

Alkali Silica Reactivity (ASR) Risk Assessment and Mitigation in Tennessee

Research Final Report from the University of Tennessee Knoxville | Ammar Abd-Elssamd and Z. John Ma | November 30, 2021

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16. Abstract Alkali-silica reaction (ASR) is recognized as a major cause of concrete deterioration. Identifying the aggregate reactivity to ASR is one of the most efficient ways for preventing concrete cracking damage in practice. Many aggregates, especially the surface aggregates, used in Tennessee have a relatively high siliceous content (e.g. gravels, siliceous limestones, granites, and quartzite). Aggregates with ASR potential in Tennessee could have been used in the existing concrete structures and will be probably used even more in the future high-volume transportation projects. This report summarizes the findings of a two-phase research project to assess and mitigate the risk of Alkali-Aggregate Reaction (AAR) in the state of Tennessee. ASR reactivity of surface aggregates from 76 different local sources in Tennessee was evaluated in Phase I. Mitigation alternatives to minimize the ASR risk of reactive aggregates were proposed in Phase II. Category guideline on the ASR reactivity property of the aggregates within Tennessee has been developed. A statewide aggregate ASR risk database with detailed field and laboratory performance is presented which can be used to prevent ASR cracking damage of statewide transportation structures.			
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Executive Summary

Higher levels of reactive silica in aggregates can be detrimental to concrete if it reacts with the alkaline cement paste. Many aggregates, especially the surface aggregates used in Tennessee, have a relatively high siliceous content (e.g., gravels, siliceous limestones, granites, and quartzite). Aggregates with Alkali Silica Reaction (ASR) potential have been used already in past projects and will be probably be used even more in future projects due to the requirements on the aggregates for riding surfaces in the Tennessee Department of Transportation (TDOT) Standard Specifications.

To address the issues of ASR in Tennessee, a two-phase research project was funded by TDOT and carried out by the University of Tennessee Knoxville (UTK) to assess and mitigate ASR. The primary aims of this study were to build a statewide aggregate ASR risk database with detailed field and laboratory performance to provide a solid foundation for guaranteeing a good long-term performance and a high-level safety of statewide transportation concrete structures. In addition, the study aimed to investigate and propose effective mitigation methods based on the published literature and performance testing to permit an economic use of reactive aggregates that normally would be excluded.

During Phase I of the study, ASR reactivity of surface aggregates from 76 different local sources in Tennessee was evaluated using common expansion tests including ASTM C1260 (mortar bars test) and ASTM C1293 (concrete prisms test). Mitigation alternatives to minimize the ASR risk of reactive aggregates were proposed in the second phase (Phase II). The field performance of some highly reactive aggregates was also investigated during Phase II to address the extent of ASR in existing structures.

The main findings from this project indicate a potential ASR risk for concrete structures and pavement lifecycle in Tennessee. For the tested aggregate samples, at least 65% are classified as ASR reactive with different degree of reactivity (i.e., moderate to very highly reactive). Out of 83 aggregate samples, 29 samples (35%) are non-reactive (R0: a non-reactive classification per ASTM 1778), 24 samples (29%) are moderately reactive (R1: a moderately reactive classification per ASTM 1778), 26 samples (31 %) are highly reactive (R2: a highly reactive classification per ASTM 1778), and 4 samples (5%) are very highly reactive (R3: a very highly reactive classification per ASTM 1778). The non-reactive aggregates are accepted for use in concrete with no further consideration of mitigation provided that the other physical properties of the aggregate render it suitable for use. To prevent damaging ASR in new concrete construction, reactive aggregates are accepted in concrete with a proper ASR mitigation using fly ash class F. A database of reactive aggregates and the optimum dosage of fly ash class F to mitigate the reactivity of aggregates are provided. Recommendation to update the TDOT specification is also provided to minimize the risk of ASR in the future concrete applications.

The study also addressed the potential risk of Alkali Carbonate Reaction (ACR) for limestone aggregates. The reactivity of limestones from Tennessee was found to be mainly driven by alkali-silica reaction and can be mitigated using appropriate dosage of fly ash class F. The contribution of ACR to the reactivity of the tested limestones from Tennessee was found to be minimum.

In addition, a survey was sent to each region within the state of Tennessee to identify the extent of ASR risk in existing structures that built 20 years ago or longer. Results of the survey indicated ASR distress has been noted in at least eight transportation structures built with concretes containing reactive limestones aggregates including two bridges, four culvert structures, and two pavements within Tennessee. This indicates a high risk of ASR not just in future concrete constructions but also in many existing transportation structures within Tennessee. Further research is needed to address and limit ASR progress in existing transportation structures.

Key Findings

- There is a potential ASR risk for concrete structures and pavement lifecycle in Tennessee, unless proper mitigation techniques are applied to mitigate the reactivity of aggregates.
- At least 65% of the tested aggregates are classified as reactive with different degree of reactivity (i.e., moderate to very highly reactive).
- The chemical composition of dolomitic limestones from Tennessee, namely the silica content (SiO_2), shows a strong correlation with the expansion measured in the concrete prisms test, indicating that most of the silica within Tennessee limestones are reactive. The reactivity of limestones from Tennessee is mainly driven by alkali-silica reaction.
- Minimum replacement levels of fly ash class F are proposed based on performance testing to limit the deleterious ASR expansion for aggregates from Tennessee.
- ASR distress has been noted in at least eight transportation structures built with concretes containing reactive limestones aggregates.

Key Recommendations

- ASR reactive aggregates identified in this project should not be used in new concrete without proper ASR mitigation. This will limit the ASR risk in future transportation structures and will maintain the long-term investment of TDOT. Economical utilization of reactive aggregate sources within Tennessee will be achieved.
- The minimum recommended dosages of fly ash class F to mitigate ASR for several aggregate types are provided in this report. These limits should be added to TDOT specification to minimize the risk of ASR in future concretes.
- The reactivity of aggregate quarries might not be constant over time. Chemical analysis or quick ASR testing (e.g., ASTM C1260 Expansion Test) should be conducted on a regular basis to detect any change in the quarry reactivity overtime. The chemical composition of carbonate aggregates such as limestones/dolomite seems to provide a good indication about aggregate reactivity. Findings from this study can provide a quick means for assessment of limestone reactivity.
- Due to the high risk of ASR in Tennessee, it is recommended to add a requirement in TDOT specification to perform quick ASR assessment testing (e.g., ASTM C1260, or chemical analysis for limestones) for any aggregates to be used in new concretes. Of course, further research is necessary to develop and/or to validate an ideal and accurate test method for assessing actual job concrete mixtures, in a relatively short period of time.

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Glossary of Key Terms and Acronyms

AAR: Alkali Aggregate Reaction

ASR: Alkali Silica Reaction

ACR: Alkali Carbonate Reaction

Chapter 1 Introduction

1.1 Background

Alkali-Aggregate Reaction (AAR) is the most recognized deterioration mechanism in concrete. It is defined as a chemical reaction in Portland cement concrete or mortar between hydroxyl ions of the alkalis (sodium and potassium) from the hydraulic cement (or other sources), and certain siliceous materials in some aggregates. Two types of AAR reaction are currently recognized depending on the nature of the reactive mineral. Alkali-silica reaction (ASR) is the most common one which involves several types of reactive silica such as amorphous silica, cryptocrystalline and microcrystalline quartz, strained quartz, opal, chert, and acidic volcanic glass. Alkali-carbonate reaction (ACR) involves certain types of carbonate rocks such as argillaceous dolomitic limestone (Folliard et al. 2006; Thomas et al. 2013). Both types of reaction, under certain circumstances, lead to deleterious expansion and cracking of the concrete which consequently causes a reduction in the service life and damage of concrete structures including bridges, pavements, walls, barriers, dams, and nuclear/power plant structures (Rajabipour et al. 2015).

The first known case of ASR in the US was recognized in the state of California in a bridge structure and reported by Stanton (1942). Stanton identified the alkali content of the cement, the type and amount of the reactive silica in the aggregate, the availability of moisture, and temperature as major factors influencing the ASR expansion in concrete. Since the 1940s, research has been mainly focused on developing reliable and rapid tools to assess aggregate reactivity (Sims and Nixon 2003; Sims and Poole 2017) and on proposing effective techniques to mitigate ASR in new and existing concrete structures (Fournier et al. 2010).

Identifying the reactivity of an aggregate to ASR is one of the most efficient ways for preventing damage in practice. There are many testing methods available with limited degree of reliability for evaluating aggregate reactivity which include chemical testing, mortar bar expansion tests, concrete prisms expansion tests, petrographic and microscopic examinations. The ASTM C1260 (mortar bars test) and ASTM C1293 (concrete prisms test) are the most recommended expansion tests for evaluating aggregate reactivity. If the results from these tests classified an aggregate as a non-deleteriously reactive, it can be accepted for use in concrete with no further consideration of mitigation. The reactive aggregates can either be rejected for use or accepted with an appropriate preventive measure. The ASR preventive measures include limiting the alkali content of the concrete, using supplementary cementing materials, using lithium-based admixtures, or a combination of these strategies, as summarized in ASTM C1778-16 guide (Standard Guide for Reducing the Risk of Deleterious Alkali-Aggregate Reaction in Concrete).

1.2 Problem Statement

Higher levels of reactive silica in aggregates can be detrimental to concrete if it reacts with the alkaline cement paste. Many aggregates, especially the surface aggregates, used in Tennessee have a relatively high siliceous content (e.g., gravels, siliceous limestones, granites, and quartzite). Aggregates with ASR potential could have been used in the past concrete projects (e.g., concrete pavements, bridges, culverts, etc.), and will probably be used more in the future high volume transportation concrete projects due to the requirements on the aggregates for

riding surfaces in the 2021 Tennessee Department of Transportation (TDOT) Standard Specifications. However, there is no category guideline on the ASR reactivity property of the aggregates within Tennessee so far. In addition, guidelines for effective mitigation methods to limit the occurrence of ASR in future concrete are required to protect the long-term investment in Tennessee.

1.3 Scope, Objectives, and Significance of the Project

A statewide aggregate ASR risk database with detailed field and laboratory performance is required to provide a solid foundation for guaranteeing a good long-term performance and a high-level safety of statewide transportation concrete structures. Therefore, this research effort was conducted to achieve the following primary objectives:

- 1) Establish an aggregate AAR risk database that includes the field and laboratory performance of different aggregates used in Tennessee, and determine ASR and ACR risk (i.e. classification of an aggregate as non-reactive, marginally reactive or highly reactive) of each type of aggregates by using comprehensive analysis of the field performance and laboratory test results.
- 2) Develop and investigate effective mitigation methods based on the published literature and performance testing to allow an economical use of reactive aggregates that normally would be excluded.
- 3) Propose guidelines to modify the current TDOT Standard Specifications by including ASR mitigation alternatives, which provide a solid foundation for a good long-term performance of a safe transportation system for the motoring public in Tennessee.

To achieve these objectives, the following scope of work was implemented in two phases:

Phase I (January 2016 – March 2018): Assessment of Aggregate Reactivity:

During this phase, aggregate samples from 76 sources used in Tennessee were collected which mainly included limestones, sand and gravels, granites, and slag samples. The reactivity of these aggregates was evaluated using common expansion tests, and the aggregates were classified as non-reactive, moderately/slowly reactive, or highly reactive.

Phase II (March 2018 – November 2021): Mitigating the Risk of ASR in Tennessee:

As a first step, reactive carbonate aggregates (e.g. limestones) with AAR potential were identified to confirm whether the cause of the measured expansion based on ASTM C1293 is ASR or ACR or a combination of both so that decisions can be made regarding the use and mitigating the reactivity of these aggregates. Chemical and mineralogical composition of carbonate aggregates were determined, and petrographic and microscopic examinations of concrete and aggregates were performed.

Then, this phase of study aimed at specifying mitigation alternatives to allow the use of reactive aggregates in future concrete structures. Performance-based testing was conducted using different combinations of supplementary cementing materials (e.g fly ash class F and granulated blast-furnace slag-GGBFS) with reactive aggregates in order to examine whether the maximum cement replacement rates specified in the 2021 TDOT Standard Specifications (e.g. 25% fly ash class F, 35% GGBFS) is sufficient to control ASR in Tennessee.

The field performance of highly reactive aggregates was also investigated to address the extent of ASR in existing structures. Visual signs of ASR distress in some existing transportation structures within Tennessee were examined, and petrographic and microscopic examinations of cores extracted from selected ASR affected structures were conducted.

1.4 Research Approach

The major research activities of the study are summarized below:

Assessment of Aggregate Reactivity

1. Literature Review: A comprehensive literature review of the state-of-the-art test methods for assessing and mitigating aggregate reactivity was conducted. The literature review focused on the current practices, types of materials used, and the types of tests used.
2. Lab Preparation: Typical materials such as cement, sodium hydroxide, and some chemical admixtures were acquired from local TDOT suppliers. Test specimen molds and experimental accessories were prepared as well as necessary equipment calibration was conducted. Ovens and a curing chamber for conditioning samples were reserved.
3. Acquiring Aggregates: Aggregate samples from 76 sources were collected from TDOT's Region 1, Region 2, Region 3, and Region 4 which mainly include limestones, sand and gravels, granites, and slag aggregates.
4. Aggregate Testing: The following tests were conducted on aggregates:
 - The physical quality results for most of aggregates were received from TDOT. Aggregates with no available testing data were examined at the University of Tennessee Knoxville (UTK) to determine their absorption and specific gravity as per ASTM C127 - 15.
 - ASTM C1260 "Standard Test Method for Potential Alkali Reactivity of Aggregates - Mortar Bars Test" was followed. In this test, the expansion of mortar bars was measured in term of length change, periodically during 14 days. The aggregate is classified as innocuous if the 14-day expansion is less than 0.10%, slowly reactive if it's 0.10 to 0.20%, or highly reactive if the expansion is greater than 0.20%. Results from this test should not be used solely for rejecting aggregates. Negative results were confirmed by using another test method (ASTM C1293).
 - ASTM C1293 "Standard Test Method for Concrete Aggregates by Determination of Length Change of Concrete Due to Alkali-Silica Reaction - Concrete Prisms Test" was followed. The expansion of concrete prisms was measured in term of length change, periodically during a one-year period. The aggregate is classified as reactive if the expansion after one year is greater than 0.04%. This test is considered as highly reliable in predicting aggregate reactivity. Thus, the reactivity of aggregates on ASTM C1260 was confirmed using ASTM C1293.
 - Aggregate reactivity was classified as per ASTM C1778 "Standard Guide for Reducing the Risk of Deleterious Alkali-Aggregate Reaction in Concrete."

Mitigating the Risk of ASR in Tennessee

5. Reactivity of Carbonate Aggregates (Limestones): This task was conducted to confirm the cause of the measured expansion in ASTM C1293, whether it's ASR or ACR or a combination of both, so that decisions can be made regarding the use and mitigating the reactivity of

these aggregates. Test was conducted to determine chemical and mineralogical composition of carbonate aggregates using X-Ray Powder Diffraction (XRD) and Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES). Petrographic and microscopic examinations of concrete and aggregates were also conducted. Thin sections of aggregates and concrete were prepared and examined using optical microscope and scanning electron microscope.

6. Mitigation of ASR Reactive Aggregates: A performance-based approach was conducted to investigate different mitigation alternatives on selected aggregates with different degrees of reactivity (e.g. moderately, highly, and very highly reactive). The following steps were followed: (1) The physical properties, chemical and mineralogical composition (e.g. calcium oxide content, alkali content, sulfate content, silica content, fineness, and glass content) of fly ash class F and GGBFS used by TDOT were collected; (2) ASTM C 1567 "Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar Bars Method)" was conducted. The following cement replacement mitigation options were investigated for a total of 20 aggregates as shown in Table 1-1. The test duration is 14 days to determine the adequacy of ASR mitigation; and (3) ASTM C 1293 "Standard Test Method for Concrete Aggregates by Determination of Length Change of Concrete Due to Alkali-Silica Reaction (Concrete Prisms Test)" was conducted. The following cement replacement mitigation options were investigated for a total of 10 aggregates as shown in Table 1-2 Testing Protocol for ASR Mitigation on ASTM C1293 – Two years. The test duration is two years to determine the adequacy of ASR mitigation.

Table 1-1 Testing Protocol for ASR Mitigation on ASTM C1567 – 14 Days

Aggregate reactivity	No. of Aggregates	Mitigation options	
Moderately/slowly reactive	10	15 % Fly ash class F	25 % -30% Fly ash class F
Highly reactive	10	20 % Fly ash class F	25 % - 30% Fly ash class F

Table 1-2 Testing Protocol for ASR Mitigation on ASTM C1293 – Two years

Aggregate reactivity	No. of Aggregates	Mitigation options			
Highly reactive	5	20 % Fly ash class F	25 % Fly ash class F	-	-
Very highly reactive	5	20 % Fly ash class F	25 % Fly ash class F	35% Fly ash class F	30% GGBFS & 20% Fly ash class F

7. Field Performance of Highly Reactive Aggregates: In collaboration with TDOT Materials and Tests Division, a regional survey was sent to each region within Tennessee to identify

the extend of ASR risk in existing structures built about 20 years ago or longer. The survey aimed at examining visual signs of ASR distress such as cracking, expansion and deformation, pop-outs, and the occurrence of surface deposits. The survey targeted the field performance of high potential reactive aggregates, namely the very highly reactive (VHR) and highly reactive (HR), within each region in the state of Tennessee. Cores were extracted from selected structures with ASR symptoms and examined microscopically to document the occurrence of ASR in existing structures.

1.5 Project Outcomes

This project will benefit TDOT in the following aspects:

1. A database of reactive aggregate sources was established. Aggregates have been classified into non-reactive, slowly/moderately reactive, and highly reactive. The non-reactive aggregate sources can be accepted for use in concrete with no further consideration of mitigation provided that the other physical properties of the aggregate render it suitable for use. The reactive aggregate source can still be used in concrete with a proper mitigation as specified in this report. Implementation of this project will limit the ASR risk in future transportation structures and maintain the long-term investment of TDOT. Economical utilization of reactive aggregate sources within Tennessee will be achieved.
2. Potential modifications for TDOT Standard Specifications are proposed based on the findings from this study to include requirements for testing aggregates for ASR and provide cement replacement mitigation options with fly ash class F for the use of reactive aggregates in concrete.
3. Risk of ASR occurrence in existing transportation structures within Tennessee has been addressed. This will allow TDOT to consider proactive measures to limit ASR damage in critical structures.

Implementation of this project will limit the ASR risk in future transportation structures and maintain the long-term investments of TDOT.

1.6 Report Outline

This report consists of five chapters. Chapter 1 (Introduction) provides the definition and background of AAR problem and the problem statement of the project. Also, the chapter includes the objectives and the significance of the study and research approach to perform the study. The main outcomes of the project are outlined.

Chapter 2 (Literature Review) includes an overview of the current methods available for assessing aggregate reactivity and their limitations, summary of ASR mitigation techniques, and the knowledge gaps currently existing in these topic areas.

Chapter 3 (Methodology) includes lists of materials and aggregate samples collected from the four regions of the state of Tennessee. The test procedures, examination methods and their criteria are summarized.

Chapter 4 (Results and Discussion) includes and discusses (1) the results from expansion tests, findings and recommendations obtained from Phase I, and (2) the results of ASR mitigation options and the risk of ASR in existing transportation structures addressed in Phase II.

Chapter 5 (Conclusion and Recommendations) includes a database of reactive aggregates and the optimum dosage of fly ash class F to mitigate the reactivity of each aggregate. Recommendations to update the TDOT specification are provided to minimize the risk of ASR in future concretes.

Chapter 2 Literature Review

2.1 Overview

Two types of alkali-aggregate reaction (AAR) are currently recognized, mainly depending on the nature of the reactive constituents. Alkali-silica reaction (ASR) involves amorphous silica (SiO_2), cryptocrystalline and microcrystalline quartz, strained quartz, cristobalite, tridymite, chalcedony, opal, or acidic glass. Alkali-carbonate reaction (ACR) involves certain types of carbonate rocks such as argillaceous dolomitic limestone similar to the Kingston aggregate from Pittsburg quarry-Ontario, Canada (Gillott 1963; Katayama 2010; Swenson and Gillott 1964). In fact, the latter type (ACR) has been the subject of intense debate among researchers (Guangren et al. 2002; Katayama 2010). It is traditionally defined as a dedolomitization process of dolomite crystals associated with considerable expansion, in which dolomite crystals react with alkalis in concrete to form brucite ($\text{Mg}(\text{OH})_2$), calcite (CaCO_3), and alkali carbonate (Na_2CO_3 or K_2CO_3) (Gillott 1963; Katayama 2010; Swenson and Gillott 1964). However, recent research based on initial findings by Katayama (Katayama 1992; Katayama 2010) indicated that the expansion and cracking of concrete made with ACR aggregates are actually caused by the alkali-silica gel that is formed due to ASR involving cryptocrystalline quartz present in the argillaceous dolomitic limestone (invisible in thin section optical microscopy). It has been concluded that the "ACR could be a mixture of deleteriously expansive ASR of cryptocrystalline quartz, and non-expansive dedolomitization of dolomitic aggregates, and that ACR is believed to be ASR, influenced more (fine aggregate) or less (coarse aggregate) by dedolomitization" (Grattan-Bellew et al. 2010; Katayama and Grattan-Bellew 2012). Nevertheless, the mitigation techniques known to prevent damaging ASR (i.e. replacement of cement with using supplementary cementing materials or using lithium-based admixtures) are reported to be ineffective in preventing ACR expansion and damages. Consequently, the aggregates susceptible to ACR are usually avoided in concrete as recommended by ASTM C1778" Standard Guide for Reducing the Risk of Deleterious Alkali-Aggregate Reaction in Concrete."

ASR in concrete causes the formation of alkali-silica gel that swells as it absorbs water from the surrounding cement paste. Swelling of the gel can lead to abnormal expansion, cracking, and eventual loss of mechanical properties of concrete (Thomas et al. 2013). The formation of ASR gel and the subsequent expansion in affected structures usually develops over several years, if not decades, before damage (for example, cracks) can be observed (Giorla et al. 2015).

There are three main conditions required for ASR to occur: the presence of reactive forms of silica in aggregates, high-alkali (pH) pore solution, and sufficient moisture. In addition, the amount of calcium available in the system, specifically in the form of calcium hydroxide ($\text{Ca}(\text{OH})_2$), is important for producing an expansive ASR gel (Thomas et al 2013). The presence of reactive forms of silica in an aggregate is the main driving force for alkali silica reaction. Although silica, SiO_2 , is a component of many rocks, however, not all forms of silica react significantly with alkali in concrete, and therefore, not all aggregates with high silica content are reactive. Thus, the alkali aggregate reactivity of an aggregate is attributed to the type and amount of reactive silica minerals in aggregates (Anaç et al. 2012; Thomas et al. 2013). Alkali ions in the pore solution of concrete (sodium and potassium ions) can come from internal sources such as the cement,

pozzolans, aggregates, admixtures, and mix water, or from external sources such as deicing salts or other sources. The role of moisture is essential for the development of ASR in concrete. Moisture allows movement and migration of alkali ions to reaction sites and produces swelling gel that causes expansion in concrete. Researchers observed that ASR expansion can occur in concrete with a relative humidity greater than 80% (Fournier et al. 2010).

Since the first discovery of ASR issues in the state of California in the late 1930s (Figure 2.1), research efforts have been primarily focused on many areas including: (1) understanding the AAR reaction mechanisms (Glasser 1991; Poole 1991; Sims and Poole 2017), (2) developing rapid and reliable test method that can accurately predict true field performance of aggregates (AASHTO-T380 2019; Latifee 2013; Sims and Nixon 2003; Stacey et al. 2016), (3) evaluating effective ASR mitigation alternatives for new concretes (ASTM-C1778 2020; Fournier et al. 2010; Thomas et al. 2008), and (4) proposing techniques for assessing and mitigating ASR in affected structures (Fournier et al. 2010; Saouma 2020). In this chapter the current state of knowledge and gaps that currently exist in the areas of aggregate reactivity assessment and the ASR mitigation alternatives for new concrete mixtures are addressed.



Figure 2.1 "Thomas Stanton of the California State Division of Highways and a Bridge Parapet Wall Showing Signs of Damage due to Alkali-Silica Reaction" (Thomas, 2013).

2.2 Assessment of Aggregate Reactivity

Identifying the reactivity of an aggregate to ASR is one of the most efficient ways for preventing damage in practice. Developing reliable testing methods for assessing aggregate reactivity and preventive measures remain major challenges for concrete industry and new concrete construction. A test method that is capable of assessing aggregate reactivity in reasonable time and accurately predict field performance of concrete is needed. In spite of the shortcomings of most of the current ASR assessment tests, they are still being used until an ideal method is developed to predict and measure aggregate reactivity. The most commonly used methods are the mortar bars test (ASTM C 1260) and the concrete prisms test (ASTM C 1293) (Rajabipour et al. 2015; Touma et al. 2001). In addition to the two expansion methods, petrographic examination of aggregates is usually performed to provide supplementary

information to the results of expansion tests. A brief summary for these methods and their limitations are provided below.

2.2.1 ASTM C 1260- Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar Bars Test)

In the ASTM C1260, mortar bar specimens (25 mm. (1 in.) x 25 mm. (1 in.) x 285 mm. (11 in.)) are cast after crushing and processing aggregate into a standard gradation as fine aggregate. Mortar bars are cast and conditioned in water at 80° C (176° F) for 24 hours and then placed in 1N NaOH solution at 80° C (176° F) for 14 days. The expansion of mortar bars is measured, in term of length change, periodically for 14 days. An aggregate is classified as innocuous if the 14 days expansion is less than 0.10%, potentially reactive if it is 0.10 to 0.20%, or reactive if the expansion is greater than 0.20%. Although this test method is commonly used as a quick tool to screen aggregate reactivity, the test is widely criticized as too severe for many aggregates (i.e. false-negative results) such as greywackes, lithic gravels, some hornfelses, gabbros, or andesites (Fournier et al. 2010). A study conducted by Folliard et al. (2006) showed that some aggregates have passed ASTM C1260 but exhibited expansion and cracks in outdoor exposure blocks and also failed the concrete prisms test (i.e. false-positive results). The limitations and the poor reliability of this test is attributed to the harsh conditioning environment imposed during testing to accelerate the ASR reaction, and also to the process of crushing-washing aggregates prior testing which might result in losing some reactive phases. Thus, it is recommended that the ASTM C1260 should not be used solely for rejecting aggregates, and negative results should be confirmed by using another more reliable test method (Touma et al. 2001).

2.2.2 ASTM C 1293 - Standard Test Method for Concrete Aggregates by Determination of Length Change of Concrete Due to Alkali-Silica Reaction

The ASTM C1293 is often considered as the most reliable test in predicting aggregate reactivity (Touma et al. 2001). In this test, concrete prisms (76 mm. (3 in.) x 76 mm. (3 in.) x 285 mm. (11 in.)) are prepared with a high alkali cement, and the alkali content of concrete is further boosted by adding NaOH to the mixing water. Concrete prisms are cast and cured at 23° C (73° F) and high humidity for 24 hours, and then placed in sealed containers over water at 38° C (100° F) for one year. The expansion of concrete prisms is measured, in term of length change, periodically during the one-year period. An aggregate is classified as reactive if the expansion after one year is greater than 0.04%. Despite the relatively good reliability of this test, the high humidity and elevated temperature during conditioning accelerates alkali leaching (Na and K ions) from prisms and subsequently underestimates the ultimate expansion of aggregates (Stacey et al. 2016). As a result, the ASTM C 1293 method requires boosting the concrete alkali loading (total alkalis in kg/m³) by adding NaOH to concrete to combat this issue of alkali leaching. However, this practice might not necessarily represent concrete in service where typically larger elements will only suffer leaching in the surface of the concrete element (Shehata 2005). In addition, the long duration for the test (one year) is one of its major drawbacks.

2.2.3 ASTM C 295 - Standard Guide for Petrographic Examination of Aggregates for Concrete

Optical petrographic examination is another method that is often used to identify most potentially reactive minerals present in aggregates for qualitative assessment of aggregate

reactivity (Touma et al. 2001). The test involves macroscopic description and microscopic analysis of aggregates (or concrete) aided by thin sections or polished surfaces. The conventional techniques for evaluating mineralogical composition of aggregates to predict their ASR potential such as point counting and x-ray diffraction have been used extensively in the literature (Alaejos and Lanza 2012; Monteiro et al. 2001; Wigum 1995). Despite the good reliability of optical examinations, they have been criticized as time consuming, very tedious, and most importantly they require an experienced petrographer to perform. Thus, several researchers have suggested that image processing techniques can provide a quick, reliable, and automated procedures for evaluating aggregate mineralogy and their microstructural features and can provide an alternative to the conventional techniques (Castro and Wigum 2012; Castro and Wigum 2012; Elhassan 2021; Wigum 1995). More research is needed to improve the reliability of petrographic examinations to accurately assess aggregate reactivity and concrete expansion.

2.2.4 New Methods under Development

Researchers have been actively investigating ways to improve the reliability of existing methods and developing new methods capable of assessing actual job concrete mixtures, in a relatively short period of time and accurately predict true field performance. Summary of test methods currently under investigation is provided below:

Accelerated Concrete-Cylinder Test (ACCT)

The ACCT method was developed by Texas A&M Transportation Institute to overcome the limitations of ASTM C1293 (e.g., alkali leaching, test duration). The method requires measuring the expansion of concrete cylinders (76 mm. (3 in.) x 152 mm (6 in.)) at a temperature over 60° C (140° F) over a period of 1 month (Liu and Mukhopadhyay 2016). The expansion is measured by placing the concrete cylinders inside a volumetric change measuring device (VCMDs), which contains a soak solution with chemistry that equals to the pore solution chemistry of concrete cylinders, as shown in Figure 2.2. The main features of ACCT are described by Liu and Mukhopadhyay (2016) and summarized below:

- Human errors associated with operation and temperature changes are eliminated in ACCT by the use of an automatic linear variable differential transducer (LVDT)-based length change measurement system, as shown in Figure 2.2.
- Alkali leaching is prevented at relatively high temperature 60° C (140° F).
- ACCT allows testing concrete at different levels of alkali.
- The proposed ACCT has the ability to test job concrete mix for ASR potential.

The preliminary results of this test have been correlated well with the standard ASTM C1293. However, studies are still ongoing to evaluate more aggregates and to adjust the test duration and expansion limit (i.e., 0.04 % expansion at 28 days for reactive aggregate).

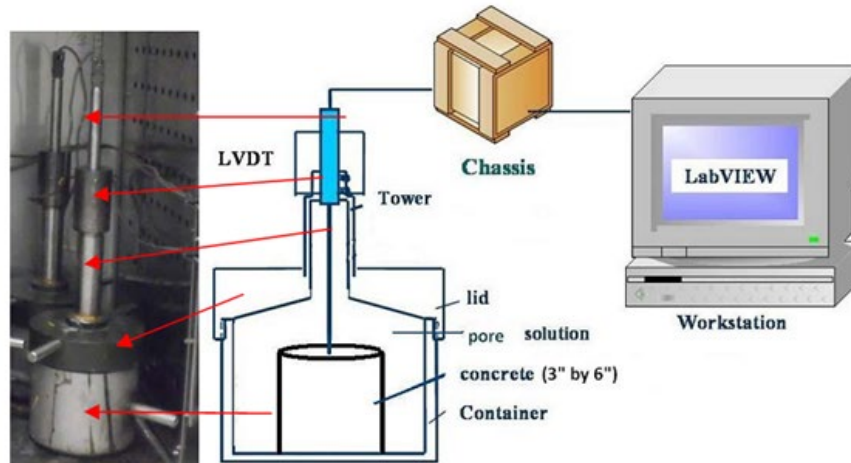


Figure 2.2 VCMD test setup ACCT (Liu and Mukhopadhyay 2016)

Miniature Concrete Prisms Test (MCPT)

The miniature concrete prisms test (MCPT) has been proposed to address the shortcomings of both the ASTM C1260 (mortar bars test) and the ASTM C1293 (concrete prisms test) methods with results obtained within 2 months compared with one year in ASTM C1293 (AASHTO-T380 2019; Latifee and Rangaraju 2015). In the MCPT method 50 mm. (2 in.) x 50 mm. (2 in.) x 285 mm. (11.25 in.) concrete prisms containing test aggregates with a maximum size of 12.5 mm. (1/2 in.) maximum size are used and proportioned similarly to the concrete used in the ASTM C1293 method. This test method allows detection of the potential for deleterious alkali-silica reaction of aggregate in miniature concrete prisms within 56 days for most of the aggregates. An additional 28 days may be necessary in the case of low/slow reacting aggregates to assess their potential reactivity. To assess the effectiveness of mitigation measures of SCMs (supplementary cementitious materials, such as fly ash, slag, silica fume, and others); the test method is conducted for 56 days (AASHTO-T380 2019).

2.3 ASR Mitigation

The occurrence of damaging ASR in concrete requires four main constituents (Rajabipour et al. 2015): (1) supply of reactive silica (mainly contained in aggregates), (2) adequate supply of alkali ions in pore solution of concrete, (3) a source of free Ca ions to bind with dissolved silica and form expansive gel, and (4) sufficient moisture to allow gel expansion. Thus, deleterious ASR can be mitigated if one or more of these constituents are eliminated (Thomas et al. 2013). Since eliminating the moisture or water from concrete is not practical in most cases, the following mitigation alternatives are typically used:

2.3.1 Use of Non-reactive Aggregate

Although this option seems to be a viable method for preventing ASR in new concrete, the option is not always practical especially where non-reactive aggregates are not available locally. Regular testing is required to ensure that aggregate sources are not reactive and aggregate quality is not changing within a pit or a quarry. This can be achieved through a combination of regular laboratory testing (i.e. petrographic examination, aggregate expansion

less than 0.04% in ASTM C1293 test or less than 0.1% in ASTM C1260 test) and/or a good record of field performance (Thomas et al. 2013).

2.3.2 Limiting the Alkali Content of Concrete

Early findings by Stanton (1942) indicated that ASR expansion in concrete is insignificant when the cement alkali content is maintained below 0.6 Na₂O_e (equivalent alkali content) (Thomas, 2013). However, later studies showed that concrete containing low alkali cement can still show damaging ASR expansion (Blaikie et al. 1996). This suggests that limiting the alkali content of the cement might not be enough for suppressing ASR as alkalis from other internal sources such as aggregates, supplementary cementitious materials, chemical admixtures, mixing water, or externally from seawater and deicing chemicals can contribute significantly to damaging ASR (Fournier et al. 2010). A limit of alkali loading of concrete below 1.8 kg/m³ (3.0 lb/yd³) Na₂O_{eq} is recommended by ASTM 1778 to minimize the risk of deleterious ASR expansion. However, this should not be used as a sole mitigation strategy for ASR in concrete (Rajabipour et al. 2015).

2.3.3 Use of Supplementary Cementitious Materials (SCMs)

Replacing cement with appropriate dosages of supplementary cementing materials (SCMs) such as fly ash, silica fume, calcined clay, metakaolin, and granulated blast-furnace slag (GGBFS) is one of the most efficient and economical mitigation options (Thomas et al. 2013). The mechanism of the pozzolanic reaction of SCMs mitigates ASR expansion through several ways (Thomas 2011): reducing the alkalinity of concrete by OH⁻ consumption and alkali binding, consumption of calcium hydroxide (Ca(OH)₂), and reducing of concrete permeability and alkali transport. The efficiency of SCMs in mitigating ASR depends mainly on the degree of aggregate reactivity and the chemistry and dosage of SCMs (Abd-Elssamd et al. 2020; Rajabipour et al. 2015). SCMs with relatively low CaO, low alkali content, or high silica content are proven to be the most effective in ASR mitigation. For example, SCMs with higher amount of CaO, such as fly ash class C and slag, need to be used at higher levels of replacement (i.e. > 40%), compared to only 15-30% of fly ash class F (low CaO content) or 10-15% of silica fume and metakaolin (high silica content).

The recently developed ASTM C1778 “Standard Guide for Reducing the Risk of Deleterious Alkali-Aggregate Reaction in Concrete” provides prescriptive and performance-based alternatives to select appropriate dosage of SCMs to mitigate ASR in new concrete construction. However, recent studies from long-term exposure sites have shown that the dosage of SCMs recommended by the AASHTO R 80-17 practice or ASTM C 1778 guide to control ASR might not be sufficient (Stacey et al. 2016; Fournier et al. 2016). In some cases, the minimum dosage of SCMs specified in ASTM C 1778 guide can exceed the maximum allowed limit in 2021 TDOT Standard Specifications (e.g., > 25% fly ash C and F and > 35% ground granulated blast-furnace slag (GGBFS)). A performance-based approach for evaluating the effectiveness of SCMs, namely fly ash class F and GGBFS, while considering the maximum cement replacement rate specified in 2021 TDOT Standard Specifications is required for cost effective mitigation against ASR.

In the light of the new environmental regulations to reduce the global CO₂ emission, a new challenge arises with the limited availability of high quality SCMs (e.g., low alkali fly ash class F) especially with the closure of coal-fired power plants and transitioning to fuels other than coal, and the fly ashes produced might no longer meet concrete specifications (Rajabipour et al. 2015).

Therefore, research is needed to find alternative sustainable means and methods of mitigating ASR expansion in concrete structures along with appropriate specification language to insure a safe transportation system for the motoring public.

2.3.4 Use of Lithium Admixtures

Lithium compound admixtures such as lithium nitrate (LiNO_3) and lithium hydroxide (LiOH) are proven efficient in mitigating ASR in new concrete. The degree to which lithium compounds mitigate expansive ASR depends mainly on aggregate reactivity and concrete alkali content (Gajda 1996; Stark 1993). The addition of lithium compounds to concrete produces a lithium-bearing ASR gel that has a greatly reduced expansion potential or even non-expansive (Farny and Kosmatka 1997) although the mechanism of mitigation is not fully understood (Rajabipour et al. 2015). The relatively high cost and the limited availability of lithium in the market are the main challenges for this alternative (Fournier et al. 2010). Thus, further research is needed for developing new ASR mitigating chemical admixtures that are cheaper and readily available.

Chapter 3 Methodology

Multiple aggregate sources across the southeastern states use aggregates for bases, concrete, and asphalt materials. Many aggregates used in Tennessee have a relatively high siliceous content (e.g., gravels, some limestones, granites). Higher levels of reactive silica in aggregates can be detrimental to concrete if it reacts with the alkaline cement paste. As discussed earlier, this study was conducted in two phases to evaluate the AAR reactivity of aggregates from 76 different sources in Tennessee (Phase I), and to investigate cost effective options to mitigate AAR of reactive aggregates (Phase II).

3.1 Expansion Tests

The reactivity of aggregates was evaluated using two expansion tests: the mortar bars tests (ASTM C1260 and ASTM C1567) and the concrete prisms test (ASTM C1293). ASTM C1260 is widely used for evaluating aggregate reactivity (Touma et al. 2001). In this study, at least three mortar bar specimens with the dimensions of 25 mm. (1 in.) x 25 mm. (1 in.) x 285 mm. (1 in.) were cast after processing aggregate into a standard gradation. The specimens were prepared with an aggregate/cement ratio of 2.25 and a water-cement ratio of 0.45 (Cement1 was used, see Section 3.4 for materials). After casting, mortar bars were placed in a moist room for 24 hours, removed from molds and placed in water at 80° C (176° F) for 24 hours. The initial length of at least three bars of each sample was measured and recorded. Then, the mortar bars were submerged in 1N NaOH solution at 80° C (176° F) for 14 days. The expansion of mortar bars was measured in term of the length change at 4, 7, 11, 14, 21, and 28 days after the initial reading. See typical steps for ASTM C1260 in Figure 3.1. The aggregate reactivity is classified according to Table 3-1. As this test has been reported to be very severe, the aggregates that failed this test were evaluated again using the ASTM C1293.

ASTM C1293 test is considered as the most accurate in predicting ASR reactivity for both fine and coarse aggregates (Touma et al. 2001). In this study, the reactivity of aggregates (coarse or fine aggregate) was determined by using a non-reactive natural sand (for the evaluation of coarse aggregates) and a non-reactive coarse aggregate (for the evaluation of fine aggregates) collected from Region 1, TN. The coarse aggregate was prepared for testing following the grading requirement specified in ASTM C1293, and the fine aggregate was used as received. At least three concrete prisms with the dimensions of 76 mm. (3 in.) x 76 mm. (3 in.) x 285 mm. (11 in.) were prepared with a cement content of 420 kg/m³ (708 lb/cy³) and a water-cement ratio of 0.45 (Cement2 was used, see Section 3.4 for materials) for each aggregate sample. The cement has a total alkali content of 0.9 ± 0.1 % Na₂O equivalent. The alkali content of concrete was increased to 1.25% Na₂O equivalent of mass of cement by adding NaOH to the mixing water, which corresponds to an alkali level of 5.25 kg/m³ (8.85 lb/cy³). Samples were cast, then cured at 23° C (73° F) in high humidity for 24 hours. Then an initial length was measured and recorded. Prisms were placed in sealed containers filled with water to a depth of 25 mm. (1 in.) above the bottom. The interior wall of the containers was lined with an absorbent fabric from the top so that the bottom of the fabric extends into the water, as recommended by ASTM C 1293. The prisms were placed in a perforated rack in the bottom of the storage container at 38 mm. (1.5 in.) above the water. The containers with prisms were placed in a curing room at 38° C (100° F). The expansion of concrete prisms was measured in term of the length change periodically during a one-year

period (at 7 days, 28 days, 56 days, 3 months, 6 months, 9 months, and 12 months). The aggregate reactivity is classified according to Table 3-1.

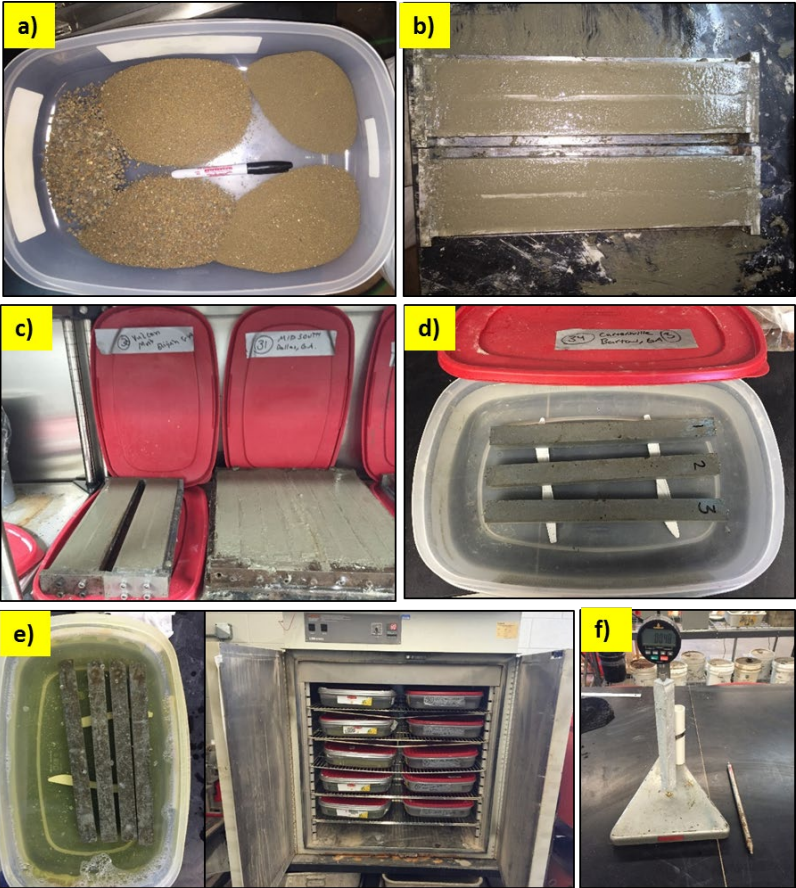


Figure 3.1 Aggregate testing per ASTM C1260: (a) aggregate preparation in standard gradation, (b) specimens casting, (c) curing for 24 hrs in a moist room, (d) samples in water at 80° C (176° F) for 24 hrs (oven curing), (e) In 1 N NaOH at 80° C (176° F) for 14 days (oven curing), (f) expansion measurement.

Table 3-1 Classification of Aggregate Reactivity per ASTM C1778

Aggregate reactivity class	Description of aggregate reactivity	1-year expansion based on ASTM C1293, %	14-day expansion based on ASTM C1260, %
R0	Non-reactive	< 0.04	< 0.10
R1	Moderately reactive	≥ 0.04, < 0.12	≥ 0.10, < 0.30
R2	Highly reactive	≥ 0.12, < 0.24	≥ 0.30, < 0.45
R3	Very highly reactive	≥ 0.24	≥ 0.45



Figure 3.2 Aggregate testing per ASTM C1293: (a) aggregate preparation in standard gradation, (b and c) conditioning containers, (d) conditioning in curing room at 38°C (100°F) for one year for evaluating aggregate reactivity and two years for evaluating mitigation alternatives.

For the ASR mitigation, a total of 30 aggregate samples with different degrees of reactivity were selected for mitigation testing, see Table 1-1 and Table 1-2 Testing Protocol for ASR Mitigation on ASTM C1293 – Two years. The mortar bars test (ASTM C1567 – 14 days) and the concrete prisms test (ASTM C1293 – 2 years) were used to determine an optimum dosage of fly ash class F to reduce the expansion below 0.1% at 14 days on ASTM C1567 or below 0.04% at two-years on ASTM 1293. The procedures of these tests are very similar to the ASTM C1260 and ASTM C1293 except for replacing the cement with a varying percentage of fly ash class F or slag. During this study, fly ash class F dosages, as shown Table 1-1, were selected to investigate the mitigation of the reactivity of 20 aggregate samples on ASTM 1567, The mitigation of the other 10 aggregate samples were evaluated using ASTM C1293 with a combination of fly ash class F dosages between 20 and 25% and a mix of slag and fly ash class F (30% GGBFS & 20% Fly ash class F), as shown in Table 1-2 Testing Protocol for ASR Mitigation on ASTM C1293 – Two years.

The criteria for evaluating ASR mitigations on either ASTM C1567 – 14 days or ASTM C1293-two years is based on the performance of aggregate under the expansion tests. According to the ASTM C1778, test method C1567 can be used to determine the performance of a specific SCM-aggregate combination to avoid the long duration of ASTM C1293. Before using ASTM C1567, it is

recommended that the results of test methods C1260 and C1293 for the aggregate being used be plotted as shown in Figure 3.3. Provided data do not fall within Zone 3, thus, test method ASTM C1567 can then be used to determine the efficacy of SCMs.

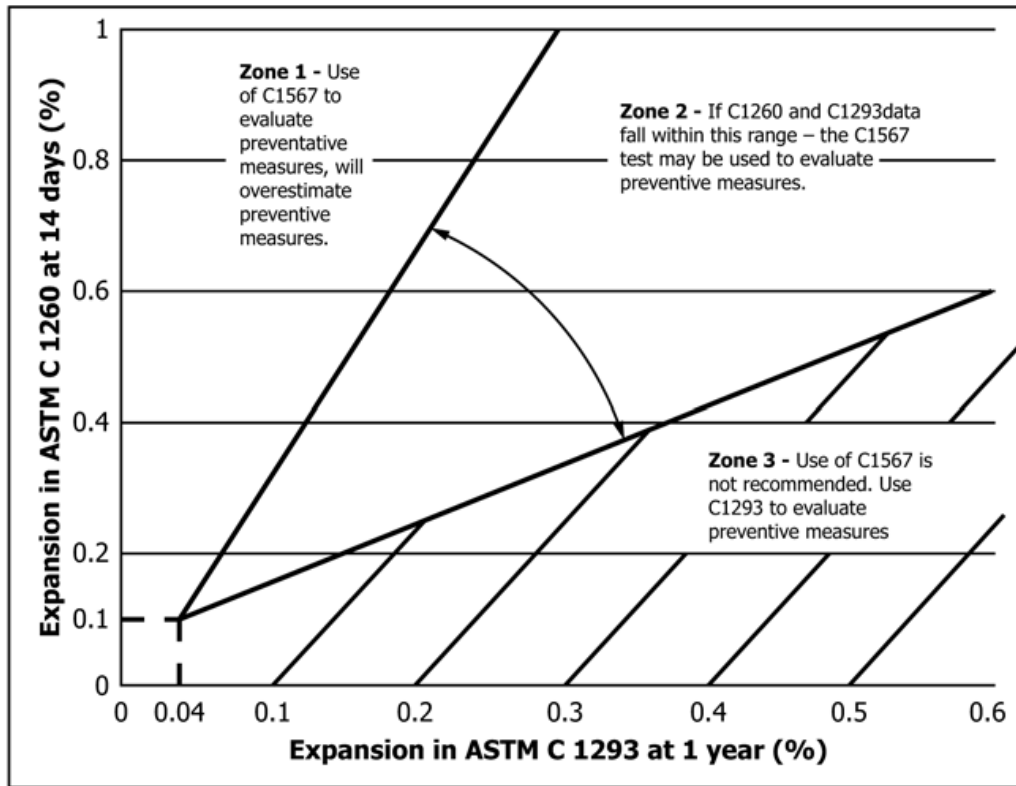


Figure 3.3 Determining Whether Test Method C1567 is Suitable for Evaluating Preventative Measures with a Specific Aggregate (ASTM C 1778)

3.2 Chemical Composition and X-ray Diffraction of Aggregate

The chemical composition and mineralogy of carbonate aggregate samples were determined using ICP-AES analysis and X-ray diffraction analysis of powder samples of aggregates, respectively. In preparation for testing, a representative sample (about 100-200 grams) was collected from the left-over aggregate (mainly size of 3/8 in., or 10 mm.) after casting the concrete prisms for ASTM C1293. The sample was ground in a mini-jaw crusher with ceramic plates and passed through a 45- μm (No. 325) sieve, see Figure 3.4. A portion of the powder from each aggregate sample (about 50 grams) was shipped to ALS USA, Inc in Reno, NV to perform a whole rock chemical analysis for the samples. A powder sample (0.200 g) is added to lithium metaborate/lithium tetraborate flux (0.90 g), mixed well and fused in a furnace at 1000°C. The resulting melt is then cooled and dissolved in 100 mL of 4% nitric acid / 2% hydrochloric acid. This solution is then analyzed by ICP-AES and the results are corrected for spectral inter-element interferences. Oxide concentration is calculated from the determined elemental concentration. For the loss on ignition (L.O.I), a powder sample (1.0 g) is placed in an oven at 1000° C (1832 ° F) for one hour, cooled and then weighed. The percent L.O.I is calculated from the difference in

weight. The total oxide content is determined from the ICP analyte concentrations and L.O.I values.

The X-ray diffraction (XRD) analysis was performed at the Joint Institute for Advanced Materials (JIAM) Diffraction Facility, located at the University of Tennessee, Knoxville. The mineral constituents of each aggregate sample were determined using a Panalytical, Inc. X-Pert Pro Multipurpose Powder Diffractometer system that linked with the ICDD (International Center for Diffraction Data) database for phase identification. The conditions for collecting the XRD data include Co-K α radiation, scanning from 5° to 85° 2 θ with a step size less than 0.013°, and analysis of the patterns using Rietveld Refinement with HighScore Plus software.



Figure 3.4 Aggregate preparation for chemical and XRD testing: (a) Mini-jaw crusher, (b & c) aggregate powder samples for testing

3.3 Petrographic Examination of Aggregate and Concrete

Examination for carbonate aggregates and concrete made with reactive aggregates was conducted using optical microscopy and SEM-EDS examinations. The SEM-EDS examination was conducted using a Phenom desktop SEM coupled with Phenom ProX EDS detector. The main objectives of the petrographic examinations are to identify potential reactive minerals within aggregate such as amorphous silica, cryptocrystalline and microcrystalline quartz, or strained quartz (SiO₂), and to detect evidence of AAR in concrete such as the presence of ASR gel, reaction rims around reactive aggregate, and any signs of dedolomitization process related to ACR. A representative sample (about 500 grams) was collected from the left-over aggregate (mainly aggregate sizes 0.5 in., and 3/8 in) after casting the concrete prisms for ASTM C1293. The aggregate samples were sent to the National Petrographic Service, Inc. to prepare a 50 x 75 mm.

(2 x 3 in.) standard polished thin section for each aggregate (about 25 – 30 μm thickness), see Figure 3.5. Polished concrete thin sections were prepared from concrete prisms after one year of conditioning under ASTM C1293. The concrete samples were cut using oil to prevent potential dissolution of ASR gel.

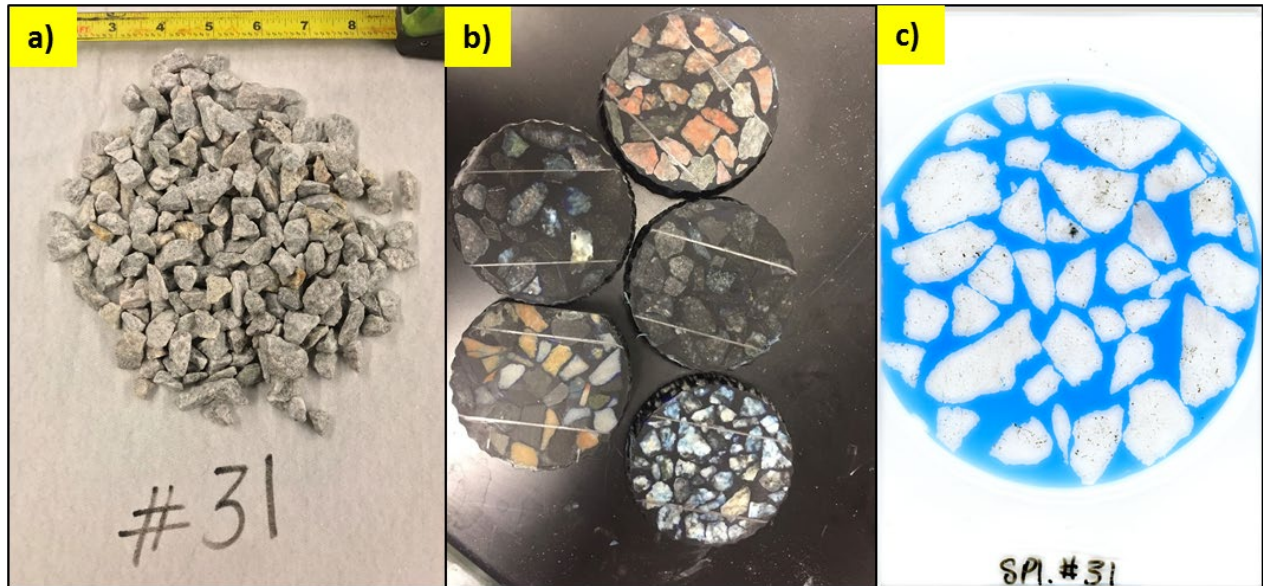


Figure 3.5 Aggregate preparation for petrographic examination: (a) aggregate sample, (b) polished section of aggregate mounted in epoxy, (c) 50 x 75 mm. (2 x 3 in.) thin section of aggregate (blue=epoxy, random shapes=aggregate particles)

3.4 Materials

3.4.1 Cement and Fly ash

Two types of Type I Portland cement (“Cement1” and “Cement2”) produced by Buzzi Unicem USA were used. Cement1 contains a relatively low equivalent alkali content (0.54% Na₂O_{eq}) and it was used to cast specimens for mortar bars expansion tests (ASTM C1260 and ASTM C1567). Cement2 contains a relatively high equivalent alkali content (1.04% Na₂O_{eq}) and it was used to cast specimens for the concrete prisms expansion test (ASTM C1293). Fly ash class F produced by Tennessee Valley Authority (TVA) fossil plant in Kingston, TN was obtained to evaluate ASR mitigation alternatives. The chemical compositions of Cement1, Cement2, and fly ash class F are shown in Table 3-2. Detailed physical and chemical properties of cements and fly ash class F are included in **Appendix A**.

Table 3-2 Chemical Composition of Cement and Fly Ash

Type	Wt/%						
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	Total Alkali (Na ₂ O+0.658 K ₂ O)
Cement1	19.8	4.5	3.5	63.1	2.9	2.8	0.54
Cement2	19.0	4.8	2.1	61.0	3.8	4.6	1.04
Fly ash F	45.6	20.2	14.01	10.0	2.1	1.59	1.99

3.4.2 Aggregate Samples

During Phase I of the project, a total of 84 aggregate samples were acquired from 76 local sources in the state of Tennessee. The samples were collected by TDOT Materials and Tests Division from the four different regions: Region 1, Region 2, Region 3, and Region 4, as shown in Figure 3.6(a). The collected samples contain several types of aggregates including: 45% limestone, 18% granite, 26% sand and gravel, 4% slag, 1 % quartz, 1 % sandstone, and 4% unclassified, as shown in Figure 3.6(b).

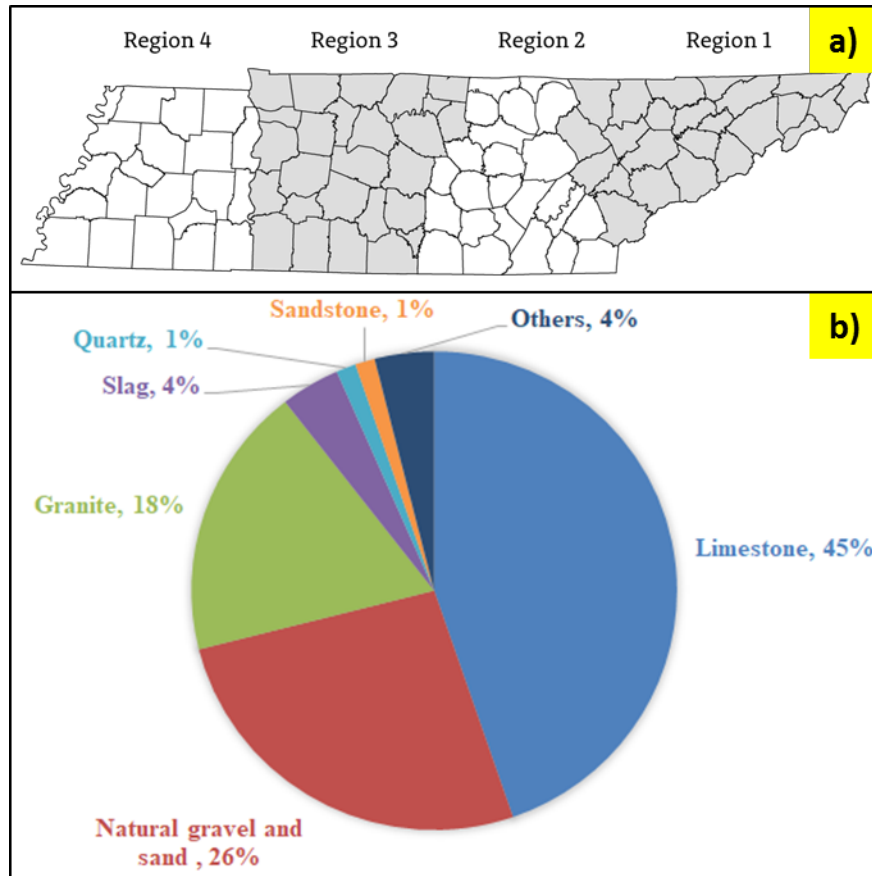


Figure 3.6 Aggregates Received from TDOT: (a) Tennessee regional map, (b) aggregate classification

Detailed list of aggregate sources and producers are summarized in Table 3-3. From each aggregate source three samples were received: a sample for physical properties testing, a processed sample for ASTM C1260 test, and a processed sample for ASTM C1293 test. Only ASTM C1293 samples were collected for Producer IDs: PL#60, PL#64, and PL#66, denoted by (*) in Table 3-3. One gravel and one natural sand samples were collected from the sources that are denoted by (**) in Table 3-3. The gravel samples collected from these sources were tested based on ASTM C1293 and the natural sand samples were tested based on the ASTM C1260. The sample collected from Producer ID PL#48 contained high amount of wood debris and clay and it was not tested in this study, denoted by (***) in Table 3-3.

Table 3-3 List of Aggregates Received from TDOT

Producer ID	Sample ID	Aggregate Type	Region
PL#1	Natural sand#1	Natural sand	1
PL#2	Limestone#2	Limestone	1
PL#3	Limestone#3	Limestone	1
PL#4	Slag#4	Slag	1
PL#5	Granite#5	Granite	1
PL#6	Natural sand#6	Natural sand	1
PL#7	Limestone#7	Limestone	1
PL#8	Limestone#8	Limestone	1
PL#9	Quartz#9	Quartz	1
PL#10	Granite#10	Granite	1
PL#11	Granite#11	Granite	1
PL#12	Granite#12	Granite	1
PL#13	Limestone#13	Limestone	1
PL#14	Granite#14	Granite	1
PL#15	Limestone#15	Limestone	1
PL#16	Gravel/sand#16**	Gravel & sand	1
PL#17	Limestone#17	Limestone	2
PL#18	Limestone#18	Limestone	2
PL#19	Limestone#19	Limestone	2
PL#20	Sandstone#20	Sandstone	2
PL#21	Natural sand#21	Natural sand	2
PL#22	Slag#22	Slag	2
PL#23	Natural sand#23	Natural sand	2
PL#24	Natural sand#24	Natural sand	2
PL#25	Natural sand#25	Natural sand	2
PL#26	Granite#26	Granite	2
PL#27	Limestone#27	Limestone	2
PL#28	Limestone#28	Limestone	2
PL#29	Limestone#29	Limestone	2
PL#30	Granite#30	Granite	2
PL#31	Granite#31	Granite	2
PL#32	Sample#32	-	2
PL#33	Granite#33	Granite	2
PL#34	Granite#34	Granite	2
PL#35	Granite#35	Granite	NC
PL#36	Granite#36	Granite	2
PL#37	Granite#37	Granite	NC
PL#38	Limestone#38	Limestone	2
PL#39	Granite#39	Granite	NC
PL#35	Granite#35	Granite	NC
PL#36	Granite#36	Granite	2
PL#37	Granite#37	Granite	NC
PL#38	Limestone#38	Limestone	2

Producer ID	Sample ID	Aggregate Type	Region
PL#39	Granite#39	Granite	NC
PL#40	Limestone#40	Limestone	3
PL#41	Limestone#41	Limestone	3
PL#42	Limestone#42	Limestone	3
PL#43	Limestone#43	Limestone	3
PL#44	Limestone#44	Limestone	3
PL#45	Natural sand#45	Natural sand	3
PL#46	Limestone#46	Limestone	3
PL#47	Limestone#47	Limestone	3
PL#48	Dirt#48***	Dirt	3
PL#49	Limestone#49	Limestone	3
PL#50	Limestone#50	Limestone	3
PL#51	Gravel/sand#51**	Gravel & sand	3
PL#52	Limestone#52	Limestone	3
PL#53	Limestone#53	Limestone	3
PL#54	Limestone#54	Limestone	3
PL#55	Limestone#55	Limestone	4
PL#56	Limestone#56	Limestone	4
PL#57	Limestone#57	Limestone	4
PL#58	Gravel/sand#58**	Gravel & sand	4
PL#59	Slag#59	Slag	4
PL#60	Limestone#60*	Limestone	4
PL#61	Gravel/sand#61**	Gravel & sand	4
PL#62	Gravel/sand#62**	Gravel & sand	4
PL#63	Gravel/sand#63**	Gravel & sand	4
PL#64	Limestone#64*	Limestone	4
PL#65	Gravel/sand#65**	Gravel & sand	4
PL#66	Limestone#66*	Limestone	4
PL#67	Gravel/sand#67**	Gravel & sand	4
PL#68	Gravel/sand#68**	Gravel & sand	4
PL#69	Natural sand#69**	Natural sand	4
PL#70	Limestone#70	Limestone	4
PL#71	Limestone#71	Limestone	4
PL#72	Sample#72	-	4
PL#73	Natural sand#73	Natural sand	4
PL#74	Gravel & sand#74**	Gravel & sand	4
PL#75	Limestone#75	Limestone	4
PL#76	Gravel & sand#76**	Gravel & sand	4

* No sample provided for ASTM C1260.

**Two samples were provided; gravel and natural sand. The gravel was tested on ASTM C1293 and the sand was tested on ASTM C1260.

***Dirt sample cannot be used in concrete (high clay/silt and fine content)

Please note that locations and producers of aggregates are confidential to TDOT.

Chapter 4 Results and Discussion

4.1 Phase I: Assessment of Aggregate Reactivity

The main objective of Phase I of this project is to evaluate the ASR reactivity of siliceous aggregates (surface aggregates) from 76 different sources in Tennessee. The aggregate reactivity was determined using both the accelerated mortar bars expansion test (ASTM C1260) and the concrete prisms expansion test (ASTM C1293- one year), and aggregate reactivity was classified per ASTM C1778 guide as shown in Table 3-1. The reactivity of all aggregates was first evaluated using the mortar bars test (ASTM C1260). The aggregates are considered as non-reactive if the 14 days expansion is less than 0.10% and as reactive if it is greater than 0.1%. As this test is reported to be very severe for some aggregate formations, the aggregates failed ASTM C1260 were evaluated again using the ASTM C1293. In this test, aggregates are considered as innocuous if the expansion at one year is less than 0.04% and potentially deleteriously reactive if the expansion at one year is greater than 0.04%.

An example of aggregate performance on ASTM C1260 is shown in Figure 4.1. The non-reactive aggregates typically show no signs of ASR distress (e.g. cracks, ASR gel, or high amount of expansion > 0.1% in ASTM C1260) (Figure 4.1 a). The reactive aggregates usually show gel deposition on the surface of mortar bar specimens (Figure 4.2) and significant expansion and cracking of the mortar bars (Figure 4.1 b-c). Some highly reactive samples with significant cracking showed warping due to the high amount of expansion (Figure 4.1d).

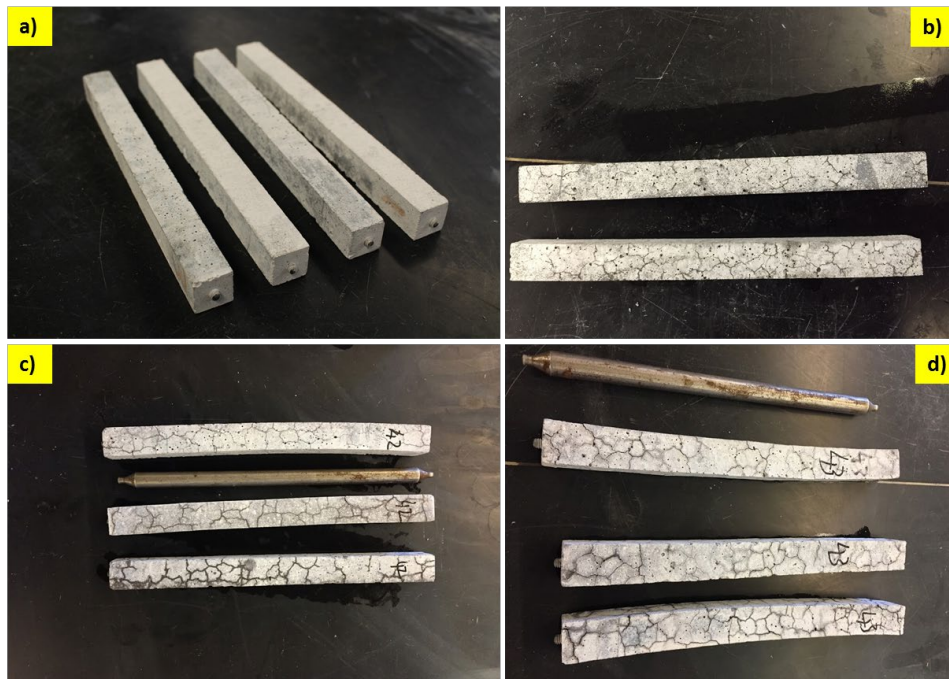


Figure 4.1 Visual signs of ASR in ASTM C1260 : (a) non-reactive aggregate with no visible signs of ASR cracks or gel, (b) moderately reactive aggregate with visible ASR cracks and gel filling cracks (darker color in cracks), (c and d) highly reactive aggregates with severe ASR cracks and warping

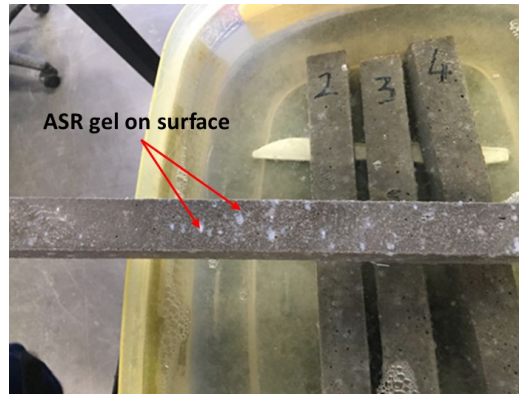


Figure 4.2 Gel deposition on the surface of mortar bars in ASTM C1260

4.1.1 Results of Expansion Tests

A total of 83 aggregate samples were tested on expansion tests to determine their ASR potential. The results of expansion tests and aggregate reactivity classification are summarized in Table 4-1, Table 4-2, and Table 4-3 for non-reactive, moderately reactive, and highly/very highly reactive aggregates, respectively. The tables show the 14-day expansion results from ASTM C1260 and the one-year expansion results from ASTM C1293. The last column shows the classification of reactivity following the classification proposed by ASTM C1778-16, Standard Guide for Reducing the Risk of Deleterious Alkali-Aggregate Reaction [AAR] in Concrete. The location and producer for each aggregate sample was not reported for confidentiality.

Results from Phase I testing program indicated a potential Alkali-Aggregate Reaction (AAR) risk for concrete structures and pavement lifecycle in Tennessee unless proper mitigation techniques are applied to mitigate the reactivity of these aggregates. For the tested aggregate samples, at least 65% are classified as AAR reactive with different degree of reactivity (i.e., moderate to very highly reactive). Out of 83 aggregate samples, 29 samples (35%) are non-reactive (R0), 24 samples (29%) are moderately reactive (R1), 26 samples (31 %) are highly reactive (R2), and 4 samples (5%) are very highly reactive (R3), as shown in Figure 4.3.

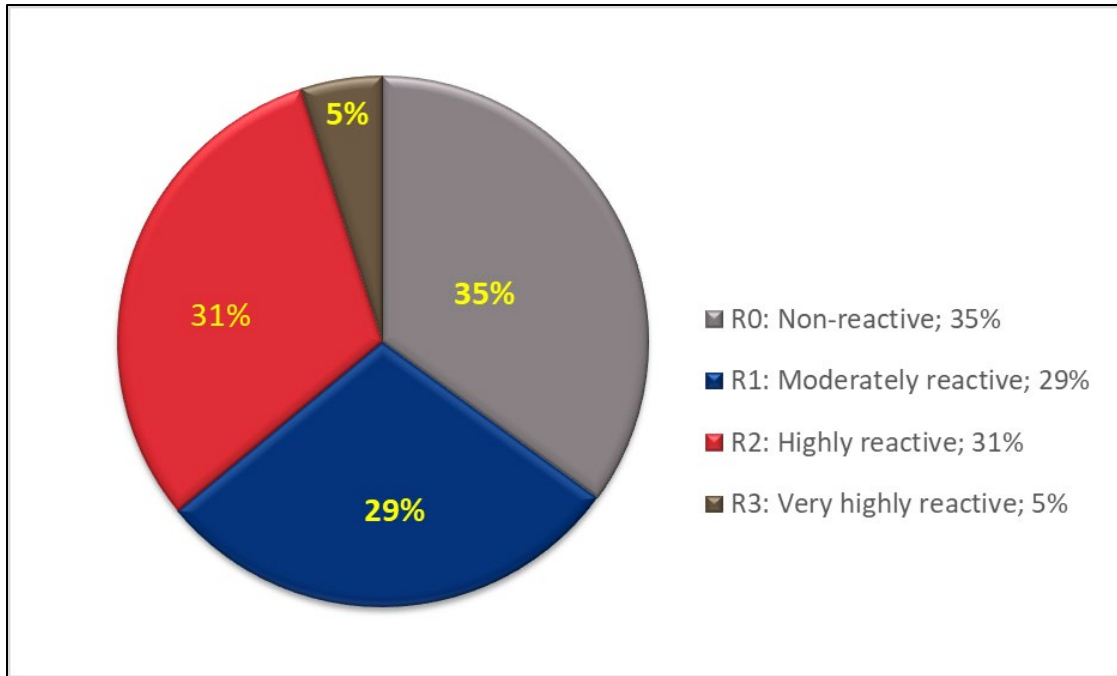


Figure 4.3 ASR Reactivity of Tennessee Aggregates (Results from 83 samples collected from 76 sources)

Table 1-1 shows a list of aggregates that are classified as non-reactive (R0). These aggregates either show an expansion less than 0.1% at 14 days on ASTM C1260 or less than 0.04% at one-year on ASTM C1293. One gravel and one natural sand sample were collected from the sources that are denoted by (**) in Table 4-1 and Table 4-2. The gravel samples collected from these sources were tested on ASTM C1293 and the natural sand samples were tested on the ASTM C1260. If the results from both expansion tests are obtained the results from ASTM C1293 (most reliable) are used to determine aggregate reactivity. Aggregate samples listed in Table 4-1 are accepted for use in concrete with no further consideration of mitigation provided that the other physical properties of the aggregate render it suitable for use (ASTM C 1778-16). Petrographic examinations were conducted for selected samples to confirm their non-reactivity.

Table 4-1 Non-Reactive (R0) Aggregate List

Producer ID	Sample ID	ASTM C1260		ASTM C1293		ASTM C1778 Classification
		14-Day Expan.%	Reactivity	1-year Expan.%	Reactivity	
Limestone Aggregates						
PL#56	Limestone#56	0.02	Non-reactive	Not applicable		Non-Reactive (R0)
PL#19	Limestone#19	0.04	Non-reactive			
PL#54	Limestone#54	0.05	Non-reactive			
PL#55	Limestone#55	0.05	Non-reactive			
PL#13	Limestone#13	0.06	Non-reactive			
PL#52	Limestone#52	0.08	Non-reactive			
PL#15	Limestone#15	0.06	Non-reactive			
PL#53	Limestone#53	0.07	Non-reactive			
PL#17	Limestone#17	0.09	Non-reactive			
PL#27	Limestone#27	0.09	Non-reactive			
PL#8	Limestone#8	0.23	Highly reactive	0.038	Non-reactive	
Granite Aggregates						
PL#33	Granite#33	0.04	Non-reactive	Not applicable		Non-Reactive (R0)
PL#26	Granite#26	0.09	Non-reactive			
PL#31	Granite#31	0.06	Non-reactive			
Natural Sand						
PL#1	Natural sand#1	0.04	Non-reactive	Not applicable		Non-Reactive (R0)
PL#24	Natural sand#24	0.05	Non-reactive			
PL#23	Natural sand#23	0.06	Non-reactive			
Gravel and Natural Sand						
PL#51	Gravel/sand#5 1**	0.09	Non-reactive	Not applicable		Non-Reactive (R0)
PL#68	Gravel/sand#6 8**	0.06	Non-reactive	0.038	Non-reactive	
PL#65	Gravel/sand#6 5**	Gravel/ Not applicable		0.038		
PL#74	Gravel/sand#7 4**			0.026		
PL#62	Gravel/sand#6 2**			0.028		
PL#63	Gravel/sand#6 3**			0.025		
PL#61	Gravel/sand#6 1**			0.03		

PL#69	Gravel/sand#6 9**		0.029		
PL#16	Gravel/sand#1 6**		0.022		
PL#58	Gravel/sand#5 8**		0.035		
Others					
PL#4	Slag#4	0.03	Non-reactive	Not applicable	Non- Reactive (R0)
PL#72	Sample#72	0.09	Non-reactive		

** Gravel and natural sand collected from the same source. The gravel was tested on ASTM C1293, and the sand was tested on the ASTM C1260.

Lists of reactive aggregates are summarized in Table 4-2 for moderately reactive aggregates (R1) and Table 4-3 for highly reactive (R2) and very highly reactive aggregates (R3). The results from this study showed a good agreement between the ASTM C1260 and ASTM C1293 in classifying aggregates as reactive. However, there is inconsistency in classifying the level of reactivity between the two tests. Although the ASTM C1260 is known to be very harsh (and therefore resulting in false ASR positive aggregates) (Folliard et al. 2006), the test seemed to underestimate the reactivity potential for most of limestone aggregates in this study. For examples, Limestone#71, Limestone#75, Limestone#49, and Limestone#47 were classified as a moderately reactive (R1) according to the ASTM C1260 but as a very highly reactive (R3) in ASTM C1293. This observation can be partially attributed to the high amount of less expansive gel that was observed on the surface of mortar bar specimens, as shown in Figure 4.2. The harsh testing conditions in ASTM C1260 as characterized by a continuous supply of an external alkaline solution at high temperature might cause the formation of high quantity of ASR gel with low expansive pressure which can leave specimens without causing significant expansion (Kawamura and Iwahori 2004). Thus, in Tables 4.2 and 4.3 the expansion results from ASTM C1293 are used to classify aggregate reactivity following the criteria shown in Table 3-1.

Table 4-2 Moderately Reactive (R1) Aggregate List

Producer ID	Sample ID	ASTM C1260		ASTM C1293		ASTM C1778 Classification
		14-Day Expan.%	Reactivity	1-year Expan.%	Reactivity	
PL#65	Gravel/sand#65 **	0.21	Reactive	Not applicable	Moderately Reactive (R1)	
PL#74	Gravel/sand#74 **	0.12	Reactive			
PL#62	Gravel/sand#62 **	0.15	Reactive			
PL#63	Gravel/sand#63 **	0.17	Reactive			
PL#61	Gravel/sand#61 **	0.16	Reactive			

PL#69	Gravel/sand#69 **	0.14	Reactive		
PL#16	Gravel/sand#16 **	0.10	Reactive		
PL#58	Gravel/sand#58 **	0.16	Reactive		
PL#40	Limestone#40	0.14	Reactive	0.045	Reactive
PL#21	Natural sand#21	0.12	Reactive	0.048	Reactive
PL#6	Natural sand#6	0.21	Reactive	0.051	Reactive
PL#25	Natural sand#25	0.17	Reactive	0.050	Reactive
PL#59	Slag#59	Fractured	Reactive	0.053	Reactive
PL#22	Slag#22	Fractured	Reactive	0.061	Reactive
PL#14	Granite#14	0.13	Reactive	0.067	Reactive
PL#64	Limestone#64	N/A	-	0.068	Reactive
PL#20	Sandstone#20	0.14	Reactive	0.071	Reactive
PL#32	Sample#32	0.19	Reactive	0.087	Reactive
PL#18	Limestone#18	0.20	Reactive	0.088	Reactive
PL#27	Limestone#27	0.12	Reactive	0.090	Reactive
PL#9	Quartz#9	0.24	Reactive	0.109	Reactive
PL#7	Limestone#7	0.20	Reactive	0.107	Reactive
PL#5	Granite#5	0.26	Reactive	0.107	Reactive
PL#28	Limestone#28	0.27	Reactive	0.110	Reactive

** Gravel and natural sand collected from the same source. The gravel was tested on ASTM C1293, and the sand was tested on the ASTM C1260.

To prevent damaging ASR in new concrete construction, the reactive aggregate listed in Tables 4.2 and 4.3 should not be used in concrete without a proper ASR mitigation. Aggregates that are quarried carbonate such as limestones were further tested to determine whether the potential reaction measured in the ASTM C1293 is of the alkali-carbonate or alkali-silica reaction. The limestone aggregates with ACR potential should be identified and avoided in concrete as per the ASTM C 1778 recommendation, further investigation for limestones reactivity is provided in the following sections.

Reactive aggregates that were not quarried carbonate (e.g. granite, quartz, natural sand and gravel, and slag) or carbonate aggregates with no ACR potential can be used in concrete with a proper ASR mitigation including the use of supplementary cementing materials (SCMs) or the use of chemical additives (i.e. lithium-based compounds) in the concrete mix (ASTM C 1778-16). ASR mitigation options were investigated in Phase II of this project and are discussed in the following sections.

Table 4-3 Highly and Very Highly Reactive (R2 and R3) Aggregate List

Producer ID	Sample ID	ASTM C1260		ASTM C1293		ASTM C1778 Classification	
		14-Day Expan.%	Reactivity	1-year Expan.%	Reactivity		
PL#46	Limestone#46	0.11	Reactive	0.118	Reactive	Highly Reactive (R2)	
PL#35	Granite#35	0.12	Reactive	0.118	Reactive		
PL#39	Granite#39	0.36	Reactive	0.122	Reactive		
PL#12	Granite#12	0.30	Reactive	0.135	Reactive		
PL#3	Limestone#3	0.18	Reactive	0.139	Reactive		
PL#10	Granite#10	0.17	Reactive	0.141	Reactive		
PL#44	Limestone#44	No sample	-	0.146	Reactive		
PL#60	Limestone#60	No sample	-	0.146	Reactive		
PL#73	Natural sand#73	0.10	Reactive	0.105	Reactive		
PL#41	Limestone#41	0.21	Reactive	0.150	Reactive		
PL#30	Granite#30	0.23	Reactive	0.151	Reactive		
PL#11	Granite#11	0.17	Reactive	0.153	Reactive		
PL#36	Granite#36	0.18	Reactive	0.158	Reactive		
PL#29	Limestone#29	0.25	Reactive	0.159	Reactive		
PL#38	Limestone#38	0.31	Reactive	0.163	Reactive		
PL#57	Limestone#57	0.24	Reactive	0.167	Reactive		
PL#44	Limestone#44	0.32	Reactive	0.167	Reactive		
PL#37	Granite#37	0.13	Reactive	0.169	Reactive		
PL#34	Granite#34	0.24	Reactive	0.180	Reactive		
PL#45	Natural sand#45	0.20	Reactive	0.173	Reactive		
PL#70	Limestone#70	0.29	Reactive	0.185	Reactive		
PL#42	Limestone#42	0.35	Reactive	0.197	Reactive		
PL#71	Limestone#71	0.10	Reactive	0.199	Reactive		
PL#67	Gravel/sand#67	0.16	Reactive	0.187	Reactive		
PL#43	Limestone#43	0.26	Reactive	0.213	Reactive		
PL#76	Gravel/sand#76	0.16	Reactive	0.213	Reactive		
PL#50	Limestone#50	0.25	Reactive	0.256	Reactive		Very Highly Reactive (R3)
PL#75	Limestone#75	0.25	Reactive	0.259	Reactive		
PL#49	Limestone#49	0.22	Reactive	0.267	Reactive		
PL#47	Limestone#47	0.19	Reactive	0.271	Reactive		
PL#48	Dirt#48	Dirt, Not tested					

Slag#59 and Slag#22 (Table 4-2) showed aggressive reactivity in the ASTM C1260 test and ASTM C1293. The mortar bars were fractured and completely damaged before reaching the age of 14 days on ASTM C1260, see Figure 4.4 . Some of the prisms on ASTM C1293 showed severe

cracks and the formation of white or ivory chalk-like deposit in slag aggregate, see Figure 4.5. The nature of reaction and the damage observed in the mortar bars and concrete prisms made with the slag samples #59 and #22 were not a typical AAR symptom and likely to be from a different reaction mechanism. These slag samples should be avoided in concrete until further investigation.

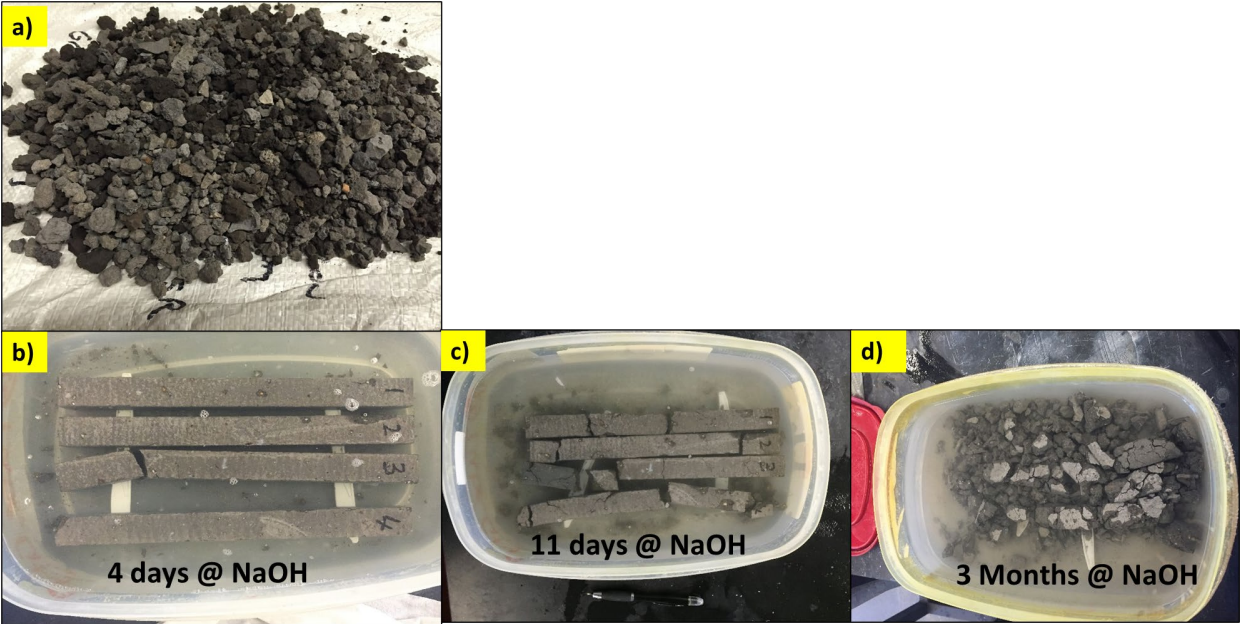


Figure 4.4 Performance of Slag#59 and Slag#22 on ASTM C1260

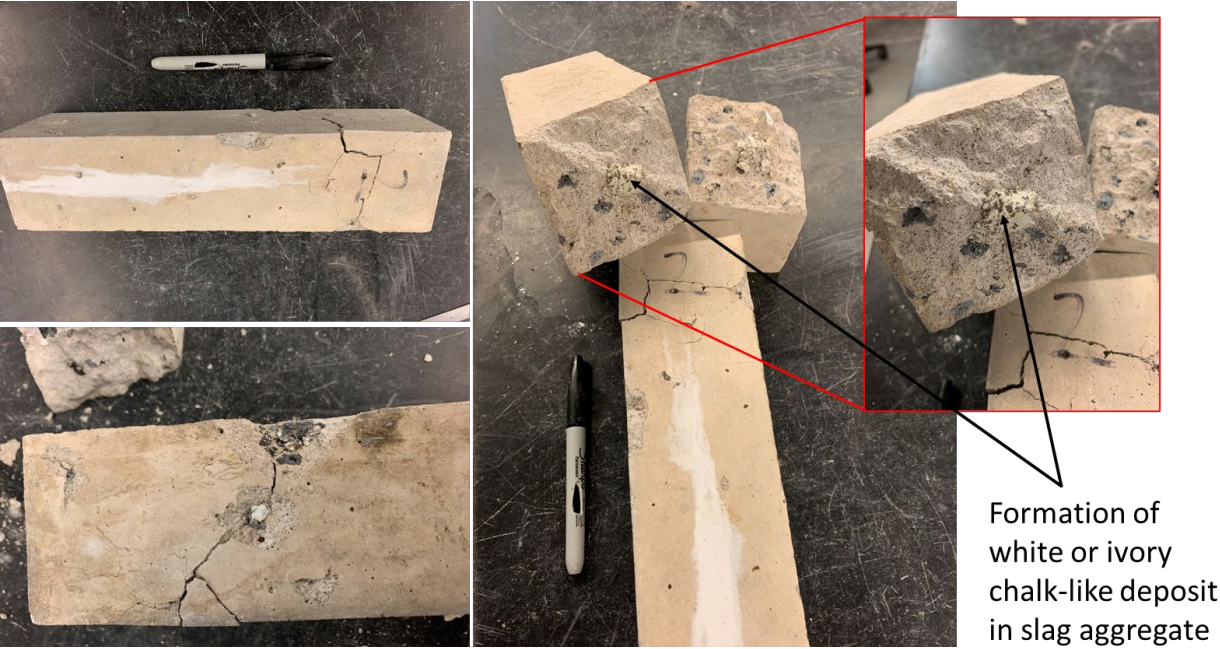


Figure 4.5 Performance of Slag#59 and Slag#22 on ASTM C1293

4.2 Phase II: Mitigating the Risk of AAR in Tennessee

A high risk of Alkali-Aggregate Reaction (AAR) for concrete transportation structures in Tennessee was addressed during Phase I of this project. The results indicated that (1) at least 65% of the tested aggregates are classified as reactive with different degree of reactivity (i.e., moderate to very highly reactive), and (2) nearly 50% of aggregates tested are carbonate rocks (i.e., limestones). This suggested a potential for both ASR and ACR issues in future concretes unless proper mitigation techniques are applied to mitigate the reactivity of these aggregate. In addition, since the highly reactive aggregates might have already been used in existing concrete structures, a potential deterioration of existing structures due to AAR might be present. Testing and tasks were conducted during this phase to address three main objectives:

- 1- Identifying reactive carbonate aggregates (e.g., limestones) with AAR potential to confirm the cause of the measured expansion in ASTM C1293, whether it's ASR or ACR or a combination of both, so that decisions can be made regarding the use and mitigating the reactivity of these aggregate. Chemical and mineralogical composition of carbonate aggregates were determined, and petrographic and microscopic examinations of concrete and aggregates were performed.
- 2- Specifying mitigation alternatives to allow the use of ASR reactive aggregates in future concrete structures. Performance-based testing was conducted using different combinations of supplementary cementing materials (e.g fly ash class F and granulated blast-furnace slag-GGBFS) with reactive aggregates.
- 3- Investigating the field performance of highly reactive aggregates to address the extent of ASR in existing structures.

Summary of results and findings from Phase II are provided in the following sections.

4.3 Phase II: Reactivity of Carbonate Aggregates from Tennessee

In this section, the reactivity and concrete expansion behavior of 26 different limestone aggregates collected from four different regions of the state of Tennessee were investigated. The study aimed to determine the cause of the measured expansion in ASTM C1293, whether it's ASR or ACR or a combination of both. Petrographic examinations including optical microscopy and scanning electron microscopy coupled with energy-dispersive spectrometry (SEM - EDS), X-ray powder diffraction, and chemical analysis using Inductively Coupled Plasma - Atomic Emission Spectroscopy (ICP-AES) were conducted on aggregates and concrete samples. A summary of the findings is provided in this section. A detailed study has been published as part of this project and can be accessed at the link below:

<https://www.sciencedirect.com/science/article/abs/pii/S0950061820319218>

A list of the 26 different limestone aggregates including their physical properties is included in Appendix B, Table B-1. The location and producer for each aggregate sample was not reported for confidentiality. The geological data for each aggregate source were collected from Macrostrat platform (Peters et al. 2010) which includes data collected from the State Geologic Map Compilation (SGMC) geodatabase of the conterminous United States. The geological data include information about lithology, age, and stratigraphy at a national scale, as summarized in Appendix B, Table B-2.

4.3.1 Limestone Aggregates Reactivity and Concrete Expansion

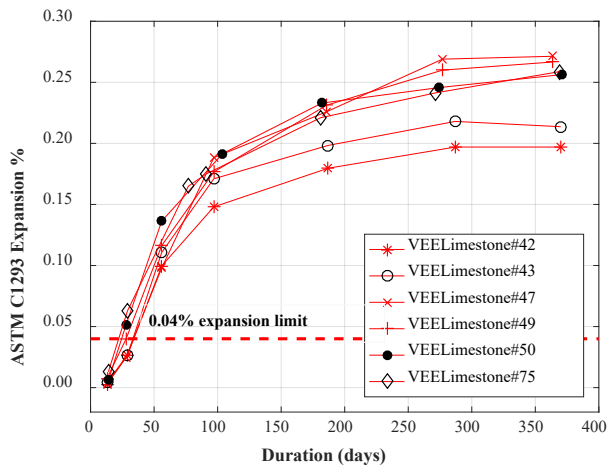
Katayama (1997 and 2016) classified rocks expansion potential into four categories based on the type of reactive minerals, rock types, and the time to reach the 0.04% expansion limit on ASTM C1293: early-expansive (<50 days), moderately- expansive (50-60 days), late-expansive (90-180 days), and extremely late-expansive (>180 days). The time to reach the 0.04% expansion limit on ASTM C1293 is considered in this study to provide information about the rate (fast/slow) of concrete expansion. The proposed classification includes four categories: Very early-expansive (VEE), Early-expansive (EE), Moderately-expansive (ME), and Late-expansive (LE) as shown in Table 4-4. The classification proposed by Katayama (1997 and 2016) is included for comparison purpose.

Table 4-4 Proposed Classification of Concrete Expansion Rate

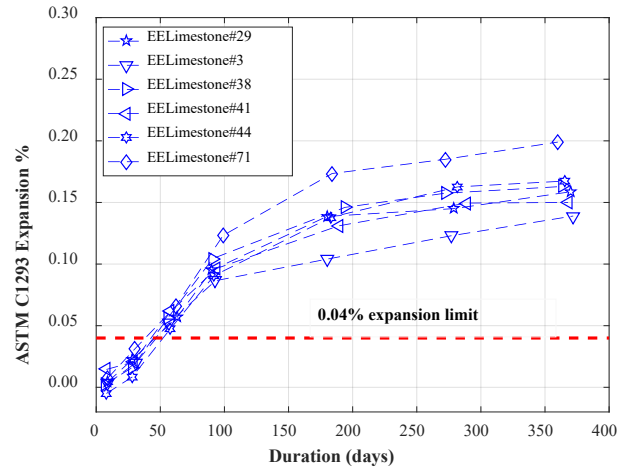
Expansion rate	Description	Time to reach expansion of 0.04% on ASTM C1293%	Katayama (1997 and 2016)
VEE	Very early- expansive	< 40 days	Early-expansive
EE	Early- expansive	40 – 50 days	
ME	Moderately-expansive	50 – 90 days	Moderately-expansive
LE	Late-expansive	>90 days	Late-expansive

The reactivity of 26 limestone aggregates was determined according to the results from the ASTM C1260 mortar bars test and the ASTM C1293 concrete prisms test as shown in Appendix B, Table B-1. The time to reach 0.04% expansion for the four categories was: 19 - 34 days for VEE; 41 - 50 days for EE; 63 - 89 days for ME; and 97 - 135 days for LE limestone aggregates, as shown in Table 4-4. Figure 4.6 shows the evolution of ASR expansion for the four categories of reactive limestone aggregates on the ASTM C1293 test, each curve represents the average of three samples. The results demonstrate that the VEE aggregates exhibited the highest expansion (between 0.20 - 0.27%) at one year. The EE and ME aggregates produced an expansion between 0.11 - 0.20% while the LE exhibited the lowest expansion (between 0.07 - 0.12%) at one year.

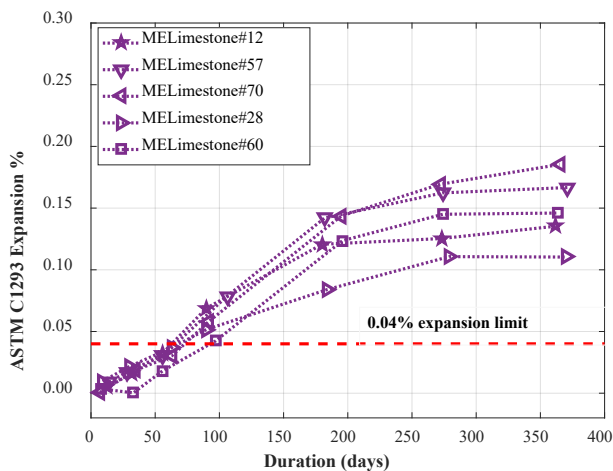
The well-known reactive argillaceous dolomitic limestone aggregate from Pittsburg quarry-Ontario, Canada (Kingston aggregate; known for ACR) (Swenson et al. 1964, Gillott et al. 1963, Hadley et al. 1961, Guangren et al. 2002) and the highly reactive siliceous limestone from the Spratt quarry in Ottawa, Canada (Spratt limestone) (Fournier et al. 2009 and Sim et al. 2003) showed very similar expansion behavior on ASTM C1293 to that of VEE and EE aggregates in this study (i.e. < 50 days to reach the 0.04% limit). Concrete structures built with Kingston and Spratt limestones showed characteristic pattern-cracking due to AAR within 3 years (Rogers 1986) and 10 years (Fournier et al. 2004) exposure, respectively.



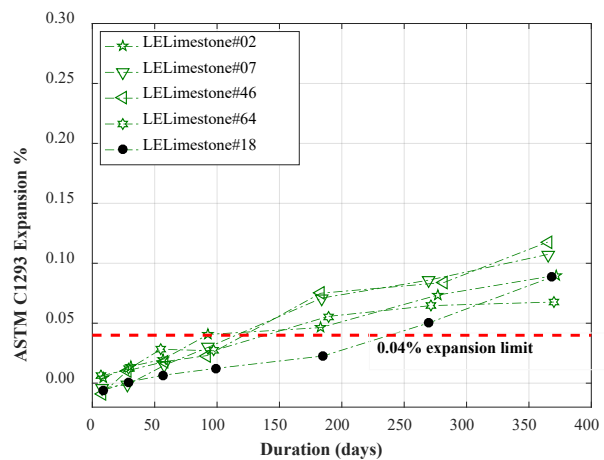
(a) Very early expansive



(b) Early expansive



(c) Moderately expansive



(d) Late expansive

Figure 4.6 The Evolution of ASR Expansion of Limestone Aggregates on ASTM C1293

4.3.2 Petrographic Examination of Aggregate and Concrete

Petrographic examinations including optical microscopy and SEM-EDS examinations of aggregates and concretes from the expansion test (ASTM C1293) were conducted on selected samples that represent different expansion potential. Observations and findings from optical microscopy are summarized in Appendix B, Table B-4. The SEM-EDS examination indicated the presence of finely dispersed silica (i.e., cryptocrystalline quartz) within carbonate matrix. The petrographic examination provided qualitative information about the rock types of aggregate, estimated major and minor constituent minerals in aggregates, identified reactive silica and minerals in aggregates, and documented evidence of alkali aggregate reaction in concrete.

The reactive siliceous components within non-reactive samples were insignificant. No visible reactive siliceous components could be identified in Limestone#13 and Limestone#55, and only trace of microcrystalline quartz or chert was noticed in limestone#56. The late expansive limestone aggregates (Limestone#2, Limestone#7, and Limestone#64) are mainly limestone

(Limestone#64) or dolomite/dolomitic limestones (Limestone#2 and Limestone#7) with minor amount of microcrystalline quartz/chert and probably clay and trace amount of sulfides/oxides. The early and moderately expansive aggregates (Limestone#3, Limestone#38, Limestone#41, Limestone#71, and Limestone#60) are mainly dolomite with small amounts of chert, dolomitic chert, and cherty dolomite (Limestone#3 and Limestone#38), or dolomitic limestone with minor amount of microcrystalline quartz (Limestone#41 and Limestone#71). The very-early expansive aggregates (Limestone#49, Limestone#50, and Limestone#75) are mainly cherty dolomite (Figure B- 1) or argillaceous dolomitic limestone (Limestone#49 and Limestone#75) (Figure B- 1 a & b) or argillaceous cherty limestone (Limestone#50) (Figure B- 1 a & b), with minor detrital quartz and possibly amorphous silica (opal) (Figure B- 1 c & d). The reactive components detected under light microscope are principally micro-crystalline quartz and chert.

Examinations of concrete samples from reactive aggregates revealed that most coarse aggregate particles are cracked or severely cracked (Figure 4.7), cracks frequently extended into paste, and ASR gel frequently filled/lined air voids and cracks. Although petrographic examinations of concrete samples showed evidence of minor dedolomitization or traditional ACR in some aggregates (Appendix B, Table B-4), the presence of significant amount of microcrystalline quartz/ chert and other reactive silica forms and the presence of ASR gel in cracks and voids confirm that the expansion of reactive limestone aggregates is mainly driven by alkali-silica reaction.

4.3.3 SEM Examinations

Several concrete thin sections were selected for SEM-EDS examinations including late expansive aggregates (Limestone#2 and Limestone#64) and very early expansive aggregates (Limestone#50 and Limestone#75). The results indicated the presence of fine dispersed silica in addition to chert (aggregation of silica). ASR gel has been detected within carbonate matrix in both the late expansive (Limestone#2) and very early expansive aggregate (limestone#75), as shown in Figure B- 1 and Figure B- 2. The ASR gel appeared to contain Mg, Na, K, Ca, and Si in addition to small amount of Al (small peak between Si and Mg). The Mg is probably related to the brucite from dedolomitization based on findings by Grattan-Bellew and Katayama (2017).

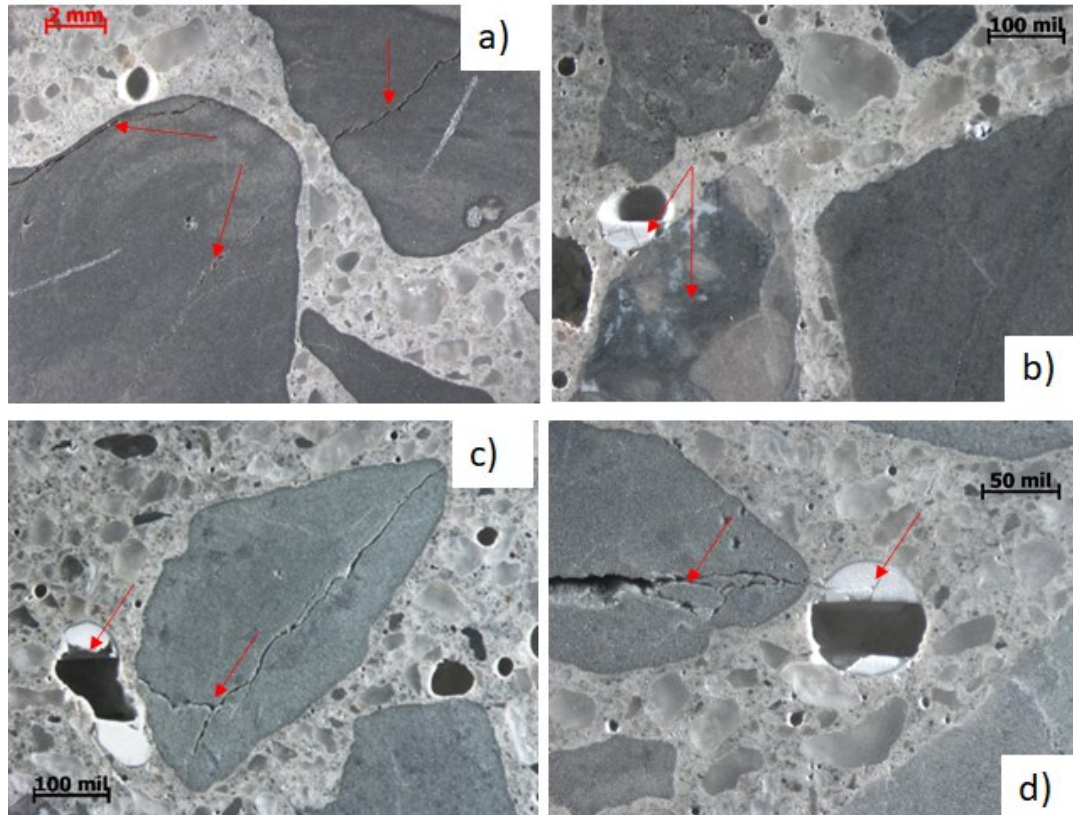


Figure 4.7 Micrographs of reactive concrete: (a) cracked coarse aggregates, (b) gel in voids and cherty limestone, (c and d) gel in voids and cracked argillaceous dolomitic limestone

4.3.4 Minerals Quantification using X-Ray Diffraction (XRD)

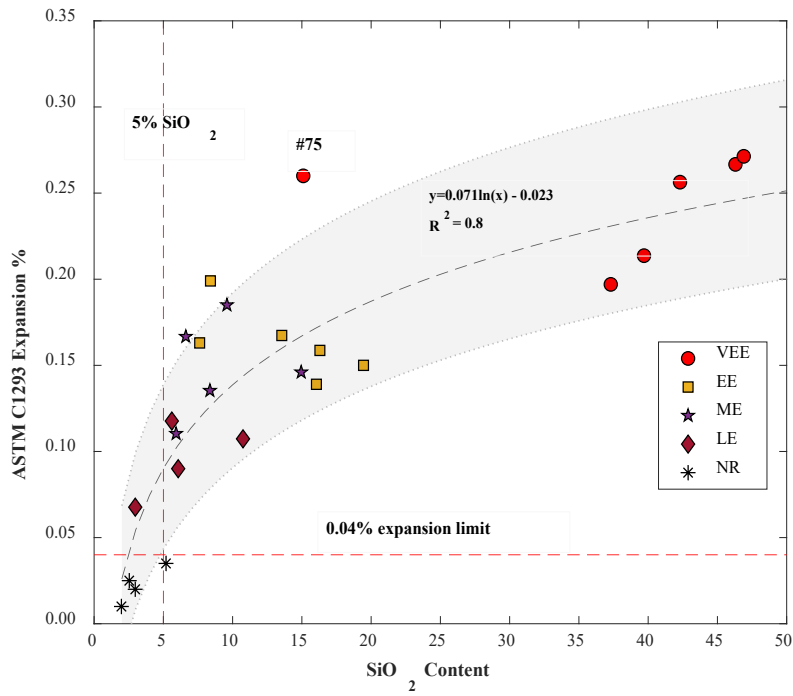
The XRD patterns are shown in Figure B- 6, Figure B- 7, and Figure B- 8 for non-reactive, moderately expansive, and very early-expansive aggregates, respectively. The mineralogical composition of each limestone aggregate was quantified using the Rietveld refinement analysis of X-ray powder diffraction patterns. Quality measures such as Rwp (weighted profile R-value) and GOF (goodness of fit) are calculated by the software to give indication about the quality of the data (Rwp) and how good the calculated pattern is fitted to the observed pattern (GOF). The mineralogical composition and quality measures of all aggregates are estimated from XRD analysis and are summarized in Appendix B, Table B-6.

The non-reactive aggregates contained relatively small amount of quartz (1.4 -2.8%) and no mica/clay minerals were detected. The late expansive and moderately expansive aggregates showed higher amount of quartz (1.7- 14.5%) and clay/mica minerals (0.7 – 5.0%) than that of non-reactive aggregates. The early expansive aggregates contained 5.5 – 20.9% quartz and up to 6.8% clay/mica content. The very early expansive aggregates showed the highest amount of both quartz (11.2 – 45%) and clay/mica minerals (5.2 -14.2%). This is clearly observed in the low two theta region of the XRD patterns (below 10° 2Theta) of the very early reactive aggregates (Table B- 6) which indicates strong peaks of clay/mica minerals.

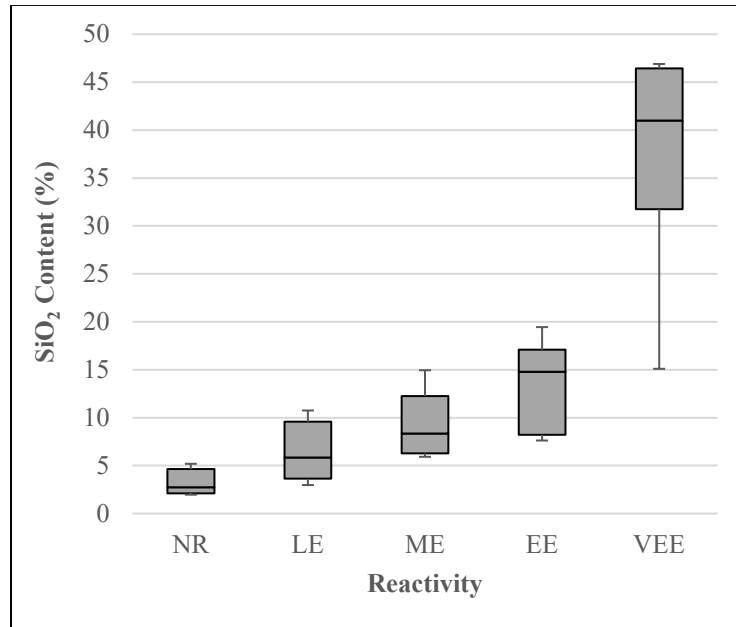
4.3.5 Chemical Composition and ASR Expansion of Limestones

The chemical composition of limestone aggregates is included in Appendix B, Table B- 5. The total silica content (SiO_2) from chemical composition showed a strong correlation with the expansion results from the concrete prisms test as shown in Figure 4.8a. The expansion at one year on ASTM C1293 increases as the silica content of aggregates increases. The Limestone#75 is excluded as an outlier. This aggregate showed very high expansion with only 15% silica content and it could be attributed to the presence of high content of very fine form of silica such as cryptocrystalline quartz. The expansion rate (the time to reach 0.04% limit on ASTM C1293) also showed strong relation to silica content as shown in the box charts in Figure 4.8b, each box chart represents the data from 5 aggregates. The box charts show that the non-reactive limestone aggregates contain no more than 5 % silica, the late expansive aggregates contain no more than 10% silica, the moderately and early expansive aggregates contain between 6 – 19% silica, and the very early expansive aggregates contain between 15 – 47% silica. Of course, the crystal size of reactive silica, for example cryptocrystalline vs. microcrystalline quartz, would play a major role on reactivity. However, studies of greater details on the effect of crystal size and reactive silica grain size were not conducted.

The alumina content seems to give an indication of limestones reactivity. In fact, the most reactive aggregates (VEE) showed the highest alumina content (2.64 – 3.90%) in comparison to non-reactive aggregates (< 1%). The high alumina content can be attributed to the presence of argillaceous matrix (a mix of clay minerals and fine quartz) as observed in petrographic examination. Dolomitic limestones with similar argillaceous matrix are known to be very reactive (Katayama 2010, Rogers 1986). In fact, the most common highly reactive carbonate rocks are mainly composed of fine grain quartz with an argillaceous matrix (Fernandes et al. 2016). This indicates that the chemical composition of limestone aggregates, namely the silica and alumina content can provide essential information about AAR reactivity. The chemical composition of carbonate aggregates has been used to screen potentially ACR aggregates, a plot of (CaO: MgO) ratio versus Al_2O_3 content (Rogers 1986 and ASTM 1778). Nevertheless, limited effort has been made to relate silica oxide or alumina oxide to reactivity involving limestones before this study, which seems to be very significant for the limestone aggregates investigated.



(a) Correlation between silica and expansion



(b) Correlation between silica and expansion rate (reactivity)

Figure 4.8 Correlation between silica content in limestone aggregate and expansion in ASTM C1293: (a) correlation between silica and expansion. (b) Correlation between silica and expansion rate (reactivity): VEE: Very early- expansive; EE: Early- expansive; ME: Moderately-expansive; LE: Late-expansive

4.3.6 Summary on Limestone Aggregates Reactivity

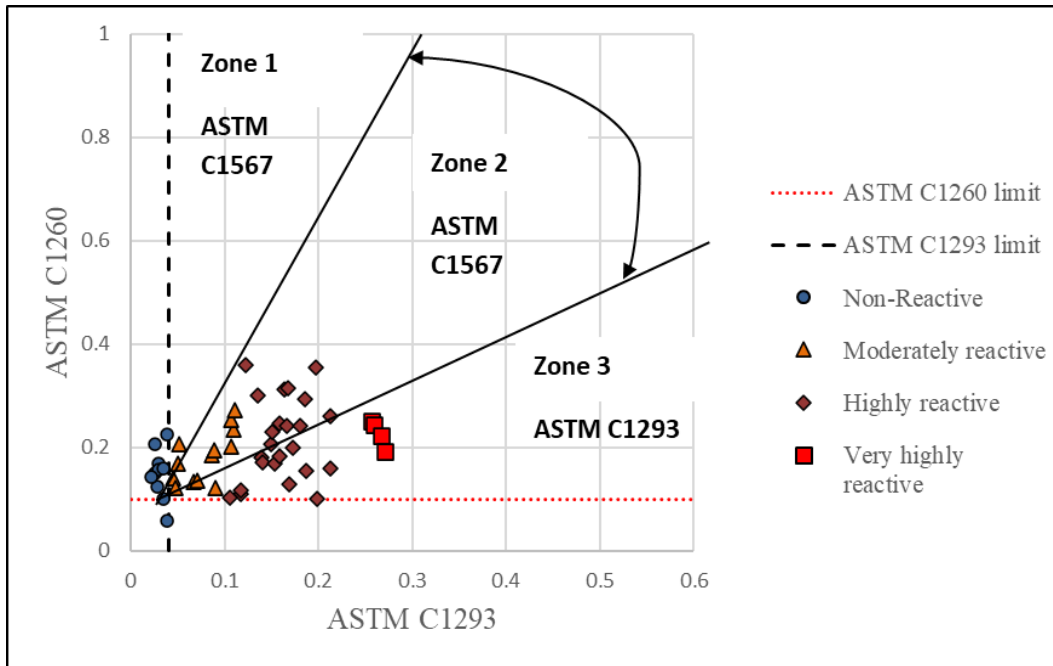
The results from this study show a strong correlation between the chemical compositions of limestones with the expansion in the concrete prisms test (ASTM C1293). Most of the silica identified within the limestones are reactive types including microcrystalline quartz and chert, amorphous silica such as opal, finely dispersed silica within argillaceous and carbonate matrices such as cryptocrystalline quartz. The presence of significant amount of microcrystalline quartz/chert and other reactive silica forms and the presence of ASR gel in cracks and voids confirm that the expansion of reactive limestone aggregates is mainly driven by alkali-silica reaction. In addition, the fly ash class F was proven effective in mitigating the reactivity of the studied limestones as discussed in the following section.

4.4 Phase II: Mitigation of ASR in Tennessee using Fly Ash and Slag

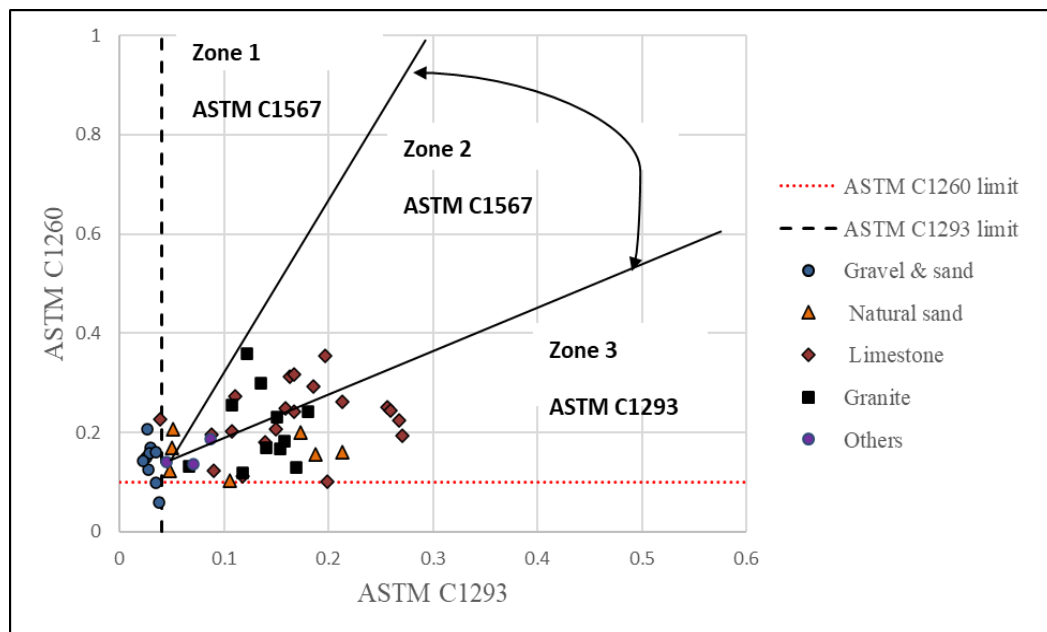
This phase also aimed at specifying mitigation alternatives to allow the use of ASR reactive aggregates in future concrete structures. Performance-based testing was conducted using different combinations of supplementary cementing materials (e.g fly ash class F and granulated blast-furnace slag-GGBFS) with reactive aggregates.

The criteria for evaluating ASR mitigations on either ASTM C1567 – 14 days or ASTM C1293-two years is based on the performance of aggregate under the expansion tests. According to the ASTM C1778, test method C1567 can be used to determine the performance of a specific SCM-aggregate combination to avoid the long duration of ASTM C1293. Before using ASTM C1567, however, it is recommended that the results of test methods ASTM C1260 and ASTM C1293 for the aggregate being used be plotted as shown in Figure 4.9 (b). Provided data do not fall within Zone 3, test method C1567 can then be used to determine the efficacy of SCMs.

A total of 30 reactive aggregates have been selected to investigate several ASR mitigation options as summarized in Section 1.4 (Table 1-1 and Table 1-2 Testing Protocol for ASR Mitigation on ASTM C1293 – Two years). The aggregate samples were selected to represent wide range of reactivity and different aggregate types. Mitigation tests based on ASTM C1293 was conducted on 10 aggregates including four very highly reactive and six highly reactive aggregates, as shown in Table 4-5. The four very highly reactive aggregates were tested under four mitigation options: 20%, 25%, 35% cement replacement with fly ash class F, and 30% GGBS plus 20% fly ash class F replacement. The six highly reactive aggregates were tested under 20%, and 25% cement replacement with fly ash class F. In addition, tests based on ASTM C1567 was conducted on a total of 20 aggregates which included 10 highly reactive aggregates and 10 moderately reactive aggregates as shown in Table 4-6. The reactivity of these aggregates was evaluated under 15%, 20%, and 25%-30% fly ash class F replacement.



(a) Performance based on aggregate reactivity



(b) Performance based on aggregate type

Figure 4.9 Performance of Aggregates on ASTM C1260 and ASTM C1293: Data are presented based on (a) aggregate reactivity and (b) aggregate type

Table 4-5 Aggregates List for ASR Mitigation on ASTM C1293

Sample ID	Aggregate Type	ASTM C1778	Mitigation options			
		Classification				
Limestone#50	Limestone	Very highly reactive	20 % Fly ash class F	25 % Fly ash class F	35% Fly ash class F	30% GGBFS & 20 % Fly ash class F
Limestone#75	Limestone					
Limestone#49	Limestone					
Limestone#47	Limestone					
Limestone#71	Limestone	Highly reactive	20 % Fly ash class F	25 % Fly ash class F		
Limestone#46	Limestone					
Natural sand#45	Natural sand					
Gravel/sand#76	Natural sand					
Granite#37	Granite					
Granite#11	Granite					

Table 4-6 Aggregates List for ASR Mitigation on ASTM C1567

Sample ID	Aggregate Type	ASTM C1778	Mitigation options	
		Classification		
Limestone#42	Limestone	Highly reactive	20 % Fly ash class F	25 % - 30% Fly ash class F
Limestone#43	Limestone			
Limestone#38	Limestone			
Limestone#29	Limestone			
Limestone#70	Limestone			
Limestone#57	Limestone			
Granite#39	Granite			
Granite#12	Granite			
Granite#34	Granite			
Granite#30	Granite			
Limestone#28	Limestone	Moderately reactive	15 % Fly ash class F	25 % - 30% Fly ash class F
Limestone#7	Limestone			
Limestone#18	Limestone			
Granite#5	Granite			
Granite#14	Granite			
Sandstone#20	Sandstone			
Quartz#9	Quartz			
Limestone#40	Limestone			
Natural sand#6	Natural sand			
Natural sand#25	Natural sand			

4.4.1 ASR Mitigation based on ASTM C1567

The mortar bars test (ASTM C1567 – 14 days) was used to determine an optimum dosage of fly ash class F to reduce the expansion below 0.1% at 14 days. During this study, fly ash dosages between of 15 - 30% by mass of cement were investigated for 20 aggregate samples as shown in Table 4-6. The mitigation results are summarized in Figure 4.10, Figure 4.11, and Figure 4.12 for limestones, granite, and natural sand samples, respectively. It should be noted that some samples collected for the purpose of evaluating ASR mitigation alternatives during 2018 have shown different expansion potential compared to that of the original samples collected during 2016. This suggests that the reactivity of aggregate quarries might not be constant over time. Chemical analysis or quick ASR testing should be conducted on a regular basis to detect any change in the quarry reactivity overtime.

Fly ash class F is known to be effective in mitigating ASR if used at sufficient levels of cement replacement (Touma et al. 2000). For the prevention of ASR, the typical recommended replacement dosage for fly ash class F is between 15 and 40% of cement depending on aggregates reactivity (ASTM 1778). Higher rates are often necessary for highly reactive aggregates. In this study, 15% fly ash class F replacement was not effective to maintain the expansion below the acceptable limit of ASTM C1567 (< 0.1% expansion at 14 days) for most of aggregates.

For highly reactive limestone aggregates (Figure 4.10), 20% fly ash class F was not sufficient for mitigating the reactivity of aggregates and at least 25% replacement was required (Limestone#28). For the moderately reactive samples (Figure 4.10), 20 – 25% should be adequate to maintain the expansion below the acceptable limit of ASTM C1567. A 30% fly ash class F replacement was effective for all samples. It is recommended to use a dosage between 25-30% for all limestone aggregates from Tennessee.

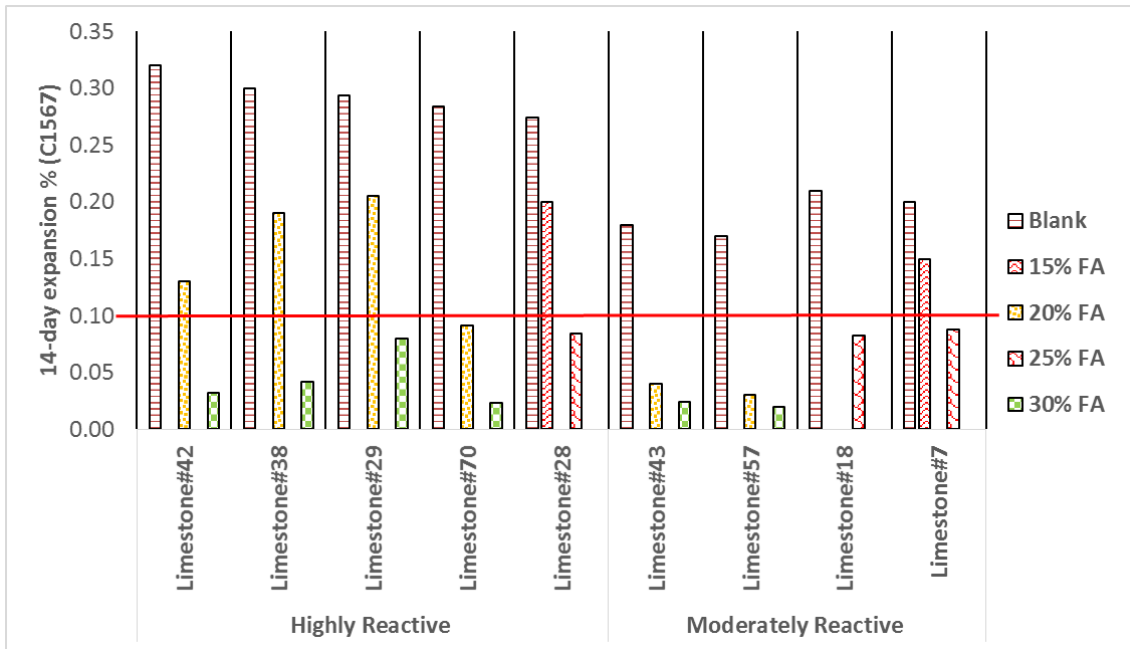


Figure 4.10 Mitigation results for limestone aggregates on ASTM C1567 (FA: Fly ash class F)

For granite aggregates, both 15% and 20% fly ash replacements were not sufficient for ASR mitigation (Figure 4.11). Highly reactive granite such as Granite#34 showed aggressive expansion even with up to 25% fly ash class F replacement. A dosage of 25% seems to be adequate for the moderately reactive samples, and it is recommended to use > 25% - 30% fly ash for all granite aggregates from Tennessee.

The majority of the natural sand samples showed moderate ASR reactivity (Table 4-2). Similar to the behavior of limestone and granite samples, the 15% fly ash replacement was not effective for mitigating the reactivity of natural sand samples. A dosage of 25% seems to be adequate for the moderately reactive samples (Figure 4.12).

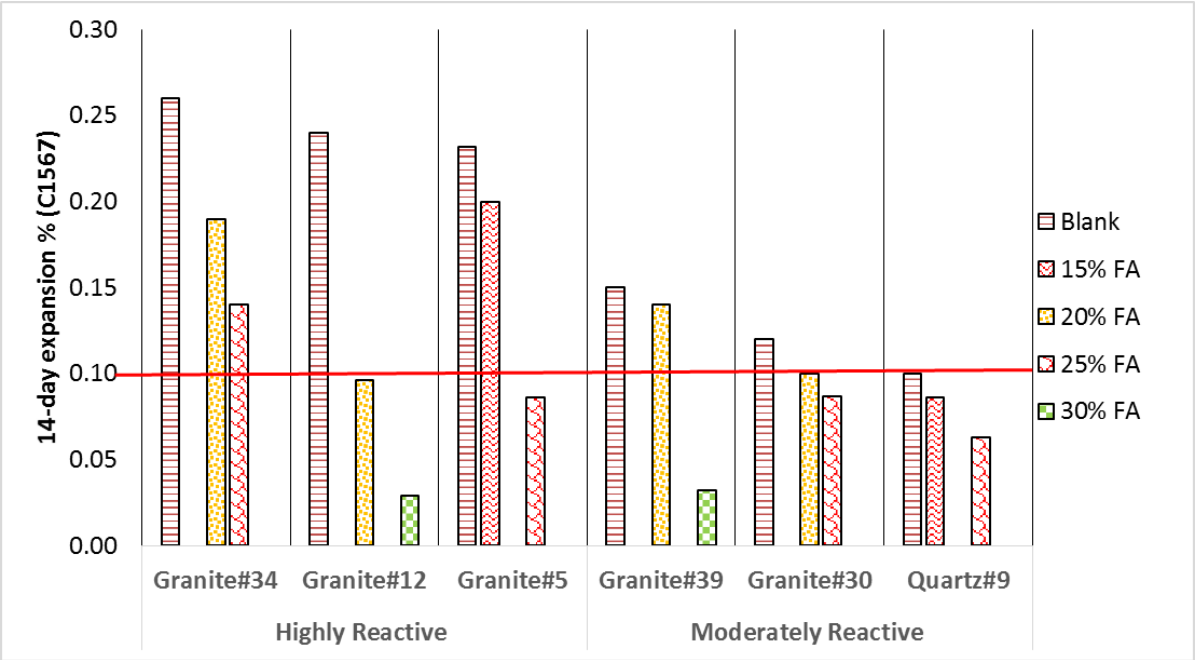


Figure 4.11 Mitigation results for granite aggregates on ASTM C1567 (FA: Fly ash class F)

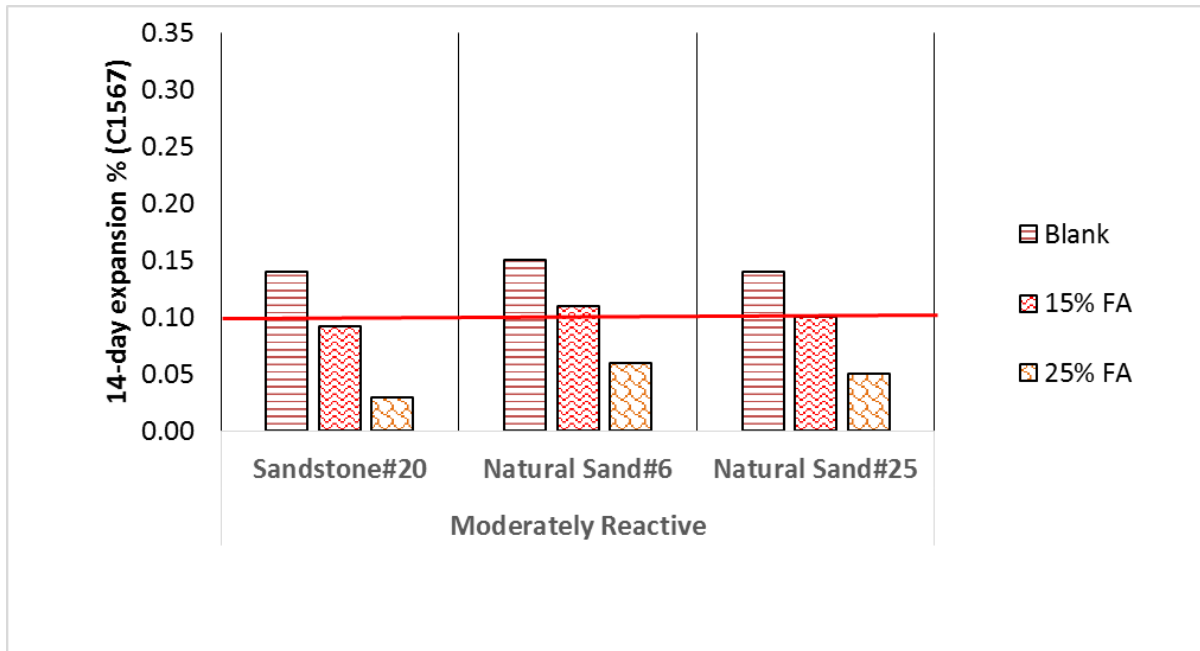


Figure 4.12 Mitigation results for natural sand on ASTM C1567 (FA: Fly ash class F)

4.4.2 ASR Mitigation based on ASTM C1293

The concrete prisms test (ASTM C1293 – 2 years) was used to determine an optimum dosage of fly ash class F and slag to reduce the expansion below 0.04% at two-years on ASTM 1293. The mitigation of 10 aggregate samples were evaluated using ASTM C1293 with a combination of fly ash class F dosages between 20-35% and a mix of slag and fly ash (30% GGBFS & 20% Fly ash class F), as shown in Table 1.2. The mitigation results are summarized in Figure 4.13, Figure 4.14, and Figure 4.15 for limestones, granite, and natural sand samples, respectively.

For highly reactive limestone aggregates (Figure 4.13), 20% fly ash class F was not sufficient for mitigating the reactivity of several limestone samples and at least 25% replacement was required to maintain the expansion below 0.04% at two years. This in agreement with the results obtained from the quick expansion test ASTM C1567. The 35% fly ash class F and 30% GGBFS / 20% fly ash class F were sufficient for all reactive limestones.

Similar observation can be drawn for granite (Figure 4.14) and natural sand samples (Figure 4.15) that the 20% fly ash class F was not sufficient for mitigating the reactivity of aggregates and at least 25% fly ash class F was required. These findings suggest that the mortar bars test (ASTM C1260 or ASTM C1567) seems to provide comparable results to that of the concrete prim test for the aggregates from Tennessee.

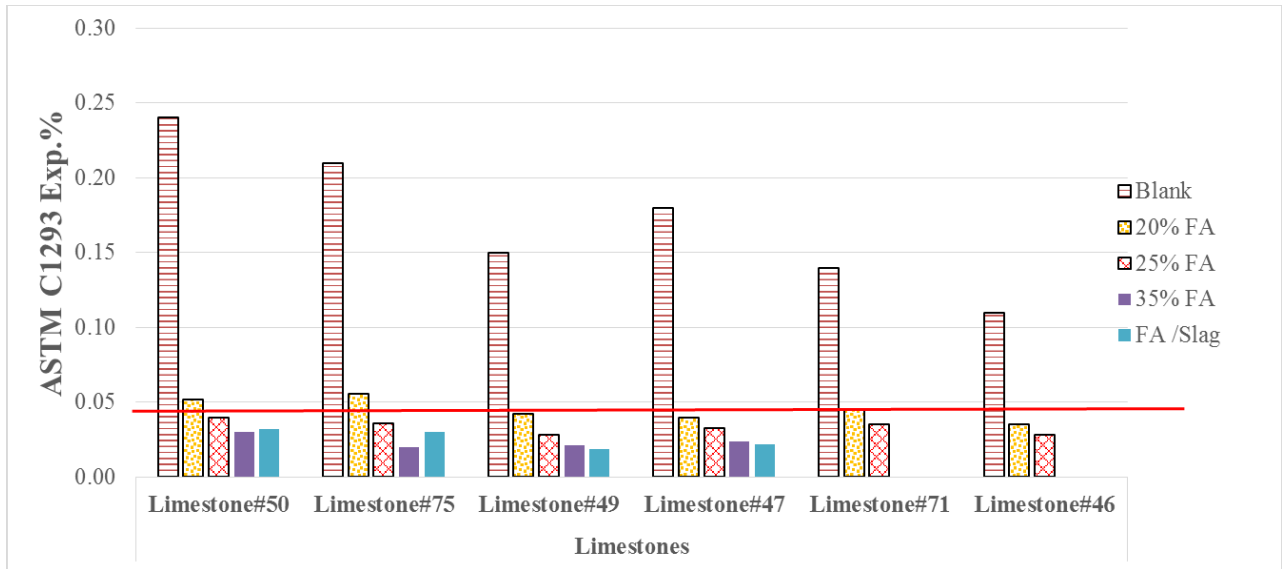


Figure 4.13 Mitigation results for limestone aggregates on ASTM C1293 (FA: Fly ash class F)

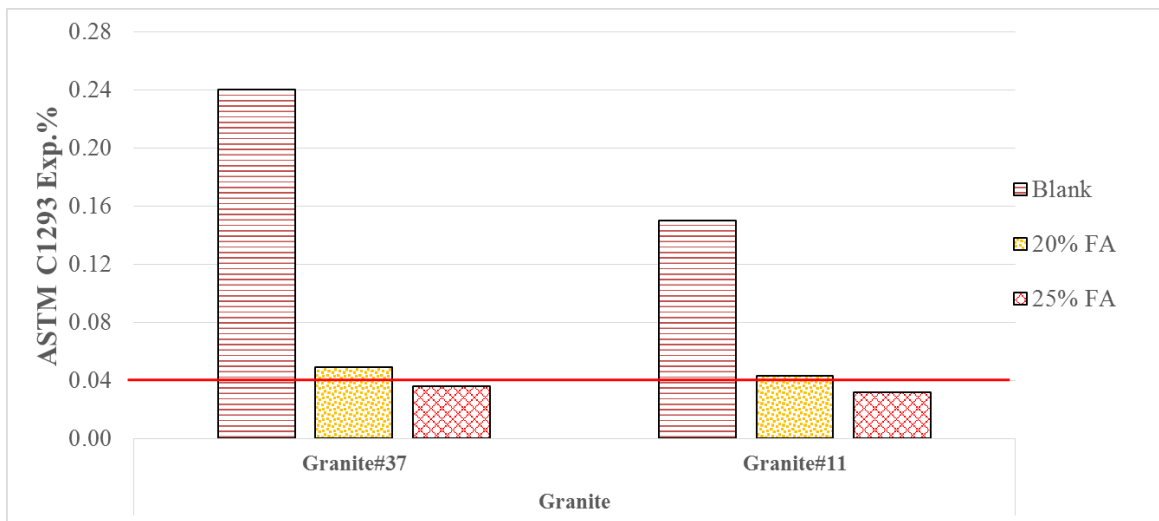


Figure 4.14 Mitigation results for granite aggregates on ASTM C1293 (FA: Fly ash class F)

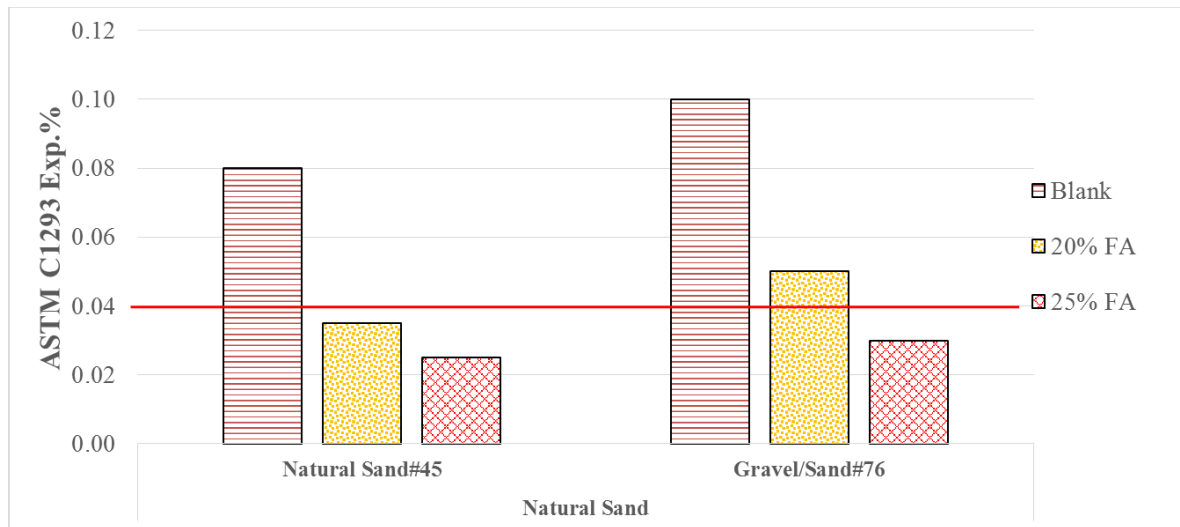


Figure 4.15 Mitigation results for natural sand on ASTM C1293 (FA: Fly ash class F)

4.4.3 Summary on ASR Mitigation in Tennessee

The mitigation alternatives were specified to allow the use of ASR reactive aggregates in future concrete structures. The performance-based testing provided recommendation for fly ash class F replacement rates to limit the deleterious ASR expansion from limestone, granite, and natural sand aggregates as shown below:

1. 15% fly ash class F is not sufficient for ASR mitigation for reactive aggregates from Tennessee.
2. For Limestone Aggregates:
 - 20% fly ash class F is not sufficient for mitigating the reactivity of highly reactive limestones. At least 25% fly ash class F is required.
 - At least 20% - 25% fly ash class F is required for moderately reactive limestones.
 - 25% - 30% fly ash class F is the recommended dosage.
3. For Granites Aggregates:
 - 20% fly ash class F is not sufficient for ASR mitigation for granites. At least 25% fly ash class F is required.
 - 25% - 30% fly ash class F is the recommended dosage.
4. For Natural Sand and Gravel:
 - 20% fly ash class F is not sufficient for ASR mitigation for reactive sands.
 - 25% fly ash class F is required for natural sands mitigation.
 - 25% fly ash class F is the recommended dosage.

4.5 Phase II: Field Performance of Highly Reactive Aggregates

Field performance of highly reactive aggregates in the state of Tennessee was investigated in this study. A high risk of Alkali-Aggregate Reaction (AAR) in Tennessee has been identified during Phase I. The need for identifying the extend of ASR risk in existing structures is necessary so that informed decision can be made toward maintaining the functionality and structural integrity of affected structures.

In collaboration with TDOT Materials and Tests Division, a regional survey was sent to each region within TN to identify the extend of ASR risk in existing structures built about 20 years ago or longer. The survey aimed at examining visual signs of ASR distress such as cracking, expansion and deformation, pop-outs, and the occurrence of surface deposits. The survey targeted the field performance of high potential reactive aggregates, namely the very highly reactive (VHR) and highly reactive (HR), within each region in the state of Tennessee. Cores were extracted from selected structures with ASR symptoms and examined microscopically to document the occurrence of ASR in existing structures. Detailed field study plan and examinations are included in Appendix C, and the main findings are summarized below.

Deleterious ASR occurrences have been confirmed in two structures: (1) a concrete pavement rehabilitated 11 years ago in Memphis, and (2) a 25-30 year old interchange structure in east Tennessee at Flag Pond, as reported in Appendix C.

Two cores from Flag Pond (cores A and B) and two cores from Memphis (cores C and D) were harvested from the structures. The cores were examined to determine whether ASR is the source of concrete deterioration. The cores from Flag Pond, TN contained highly reactive sand and showed significant cracking filled with ASR gel. The cores from the concrete pavement in Memphis, TN contained highly reactive limestone aggregate with high amount of chert and microcrystalline quartz, similar to the reactive particles observed in the very early expansive limestones (VHR) in this study. The examination confirmed the existence of ASR deterioration mechanism in the two structures.

In addition, ASR distress has been noted in at least six other structures built with concretes containing reactive limestones aggregates including two bridges and four culvert structures within TDOT Region 1 and Region 2 as summarized in Table 4-7. This indicates that there is a high risk of ASR not just in future concrete construction but also in many existing transportation structures within Tennessee which should be investigated to limit future deterioration.

Table 4-7 Results of TDOT Regional Survey on the Performance of Reactive Aggregates

TDOT region	Reactive Aggregates	Structures*	Possible ASR symptoms
1	Rogers Group - Caryville	1.Campbell County Bridge # 07-0A006-00.00 crossing Elk Creek	map cracking was noted throughout the wing walls and backwall
		2.Campbell County Double Barrel Culvert # 07-0A071-00.28 crossing Branch of Stinking Creek	map cracking was noted throughout the headwalls and wing walls.
		3.Campbell County Triple Barrel Culvert # 07-0A158-00.10 Ivydell Rd over Ollis Creek	map cracking was noted throughout the inlet headwall and wing walls.
2	Rogers Group - Dayton	1.Rhea County Triple Barrel Culvert # 72-SR060-05.32 over Broyles Branch	map cracking was noted throughout the right headwall and right-wing walls
		2.Rhea County Triple Barrel Culvert # 72-SR030-15.84 over Washington Creek	map cracking was noted throughout the right and left headwall and wing walls
		3.Rhea County Bridge # 72-SR030-17.26 over Tennessee River	map cracking was noted on the deck/wearing surface, parapet wall, pier cap, and wing walls.
3	Rogers Group - Gordonsville	1.Smith County Bridge # 80-SR053-05.94 over Mulherrin Creek	No apparent ASR symptoms
		2. Smith County Bridge # 80-SR025-12.78 over the Cumberland River	No apparent ASR symptoms
	Pine Bluff Sand	Davidson County Concrete Pavement SR045 LM 7.20 to LM 7.256	Map cracking was identified in this concrete pavement
4	Vulcan - Holladay	Benton County Bridge # 03-SR001-04.33 over CSX R.R.	No apparent ASR symptoms
	Vulcan - Rossville	Fayette County Bridge # 24-SR057-04.16 over Norfolk Southern R.R.	No apparent ASR symptoms
	Ruleman Sand - Brighton	Haywood County Bridge # 38-SR076-10.08 over I-40 (Exit 56)	No apparent ASR symptoms

*The bridge numbers listed are named by the following convention: County Number - State Route/County Road - Log Mile.

Chapter 5 Conclusion

5.1 Summary

This study was funded by the Tennessee Department of Transportation (TDOT) and carried out by the University of Tennessee Knoxville to assess and mitigate the risk of Alkali Silica Reaction (ASR) in Tennessee. The primary aims of this study were to build a statewide aggregate ASR risk database with detail field and laboratory performance to provide a solid foundation for guaranteeing a good long-term performance and a high-level safety of statewide transportation concrete structures. In addition, the study aimed to investigate and propose effective mitigation methods based on the published literature and performance testing to permit an economic use of reactive aggregates that normally would be excluded.

To achieve the objectives of this project, the scope of work was implemented in two phases (Phase I and Phase II). During Phase I ASR reactivity of surface aggregates from 76 different local sources in Tennessee was evaluated using common expansion tests including ASTM C1260 (mortar bars test) and ASTM C1293 (concrete prisms test). Mitigation alternatives to minimize the ASR risk of reactive aggregates were proposed in the second phase (Phase II). The field performance of some highly reactive aggregates was also investigated during Phase II to address the extent of ASR in existing structures.

The main findings from this project indicated a potential ASR risk for concrete structures and pavement lifecycle in Tennessee unless proper mitigation techniques are applied to mitigate the reactivity of aggregates. A database of reactive aggregates and the optimum dosage of fly ash class F to mitigate the reactivity of aggregates were provided. Aggregate reactivity database should be supported with continuous testing and sampling as reactivity of aggregate quarries might not be constant over time. Chemical analysis or quick ASR testing should be conducted on a regular basis to detect any change in the quarry reactivity overtime. Recommendation to update the TDOT specification were provided to minimize the risk of ASR in future concretes. The project also addressed the potential risk of Alkali Carbonate Reaction (ACR) for limestone aggregates. The reactivity of limestones from Tennessee is mainly driven by alkali-silica reaction and can be mitigated using appropriate dosage of fly ash class F. The contribution of ACR to the reactivity of the tested limestones from Tennessee was found to be minimum.

The methodology for conducting the two-phase project and the lists of aggregate samples collected from the four regions of the state of Tennessee are provided in Chapter 3. The observations, conclusions, and the recommendations from each phase are included in Chapter 4 and summarized below.

5.2 Phase I Findings and Conclusions

Aggregate samples from 76 sources were collected from TDOT's Region 1, Region 2, Region 3, and Region 4 which mainly included limestones, sand and gravels, granites, and slag aggregates. The aggregate reactivity was determined using both the accelerated mortar bars expansion test (ASTM C1260) and the concrete prisms expansion test (ASTM C1293- one year). The reactivity of all aggregates was first evaluated using the mortar bars test (ASTM C1260). The aggregates were considered as non-reactive if the 14 days expansion is less than 0.10% and as reactive if it was

greater than 0.1%. As this test is reported to be very severe for some aggregate formations, the aggregates failed ASTM C1260 were evaluated again using the ASTM C1293. The degree of aggregate reactivity was classified per ASTM C1778 guide (Table 3.1) into four main categories: R0 (Non-Reactive), R1 (Moderately Reactive), R2 (Highly Reactive), and R3 (Very Highly Reactive). The results of this phase support the following conclusions:

1. For the tested aggregate samples, at least 65% are classified as AAR reactive with different degree of reactivity (i.e., moderate to very highly reactive). Out of 83 aggregate samples, 29 samples (35%) are non-reactive (R0), 24 samples (29%) are moderately reactive (R1), 26 samples (31 %) are highly reactive (R2), and 4 samples (5%) are very highly reactive (R3), see Figure 4.3.
2. Aggregate samples listed in Table 4.1 are considered non-reactive and accepted for use in concrete with no further consideration of mitigation provided that the other physical properties of the aggregate render it suitable for use.
3. To prevent damaging ASR in new concrete construction, the reactive aggregates listed in Tables 4.2 and 4.3 should not be used in concrete without a proper ASR mitigation as summarized in Section 5.3 below.
4. Slag#59 and Slag#22 (Table 4.2) showed aggressive reactivity in the ASTM C1260 test and ASTM C1293. The nature of reaction and the damage observed in the mortar bars and concrete prisms made with the slag samples were not a typical AAR symptom and likely to be from a different reaction mechanism. These slag samples should be avoided in concrete until further investigation.

5.3 Phase II Findings and Conclusions

Tests were conducted during this phase to address three main objectives: (1) identify reactive carbonate aggregates (e.g., limestones) with alkali-aggregate reactive (AAR) potential to confirm the cause of the measured expansion in ASTM C1293, whether it's ASR or ACR or a combination of both; (2) performance-based testing was conducted using different combinations of supplementary cementing materials (e.g fly ash class F and granulated blast-furnace slag-GGBFS) with reactive aggregates to specify mitigation alternatives for reactive aggregates ; and (3) investigate the field performance of highly reactive aggregates to address the extent of ASR in existing structures. The results of this phase support the following conclusions:

1. The results from this study showed a strong correlation between the chemical compositions of limestones, namely SiO₂ content, and the expansion in the concrete prisms test (ASTM C1293). Most of the silica identified within the limestones were reactive types including microcrystalline quartz and chert, amorphous silica such as opal, finely dispersed silica within argillaceous and carbonate matrices such as cryptocrystalline quartz. The presence of significant amount of microcrystalline quartz/ chert and other reactive silica forms and the presence of ASR gel in cracks and voids confirm that the expansion of reactive limestone aggregates is mainly driven by alkali-silica reaction. In addition, the fly ash class F was proven effective in mitigating the reactivity of the studied limestones as discussed in the following section.
2. The performance-based testing provided recommendation for fly ash class F replacement rates to limit the deleterious ASR expansion from limestone, granite, and natural sand aggregates as shown below:

- 15% fly ash class F is not sufficient for ASR mitigation for all reactive aggregates from Tennessee.
- 20 % fly ash class F is not sufficient for ASR mitigation for granites, natural sand, and highly reactive limestone aggregates.
- The minimum recommended dosage of fly ash class F to mitigate ASR for several aggregate types is provided in Table 5-1. These limits should be added to TDOT Specification to minimize the risk of ASR in future concretes.

Table 5-1 Minimum Levels of Fly Ash Class F for ASR Mitigation (% by mass)

Aggregate Type	Aggregate-Reactivity Class Per ASTM C1778			
	Non-Reactive (R0)	Moderately/ Slowly reactive (R1)	Highly Reactive (R2)	Very Highly Reactive (R3)
Limestone /dolomite	Accepted for use in concrete with no mitigation	≥ 20 – 25 %	≥ 25%	≥ 25 – 30 %
Granite/quartz bearing rocks		≥ 25%	>25 – 30%	N/A*
Natural Sand /gravel		≥ 25%	≥ 25%	N/A*

* No aggregate was tested with this category.

3. The minimum proposed levels of fly ash class F (Table 5-1) are based on aggregate performance in the expansion tests under laboratory conditions. Although the cement content and concrete alkali loading (total alkalis in kg/m³) in these evaluation methods are higher than what would be found in most concrete elements in the field, evidence of deleterious ASR have been report in outdoor exposure blocks made with SCM dosages comparable to Table 5-1 (Stacey et al. 2016). Hence, the limits proposed above should not be considered conservative. Nevertheless, concrete with low total alkali content (i.e., < 3.0 lb/yd³ Na₂Oeq) and limited exposure to moisture might not show ASR distress even if made with highly reactive aggregates.
4. The reactivity of aggregate quarries might not be constant over time. Chemical analysis or quick ASR testing (e.g., ASTM C1260) should be conducted on a regular basis to detect any change in the quarry reactivity overtime. The chemical composition of carbonate aggregates such as limestones/dolomite seems to provide good indication about aggregate reactivity. Detailed study has been published as part of this project and can be accessed at the link below. Findings from this study can provide a quick means for assessment of limestone reactivity.
<https://www.sciencedirect.com/science/article/abs/pii/S0950061820319218>
5. The results from this study showed a good agreement between the ASTM C1260 and ASTM C1293 in classifying aggregates as reactive. However, there is inconsistency in classifying the level of reactivity between the two tests. Nevertheless, and due to the high risk of ASR in Tennessee, it is recommended to add a requirement in TDOT specification to perform quick ASR assessment testing (e.g., ASTM C1260, or chemical analysis for

limestones) for any aggregates to be used in new concretes. Of course, further research is necessary to develop and/or validate an ideal and accurate test method for assessing actual job concrete mixtures, in a relatively short period of time.

6. ASR distress has been noted in at least eight transportation structures built with concretes containing reactive limestone aggregates including two bridges, four culvert structures, and two pavements within Tennessee. This indicates a high risk of ASR not just in future concrete constructions but also in many existing transportation structures within Tennessee. Further research is needed to address and limit ASR progress in existing transportation structures.

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Appendix A
Properties of Cement and Fly Ash

Appendix B
Properties of Limestone Aggregates

Appendix C
Field Performance of Reactive Aggregates

Appendix A: Properties of Cement and Fly Ash

A.1 Properties of Fly Ash Class F



Client: Mr. Tom Hendrix
 The SEFA Group
 P.O. Box 6
 Moncks Corner, SC 29461

Date: October 8, 2018
 TEC Services I.D.: TEC 06-0509
 Lab No.: 18-863-KFP

REPORT OF FLY ASH TESTS				
Sample I.D. No.: KFP073018		Date Sampled: July 30, 2018		
Manufacturer: Kingston Station		Date Received: August 7, 2018		
Chemical Analysis	Results (wt%)	Specification (Class F)		
		ASTM C618-17a	AASHTO M295-11	
Silicon Dioxide (SiO ₂)	45.6	---	---	
Aluminum Oxide (Al ₂ O ₃)	20.2	---	---	
Iron Oxide (Fe ₂ O ₃)	14.01	---	---	
Sum of Silicon Dioxide, Iron Oxide & Aluminum Oxide (SiO ₂ +Al ₂ O ₃ +Fe ₂ O ₃)	79.8	70 % min.	70 % min.	
Calcium Oxide (CaO)	10.0	---	---	
Magnesium Oxide (MgO)	2.1	---	---	
Sodium Oxide (Na ₂ O)	0.96	---	---	
Potassium Oxide (K ₂ O)	1.57	---	---	
"Sodium Oxide Equivalent (Na ₂ O+0.658K ₂ O)"	1.99	---	---	
Sulfur Trioxide (SO ₃)	1.59	5 % max.	5 % max.	
Loss on Ignition	1.4	6 % max.	5 % max.	
Moisture Content	0.1	3 % max.	3 % max.	
Available Alkalies				
Sodium Oxide (Na ₂ O) as Available Alkalies	0.35	---	---	
Potassium Oxide (K ₂ O) as Available Alkalies	0.65	---	---	
Available Alkalies as "Sodium Oxide Equivalent (Na ₂ O+0.658K ₂ O)"	0.78	---	1.5 % max.*	
Physical Analysis				
Fineness (Amount Retained on #325 Sieve)	11.8%	34 % max.	34 % max.	
Strength Activity Index (Using Lehigh Leeds Alabama Portland Cement)				
At 7 Days:				
Control Average, psi: 4980	Test Average, psi: 4580	92%	75 % min. [†] (of control)	75 % min. [†] (of control)
At 28 Days:				
Control Average, psi: 5840	Test Average, psi: 6000	103%	75 % min. [†] (of control)	75 % min. [†] (of control)
Water Requirements (Test H ₂ O/Control H ₂ O)				
Control, mls: 242	Test, mls: 229	95%	105% max. [†] (of control)	105% max. [†] (of control)
Autoclave Expansion:		-0.02%	± 0.8 % max.	± 0.8 % max.
Uniformity Requirements		Variation		
Specific Gravity: 2.50	Average: 2.52	-0.8%	5 % max. from average	5 % max. from average
% Retained #325 Sieve: 11.8	Average: 9.2	2.6%	5 % max. from average	5 % max. from average

[†] Meeting the 7 day or 28 day strength activity index will indicate specification compliance

* Optional

The results of our testing indicate that this sample complies with ASTM C618-17a and AASHTO M295-11 specifications for Class F pozzolans.

Respectfully Submitted,
 Testing, Engineering & Consulting Services, Inc.

Dean Roosa
 Project Manager

Shawn McCormick
 Laboratory Principal



Testing, Engineering & Consulting Services, Inc.
 235 Buford Drive | Lawrenceville, GA 30046
 770-995-8000 | 770-995-8550 (F) | www.tecservices.com



A.2 Properties of Low Alkali Cement (Cement1)



Buzzi Unicem USA

Chattanooga Plant
P.O. Box 4304
1201 Suck Creek Road
Chattanooga, TN 37405
Phone: (423) 886-0800
Fax: (423) 886-4851

Mill Test Report

Cement Type: T-1/II Low Alkali
Manufacture Date: February, 2016
Silo Number: _____
From: February 1, 2016
To: February 29, 2016

Chemical

SiO ₂ (%)	<u>19.8</u>
Al ₂ O ₃ (%)	<u>4.5</u>
Fe ₂ O ₃ (%)	<u>3.5</u>
CaO (%)	<u>63.1</u>
MgO (%)	<u>2.9</u>
SO ₃ (%)	<u>2.8</u>
Total Alkali (Na ₂ O + 0.658K ₂ O)	<u>0.54</u>
Ignition Loss	<u>1.4</u>
Insoluble Residue (%)	<u>0.25</u>
C ₃ S (%)	<u>63.2</u>
C ₂ S (%)	<u>9.1</u>
C ₃ A (%)	<u>6.1</u>
C ₄ AF (%)	<u>10.6</u>
C ₃ S + 4.75C ₃ A	<u>92.3</u>
CO ₂ (%)	<u>1.2</u>
Limestone (%)	<u>3.0</u>
CaCO ₃ in Limestone (%)	<u>90.9</u>

Physical

Time of Set (Vicat)		
Initial Set (min.)	<u>111</u>	
Final Set (min.)	<u>274</u>	
Compressive Strength	PSI	MPa
1 Day	<u>2237</u>	<u>15.4</u>
3 Day	<u>3611</u>	<u>24.9</u>
7 Day	<u>4528</u>	<u>31.2</u>
28 Day	<u>5743</u>	<u>39.6</u>
Cube Flow	<u>109</u>	
Fineness, Blaine (cm ² /g)	<u>3676</u>	
325 Mesh (%)	<u>95.0</u>	
Air Content (%)	<u>7.7</u>	
Normal Consistency (%)	<u>24.7</u>	
False Set (%)	<u>68</u>	
Autoclave Expansion (%)	<u>0.01</u>	

We certify that the above described cement, at the time of shipment, meets the chemical and physical requirements of ASTM C-150, AASHTO M-85, or ASTM C-91.

W. K. Dack

A.3 Properties of High Alkali Cement (Cement2)



Buzzi Unicem USA

Stockertown Plant
501 Hercules Drive

Stockertown, PA 18083
Phone:
Fax:

Mill Test Report

Cement Type: Type I Light
Manufacture Date: N/A
Silo Number: _____

From: November 1, 2018
To: November 30, 2018

Chemical		Physical		
SiO ₂ (%)	<u>19.8</u>	Time of Set (Vicat)		
Al ₂ O ₃ (%)	<u>4.2</u>	Initial Set (min.)	<u>104</u>	
Fe ₂ O ₃ (%)	<u>2.1</u>	Final Set (min.)	<u>209</u>	
CaO (%)	<u>61.6</u>	Compressive Strength	PSI	MPa
MgO (%)	<u>3.9</u>	1 Day	<u>2387</u>	<u>16.3</u>
SO ₃ (%)	<u>4.5</u>	3 Day	<u>4074</u>	<u>28.1</u>
Total Alkali (Na ₂ O + 0.658K ₂ O)	<u>0.81</u>	7 Day	<u>5122</u>	<u>35.3</u>
Ignition Loss	<u>2.0</u>	28 Day	<u>6090</u>	<u>42.0</u>
Insoluble Residue (%)	<u>0.65</u>	Cube Flow		
C ₃ S (%)	<u>54.6</u>	Fineness, Blaine (cm ² /g)	<u>3965</u>	
C ₂ S (%)	<u>14.9</u>	325 Mesh (%)	<u>92.1</u>	
C ₃ A (%)	<u>7.5</u>	Air Content (%)	<u>5.9</u>	
C ₄ AF (%)	<u>6.4</u>	Normal Consistency (%)	<u>26.7</u>	
C ₃ S + 4.75C ₃ A	<u>90.2</u>	False Set (%)	<u>76</u>	
CO ₂ (%)	<u>1.2</u>	Autoclave Expansion (%)	<u>0.12</u>	
Limestone (%)	<u>2.0</u>	ASTM C563 (%)	<u>4.50</u>	
CaCO ₃ in Limestone (%)	<u>76.1</u>	ASTM C1038 (%)	<u>0.009</u>	

We certify that the above described cement, at the time of shipment, meets the chemical and physical requirements of ASTM C-150-17, AASHTO M-85, or ASTM C-91.

William H. Fink

William Fink, Manager of Quality Control

Date: 12/10/2018 8:13:51AM

Measurement

Type:	Routine
Archive:	cement
Application:	cement
Sample:	T-I M-25-16
Sum (%):	100.0000
Init weight:	1.3 g
Flux weight:	5.2 g
Final weight:	6.5 g
LOI:	2.38 %
Norm.factor:	0.9998

Compound	Value	Unit	Status
SiO2	19.02	%	
Al2O3	4.75	%	
TiO2	0.21	%	
P2O5	0.185	%	
Fe2O3	2.13	%	
CaO	60.96	%	
MgO	3.80	%	
SO3	4.64	%	
Mn2O3	0.095	%	
Na2O	0.326	%	
K2O	1.08	%	
Total Alkali	1.04	%	
Cl	0.002	%	
Aluminium Ratio	2.24	NONE	
Silica Ratio	2.76	NONE	
C3S	55.42	%	
C2S	12.69	%	
C3A	9.00	%	
C4AF	6.47	%	
L.O.I.	2.38	%	
M.SO3	3.46	NONE	
SrO	0.293	%	
ZnO	0.051	%	
F	0.071	%	
Cr2O3	0.012	%	
H2O	0.08	%	

Appendix B: Properties of Limestone Aggregates

Table B- 1 List of Limestone Aggregate Samples and Location

No	Sample	Location within Tennessee	Physical properties as provided by aggregate producer			
			Bulk specific gravity	Absorption %	Los Angeles abrasion	Weight loss due to sulfate attack %
1	Limestone #13	Region 1	2.74	0.3	20	1
2	Limestone #2	Region 1	2.78	0.5	21	1
3	Limestone #7	Region 1	2.72	0.3	20	0
4	Limestone #12	Region 1	2.78	0.7	-	-
5	Limestone #3	Region 1	2.72	0.6	23	2
6	Limestone #19	Region 2	2.63	0.9	24	5
7	Limestone #28	Region 2	2.68	0.6	25	4
8	Limestone #29	Region 2	2.74	0.7	23	4
9	Limestone #38	Region 2	-	-	-	-
10	Limestone/sandstone* #18	Region 2	2.71	0.5	26	1
11	Limestone #55	Region 3	2.40	3.3	18	3
12	Limestone #46	Region 3	2.69	0.3	24	5
13	Limestone #41	Region 3	2.64	0.9	28	3
14	Limestone #44	Region 3	2.75	0.5	23	5
15	Limestone #49	Region 3	2.55	2.1	19	13
16	Limestone #47	Region 3	2.61	1.4	27	8
17	Limestone #50	Region 3	2.63	0.9	24	1
18	Limestone #43	Region 3	2.38	2.2	24	6
19	Limestone #42	Region 3	2.64	0.7	25	1
20	Limestone #56	Region 4	2.60	1.5	24	9
21	Limestone #64	Region 4	2.57	1.9	25	15
22	Limestone #57	Region 4	2.62	1.2	20	7
23	Limestone #60	Region 4	2.61	1.0	18	3
24	Limestone #70	Region 4	-	-	-	-
25	Limestone #71	Region 4	-	-	-	-
26	Limestone #75	Region 4	-	-	-	-

* This aggregate is found to be a clay- and carbonate-cemented sandstone based on petrographic examination rather than limestone as originally identified in field

Table B- 2 Geological Data for Limestones Aggregate Sources

Region	Sample	Geological data for aggregate sources (Peters et al. 2010)		
		Name	Age	lithologies
Region 1	Limestone #13	Jonesboro Limestone; Mascot Dolomite; Kingsport Formation;	Cambrian – Ordovician Guzhangian – Floian (498.2 – 471.6 Ma)	Major: {limestone,dolostone}, Incidental: {sandstone}
	Limestone #2	Mascot Dolomite; Kingsport Formation	Ordovician -Stage 10 – Floian (485.4 – 471.2834 Ma)	Major: {dolostone,limestone}, Minor: {sandstone}. Fine-grained, well-bedded cherty dolomite
	Limestone #7	Jonesboro Limestone; Mascot Dolomite; Kingsport Formation;	Cambrian – Ordovician Guzhangian – Floian (498.2 – 471.6 Ma)	Major: {limestone,dolostone}, Incidental: {sandstone}. Numerous interbeds of dark-gray dolomite.
	Limestone #12	Copper Ridge Dolomite	Cambrian- Guzhangian – Tremadocian (497.85 - 478.9834 Ma)	Major: {dolostone}, Minor: {chert} Coarse, dark-gray, knotty dolomite, medium-grained, well- bedded dolomite; abundant chert
	Limestone #3	Newala Formation; Mascot Dolomite; Kingsport Formation; Longview Dolomite; Chepultepec Dolomite	Ordovician -Stage 10 – Dapingian (485.4 – 468.55 Ma)	Major: {dolostone,limestone}, Minor: {sandstone} Dolomite - Light-gray, fine-grained, well-bedded cherty dolomite; chert-matrix quartz sandstone at base
Region 2	Limestone #19	Monteagle Limestone	Mississippian -Visean (340.3125 – 332.05 Ma)	Major: {limestone}, Incidental: {chert} (sand, shale, carbonate Limestone, chert.
	Limestone #28	Bangor Limestone and Hartselle Formation	Mississippian – Visean – Serpukhovian (333.525 – 326.15 Ma)	Major: {limestone}, Incidental: {sandstone, shale}
	Limestone #29	Newala Formation, Mascot Dolomite, and Kingsport Formation	Ordovician – Termadocian – Dapingian (477.7 – 470 Ma)	Major: {dolostone,limestone}, Minor: {sandstone}, Dolomite - Light-gray, fine-grained, well-bedded cherty dolomite; chert-matrix quartz sandstone at base
	Limestone #38	Newala Formation; Mascot Dolomite; Kingsport Formation; Longview Dolomite; Chepultepec Dolomite	Cambrian – Ordovician Tremadocian – Dapingian (477.7 – 470 Ma)	Major: {dolostone,limestone} Siliceous dolomite and magnesian limestone sequence.
	sandstone#18	N/A		
Region 3	Limestone #55	Ridley Limestone Lebanon Limestone	Ordovician – Sandbian (457.4595 - 456.9275 Ma)	Major: {limestone} brownish-gray limestone, fine-grained, with minor mottlings of magnesian limestone; slightly cherty.
	Limestone #46	Carters Limestone	Ordovician – Sandbian (456.7375 - 456.5475 Ma)	Major: {limestone}, Incidental: {bentonite}. Fine-grained, yellowish-brown limestone; very slightly cherty with scattered mottlings of magnesian limestone in lower part
	Limestone #44	Bigby-Cannon Limestone and Hermitage Formation	Ordovician – Sandbian (456.5 - 454.525 Ma)	Major: {limestone, calcarenite}, Minor: {shale}, Incidental: {coquina} sandy and argillaceous limestone with shale; nodular shaly limestone; coquina; and phosphatic calcarenite.

Region	Sample	Geological data for aggregate sources (Peters et al. 2010)		
		Name	Age	lithologies
	Limestone #41	St. Louis Limestone and Warsaw Limestone	Mississippian -Visean (342.4375 – 338.4 Ma)	Major: {limestone}, Incidental: {shale}, Fine-grained, brownish-gray limestone, dolomitic and cherty. Warsaw Limestone - Coarse-grained, gray, cross bedded limestone; some what shaly
	Limestone #49			
	Limestone #47			
	Limestone #50			
	Limestone #43			
	Limestone #42			
Region 4	Limestone #56	Carters Limestone	Ordovician – Sandbian (456.7374 - 456.5475 Ma)	Major: {limestone}, Incidental: {bentonite}
	Limestone #64	N/A		
	Limestone #57	St. Louis Limestone and Warsaw Limestone	Mississippian -Visean (342.4374– 338.4 Ma)	Major: {limestone}, Incidental: {shale} Fine-grained, brownish-gray limestone, dolomitic and cherty.
	Limestone #60	N/A		
	Limestone #70	Ste. Genevieve Limestone	Mississippian -Visean (340.3125 – 335 Ma)	Limestone, Limestone, light- to medium gray, finely to coarsely crystalline, thick bedded, some beds oolitic, abundant fossil fragments, especially crinoid fragments
	Limestone #71	Pegram Formation; Camden Formation; Harriman Formation; Flat Gap Limestone; Ross Formation	Devonian – Lochkovian – Givetian (417.8 – 383.95 Ma)	Major: {limestone}, Minor: {chert, clay}, Incidental: {shale, sandstone} Light gray novaculitic chert and tripolitic clay; and minor siliceous limestone.

Table B- 3 Aggregate reactivity and concrete expansion

No	Sample IDs	ASTM C1260		ASTM C1293			Proposed classification
		Expansion (14 days) %	Reactivity (C1778)	Expansion (1 year) %	Reactivity (C1778)	Time to reach 0.04% expansion (days)	
1	Limestone #56	0.02	R0	0.02	Non-Reactive		
2	Limestone #19	0.04	R0	0.03			
3	Limestone #13	0.06	R0	0.02			
4	Limestone #55	0.05	R0	0.03			
5	Limestone #2	0.12	R1	0.09	R1	97	Late-expansive (LE)
6	Limestone #7	0.20	R1	0.11	R1	115	
7	Limestone #46	0.11	R1	0.12	R2	122	
9	Limestone #64	N/A	-	0.07	R1	135	
10	Limestone #18*	0.20	R1	0.09	R1	207	
8	Limestone #60	N/A	-	0.15	R2	89	Moderately-expansive (ME)
11	Limestone #12	0.30	R2	0.14	R2	63	
12	Limestone #28	0.27	R1	0.11	R1	69	
13	Limestone #57	0.24	R1	0.17	R2	66	
14	Limestone #70	0.29	R1	0.19	R2	73	
15	Limestone #29	0.25	R1	0.16	R2	46	Early-expansive (EE)
16	Limestone #3	0.18	R1	0.14	R2	47	
17	Limestone #38	0.31	R2	0.16	R2	45	
18	Limestone #41	0.20	R1	0.15	R2	43	
19	Limestone #44	0.32	R2	0.17	R2	50	
20	Limestone #71	0.10	R1	0.20	R2	41	Very-early-expansive (VEE)
21	Limestone #49	0.22	R1	0.27	R3	28	
22	Limestone #47	0.19	R1	0.27	R3	34	
23	Limestone #50	0.25	R1	0.26	R3	24	
24	Limestone #43	0.26	R1	0.21	R2	33	
25	Limestone #42	0.35	R2	0.20	R2	34	
26	Limestone #75	N/A	-	0.26	R3	19	

R0: non-reactive, R1: moderately-reactive, R2: highly-reactive, R3: very highly-reactive

*This aggregate is a clay- and carbonate-cemented sandstone rather than limestone as originally identified in field.

Table B- 4 Optical Characterization of Limestone Aggregates and Concrete Samples

Reactivity	Sample IDs	Aggregate Classification per AEE	Rocks in Aggregate / Major Characteristics	Major Minerals and Descriptions
Non-reactive (NR)	Limestone#13	Aggregate	<ul style="list-style-type: none"> Mainly medium or coarse grained dolomite; small amounts of dolomitic limestone. No visible reactive siliceous components. 	Major: dolomite, calcite Minor to trace: sulfides and clay
	Limestone#55	Aggregate	<ul style="list-style-type: none"> Mainly micritic limestone and dolomitic limestone. The latter contains more and larger dolomite rhombs than “typical” ACR reactive rock described in literature. No visible reactive siliceous components. 	Calcite and dolomite. Trace amounts of clay?
	Limestone#56	Aggregate	<ul style="list-style-type: none"> Mainly limestone. Small amounts of dolomite. No significant amounts reactive siliceous components. 	Mainly calcite and dolomite. Trace sulfides and microcrystalline quartz or chert.
Late-expansive (LE)	Limestone#2	Aggregate	<ul style="list-style-type: none"> Mainly dolomite (approx.. 22 particles) with one chert particle 	Mainly dolomite and calcite; minor microcrystalline quartz and probably clay; trace sulfides/oxides
		Concrete	<ul style="list-style-type: none"> ASR gel lines a few voids; frequent internal cracks in coarse aggregate particles; paste generally does not exhibit cracking. Evidence of minor dedolomitization or ACR. 	
	Limestone#7	Aggregate	<ul style="list-style-type: none"> Dolomite, argillaceous dolomitic limestone, and limestone; contained many clastic quartz grains that may not be ASR reactive; Minor, localized chert 	Major: dolomite, calcite Minor: quartz, clay, mica, bituminous/carbonaceous material
		Concrete	<ul style="list-style-type: none"> ASR gel lines a few voids and microcracks; frequent internal cracks in coarse aggregate particles that occasionally extended into paste; paste generally does not exhibit cracking. Evidence of minor dedolomitization or ACR. 	
	Limestone#64	Aggregate	<ul style="list-style-type: none"> Mainly limestone and dolomitic limestone; a few chert particles (in concrete specimen) 	Major: Calcite Minor: dolomite, quartz
		Concrete	<ul style="list-style-type: none"> ASR gel lines a few voids (mainly associated with chert particles); less frequent internal cracks in coarse aggregate particles than Samples 2 and 7 (aggregate in Sample 64 is in better condition); paste generally does not exhibit cracking. Evidence of frequent dedolomitization. 	
	Limestone/Sandstone#18	Aggregate	<ul style="list-style-type: none"> Fe-cemented sandstone consists of both siliceous and carbonate grains/clasts. 	Calcite, quartz, and goethite or other Fe-containing phases
Concrete		A few coarse aggregate particles cracked. ASR gel lines portion of cracks and in a few voids. Reactive components are likely strained quartz in sandstone and microcrystalline silica cement.		
Early and Moderately expansive (EE)	Limestone#60	Aggregate	<ul style="list-style-type: none"> Mainly limestone; a couple of cherty limestone particles observed in the thin section examination 	Major: calcite Minor: microcrystalline quartz/chert
		Concrete	ASR gel lined a few voids. Observations made on saw-cut sections only.	
	Limestone#3	Aggregate	<ul style="list-style-type: none"> Mainly dolomite. A few dolomite particles contain small amounts of interstitial chert or micro silica between dolomite rhombs (cherty dolomite) 	Major: dolomite Minor: microcrystalline quartz, possibly clay and opal-CT?
		Concrete	<ul style="list-style-type: none"> ASR gel lined a few voids. 	
Limestone#38	Aggregate	<ul style="list-style-type: none"> Mainly dolomite; small amounts of chert, dolomitic chert, and cherty dolomite 	Major: dolomite, microcrystalline quartz Minor: calcite and clay minerals	

Reactivity	Sample IDs	Aggregate Classification per AEE	Rocks in Aggregate / Major Characteristics	Major Minerals and Descriptions
		Concrete	<ul style="list-style-type: none"> ASR gel lined many voids. 	
	Limestone#41	Aggregate	<ul style="list-style-type: none"> Dolomitic limestone and smaller amounts of arenaceous cherty limestone. 	Major: calcite, dolomite, quartz grains (not or less reactive), and microcrystalline quartz Minor to trace: gypsum?
		Concrete	<ul style="list-style-type: none"> Microcracks in coarse aggregate particles; ASR gel lined a few voids. 	
	Limestone#71	Aggregate	<ul style="list-style-type: none"> Principally limestone of different crystal size, from coarse marble-like calcite to micritic calcite. One particle contains significant amounts of chert based on thin-section examination. 	Major: calcite <ul style="list-style-type: none"> Minor to trace: microcrystalline quartz/chert
		Concrete	<ul style="list-style-type: none"> ASR gel lined many voids. 	
Very-early expansive (VEE)	Limestone#49	Aggregate	<ul style="list-style-type: none"> Mainly cherty dolomite, cherty dolomitic limestone, and shaley or argillaceous dolomitic limestone Small amounts of dolomite, marble and calc-silicate (large carbonate crystals with micro-silica) Particles are mainly dark gray to black 	<ul style="list-style-type: none"> Major: dolomite, quartz (principally micro-crystalline), calcite Minor: opal-CT (?) in shaley dolomite/limestone, sulfides (pyrite), gypsum, mica/clay, carbonaceous/organic matter, chlorite Acid-insoluble residue appeared to be high
		Concrete	<ul style="list-style-type: none"> Most coarse aggregate particles are cracked or severely cracked Cracks frequently extended into paste ASR gel frequently filled/lined air voids, occasionally occurred in cracks 	
	Limestone#50	Aggregate	Mainly limestone and argillaceous cherty limestone, with minor detrital quartz and possibly amorphous silica (opal)	Calcite, quartz, dolomite, opal-CT (?), carbonaceous/organic matter, trace anhydrite and pyrite
		Concrete	<ul style="list-style-type: none"> Most or majority coarse aggregate particles are cracked or severely cracked Cracks frequently extended into paste ASR gel frequently filled/lined air voids, occasionally occurred in cracks Chert or cherty limestone appeared to be in better condition than black/dark gray argillaceous cherty limestone 	
	Limestone#75	Aggregate	<ul style="list-style-type: none"> Mainly argillaceous dolomitic limestone and small amounts of marble A small portion of the argillaceous dolomitic limestone may be alkali-carbonate reactive Argillaceous dolomitic limestone particles are mainly greenish gray; marble particles are gray 	<ul style="list-style-type: none"> Major: calcite and dolomite Minor: quartz, clay, carbonaceous/organic matter, pyrite Overall appeared less reactive silica components than 49 and 50
		Concrete	Argillaceous dolomitic limestone particles are generally affected by AAR and cracked Marble particles are in good condition and free of evidence of AAR	

Table B- 5 Chemical Analysis Results (ICP-AES)

Sample	Reactivity	Wt/%														CaO/ MgO	Rock classification based on CaO:MgO ratio (Chilingar 1960)
		SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	Cr ₂ O ₃	TiO ₂	MnO	P ₂ O ₅	SrO	LOI	Total		
Limestone #56	Non- reactive (NR)	1.97	0.46	0.18	51.4	3.82	0.02	0.21	<0.002	0.02	0.01	0.01	0.06	43.2	101.36	13.5	Slightly dolomitic limestone
Limestone #19		2.97	0.21	0.09	52.2	2.57	0.01	0.06	0.002	0.01	0.01	0.07	0.04	42.8	101.04	20.3	Slightly dolomitic limestone
Limestone #13		5.19	1.08	0.58	37.3	13.80	0.05	0.80	0.002	0.05	0.01	0.01	0.03	42.5	101.41	2.7	Dolomitic limestone
Limestone #55		2.54	0.57	0.24	50.2	3.65	0.02	0.22	<0.002	0.03	0.01	0.01	0.06	42.8	100.35	13.8	Slightly dolomitic limestone
Limestone #2	Late- expansive (LE)	6.07	1.05	0.40	32.2	17.10	0.01	0.58	0.002	0.04	0.01	0.01	0.01	43.2	100.68	1.9	Slightly calcite dolomite
Limestone #7		10.75	1.24	0.44	41.5	8.16	0.05	0.70	0.002	0.05	0.01	0.02	0.05	39.0	101.98	5.1	Dolomitic limestone
Limestone #46		5.61	2.04	0.77	50.1	1.86	0.05	0.52	0.006	0.07	0.01	0.02	0.05	40.3	101.42	26.9	Slightly dolomitic limestone
Limestone #64		2.97	0.48	0.23	50.1	4.67	0.03	0.17	0.003	0.03	0.01	0.05	0.03	42.9	101.67	10.7	Slightly dolomitic limestone
Sandstone* #18		25.3	3.17	9.77	32.6	1.88	0.31	0.62	0.003	0.17	0.49	0.54	0.05	27.0	101.91	17.3	Sandstone
Limestone #28	Moderately - expansive (ME)	5.92	0.88	0.45	46.8	4.95	0.06	0.17	0.002	0.05	0.02	0.02	0.05	41.1	100.47	9.5	Slightly dolomitic limestone
Limestone #60		14.95	0.36	0.13	47.4	1.01	0.02	0.09	0.002	0.02	0.01	0.04	0.05	36.9	100.98	46.9	Slightly dolomitic limestone
Limestone #12		8.36	0.89	0.34	28.4	19.45	0.03	0.66	<0.002	0.03	0.02	0.01	0.01	42.4	100.6	1.5	Dolomite
Limestone #57		6.62	0.68	0.27	48.7	4.13	0.03	0.15	0.002	0.03	0.01	0.06	0.07	40.9	101.65	11.8	Slightly dolomitic limestone
Limestone #70		9.59	0.83	0.36	43.2	6.67	0.05	0.16	0.003	0.05	0.01	0.05	0.07	39.8	100.84	6.5	Dolomitic limestone
Limestone #29	Early- expansive (EE)	16.3	3.68	1.38	27.7	14.4	0.04	1.48	0.003	0.17	0.03	0.07	0.01	35.8	101.07	1.9	Slightly calcite dolomite
Limestone #3		16.05	1.26	0.31	27.6	16.5	0.03	0.52	0.002	0.04	0.01	0.01	0.02	38.5	100.85	1.7	Slightly calcite dolomite
Limestone #38		7.62	0.72	0.21	37.0	13.25	0.02	0.32	<0.002	0.03	0.01	0.01	0.02	41.9	101.11	2.8	Calcite dolomite
Limestone #41		19.45	1.81	0.96	38.8	4.34	0.17	0.5	0.004	0.13	0.01	0.07	0.03	33.3	99.58	8.9	Dolomitic limestone
Limestone #44		13.55	0.90	0.24	29.2	16.65	0.02	0.57	<0.002	0.03	0.01	0.02	0.01	39.2	100.4	1.8	Slightly calcite dolomite
Limestone #71		8.4	1.86	0.78	47.3	2.7	0.04	0.78	0.002	0.1	0.04	0.01	0.02	38.9	100.94	17.5	Slightly dolomitic limestone
Limestone #49	Very-early- expansive (VEE)	46.3	3.90	1.61	17.05	7.39	0.25	1.10	0.006	0.22	0.02	0.07	0.02	21.2	99.16	2.3	Calcite dolomite
Limestone #47		46.9	3.56	1.32	19.0	5.76	0.33	0.94	0.006	0.24	0.01	0.06	0.06	20.6	98.81	3.3	Calcite dolomite
Limestone #50		42.3	3.57	1.38	27.5	1.68	0.34	0.92	0.005	0.25	0.01	0.04	0.05	22.6	100.67	16.4	Slightly dolomitic limestone
Limestone #43		39.7	2.77	1.07	24.1	4.81	0.14	0.80	0.006	0.16	0.01	0.09	0.04	24.4	98.12	5.0	Dolomitic limestone
Limestone #42		37.3	2.64	1.05	28.9	2.23	0.28	0.68	0.004	0.2	0.01	0.05	0.06	25.0	98.41	13.0	Slightly dolomitic limestone
Limestone #75		15.1	2.83	1.14	40.7	4.27	0.06	1.06	0.002	0.14	0.04	0.03	0.03	35.6	101.01	9.5	Slightly dolomitic limestone
Examples of typical pure limestone rocks (Missouri Department of Natural Resources)																	
Calcite limestone		0	0	0	56.07	0	0	0	0	0	0	0	0	43.9	99.97	infinity	limestone
Magnesium limestone		0	0	0	54.49	1.31	0	0	0	0	0	0	0	44.2	100	41.6	Slightly dolomitic limestone
Dolomitic limestone		0	0	0	45.01	9.40	0	0	0	0	0	0	0	45.6	100.01	4.79	Dolomitic limestone
Calcite dolomite		0	0	0	34.77	18.14	0	0	0	0	0	0	0	47.2	100.11	1.92	Slightly calcite dolomite
Dolomite		0	0	0	30.67	21.64	0	0	0	47.7	0	0	0		100.01	1.68	Slightly calcite dolomite

*This aggregate is a clay- and carbonate-cemented sandstone rather than a limestone as originally identified in field

Table B- 6 Mineralogical Composition of Limestone Aggregates Using XRD Analysis

Reactivity	Sample IDs	Wt/%							Quality measures	
		Calcite	Dolomite	Ankerite	Feldspar	Mica /Clay	Quartz	Others	R _{wp}	GOF
						Illite and Muscovite				
NR	Limestone #56	80.8	14.2	2.0	1.6	-	1.4	-	12.17	1.47
	Limestone #19	80.3	13.9	2.0	1.0	-	2.8	-	9.36	1.14
	Limestone #13	26.3	63.6	5.0	3.5	-	1.6	-	11.87	1.54
	Limestone #55	77.5	18.3	0.9	1.8	-	1.5	-	12.38	1.51
LE	Limestone #2	10.0	82.0	1.1	1.5	1.1	4.3	-	13.95	1.81
	Limestone #7	51.6	33.6	2.0	4.1	0.7	8.0	-	13.44	1.69
	Limestone #60	79.9	3.2	1.1	-	1.3	14.5	-	11.12	1.37
	Limestone #46	83.3	6.2	1.4	0.9	5.0	3.0	0.5 Pyrite	12.31	1.53
	Limestone #64	75.6	19.6	1.5	-	1.6	1.7	-	12.40	1.50
ME	Limestone #12	0.3	88.8	1.1	2.6	1.3	5.7	0.2 Pyrite	20.74	2.82
	Limestone #57	-	-	-	-	-	-	-	-	-
	Limestone #28	68.4	24.2	0.8	0.5	1.3	4.8	-	12.34	1.52
	Limestone #70	53.3	34.2	1.4	-	1.9	9.1	0.3 Chlorite	14.87	1.89
EE	Limestone #29	7.5	72.0	2.0	1.7	6.8	10.0	-	10.99	1.52
	Limestone #3	3.1	78.3	0.9	1.3	2.7	13.7	-	15.05	2.15
	Limestone #38	24.2	66.2	0.8	1.3	1.5	6.1	-	14.36	1.98
	Limestone #41	49.1	20.3	0.4	2.1	2.5	20.9	3.1 Gypsum, 0.6 Pyrite, 1.0 Anhydrite	13.75	1.79
	Limestone #44	5.0	79.0	1.3	2.1	1.6	11.0	-	14.93	1.97
	Limestone #71	75.4	9.3	3.1	1.5	5.2	5.5	-	12.95	1.61
VEE	Limestone #49	5.1	32.7	1.6	-	14.2	42.3	1.0 Magnesium oxide carbonate 0.6 Chlorite 1.6 Gypsum 0.9 Pyrite	10.36	1.48
	Limestone #47	13.3	24.0	4.0	2.8	7.1	44.0	1.8 Anhydrite , 0.4 Pigeonite 0.4 Titanium silicon, 1.5 Gypsum 0.7 Pyrite	10.17	1.43
	Limestone #50	39.0	0.8	5.3	2.7	6.0	45.0	1.1 Pyrite ,0.3 Gypsum	11.54	1.59
	Limestone #43	27.6	20.8	2.4	0.4	8.3	38.9	0.8 Pyrite, 0.8 Gypsum	12.20	1.67
	Limestone #42	45.8	1.3	3.6	2.4	7.0	38.8	0.6 Pyrite, 0.5 Gypsum	13.09	1.75
	Limestone #75	63.0	18.2	2.0	-	5.2	11.2	0.3 Pyrite, 0.1 Gypsum	11.12	1.44
	Examples of typical pure limestone and dolomite rocks (
Calcite limestone	100	0	0	0	0	0	0	0	N/A	
Magnesium limestone	94.0	6.0	0	0	0	0	0	0		
Dolomitic limestone	57.0	43.0	0	0	0	0	0	0		
Calcite dolomite	17.0	83.0	0	0	0	0	0	0		
Dolomite	1.0	99.0	0	0	0	0	0	0		

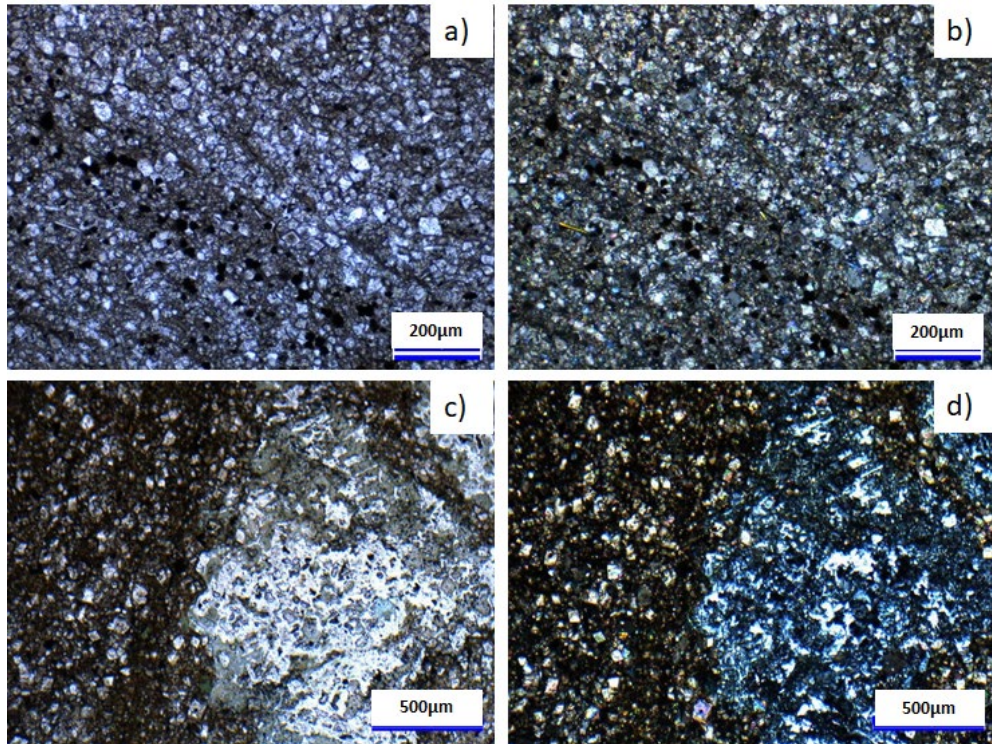


Figure B- 1 Optical micrographs of various silica forms in the limestone aggregates under plane (left) and crossed polarizer (right): (a&b) argillaceous dolomitic limestone, (c&d) cherty dolomite

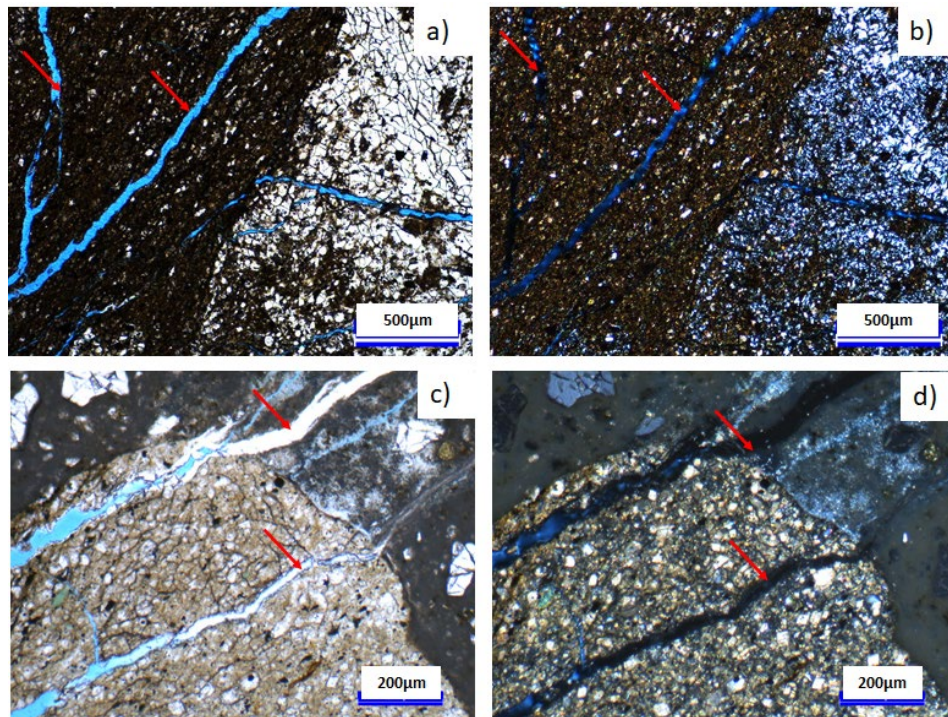


Figure B- 2 Optical micrographs of various silica forms in the limestone aggregates under plane (left) and crossed polarizer (right): (a&b) Argillaceous Cherty Dolomite, (c&d) Shaley dolomite. ASR gel fills cracks indicated by red arrows.

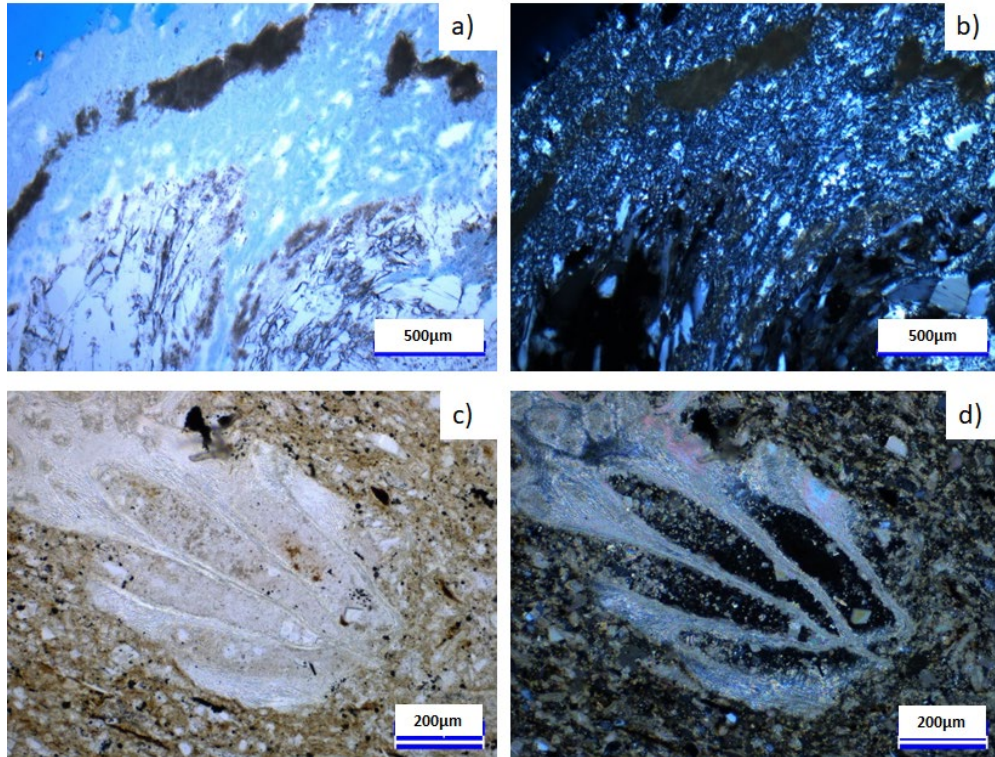


Figure B- 3 Optical micrographs of various silica forms in the limestone aggregates under plane (left) and crossed polarizer (right): (a&b) meta chert, (c&d) Opal, amorphous silica

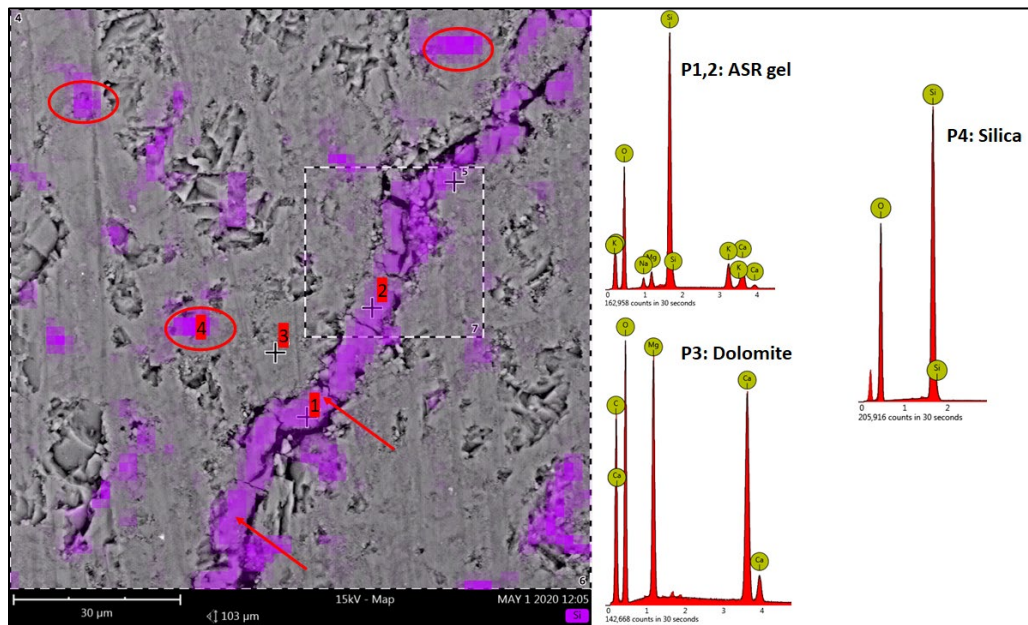
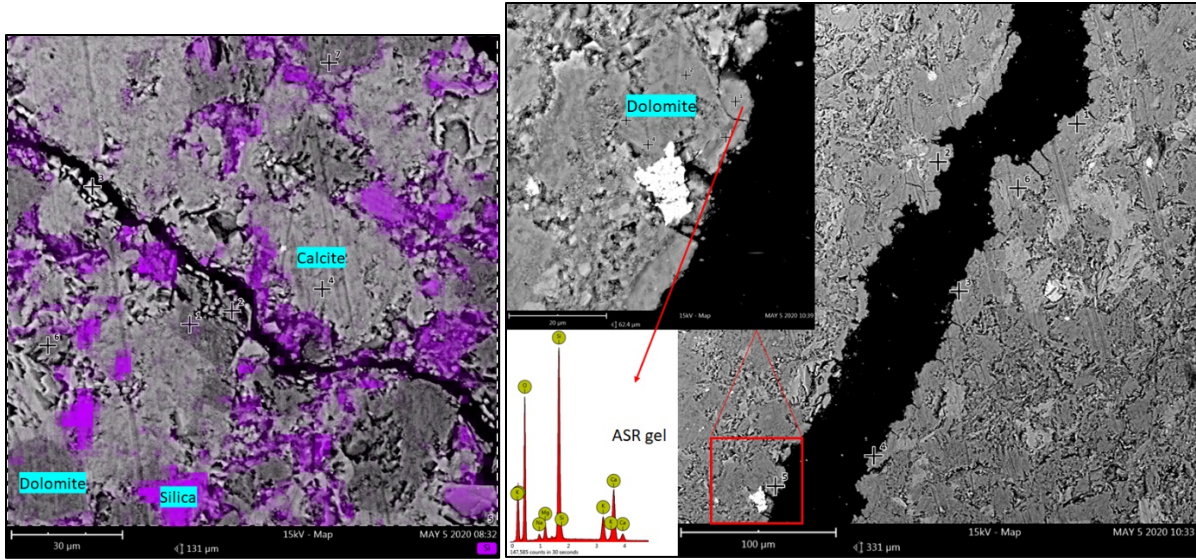


Figure B- 4 SEM micrograph from Limestone#2: Dolomite particle showing fine disperse silica (purple color) and magnesium-silica gel (ASR gel). The micrograph is generated by overlapping the silica map (purple) on backscatter image. EDS spot analysis showing the composition of AS gel (red arrows) and dispersed silica (red circles) with dolomite particle.



(a) Fine disperse silica

(b) ASR gel lining cracks

Figure B- 5 SEM micrographs from Limestone#75: (a) dolomitic limestone particle showing fine dispersed silica, (b) magnesium-alkali-silica gel (ASR gel) lining cracks.

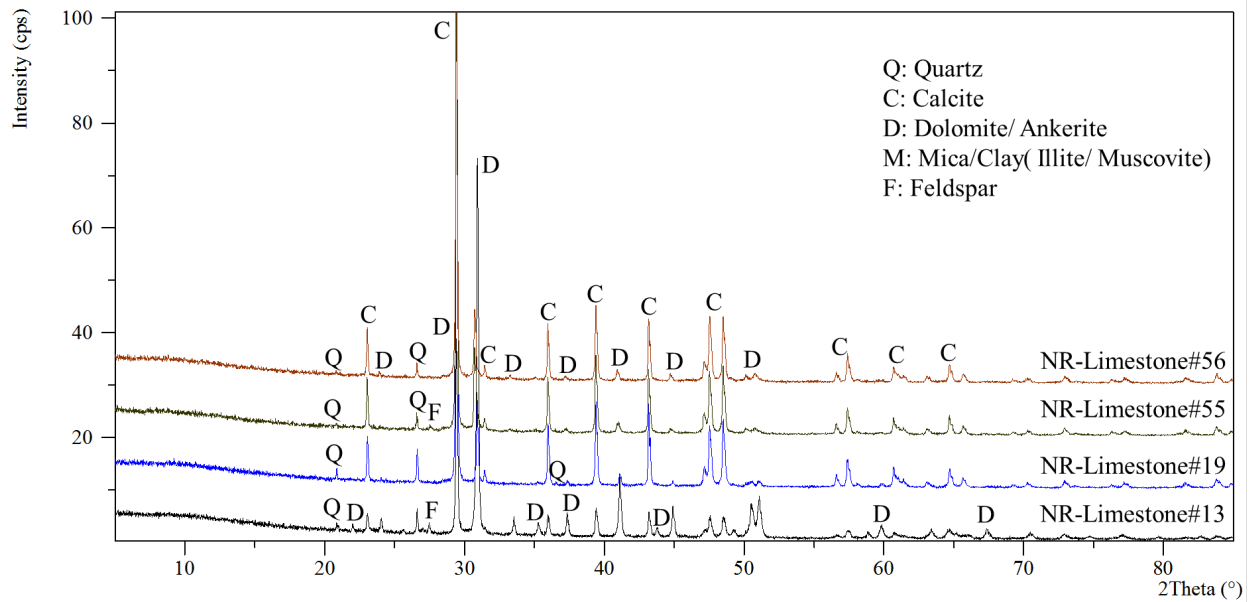


Figure B- 6 XRD pattern for non-reactive aggregates

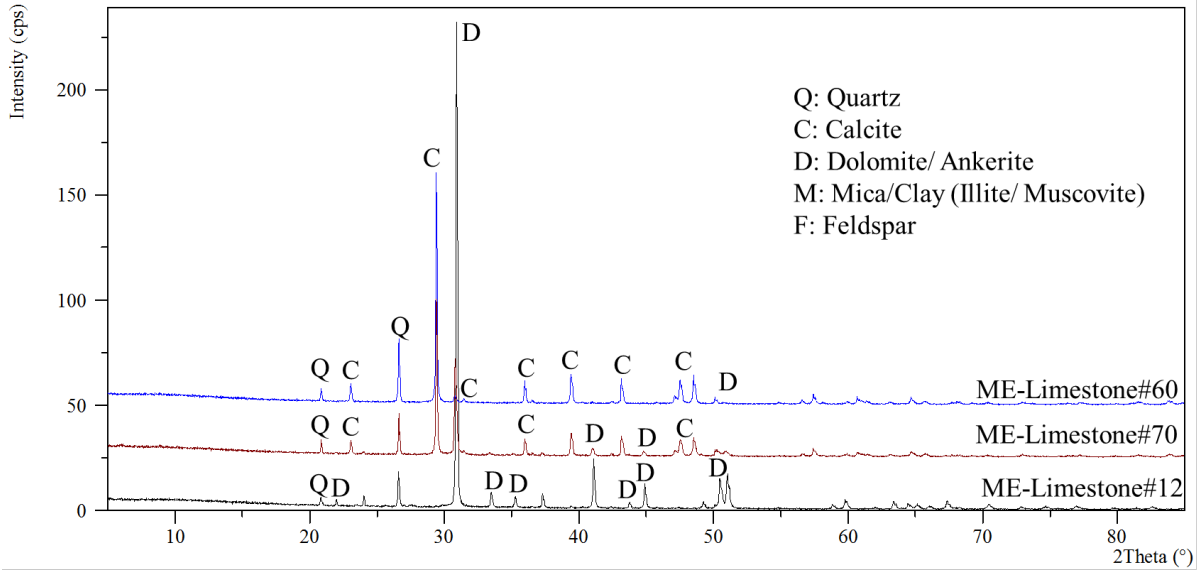


Figure B- 7 XRD pattern for moderately-expansive aggregates

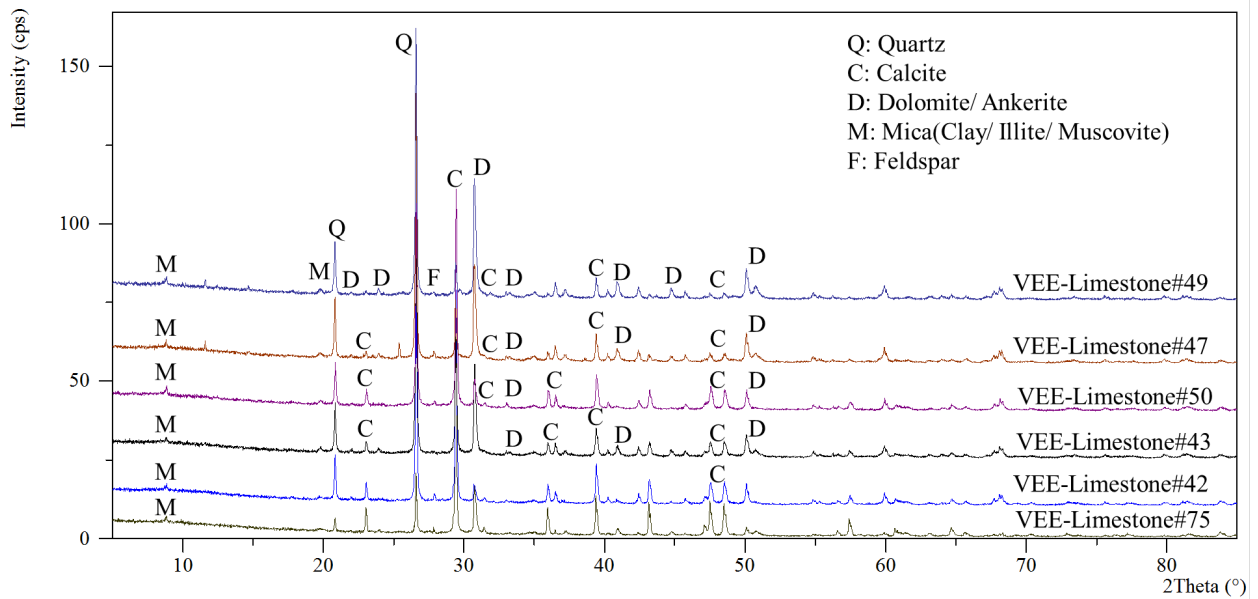


Figure B- 8 XRD pattern for very early-expansive aggregates

Appendix C: Field Performance of Reactive Aggregates

C.1 Purpose

Field performance of reactive aggregates in the state of Tennessee was investigated. The need for identifying the extend of ASR risk in existing structures is necessary so that informed decision can be made toward maintaining the functionality and structural integrity of affected structures.

C.2 Scope

High risk of Alkali-Aggregate Reaction (AAR) in Tennessee was identified based on this study. To study the performance of reactive aggregates in the field, structures with high potential of ASR were identified according to the following steps.

Step 1: Sources with high potential reactive aggregates, namely the very highly reactive (VHR) and highly reactive (HR), within each region in the state of Tennessee were selected and their use in concrete pavement and highway structures were surveyed. The target aggregate sources for each region were summarized in Tables C-1, C-2, C-3, and C-4.

Step 2: In collaboration with TDOT Materials and Tests Division, a TDOT regional survey was sent to each region to receive inputs for the following requests:

- a) Please provide suggestions for at least three highway/interstate structures (concrete pavements, concrete bridges, or concrete barriers) that were constructed more than 20 years ago with some of the aggregate sources shown in the table relevant to each region (Tables C-1 to C-4).
- b) During a regular/recent TDOT inspections, please indicate whether any of the following symptoms of Alkali-Silica Reaction (ASR) have been encountered in the structures identified in (a) above:
 - I. Cracking: If yes, please includes map-cracking (or longitudinal cracking) and associated gel staining around cracks in a median highway barrier or in concrete walls, decks, beams, and other structural elements.
 - II. Expansion and deformation can cause relative movement of adjacent concrete members, lead to closure of joints, and ultimately cause spalling of concrete at joints.
 - III. POP-OUTS induce the detachment of a portion of the skin of concrete.
 - IV. Surface Deposits

Step 3: If ASR symptoms are encountered in field structures, cores were extracted from selected cases and examined at UTK to identify whether ASR is the cause of the deterioration mechanism.

Step 4: The performance of some of highly reactive aggregates in the field was documented.

Table C- 1 Target aggregates for Region 1

No	ID	Location	County, TN	Producer	Type	Reactivity
1	Granite#35	Confidential record (TDOT)			Granite	HR
2	Granite#39	Confidential record (TDOT)			Granite	HR
3	Granite #10	Confidential record (TDOT)			Granite	HR
4	Granite #11	Confidential record (TDOT)			Granite	HR
5	Limestone#3	Confidential record (TDOT)			Limestone	HR

Table C- 2 Target aggregates for Region 2

No	ID	Location	County, TN	Producer	Type	Reactivity
1	Granite#30	Confidential record (TDOT)			Granite	HR
2	Granite #34	Confidential record (TDOT)			Granite	HR
3	Granite #36	Confidential record (TDOT)			Granite	HR
4	Granite #37	Confidential record (TDOT)			Granite	HR
5	Granite #38	Confidential record (TDOT)			Limestone	HR
6	Granite #29	Confidential record (TDOT)			Limestone	HR

Table C- 3 Target aggregates for Region 3

No	ID	Location	County, TN	Producer	Type	Reactivity
1	Limestone #42	Confidential record (TDOT)			Limestone	VHR
2	Limestone #43	Confidential record (TDOT)			Limestone	VHR
3	Limestone #47	Confidential record (TDOT)			Limestone	VHR
4	Limestone #49	Confidential record (TDOT)			Limestone	VHR
5	Limestone #50	Confidential record (TDOT)			Limestone	VHR
6	Limestone #41	Confidential record (TDOT)			Limestone	HR
7	Limestone #44	Confidential record (TDOT)			Limestone	HR
8	Natural sand#45	Confidential record (TDOT)			Natural sand	HR

Table C- 4 Target aggregates for Region 4

No	ID	Location	County, TN	Producer	Type	Reactivity
1	Limestone #75	Confidential record (TDOT)			Limestone	VHR
2	Limestone #71	Confidential record (TDOT)			Limestone	HR
3	Limestone #60	Confidential record (TDOT)			Limestone	HR
4	Limestone #66	Confidential record (TDOT)			Limestone	HR
5	Natural sand#67	Confidential record (TDOT)			Natural sand	HR
6	Natural sand #73	Confidential record (TDOT)			Natural sand	HR
7	Natural sand #76	Confidential record (TDOT)			Natural sand	HR

C.3 Results of the TDOT Survey

The survey targeted the field performance of high potential reactive aggregates, namely the very highly reactive (VHR) and highly reactive (HR), within each region in the state of Tennessee. The results of the regional survey are summarized in Table C- 5.

Table C- 5 Results of TDOT Regional Survey on the Performance of Reactive Aggregates

TDOT region	Reactive Aggregates	Structures*	Possible ASR symptoms
1	Rogers Group – Caryville	1.Campbell County Bridge # 07-0A006-00.00 crossing Elk Creek	map cracking was noted throughout the wing walls and backwall
		2.Campbell County Double Barrel Culvert # 07-0A071-00.28 crossing Branch of Stinking Creek	map cracking was noted throughout the headwalls and wing walls.
		3.Campbell County Triple Barrel Culvert # 07-0A158-00.10 Ivydell Rd over Ollis Creek	map cracking was noted throughout the inlet headwall and wing walls.
2	Rogers Group – Dayton	1.Rhea County Triple Barrel Culvert # 72-SR060-05.32 over Broyles Branch	map cracking was noted throughout the right headwall and right-wing walls
		2.Rhea County Triple Barrel Culvert # 72-SR030-15.84 over Washington Creek	map cracking was noted throughout the right and left headwall and wing walls
		3.Rhea County Bridge # 72-SR030-17.26 over Tennessee River	map cracking was noted on the deck/wearing surface, parapet wall, pier cap, and wing walls.
3	Rogers Group – Gordonsville	1.Smith County Bridge # 80-SR053-05.94 over Mulherrin Creek	No apparent ASR symptoms
		2. Smith County Bridge # 80-SR025-12.78 over the Cumberland River	No apparent ASR symptoms
	Pine Bluff Sand	Davidson County Concrete Pavement SR045 LM 7.20 to LM 7.256	Map cracking was identified in this concrete pavement
4	Vulcan – Holladay	Benton County Bridge # 03-SR001-04.33 over CSX R.R.	No apparent ASR symptoms
	Vulcan – Rossville	Fayette County Bridge # 24-SR057-04.16 over Norfolk Southern R.R.	No apparent ASR symptoms
	Ruleman Sand – Brighton	Haywood County Bridge # 38-SR076-10.08 over I-40 (Exit 56)	No apparent ASR symptoms

*The bridge numbers listed are named by the following convention: County Number – State Route/County Road – Log Mile.

C.4 Confirmed ASR Cases

Two possible cases of ASR occurrence were identified by TDOT in two locations Figure C- 1: (a) an interchange structure in east Tennessee near Flag Pond (Figure C- 2), and (b) a concrete pavement in in Memphis (Figure C- 3). TDOT collected two core samples from each site and delivered to the research team at UT for examination. Information about the cores and the affected structures are summarized in Table C-6. The cores are examined by the research team at UTK to determine whether ASR is the source of concrete deterioration. Observations and findings are provided below.

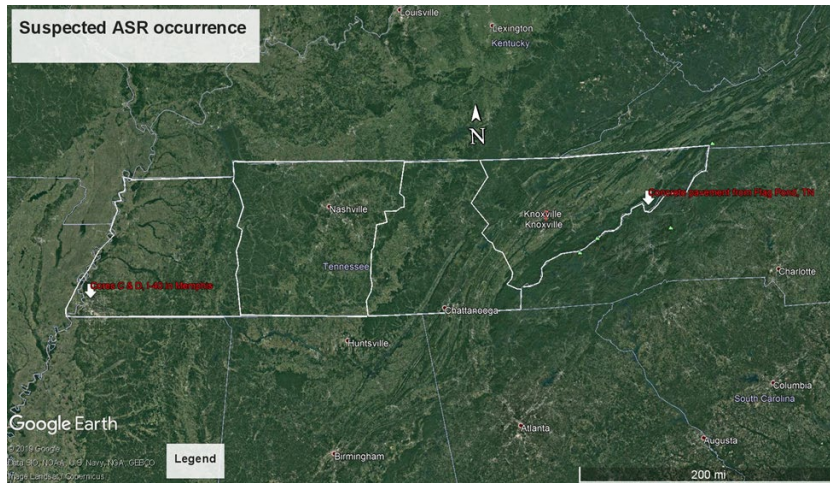


Figure C- 1 Suspected cases for ASR occurrence in TN



Figure C- 2 Cracking in concrete pavement and barrier wall in Flag Pond, TN (Photo credit: Derek Gaw-TDOT)



Figure C- 3 Cracking of a concrete pavement in Memphis, TN (Photo credit: Derek Gaw-TDOT)

Table C- 6 Structures and Cores Information

Structure information				Cores information			
Structures	Location	Age of structure	ASR symptoms	Core ID	Location within structure	Aggregates	Coring direction
Interchange	Flag Pond, TN	25-30 years	Cracking in concrete pavement, the barrier wall, and the bridge deck	Core A	Concrete pavement	Limestone and sand	Vertically
				Core B	Bridge Abutment	a lightweight aggregate and sand	Horizontally
Concrete pavement	Memphis, TN	39 Years, and Rehabilitated 11 years ago.	Cracking in old concrete and the new concrete from rehab project	Core C (11 years old)	Full depth concrete patch of a concrete pavement	Limestone	Vertically
				Core D (39 years old)	Concrete pavement	Limestone	Vertically

C.4.1 Methodology

Microscopic examinations using petrographic microscope and scanning electron microscopy (SEM) were conducted on thin sections produced from concrete cores (Figure C- 4). The examination objective was to determine and document ASR evidence in the concrete such as the presence of ASR gel and its composition, the occurrence of cracks and gel within aggregates, paste, and air voids. The presence of reactive silica within aggregates was also documented. Prior to SEM examinations, thin sections were carbon coated to prevent charging the samples during the examinations.

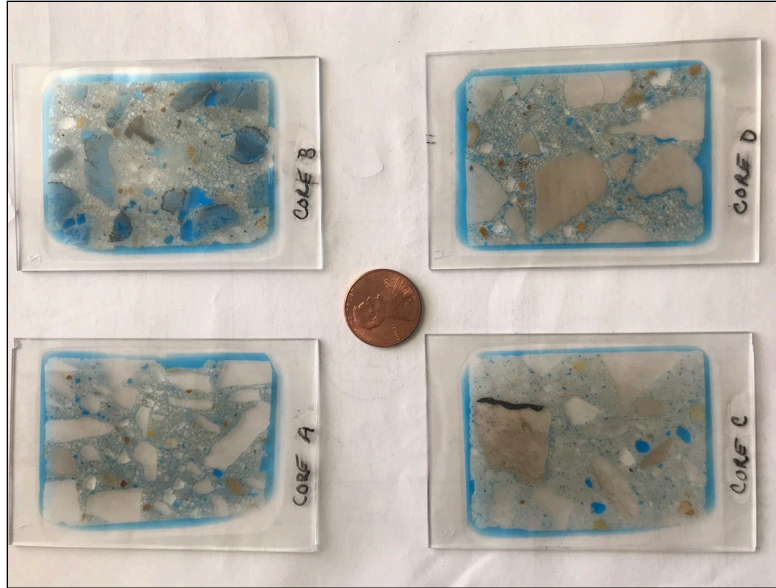


Figure C- 4 Thin sections of concrete cores

C.4.2 Testing and Evaluation

Case 1: Interchange structure in Flag Pond, TN

Visual inspection of cores: The interchange structure under evaluation is 25 to 30 years old, which manifests cracking in concrete pavement, the barrier wall, and the bridge deck. The visual inspection of Core A, which was extracted vertically from the concrete pavement, shows significant cracking in concrete and within aggregates as shown in Figure C- 5.

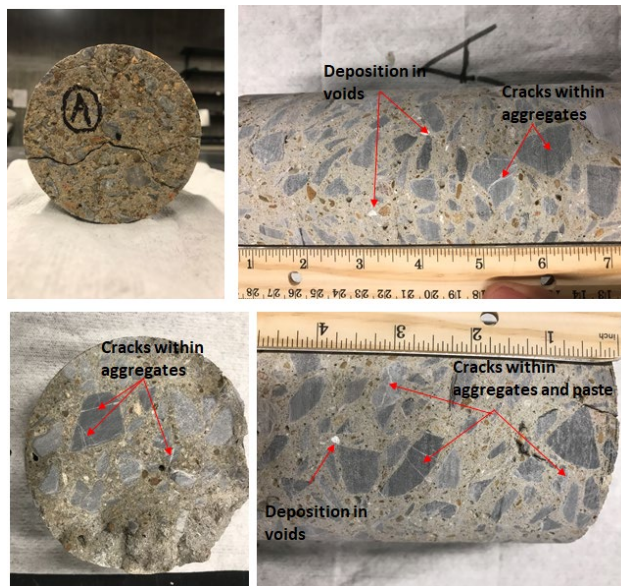


Figure C- 5 Visual inspection of Core A

Deposition of white materials within air voids suggests possible ASR gel occurrence. The second core from the structure (Core B) was extracted horizontally from the bridge abutment and does not show many cracks as in Core A. However, white materials were observed within air voids in Core B, as shown in Figure C- 6.

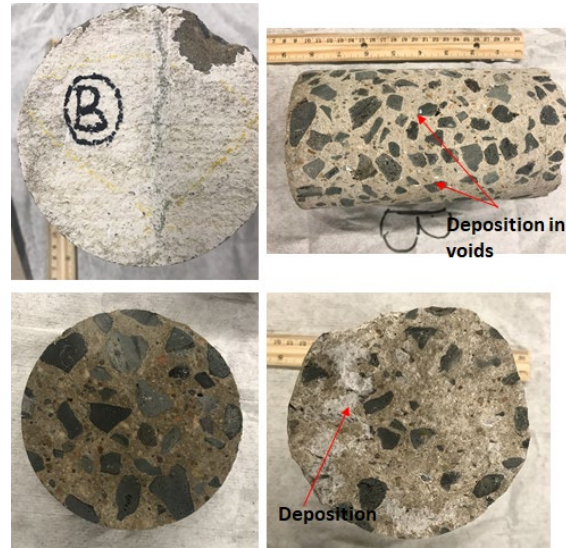


Figure C- 6 Visual inspection of Core B

Microscopic examinations

Optical observations: The coarse aggregate in Core A is mainly medium to coarse grained dolomite with small amounts of dolomitic limestone and micritic calcite, see Figure C- 7. Fine grained calcite/dolomite matrix usually contains fine disperse reactive silica as observed in several reactive limestones within the current ASR study. Empty and filled cracks were observed within several coarse aggregates in Core A. The fine aggregate fraction in both Core A and Core B seemed to be highly reactive with confirmed occurrence of ASR cracks and gel. Figure C- 8 shows an example of reactive fine aggregate particles in Core B. The examination of some of the fine aggregate particles indicates the presence of finely disperse quartz (microcrystalline and possibly cryptocrystalline quartz) in a clay-like matrix, micas and clay as shown Figure C- 8(A) and Figure C- 8(B). The fine aggregate particles showed cracks filled with ASR gel as confirmed by SEM examinations.

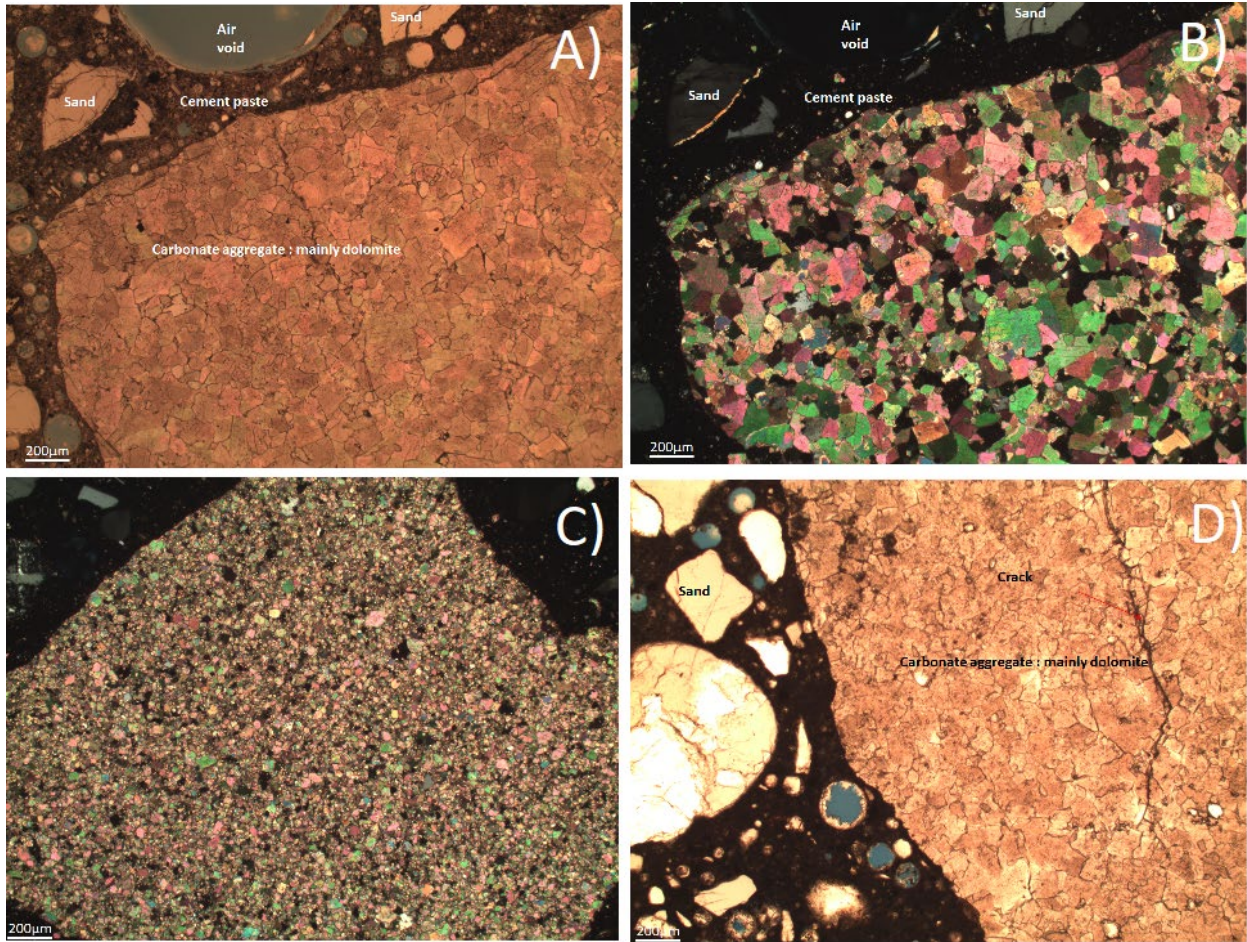


Figure C- 7 Optical micrographs of CoreA: (A &B) coarse grain dolomite matrix under plain (A) and crossed polarizer (B); C) fine grained calcite-dolomite matrix with possible fine disperse silica (under crossed polarizer); (D) coarse-grained calcite-dolomite matrix with cracks (under plain polarizer).

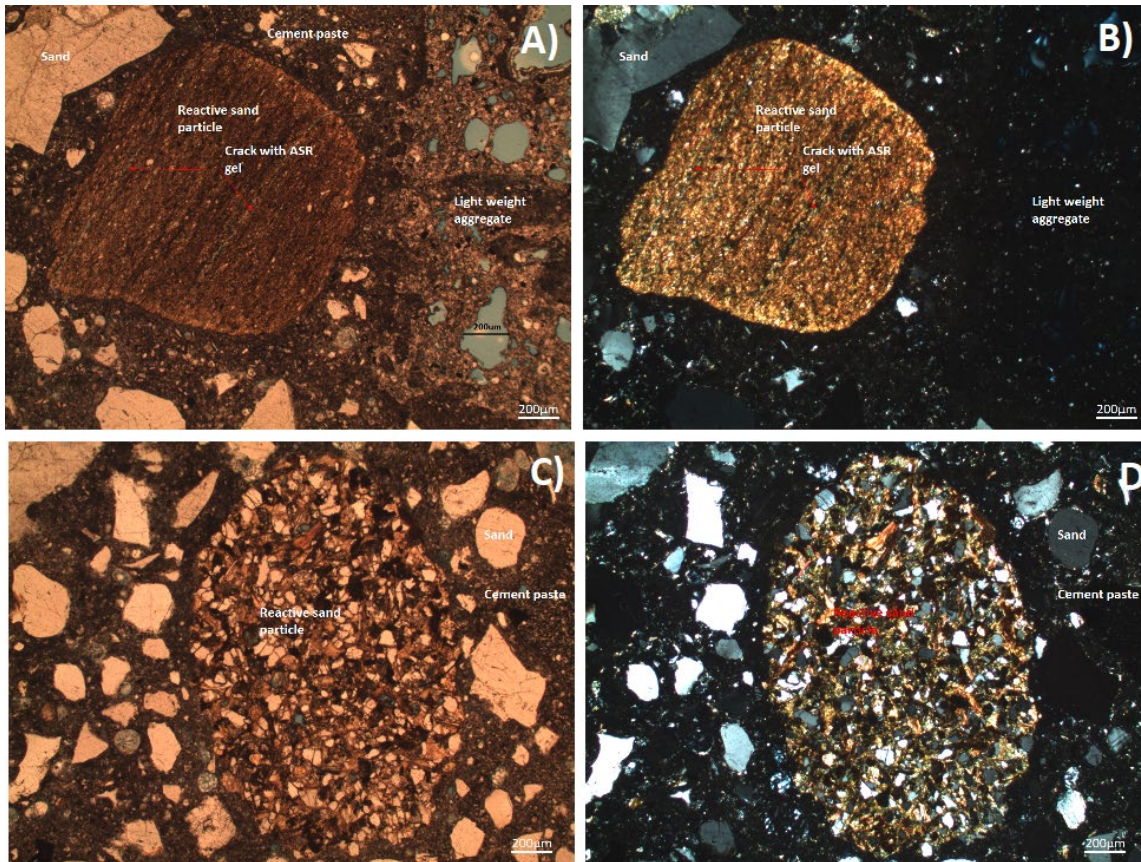


Figure C- 8 Optical micrographs from Core B under plain (left) and crossed polarizer (right) showing reactive fine aggregates.

Scanning electron microscopy (SEM) observations: The SEM examinations confirmed the presence of highly reactive sand particles (severely cracked) with ASR gel filling cracks within particles and extending to the cement paste (Figure C- 9 to Figure C- 3). The chemical composition of fine aggregate and ASR gel was determined using an EDS detector within the SEM machine. The dolomite coarse aggregates also showed cracks, but no ASR gel was observed in the coarse aggregate within the thin section (Figure C- 3). These observations confirm the presence of ASR deterioration mechanism in the fine aggregate fraction of the concrete.

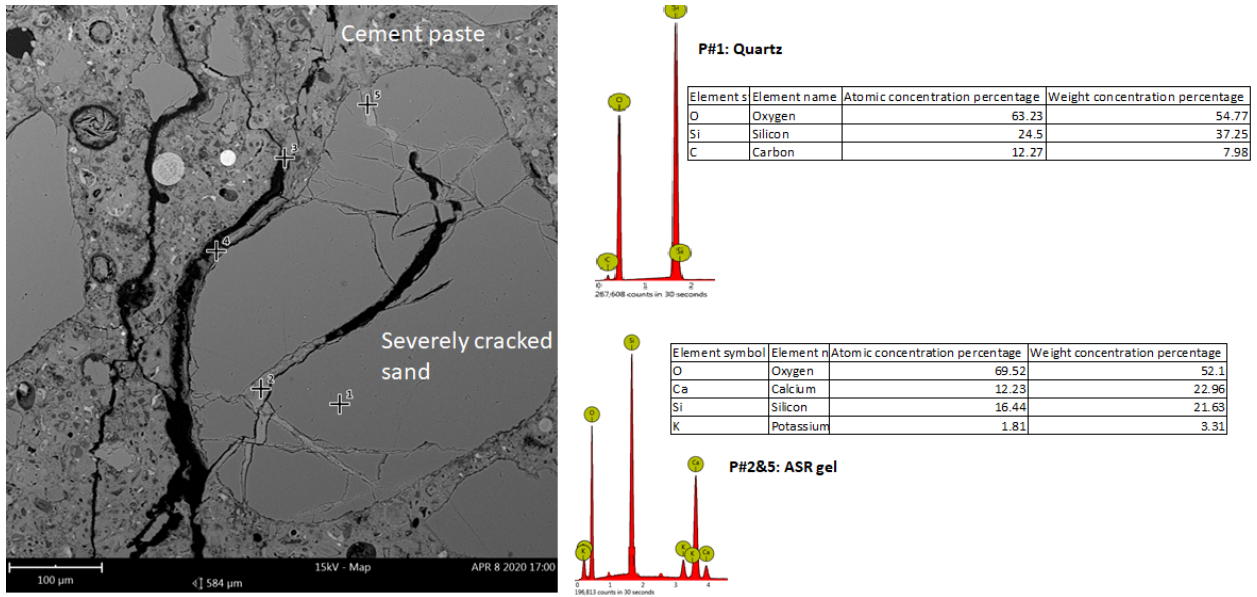


Figure C- 9 SEM micrographs from Core A showing chemical composition of sand and ASR gel. (The carbon shown in chemical compositions is mainly from coating the samples with carbon for SEM examination)

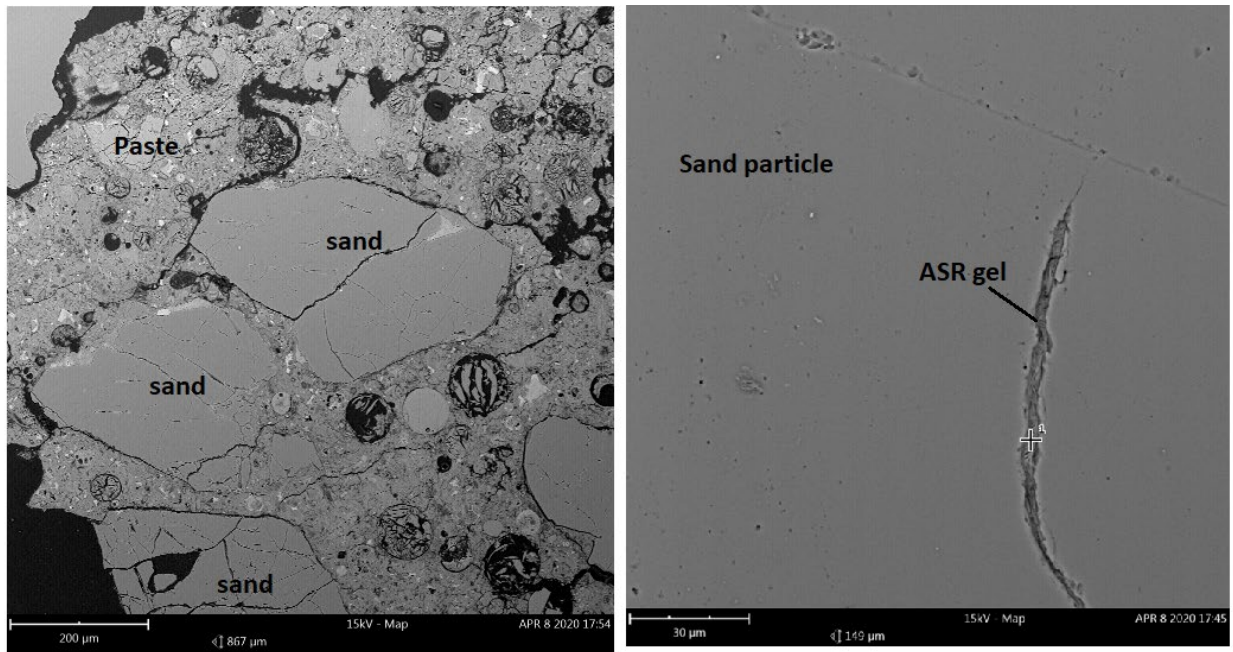


Figure C- 1 SEM micrographs from Core A: Severely cracked sand particles with ASR gel

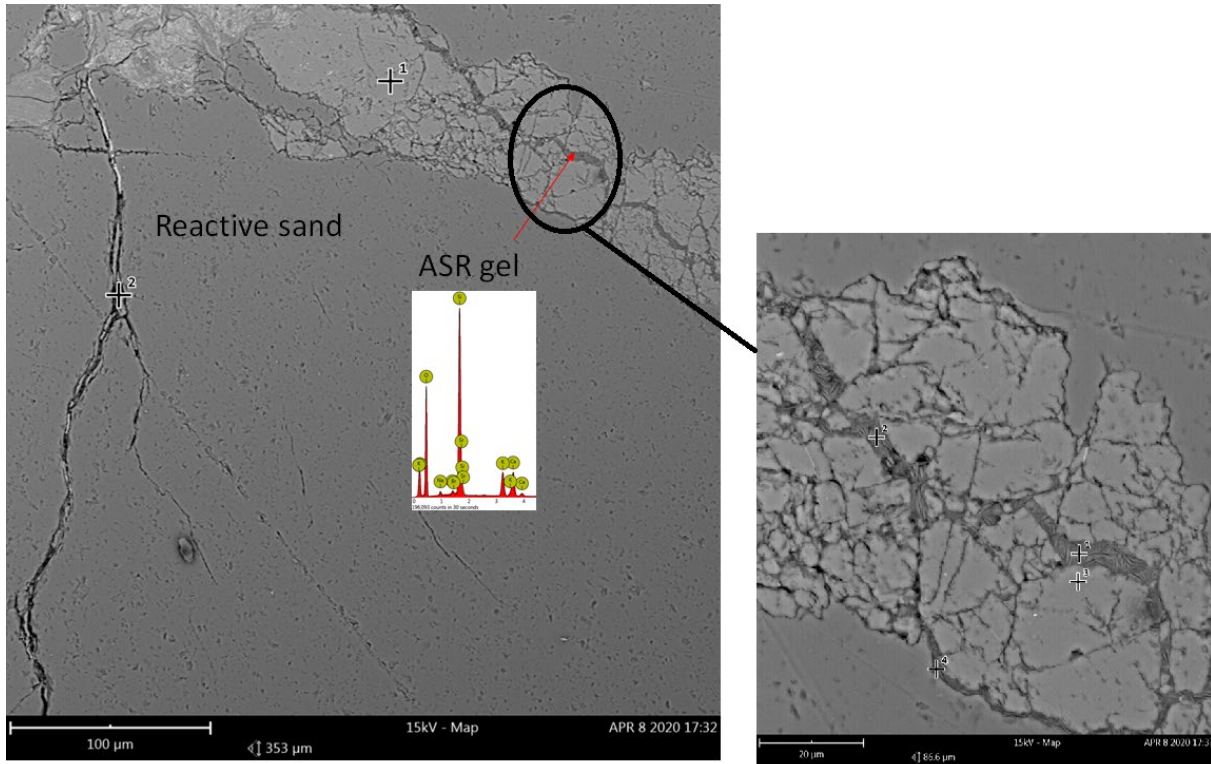


Figure C- 2 SEM micrographs from Core A: ASR gel within reactive sand

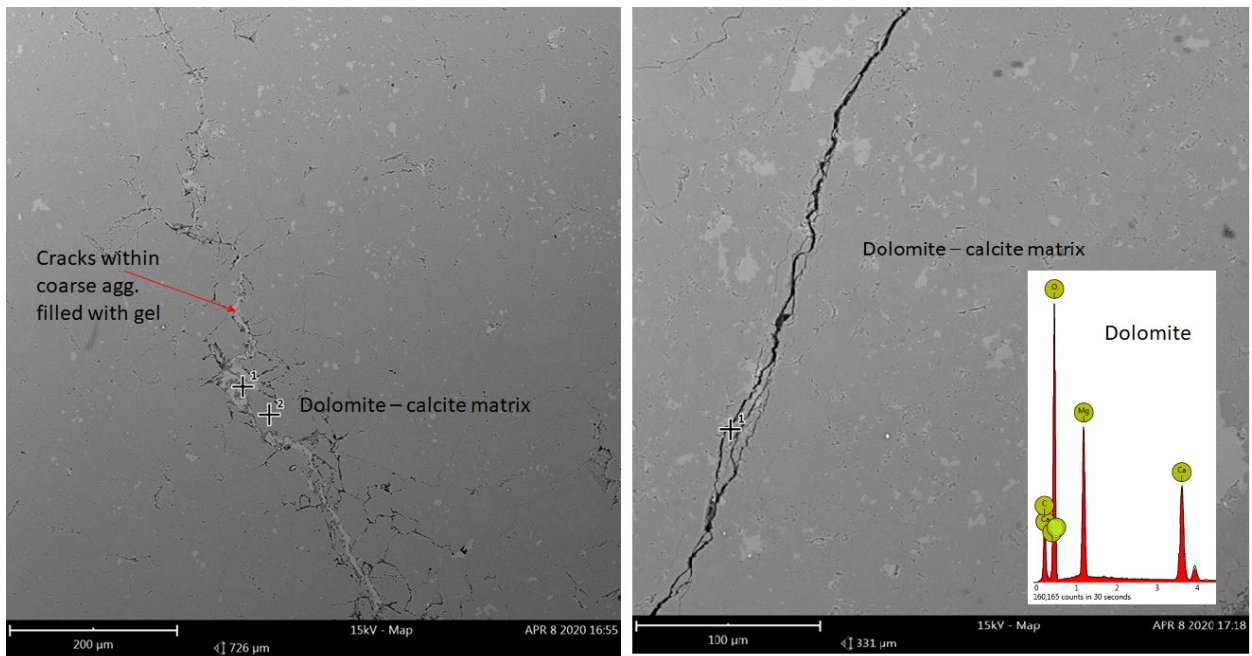


Figure C- 3 SEM micrographs from Core A: Cracks within dolomite coarse aggregates the material filling cracks with the carbonate aggregate is probably calcite (CaCO_3).

Case 2: Concrete pavement in Memphis, TN

Visual inspection of cores: The concrete pavement under investigation was originally constructed in 1980 (39 years old) and had a rehab project 11 years ago. The concrete pavement shows cracking throughout the original concrete as well as in the new patches from the rehab project. Core samples were collected from the original concrete (Core D) as well as from a patch area (Core C). The visual inspections of cores C and D showed cracking in concrete and within the dark gray / black coarse aggregates as shown in Figure C- 4 and Figure C- 5. Deposition of white materials within the air voids suggests possible ASR gel occurrence.

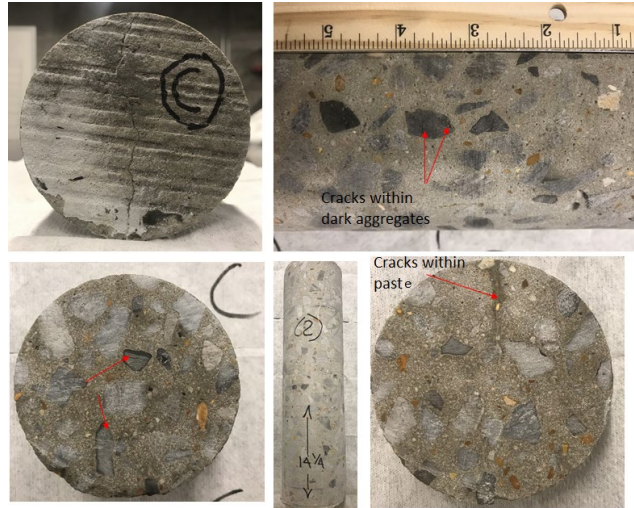


Figure C- 4 Visual inspection of Core C



Figure C- 5 Visual inspection of Core D

Microscopic examinations

Optical observations: The coarse aggregates in cores C and D are mostly limestones. The limestone in core C contains fine calcite and dolomite crystals with fine disperse silica (Figure C- 6). The particle shown in Figure C- 6 (A-D) appears to contain significant amount of potentially reactive silica. Some of the coarse-aggregate particles contain high amount of chert and microcrystalline silica as shown in Figure C- 7. The coarse aggregates in Core D also contain reactive silica: quartz with sub-grain boundaries, Figure C- 8 (A-B); fine grained calcite matrix with fine disperse silica (Figure C- 8 C-D); and some amorphous silica within limestone, Figure C- 8 (E-F). Empty and filled cracks within coarse aggregates have been observed in cores C and D.

Reactive aggregate particles shown in Figure C- 7 (Core C) are similar to the reactive particles observed in the early/highly expansive limestones (EE/HR) examined in the current ASR project. Such aggregates can show ASR deterioration within 10 years after construction, consistent with the possible ASR deterioration of the new patch of concrete pavement within 11 years after construction.

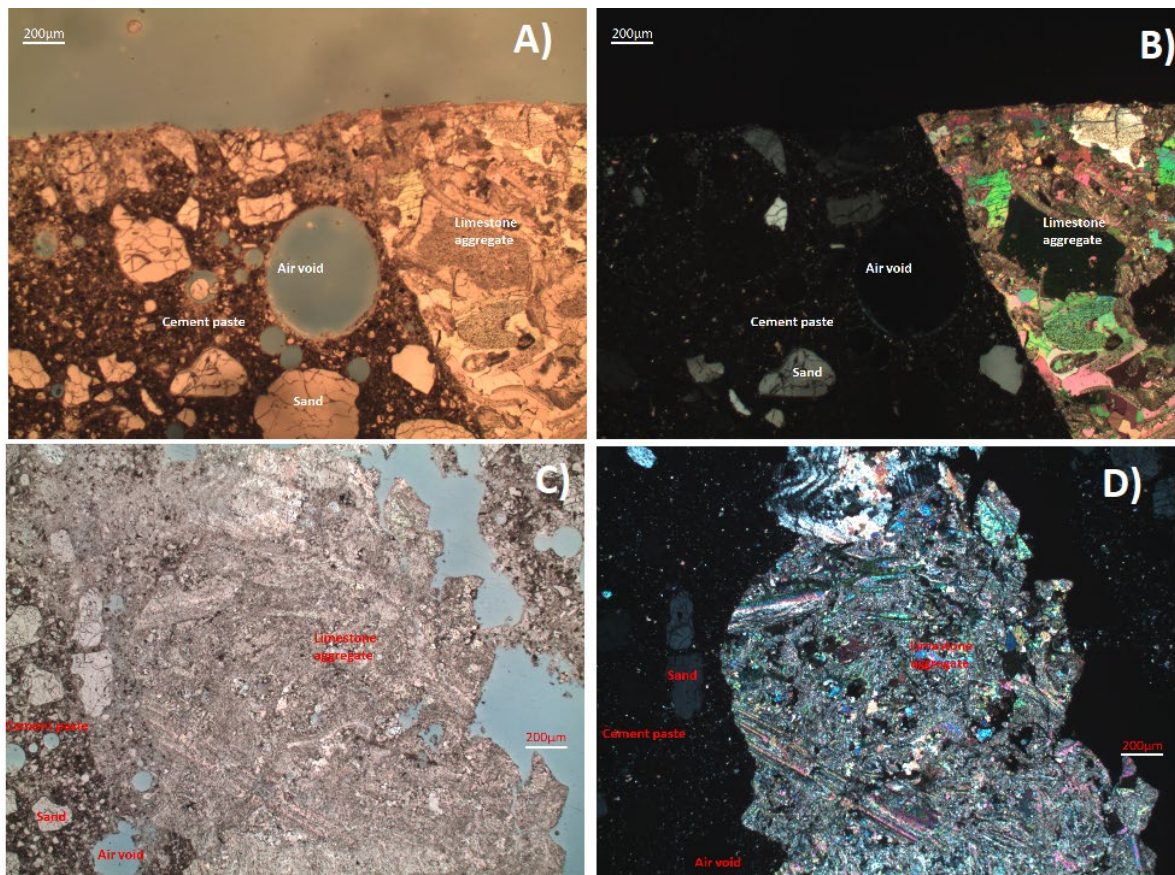


Figure C- 6 Optical micrographs from Core C under plain (left) and crossed polarizer (right) showing limestone with fine-grain calcite crystals and potentially fine reactive silica.

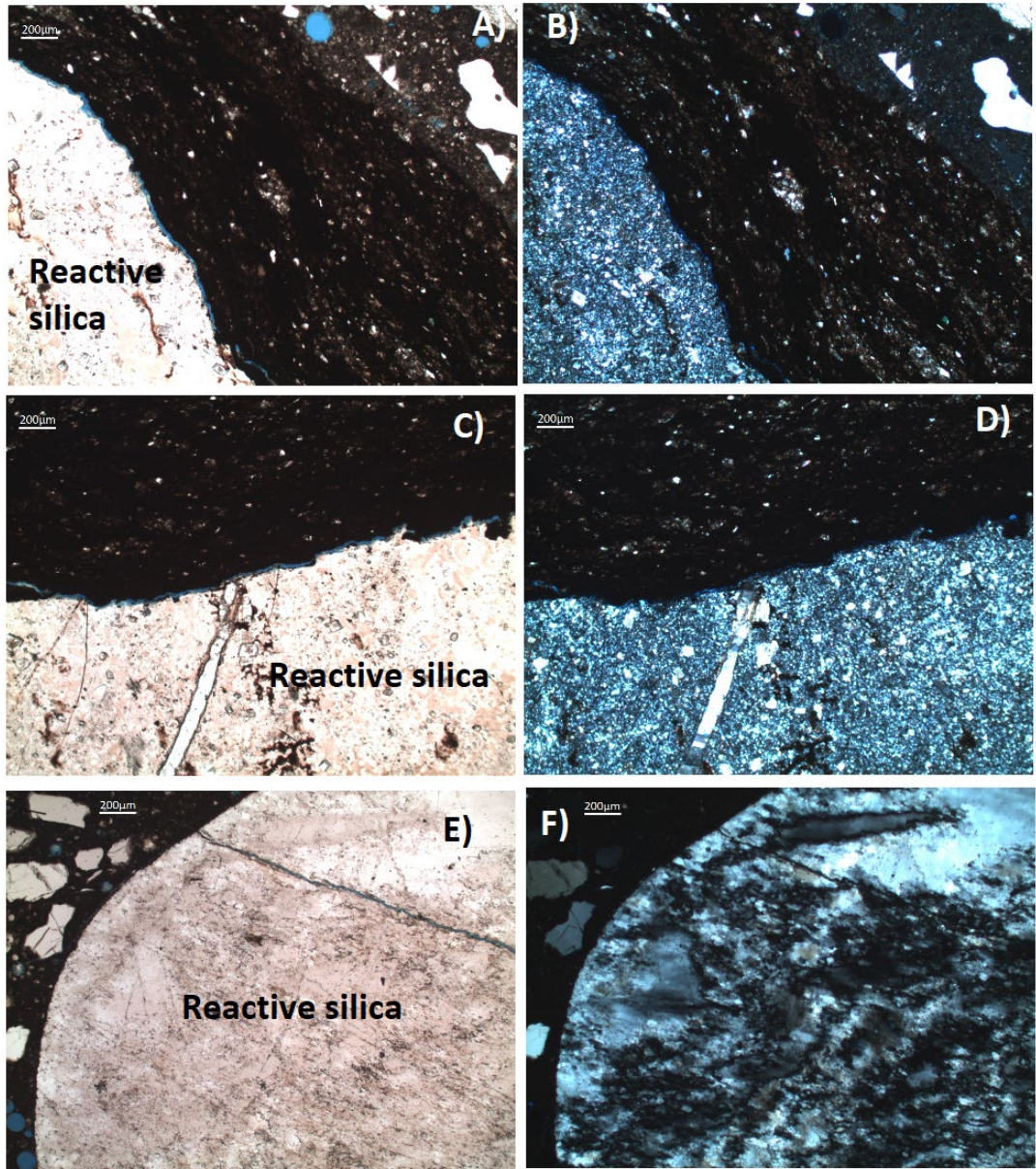


Figure C- 7 Optical micrographs from Core C under plain (left) and crossed polarizer (right) showing the presence of highly reactive silica (chert A-D) and microcrystalline quartz (E-F) within coarse aggrates.

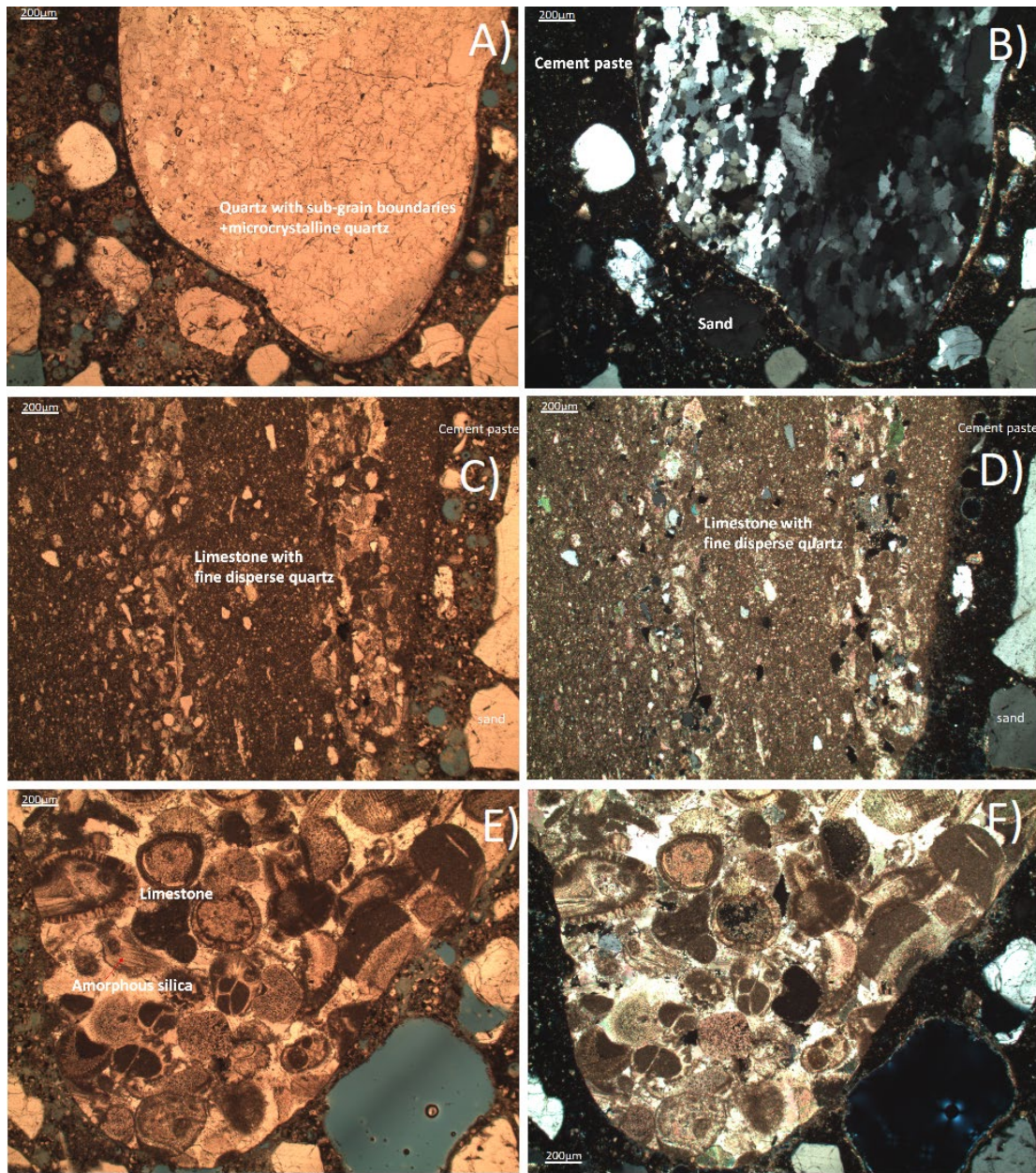


Figure C- 8 Optical micrographs from Core D under plain (left) and crossed polarizer (right) showing the presence of reactive silica: (A &B: quartz with sub-grain boundaries); (C&D) fine-grain calcite/dolomite matrix with fine disperse silica; and limestone with some amorphous silica (E &F)

Scanning electron microscopy (SEM) observations: Significant amount of ASR gel was observed in Core C within chert, Figure C- 9 (A-B), and carbonate particles, Figure C- 9 (C-D). The ASR gel within the carbonate particle in Figure C- 9(D) appeared to contain small amounts of Mg and Na, the Mg is probably related to the brucite from dedolomitization, consistent with observations from reactive carbonate aggregates in literature. Some of dolomite diamond-like crystals appeared to exhibit a reaction rim which can suggest a dedolomitization process (Traditional ACR). Cracks with ASR gel extending from reactive particles to the cement paste were observed as shown in Figure C- 19. ASR gel and cracks

were also observed in Core D as shown in Figure C- 10. These observations confirm the presence of ASR deterioration mechanism in the concrete pavement.

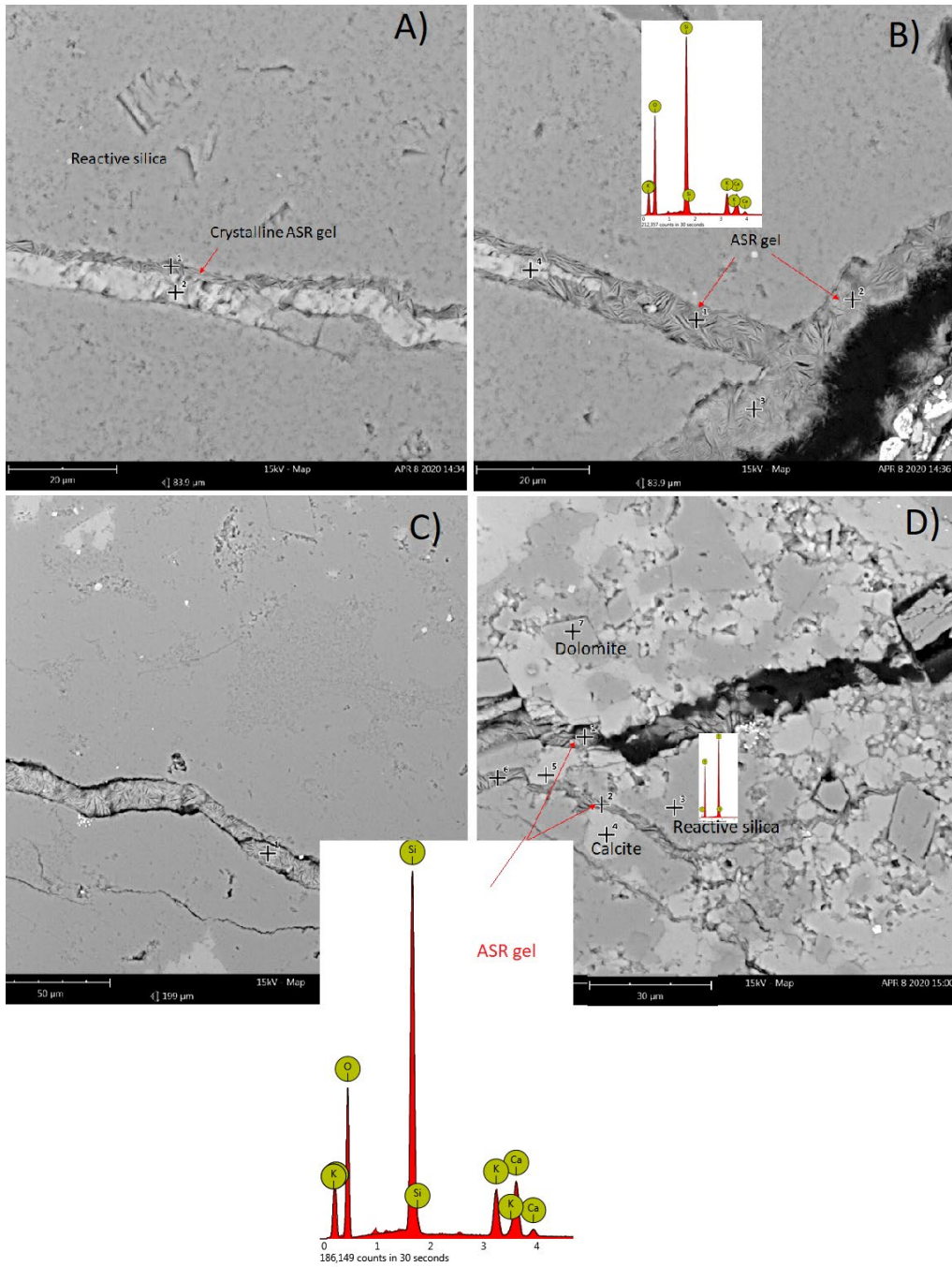


Figure C- 9 SEM micrographs from Core C: (A &B) ASR gel within chert particles; (C& D) ASR gel within limestone particles

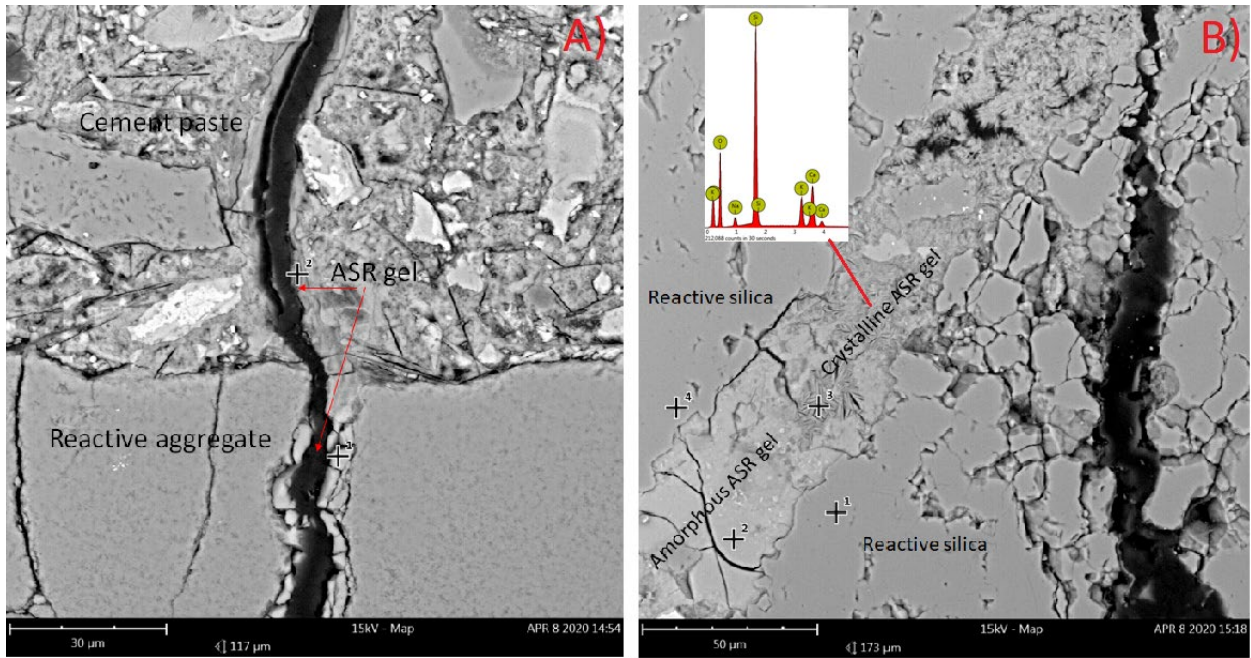


Figure C- 19 SEM micrographs from Core C: (A) crack with ASR gel extending to the paste, (B) crack with crystalline and amorphous ASR gel in reactive aggregate

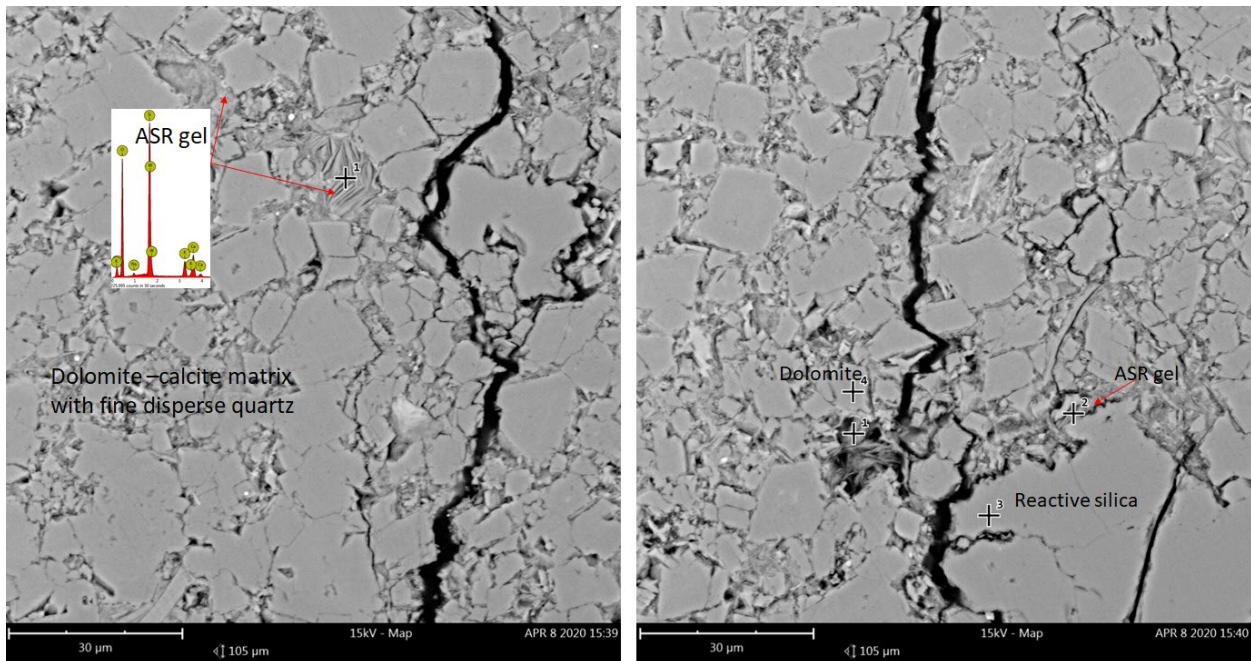


Figure C- 10 SEM micrographs from Core D: showing cracks and ASR gel within reactive dolomite aggregates

C.4.3 Conclusion

Typical symptoms of ASR deterioration mechanism were observed in two structures within the state of Tennessee. The first case is a 25-30 year old interchange structure in east Tennessee near Flag Pond, TN which manifests cracking in concrete pavement, the barrier wall, and in the bridge deck. The second case is a concrete pavement in Memphis, TN that was originally constructed in 1980 (39 years old) and had a rehab project 11 years ago. The concrete pavement shows cracking throughout the original concrete as well as in the new patches from the rehab project.

Two core samples were collected from each site and delivered to the research team at UTK to determine whether ASR is the source of the concrete deterioration. Petrographic thin sections were prepared from the cores and examined under the optical microscope and scanning electron microscope (SEM). The examinations of the cores confirmed the existence of ASR deterioration mechanism in the two structures. The siliceous fine aggregate used in the interchange structure in Flag Pond, TN seemed to be very reactive as indicated by the significant cracking and ASR gel within the particles. The ASR deterioration in the concrete pavement in Memphis, TN seemed to be caused by a highly reactive limestone aggregate.