conference on Alkali-Aggregate Reaction in Concrete, Beijing, China, pp. 314–323.

Grosbois, M. D. and E. Fontaine (2000). Evaluation of the potential alkali-reactivity of concrete aggregates: performance of testing methods and a producer’s point of view. In Proceedings of the 6th International Conference on Alkali-Aggregate Reaction in Concrete, pp. 267–276.

Hooton, D. R. (2012). Recent advances in ASR test methods and understanding mitigation mechanisms, Part 2, ACI Convention, March 18–21, Dallas, TX.

Ideker, J. H., B. L. East, K. J. Folliard, M. D. Thomas, and B. Fournier (2010). “The current state of the accelerated concrete prism test.” Cement and Concrete Research 40(4): 550–555.

Liu, K. W. and A. K. Mukhopadhyay (2014a). “A kinetic-based ASR aggregate classification system.” Construction and Building Materials 68: 525–534.

Liu, K. W. and A. K. Mukhopadhyay (2014b). “Alkali-silica reaction in a form of chemical shrinkage.” Civil Engineering and Architecture 2(6): 235–244.

Liu, K. W. and A. K. Mukhopadhyay (2015). “Accelerated concrete-cylinder test for alkali–silica reaction.” Journal of Testing and Evaluation 44(3): 1229–1238.

Liu, K., A. Mukhopadhyay, X. Shi, and J. Hsu (2018). “Chemical approaches to prevent alkali-silica reaction in concrete–A review.” Engineering Solid Mechanics 6(3): 201–208.

Marks, V. J. (1996). Characteristics of Iowa fine aggregate. No. MLR-92-6, Iowa Department of Transportation, Highway Division, Office of Materials.

Mukhopadhyay, A. K. and K. W. Liu (2014). ASR testing: a new approach to aggregate classification and mix design verification. FHWA/TX-14/0-6656-1, Texas. Deptartment of Transportation, Research and Technology Implementation Office.

Ponce, J. M. and O. R. Batic (2006). “Different manifestations of the alkali-silica reaction in concrete according to the reaction kinetics of the reactive aggregate.” Cement and Concrete Research 36: 1148–1156.

Pour-Ghaz, M., R. Pragg, J. Castro, and J. Weiss (2012). Can acoustic emission be used to detect alkali-silica reaction earlier than length change tests? In Proceedings of the 14th International Conference on Alkali-Aggregate Reaction in Concrete, Austin, TX.

Ranc, R. and L. Debray (1992). Reference test methods and a performance criterion for concrete structures. The 9th International Conference on Alkali-Aggregate Reaction in Concrete, London.

Swamy, R. (1992). “Testing for alkali-silica reaction.” The alkali-silica reaction on concrete. London, CRC Press: 54–95.

Touma, W.D. Fowler, R. Carrasquilli, K. Folliard, and N. Nelson (2001). “Characterizing alkali-silica reactivity of aggregates using ASTM C 1293, ASTM C 1260, and their modifications.” Transportation Research Record: Journal of the Transportation Research Board 1757: 157–165.