7-2015

Alkali Silica Reaction Mitigation Using High Volume Class C Fly Ash

William Joseph Phillips
University of Arkansas, Fayetteville

Recommended Citation

Phillips, William Joseph, "Alkali Silica Reaction Mitigation Using High Volume Class C Fly Ash" (2015). *Theses and Dissertations*. 1306.
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Alkali Silica Reaction Mitigation Using High Volume Class C Fly Ash

A thesis submitted in partial fulfillment
Of the requirements for the degree of
Masters of Science in Civil Engineering

By
William J. Phillips
Missouri University of Science & Technology
Bachelors of Science in Civil Engineering, 2013

July 2015
University of Arkansas

This thesis is approved for recommendation to the Graduate Council

Dr. W. Micah Hale
Thesis Director

Dr. Ernest Heymsfield
Committee Member

Dr. Clinton M. Wood
Committee Member

ABSTRACT

Alkali-Silica Reaction (ASR) is a neutralization reaction that occurs between an acid (silicic acid) and a basic pH pore solution (Calcium Oxide, Potassium Oxide, and Sodium Oxide). ASR causes deleterious expansion within concrete, which can cause durability issues decreasing the life span of concrete. ASR in concrete has been found in increasing quantities since its discovery in 1940 by Stanton. Several cases of ASR have occurred in Arkansas near Fayetteville, Pine Bluff, and Little Rock. The purpose of this research was to develop preventative measures using Class C fly ash in concrete, which contains the moderately reactive aggregates found in the Arkansas River.

The research used locally available fly ashes in order to represent the materials used in conjunction with the Arkansas River fine aggregates. The research includes three regional, Class C fly ashes. Two fine aggregate (sand) sources are included in order to evaluate the ability of Class C fly ashes in preventing ASR. The first fine aggregate evaluated was Arkansas River sand from Van Buren, AR. This is a moderately reactive aggregate that was used and is currently used in concrete throughout the region. In addition to the river sand, a highly reactive fine aggregate (Jobe-Newman), was evaluated to determine the ability of Class C fly ashes in preventing ASR when aggregates of different levels of reactivity are used. Jobe-Newman aggregate has been documented by many researchers as a highly reactive source of silica. Class F fly ashes have been previously prescribed for preventing ASR when there is a source of reactive aggregates (ACI Committee 221 1998). However, the availability of Class F fly ash in regions, such as Arkansas, is somewhat limited compared to the availability of Class C fly ash. This research examines the use Class C fly ash for preventing ASR in concretes containing moderately reactive aggregates.

Based upon the AMBT results for Arkansas River sand Class C fly ash was found to be able to impede alkali silica reaction to the point of making concrete non-reactive based upon the accelerated mortar bar test as defined by ASTM C1260 and ASTM C1567. Also, based on the accelerated mortar bar test results recommendations were made as to how to better classify fly ashes compared to the current ASTM C618 including placing limits on MgO content and analyzing fly ashes by a ratio of sum of alkalis: sum of oxides instead of simply classifying a fly ash based upon sum of oxides.

ACKNOWLEDGMENTS

First I would like to thank Headwaters for donating the fly ash needed for the testing. Also I would like to thank Matthew Widener, Doddridge Davis, and Sydney Dickson for helping in mixing the specimens and donating their time when they didn't have to help me. I would also like to thank the two previous people doing research on this subject Cameron Murray and Richard Deschenes Jr. for setting up the ground work for my research. Also I would like to thank all the people at the ENRC who were always willing to help me especially David Peachee who several times gave me good ideas from a different perspective than mine that I truly appreciated.

I would like to specifically thank Richard Deschenes Jr. for helping to further my knowledge on ASR whether it involve fly ash, pessimum effects, mechanism, or the general history. Not only did he help me grow in my knowledge, but he was always helpful when I tried to improve our testing apparatuses, when I needed someone to look over my papers, or check calculations. Without his help I would have had a much more difficult time getting accurate results and being able to get to a point where I could submit a thesis.

I would like to thank Dr. Micah Hale for always having an open door policy and not only responding during work hours but being patient enough to help me on nights or weekends when I had questions. Moreover his several revisions on my thesis to improve its quality and clarity. Also without him I don't know if I would have ended up being interested in materials testing enough to take the job I did without working for him on this research. Whenever I had an idea to improve our work conditions he would always be willing to work with me whether it be a new set of forms or a small environmental chamber for the CPT's.

Finally I would like to thank the teachers of the department. I really enjoyed being in a close knit department and being able to learn from the teachers in an enjoyable environment

whether the topic be concrete and structures or soils and foundations. I know coming out of school I have a well-rounded education which is priceless. I also appreciate the teachers on my committee, often students forget the amount of time it takes to read through and analyze a thesis that can easily take up time outside of the typical 8 to 5 schedule.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOTATIONS

AAR – Akali Aggregate Reaction

ACI – American Concrete Institute

ACR – Alkali Carbonate Reaction

AHTD – Arkansas State Highway Transportation Department

Al_2O_3 – Aluminum Oxide

AMBT – Accelerated Mortar Bar Test

ASR – Akali Silica Reaction

ASTM – American Standards of Testing Materials

CaO – Calcium Oxide

CH – Calcium Hydroxide

CSA – Canadian Standards Association

CSH – Calcium Silicate Hydrate

CPT – Concrete Prism Test

DH – Dolet Hills, Louisiana Class F fly ash

Fe_2O_3 – Iron Oxide

K_2O – Potassium Oxide

MK – Muskogee, Oklahoma Class C fly ash

ML – Martin Lake, Alabama Class F fly ash

Na_2O – Sodium Oxide

NaOH – Sodium Hydroxide

NK – Newark, Arkansas Class C fly ash

SI – Sikeston, Arkansas Class C fly ash

SiO_2 – Silicon Dioxide

WB – White Bluff, Arkansas Class C fly ash

TERMINOLOGY

Terminology shall conform to ASTM C125 and ASTM C294.

CHAPTER 1: INTRODUCTION AND RESEARCH OBJECTIVES

1.1 INTRODUCTION

Alkali Silica Reaction (ASR) is a chemical reaction between an acid and a base. The bases in the reaction are the alkalis (CaO, K_2O, and Na_2O), which are present in the alkaline pore solution in the concrete. The silicic acid (H_4SiO_4) is the other half of the reaction, which lies within the aggregates. The reaction takes place within the paste aggregate interface and forms an alkali-silica gel. The gel swells within the concrete and fills the internal voids in the concrete. This causes expansive pressure in the concrete surrounding the aggregate. When the expansive pressure exceeds the tensile strength of the concrete, cracking occurs and can eventually propagate throughout the concrete. ASR can also lead to concrete spalling, loss of concrete strength, and corrosion of reinforcement from the cracking.

The neutralization reaction, ASR, is controlled by two main factors (ACI Committee 221 1998). First, the alkali content of the cement which is reported as total alkali equivalents (Na_2O_e). The alkali content controls the pore pressure alkalinity of the cement (Diamond 1989). Second, the presence and composition of reactive siliceous materials within the aggregate determines the rate of reaction (ACI Committee 221 1998). Another factor that influences the development of alkali-silica gel, is the presence of calcium in the concrete pore solution. A source of calcium is necessary for the gel to form. Alkali-silica gel will form with any calcium not only calcium hydroxide, CH (Diamond 1989). Alkali-silica gel also requires a minimum amount of available moisture for deleterious expansion to occur. Deleterious expansion of concrete specimens will cease when the internal relative humidity falls below 80 percent. The ambient temperature of the concrete specimen may also influence the rate of deleterious expansion; the ASR reaction rate accelerates as temperature increases (ACI Committee 221 1998).

ASR has become an infrastructure problem in concrete structures around the world, especially in regions with high ambient temperatures and relative humidity greater than 80 percent (Diamond 1989). The State of Arkansas is currently experiencing the detrimental effects of ASR. This is partially due to the state's ambient conditions, but another factor is the fine aggregate. Fine aggregate dredged from the Arkansas River, contains chalcedony which is recognized as the second most reactive aggregate next to opal (ACI Committee 201 1991). The Arkansas River is the source for fine aggregate for the majority of the state and will continue to be. Therefore, this research program will examine the use of Class C fly ash as a possible means to prevent ASR in concrete structures and pavements cast in Arkansas.

1.2 OBJECTIVES

The objective of the research project is to prevent future occurrences of ASR in Arkansas through the addition of Class C fly ash in concrete. To achieve this objective, six locally available fly ashes were examined at cement replacement rates of 0 to 40 percent. To initiate ASR, two reactive aggregates were included in the study.

Chapter 2: LITERATURE REVIEW

2.1 ASR LITERATURE

Alkali Silica Reaction (ASR) was first sited for a failure of a structure in California; the structure was the King City Bridge (Stanton 1940). The failure was in the pile caps due to excessive cracking; however, neither the concrete piles nor the concrete trestle showed excessive cracking which led to an investigation of the cause of the excessive cracking within the pile cap. Thomas Stanton was the first researcher to identify and correlate an expansive reaction of the concrete to the reaction between cement and aggregates (Stanton 1940). Mortar bars were cast with several aggregate and cement combinations. The mortar bars were stored in sealed containers to control the environmental conditions. The mortar bars were measured monthly for several years for deleterious expansion. Several of the mortar bars included the same type of fine aggregate used in the bridge pile caps; expansion was measured within a few months. Stanton also tested other aggregates and found deleterious expansion only in some of the mixtures that contained high alkali cement. Stanton found that when the alkali level was greater than 0.45 percent in the cements, deleterious expansion occurred in the concrete mixture (Stanton 1940). Stanton is cited as the researcher to discover ASR and several of his test methods are used to this day including the mortar bar test method.

After his initial paper in 1940, a second paper was written in 1942 (Stanton 1942). In this paper, Stanton found that the cause of the expansion was the reaction between the silica and the cement. Due to this reaction Stanton stated that the cement alkali levels should be limited to 0.60 percent or less in order to prevent ASR. This value is used to this day to specify a cement as being a low alkali cement. Stanton also realized the necessity of identifying reactive aggregates and he determined that using a high alkali would accelerate the reaction. This postulation (using a high alkali cement) is currently used in ASTM C1260 and ASTM C1567 for testing the reactivity of aggregates.

The next major paper analyzing the potential mechanisms of ASR was written by T. C. Powers (Powers 1955). This paper was important as it theorized how the reaction occurred. The theory postulated that a caustic reaction with reactive silica produced abnormal swelling due to the formation of an alkali silica complex which was not in equilibrium with the lime. While this paper was not entirely correct, this paper found that the aggregate was reacting with the highly alkaline cement to produce the expansion. Also this paper increased the understanding of the importance of the pore solution in its ability to increase the reaction rate. This was the first paper to theorize that the pore solution could be causing the reaction through osmosis. This paper was also the first to realize that the alkali-silica gel imbibed water which caused the gel to expand. Powers proposed that as the alkali to silica ratio increased, the rate of expansion also increased. The final addition made by Powers to the understanding of the ASR mechanisms was by how he explained the ASR swells within the sample eventually causing cracks due to the ASR gel having no outlets for the fluid.

While Powers explained many of the bases behind the ASR mechanism, Diamond made correlations between the cement’s alkali content and the water to cement ratio of the concrete (1989). Furthermore Diamond found that the specific alkali (Ca, K, or Na) or its form did not matter when it came to causing ASR. Diamond concluded that all alkalis should be included in the chemical analysis of the binder. Therefore, any alkali can dissolve the reactive silica present in the aggregate into the pore solution and can form ASR gel if a source of calcium is available. This is important as it points out that including all alkalis in the analysis can provide a more accurate understanding of how expansive a concrete mixture can become.

2.2 ASR FLY ASH LITERATURE

In the 1990's, the amount of research that examined using fly ash and other supplementary cementitious materials (SCM) to replace some of cement in the concrete increased (Thomas 1995). The popularity of fly ash and other SCMs increased because of their ability to decrease the amount of alkalis in the binder, their ability to reduce the concrete's permeability, and their ability to consume the excess CaO in the pore solution. This last benefit is key in preventing the ASR gel because there is less available calcium in the pore solution. Calcium is needed to react with the reactive silica to produce ASR gel (Thomas 1995). Fly ash also has the added benefit of reducing the price of the concrete mixture since fly ash is less expensive than cement.

Research performed by Thomas also showed the benefit of using reactive sands to examine the effectiveness of the fly ashes to prevent ASR (1995). Results were attained more quickly than when more slowly reactive aggregates were used. However, it should be noted that short test durations are inappropriate when mixtures contain SCMs because they react more slowly than portland cement. This is why standards and researchers recommend extending the test duration for both the Accelerated Mortar Bar Test (AMBT) and the Concrete Prism Test (CPT) (Shehata 2000; ASTM C1293). Thomas also found that for fly ashes with higher CaO contents, there was a need for higher fly ash replacement rates. This was also the first paper to mention how Class C fly ashes cover a much broader spectrum of reactivity due that the variability in Class C fly ash is not as well defined as the Class F fly ash (Thomas 1995).

Duchesne and Berube also conducted ASR research on concrete mixtures containing SCMs. They observed no significant expansion in concrete specimens that had an alkali hydroxide content of 0.65N or less (1994). They determined that this limit was easier to achieve as the alkali content of the SCM and cement decreased and the total quantity of SCMs increased. Duchesne and Berube determined that Class F fly ashes were more effective at impeding ASR expansion, however at higher replacement rates, Class C fly ash was as effective as Class F fly as in preventing ASR. Therefore, Class C fly ash could be used to prevent ASR in areas where Class F fly ash was not available. Their study was based upon changing the binder content in order to reduce the alkali content of the concrete which would prevent ASR from occurring. This approach is most often the best option because the local aggregates are the most cost effective to use. On the contrary, shipping costs generally prohibit the use of non-reactive aggregates from non-local sources.

Malvar also examined the ability of fly ash to prevent ASR. Malvar stated that the typical Class F fly ash replacement rates for preventing ASR should be between 15 percent and 45 percent (Rogers et al. 2000; Malvar, 2001; and ACI 22. 1R, 1998). Malvar stated that Class C fly ash did not reduce permeability as much as a Class F fly ash at the same replacement rate. Malvar stated that both Class C and F fly ashes can produce a pessimum effect in concrete. The pessimum effect can cause increased expansions in concrete specimens if the replacement rate is too low. Typical fly ash replacement rates, both Class C and Class F, where the pessimum effect occurs are between 10 and 20 percent and for some Class C fly ashes it can be as high as 35 percent. This range is dependent on the CaO content of the fly ash. Malvar cited other researchers—Dunstan, 1982; Malhotra et al. 1994; and Rogers et al. 2000—whose results showed an increase in expansion due to the addition of fly ash at certain replacement rates.

Malvar recommended that fly ash be classified based on their chemical composition (2006). Test data from 5 different studies were used, and the results showed that the ratio of the sum of the alkalis to the sum of the oxides in the fly ash was the best indicator to how well the fly ash would prevent ASR from occurring. Canadian Standards Association (CSA) currently uses the CaO percentage to determine fly ash type. ASTM C618 currently uses sum of oxides to determine fly ash type. Malvar concluded that using the entire chemical composition provides the most accurate picture of how well the fly ash will prevent ASR (2006).

Shehata and Thomas recommended that ASTM C618 be updated to include the CaO percentage when determining the fly ash classification (2000). This is similar to the CSA A23.5 standard for alkali aggregate reactivity. This proposed change would separate Class C fly ashes into a CI and CH classification. CI fly ashes would have a CaO content between 8 percent and 20 percent, while CH fly ashes would have over 20 percent CaO. Their findings showed that all fly ashes included in their study reduced expansion due to ASR as measured by the CPT. The results also showed that the expansion rate decreased as the fly ash content increased of any type of fly ash. Class C or F. At a specific fly ash replacement rate, the expansion generally increased as calcium content of the fly ash increased. Finally they concluded that the AMBT provided a reasonable indication of how a particular fly ash would perform in the CPT (qtd. ASTM C1260 2000; qtd. ASTM C1567 2000; qtd. ASTM C1293 2000). This was a significant finding because many researchers believed the CPT best represented real-world conditions when compared to the AMBT. Therefore, if a concrete mixture can pass the CPT, then the likelihood of ASR occurring in the field is typically low (Shehata 2001). This was important because many researchers recommend performing the CPT for two years to ensure reliable results whereas the AMBT requires only 14 or 28 days.

The American Concrete Institute (ACI), Committee 221, Aggregates, prepared the state of the art report, ACI 221.1R 98, on Alkali-Aggregate Reactivity which included Alkali Carbonate Reaction (ACR) and Alkali Silica Reaction (ASR). This report stated Class F fly ashes can prevent ASR at cement replacement rates of 15 to 30 percent by mass. The report also states that Class C fly ashes may be less efficient in reducing ASR expansions and may require replacement rates greater than 30 %. The report lists three ASR related benefits from using fly ash in concrete:

1. The Calcium Silicate Hydrate (CSH) that is produced from the pozzolanic reaction has a lower CaO: SiO_2 (C/S) ratio than the CSH that is produced when the calcium silicates from the portland cement react with water. This CSH gel with a lower C/S has a greater capacity to entrap alkalies and reduce the pH of the concrete pore fluid.

2. The pozzolanic reaction consumes calcium hydroxide (CH) which is an abundant hydration product in concrete. The ASR gel that forms in a paste with reduced amounts of calcium hydroxide may have lower swelling characteristics.

3. The pozzolanic reaction produces a denser paste by reducing the amount of calcium hydroxide and producing additional CSH gel. The additional CSH is at the paste-aggregate interface. This reduces the mobility of ions and possibly slows the ASR reaction rate. It also reduces the concrete's permeability which helps prevent external moisture and alkalis from entering the concrete.

2.3 ASR TEST METHODS

There are many test methods used to predict whether ASR will occur or assist materials used to prevent ASR. The test methods included in this study were the AMBT and the CPT (ASTM C1260; ASTM C1567; ASTM C1293). The current test methods are shown in Figure 2.1. This figure divides the tests into ones that examine the aggregates and ones that examines the cement and aggregate combinations.

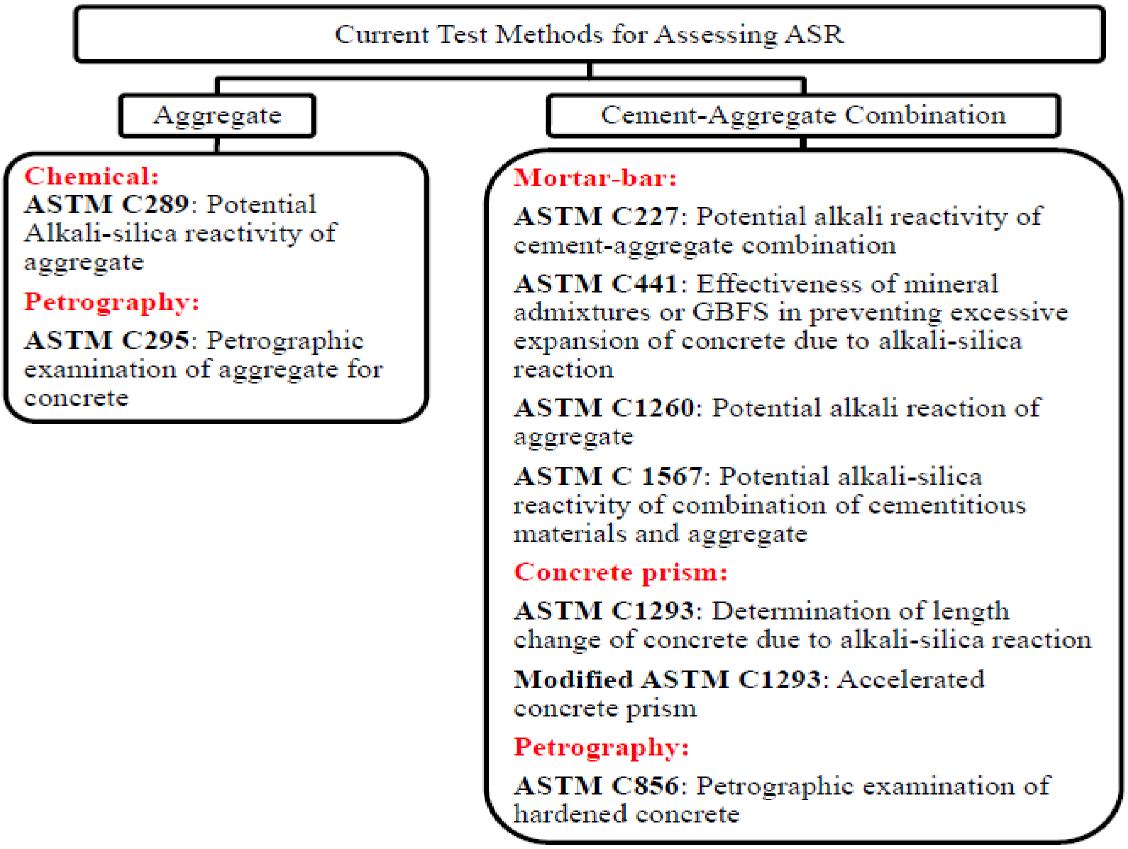

Figure 2.1 – Current Test Methods for Assessing ASR used with Permission of Richard Deschenes (Deschenes 2014)

AMBTs are known for having the most aggressive test environment. Following a 24 hour curing period, AMBT specimens, which are 1" x 1" by 11", are demolded and placed in a heated water bath for 24 hours at a temperature of 176°F ± 2°F to remove expansion due to temperature change. After 24 hours, the specimens are removed and their initial length is measured using a length change comparator (Figure 2.2). After the initial reading, the specimens are placed in a 1 N sodium hydroxide solution within a water proof container and returned to the heated water bath. Measurements are taken at 0 (initial), 4, 7, 14, 21, and 28 days. Due to the aggressive test conditions (the highly alkaline solution, the 100 percent relative humidity, and the high temperature), the results are generally conservative for all aggregates except for granitic gneisses and a few other aggregates as stated in ASTM C1567. The aggregates tested in this research project do not contain any of the aforementioned aggregates.

Figure 2.2 – AMBT left to right specimens. Specimens in molds, and specimens in alkali bath (Deschenes 2014)

The test produces results very quickly and also detects reactivity in slowly reactive aggregates (ACI Committee 221 1998). The test conditions are severe and often cause expansion in aggregates that perform well in field concrete mixtures (Thomas et al. 2006). This is due to the high water temperature when compared to ambient air temperature. The storage of the mortar specimens in an alkaline solution also contributes to its severity. The storage in high alkaline solution increases the pH of the pore solution which forces the neutralization reaction. Due to the test's severity, if aggregates pass ASTM C1260 or ASTM C1567, the chance of ASR occurring is small if the aggregate do not contain granitic gneisses or metabasalts. This was important as both of the aforementioned rock types have been found to be deleteriously expansive in field performance even though their expansion in the AMBT was shown to be non-reactive after 14 day readings required by the ASTM (ASTM C1260).

In the CPT, the expansion of concrete specimens is measured over the course of at least one year (ASTM C1293). The CPT examines concrete mixtures whereas the AMBT examines mortar mixtures. CPT specimens are cast with cement having an alkali content of approximately

0.90 percent. The alkali content is then increased to 1.25 percent using sodium hydroxide. When mixtures contain high volumes of fly ash, the testing duration is increased to 2 years. This accounts for the pozzolanic reaction of the fly ash when compared to mixtures containing only portland cement. For the CPT, concrete prisms have dimensions of 3” x 3” x 11”. The test is generally considered a better predictor of ASR potential that the AMBT. This is due to a lower temperature (100°F ± 4°F), a larger specimen size, using concrete instead of mortar, and not being stored in a high alkaline solution. Another test is the Modified Concrete Prism Test or Accelerated Concrete Prism Test (ACPT). This test is similar to the CPT with the exception of test duration and temperature (Fournier et al. 2004). The ACPT test duration is typically 3 months and with high volume SCM replacement the test should be performed for 6 months. In the ACPT, specimens are stored at 140°F ± 4°F.

One of the more reliable tests involves casting exposure blocks (Rogers, Lane, and Hooton 2001). The exposure blocks are cast with a high alkali cement and then boosted to 1.25 percent using sodium hydroxide pellets. These blocks are 15” x 15” x 28” and are stored outdoors. The blocks are monitored for expansion for a minimum 5 years. While this test takes the longest to obtain results, the method produces very few false positives or negatives.

Other test methods include a petrographic analysis of the aggregate. In this test, the type and amount of reactive silica in a sample of aggregate is determined. High skill is required to properly perform this test. This test only determines if a fine aggregate contains reactive silica. The test does not determine how the aggregate will react with cement. Similar to a petrographic analysis is ASTM C856. In this test, cores taken from existing concrete are split and polished. After polishing, the sample is marked into a matrix and the number of cracks and ASR gel filled air voids are counted in each box of the matrix. Based upon the number of cracks and filled air voids, the amount of ASR damage in the specimen can be determined.

2.4 CONCLUSION

The literature showed that the addition of Class C or Class F can prevent ASR from occurring when reactive aggregates are used. Researchers have shown that expansion due to ASR decreases as the fly ash content, either Class C or F, increases. ACI Committee 221 recommended Class F fly ash contents of 15 to 30 percent and Class C fly ash contents of greater than 30 percent may be necessary to prevent ASR. However, there is limited data on moderately reactive aggregates, such as that obtained from the Arkansas River. This research project will determine the amount of Class C fly ash required to prevent ASR in concrete containing moderately reactive aggregate. The research will also recommend the content of Class C fly necessary to prevent ASR when the concrete contains highly reactive aggregates. Finally, the project will determine the most effective fly ash composition in preventing ASR.

CHAPTER 3: TESTING PROGRAM

3.1 INTRODUCTION

The goal of the research project was to determine if Class C fly ash could be used to prevent ASR from occurring in concrete mixtures containing fine aggregate from the Arkansas River. The AMBT (ASTM C1260 and 1567) and CPT (ASTM C1293) were used to determine the effectiveness of the fly ashes. Four locally available Class C fly ashes and two regionally available Class F fly ashes were included in the study. The replacement rates ranged from zero to 40 percent. To ensure ASR occurred, several mixtures were cast with a fine aggregate, Jobe-Newman that has been a documented source of reactive silica.

Class C and Class F fly ashes were examined to compare how effectively Class C fly ash prevents ASR when compared to Class F fly ashes. It has been documented in the literature that Class F is more effective than Class C fly ash in preventing ASR (ACI Committee 221 1998). However, Arkansas only produces Class C fly ash, and it can be cost prohibitive to transport Class F fly ash to Arkansas. Also, fine aggregate from the Arkansas River in Van Buren, AR is classified as potentially deleteriously, and therefore Class C fly ash may prevent ASR when Arkansas River Sand is used due to the lower reactivity when compared to jobe sand.

3.2 MATERIALS

The materials used in the concrete specimens included fine aggregate (sand), coarse aggregate, cement, fly ash, water, and sodium hydroxide (NaOH) pellets. Understanding the different materials used and their purpose reveals the reasoning for the testing and provides insight into the results. Each material used in the research program is discussed in greater detail in the following sections.

3.2.1 FINE AGGREGATES

One of the fine aggregates included in this study was obtained from the Arkansas River in Van Buren, AR. This aggregate was used in the I-540 barrier wall. Based on the petrography report obtained from Construction Technologies Laboratory Group (CTL Group), this fine aggregate, specifically chalcedony, was the source of reactive silica (CTL Group 2012). Previous testing at the University of Arkansas has also confirmed that this fine aggregate was potentially reactive based the results of the AMBT (ASTM C1260). Figure 3.1 shows that mortar bars containing this fine aggregate (labeled FSRS Spec. and FSRS Natural) has an expansion greater the 0.10% but less than 0.20% at 14 days of age. At this expansion, ASTM C1260 defines the aggregate as being potentially reaction. The Figure 3.1 terms Coarse, Spec, and Natural refer to the fine aggregate gradation.

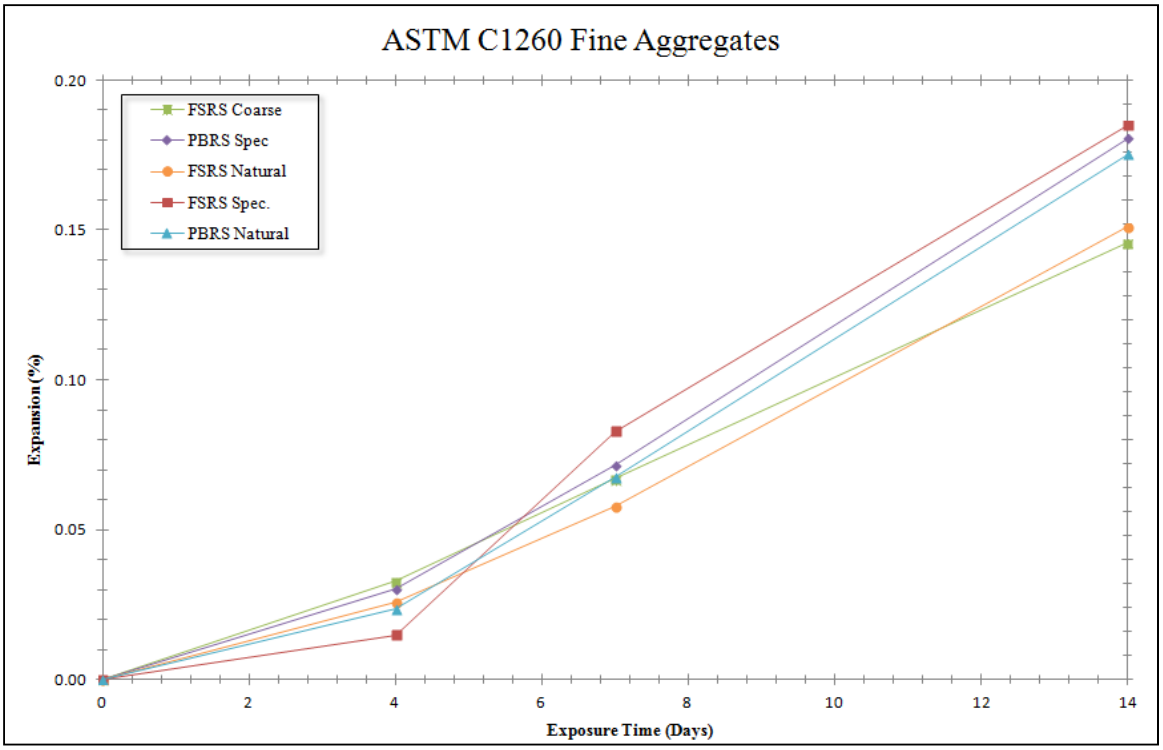

Figure 3.1 – AMBT of Arkansas River Fine Aggregate (Deschenes 2014)

The second fine aggregate included in the research project was a combination of 60 percent Arkansas River Sand and 40 percent Jobe-Newman Sand from El Paso, Texas. The Jobe-Newman fine aggregate has been classified as highly reactive (Deschenes 2014). Results from the accelerated mortar bar testing conducted previously at the University of Arkansas on specimens cast using this aggregate blend are shown below in Figure 3.2. Once again, ASTM C1260 defines an aggregate as being potentially reactive if the expansion is between 0.10 and 0.20% and reactive at expansions greater than 0.20 percent. For the samples in Figure 3.2, the Jobe-Newman fine aggregate accounted for 20 percent and 40 percent of the fine aggregate. The 40 percent Jobe-Newman specimens had expansions greater than 0.5 percent expansions at 14 days of age. Based on these results, a replacement rate of 0.40 percent was chosen to ensure ASR would occur in the concrete specimens. Also, if the Class C fly ash could prevent expansion in a mixture containing 40 percent Jobe-Newman, then Class C fly ash should be able to prevent ASR in mixtures containing fine aggregate from the Arkansas River.

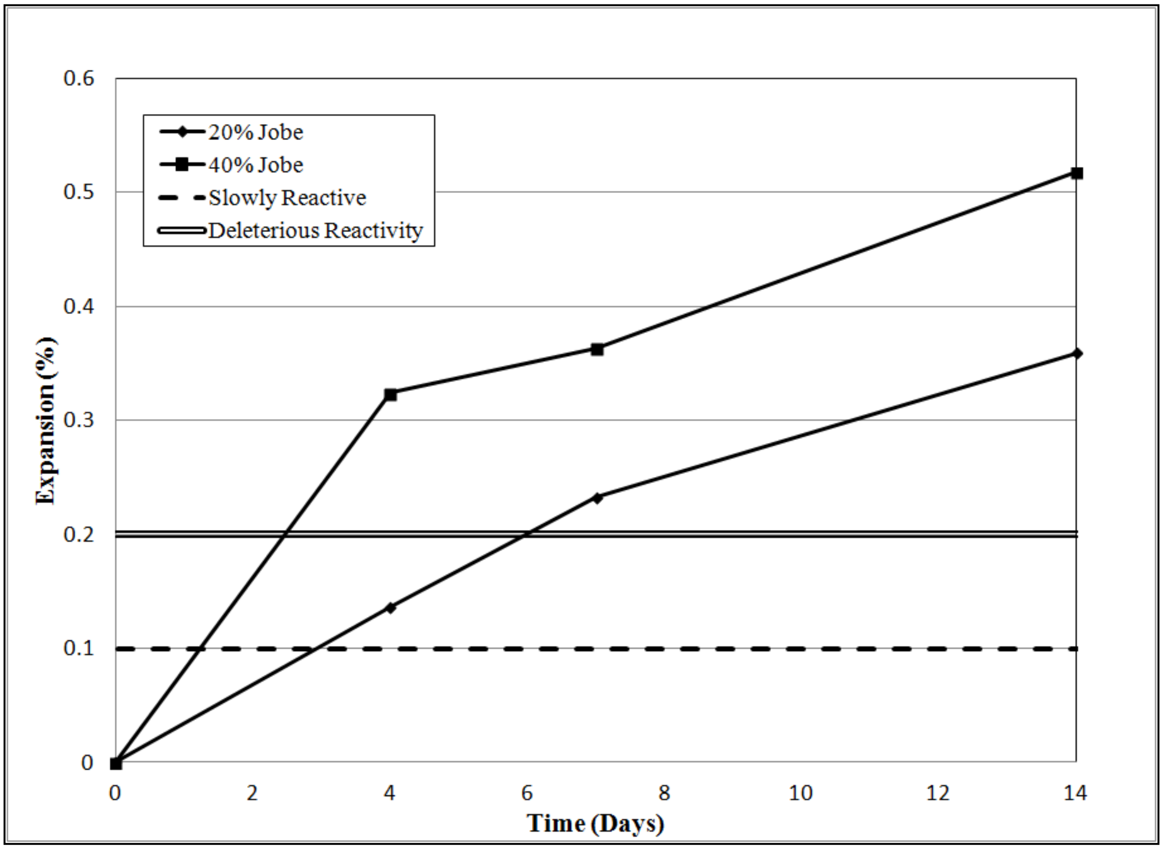

Figure 3.2 – Expansion of AMBT Specimens Containing Jobe – Newman Fine Aggregate (Deschenes 2014)

3.2.2 COARSE AGGREGATE

A crushed limestone served as the coarse aggregate in the study. The coarse aggregate had a nominal maximum aggregate size of 1.0 in. and a specific gravity of 2.50. Prior research conducted at the University of Arkansas determined that the coarse aggregate was non-reactive (Deschenes 2014). Since the fine aggregate was potentially reactive and the blended aggregates, which included the Jobe-Newman, were reactive, including reactive coarse aggregate in the testing program was not necessary.

3.2.3 FLY ASHES

Four Class C fly ashes and two Class F fly ashes were included in the study. These fly ashes tested conformed to ASTM C618. The requirements of ASTM C618 are shown in Table

3.1. The sum of Silicon Dioxide (SiO_2), Aluminum Oxide (Al_2O_3), and Ferrous Oxide (Fe_2O_3) is the only difference, based on ASTM C618, between Class F and Class C fly ash.

Table 3.1 – Fly Ash Classification ASTM C618

ASTM C618	Fly Ash	
	Class F	Class C
$SiO_2 + Al_2O_3 + Fe_2O_3$	70.0 % min.	50.0 % min.
SO_3	5.0 % max.	5.0 % max.
Moisture Content	3.0 % max.	3.0 % max.
Loss on Ignition	6.0 % max.	6.0 % max.

The fly ashes evaluated in the study included Class C fly ash from the following power plants: White Bluff, Arkansas; Newark, Arkansas; Sikeston, Missouri; and Muskogee, Oklahoma. The Class F fly ashes were from power plants located in Martin Lake in Tatum, TX and Mansfield, LA (listed as Dolet Hills). The chemical composition data for the fly ash sources are shown in Table 3.2. Typically the higher the oxide content in the fly ash, the lower the expansion due to ASR. The potential for ASR in a concrete decreases as the the alkali content (CaO, K_2O, Na_2O, and MgO) decreases in fly ash. The current classification system (ASTM C618) as shown in Table 3.1 only includes the oxides content. Shehata recommended changing the classification to use the CaO content of the fly ash (2000). However, Malvar found that using both the oxide content and the alkali content was a better predictor of how affective fly ash impedes ASR (2006). Based upon Malvar's findings the total alkali content to total oxide ratio would be more accurate and should be used to analyze the effectiveness of the fly ash in preventing ASR (2006). The total alkali to total oxide ratio along with the CaO/SiO_2 is shown in Table 3.3 for all fly ashes included in the study.

Table 3.2 – Cementitious Material Properties

Fly Ash	Chemical Compositions (%)								
	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	MgO	$\sum$ Oxides	$\sum$ Alkalis
White Bluff (WB)	36.73	21.49	5.68	22.70	1.48	0.57	4.30	63.90	29.05
Newark (NK)	36.42	20.07	6.20	24.24	1.52	0.56	4.72	62.69	31.04
Sikeston (SI)	42.43	21.33	5.43	20.28	1.18	0.71	4.43	69.19	26.60
Muskogee (MK)	36.68	20.99	6.01	25.17	N/A	N/A	5.14	63.68	30.31
Martin Lake (ML)	50.34	20.68	8.58	10.46	0.67	0.67	2.64	79.60	14.82
Dolet Hills (DH)	58.75	19.78	9.77	5.46	0.90	0.90	1.74	88.30	9.40
0. 89% Alkali Cement	19.88	4.09	3.60	63.50	0.25	0.48	2.12	27.57	66.35

Table 3.3 – Fly Ash Composition Analysis

Fly Ash	CaO/SiO_2	$\sum$ Alkalis / $\sum$ Oxides
White Bluff (WB)	0.62	0.45
Newark (NK)	0.67	0.50
Sikeston (SI)	0.48	0.38
Muskogee (MK)	0.69	0.48
Martin Lake (ML)	0.21	0.19
Dolet Hills (DH)	0.09	0.11
0. 89% Alkali Cement	3.19	2.41

3.2.4 CEMENT

Two sources of Type I/II portland cement was used in all mortar mixtures. The first cement had an alkali content of less than 0.60%. This cement was used for the AMBT as the alkali content does not matter since the specimens were submerged in a 1 N NaOH solution. This solution provides unlimited alkalis to the test specimens and therefore the alkali content of the cement is not a factor. The second cement had an alkali content of 0.89%. This cement was used for the CPT (ASTM C1293). This test requires the cement have 0.9 ± 0.1% alkali content. This prevents alkali from being depleted from the pore solution which would result in an inaccurate test.

3.2.5 SODIUM HYDROXIDE

Sodium hydroxide (NaOH) is a water-soluble compound which is used to boost the alkalinity (pH) in the concrete to force the ASR to occur as long as the sand is reactive. NaOH dissolves the reactive silica into the pore solution without causing increased expansion. If calcium was used to increase pH, such as $Ca(OH)_2$ (slaked lime), the calcium would increase expansion in the specimen rendering inaccurate results since the cement would react for reasons other than increased pH.

3.3 EXPERIMENTAL PROCEDURES

3.3.1 AMBT

The AMBT was performed in accordance with ASTM C1260 and ASTM C1567. The test duration and inclusion of SCMs was the only difference between ASTM C1260 and C1567. The test duration for ASTM C1260 was 14 days and for ASTM C1567 the duration is 28 days. The extended duration for ASTM C1567 accounts for the addition of SCMs. The mortar mixtures in ASTM C1260 contain only portland cement.

For each mixture tested, three mortar bars were cast with dimensions of 1” x 1” x 11”. The specimens were cured for a day at a minimum relative humidity of 50% and at 73.4 ºF ± 2 ºF. After the specimens were removed from their molds, they were placed in a water bath for 24 hours at a temperature of 176 ºF ± 2 ºF. After initial readings, the specimens were submerged in a 1 N solution of NaOH and in a water tight container. The container was then placed back into the water bath residing at a temperature of 176 ºF ± 2 ºF. Expansion readings were taken at 0, 4, 7, 14, 21, and 28 days using a micrometer. The readings were converted into percent strain for analysis. According the ASTM standards, if the mortar bar expansion was less than 0.10 percent at 14 days for ASTM C1260 or at 28 days for ASTM C1567, the aggregate was classified as non-reactive. If the expansion was between 0.1 and 0.2 percent at 14 days (ASTM C1260) or 28 days (ASTM C1567), the aggregate was considered potentially reactive. If the expansion was greater than 0.2 percent expansion at 14 (ASTM C1260) or 28 days (ASTM C1567), the aggregate was considered deleteriously reactive.

ASTM C1260 and ASTM C1567 prescribe mixture proportions used to cast the mortar specimens. The mixture proportions are shown in Table 3.4. The mixture proportions are identical except for the inclusion of fly ash for the ASTM C1567. The ASTMs specify the amount of fine aggregate retained on the #8, 16, 30, 50, and 100 sieves. For the mixtures containing the Jobe-Newman aggregate, 40% of the aggregate mass listed in the table was replaced with Jobe-Newman. To examine the effect of fly ash, a percentage (0, 20, 30, or 40%) of the binder content was replaced with either Class C or Class F fly ash.

The AMBT testing matrix is shown in Table 3.5. A total of 35 mortar mixtures were examined with either ASTM C1260 or ASTM C1567. Each fly ash was cast at replacement rates of 20, 30, or 40 percent. All fly ashes were cast with either fine aggregate from the Arkansas

River or a combination of 60 percent Arkansas River fine aggregate and 40 percent Jobe-Newman fine aggregate.

Table 3.4 – Mixture proportions (ASTM C1260 and C1567)

Material	Mass (g)
Fine aggregate retained on #8 sieve	99
Fine aggregate retained on #16 sieve	247.5
Fine aggregate retained on #30 sieve	247.5
Fine aggregate retained on #50 sieve	247.5
Fine aggregate retained on #100 sieve	148.5
Binder (cement and fly ash)	440
Water	206.8

Table 3.5- Testing Matrix for the AMBT (ASTM C1260 & ASTM C 1567)

Fly Ash Source	Fine Aggregate	
	AR River Sand, Van Buren	Van Buren + 40% Jobe
Control – No fly ash	X	X
Class C - White Bluff (WB)	X*	X*
Class C – Newark (NK)	X*	X*
Class C – Sikeston (SI)	X*	X*
Class C – Muskogee (MK)	X*	-
Class F – Dolet Hills (DH)	X*	X*
Class F – Martin Lake (ML)	X*	X*

* - 20, 30, and 40% fly ash replacement rates

3.3.2 CPT

The CPT was performed in accordance with ASTM C1293. In this test, the expansion of a set of three concrete prisms with dimensions of 3” x 3” x 11” was measured over a duration of one year. The mixture proportion used to cast the prisms is prescribed by ASTM C1293 and is shown in Table 3.6. For the mixtures containing the Jobe-Newman aggregate, 40 percent of the aggregate mass listed in the table was replaced with Jobe-Newman. To examine the effect of fly ash, a percentage (0, 20, or 40 percent) of the binder content was replaced with either Class C or Class F fly ash.

After casting, the specimens were stored in the environmental chamber for 24 hours at a minimum relative humidity of 50% and at 73.4 ºF ± 2 ºF. After the initial 24 hours, the length of the specimens was measured using a micrometer. The specimens were then placed in a watertight container and placed in a water bath at a temperature of 100 ºF ± 2 ºF. For each of the readings other than the initial reading, the containers were removed from the water bath and placed in the environmental chamber which was maintained at 73.4 ºF ± 2 ºF for 24 hours prior to taking readings. Readings were taken at 1, 7, 28, 56, 90, 180, 270, 365, 455, 545, 635, and 730 days. The readings were taken for an additional year because of the high volume of fly ash that some of the mixtures contained.

The CPT testing matrix is shown below in Table 3.7. This matrix is similar to the AMBT matrix with the exception of the 30% fly ash mixtures. Due to the duration of the test and the required curing space, the 30% replacement rates were removed from the CPT matrix. Additionally, the 20 and 40% replacement rates were the worst (most expansion) and best (least expansion) mixtures respectively examined in the AMBT.

Table 3.6- CPT Batch Weight Van Buren Fine Aggregate Mixture (ASTM C1293)

Material	Weight (lb)
Fine aggregate	36.1
Coarse Aggregate Retained ½" sieve	17.71
Coarse Aggregate Retained 3/8" sieve	17.71
Coarse Aggregate Retained #4 sieve	17.71
Binder (cement and fly ash)	20.98
Water	8.57
Sodium Hydroxide	0.01

Table 3.7 - Testing Matrix for the CPT (ASTM C1293)

Fly Ash Source	Fine Aggregate	
	AR River Sand, Van Buren	Van Buren + 40percent Jobe
Control – No fly ash	X	X
Class C - White Bluff (WB)	X$^+$	X*
Class C – Newark (NK)	X$^+$	X*
Class C – Sikeston (SI)	X$^+$	X*
Class F – Dolet Hills (DH)	X*	X*
Class F – Martin Lake (ML)	X*	X*

* - 40% fly ash replacement rates

$^+$ - 20 and 40% fly ash replacement rates

Chapter 4: RESULTS

4.1 INTRODUCTION

This chapter presents the results from the AMBT and CPT. The AMBT was conducted first, then followed by the CPT. The goal of the research program was to determine the amount of Class C fly ash that was necessary to prevent ASR in concrete mixtures containing fine aggregate from the Arkansas River according to ASTM C1260/C1567 and ASTM C1293.

4.2 AMBT DATA

The AMBT tests were performed in accordance to ASTM C1260 and ASTM C1567. All readings were taken after the standard cure day and temperature acclimation day at 176°F ± 4°F. This was done to ensure that ambient temperatures did not affect the expansion readings. For ASTM C1260, the test duration was 14 days. For ASTM C1567, expansion was measured for 28 days. The additional 14 days was added to account for the pozzolanic reaction.

4.2.1 AMBT DATA FOR ARKANSAS RIVER SAND

The AMBT data are shown in Figures 4.1 through 4.3. In these figures, the mortar mixtures contain fly ash at replacement rates of 20, 30, or 40 percent and fine aggregate from the Arkansas River. In each of the graphs, VB represents the Arkansas River Sand. The Class C fly ashes are Muskogee (MK), Newark (NK), Sikeston (SI), and White Bluff (WB). The Class F fly ashes are Dolet Hills (DH) and Martin Lake (ML). The number after the designation represents the fly ash content. For example, mixture “VB WB 20” contains fine aggregate from the Arkansas River and 20 percent Class C fly ash from White Bluff.

Shown in Figure 4.1 is the expansion data for all the mixtures containing 20 percent fly ash. The figure shows that the control mixture (VB Control) expanded almost 0.24 percent in 28 days which would classify the aggregate as deleteriously reactive. The addition of fly ash, all sources and types, reduced the expansion. For five of the six fly ashes, 20 percent fly ash reduced the 28 day expansion by over 50 percent. With the 20 percent addition of these fly ashes, the aggregate would be classified as non-reactive. The only mortar mixture that did not observe this reduction in expansion was the mixture containing Class C fly ash from Muskogee (VB MK 20). For this fly ash, the MgO content was above 5.0 percent and was the only fly ash with that high of MgO content. MgO content has been correlated to aggregate unsoundness due to its potential to form $Mg(OH)_2$ leading to the release of alkalis into the cement paste increasing ASR (Diamond 1981). Excluding the mixture containing the Muskogee fly ash, there was very little difference between the Class C and Class F fly ashes when cast with the fine aggregate from the Arkansas River. Therefore, based on ASTM C1567 and excluding fly ash with a MgO content greater than 5.0 percent, 20% fly ash (either Class C or Class F) would be effective in preventing ASR in mixtures containing fine aggregate from the Arkansas River.

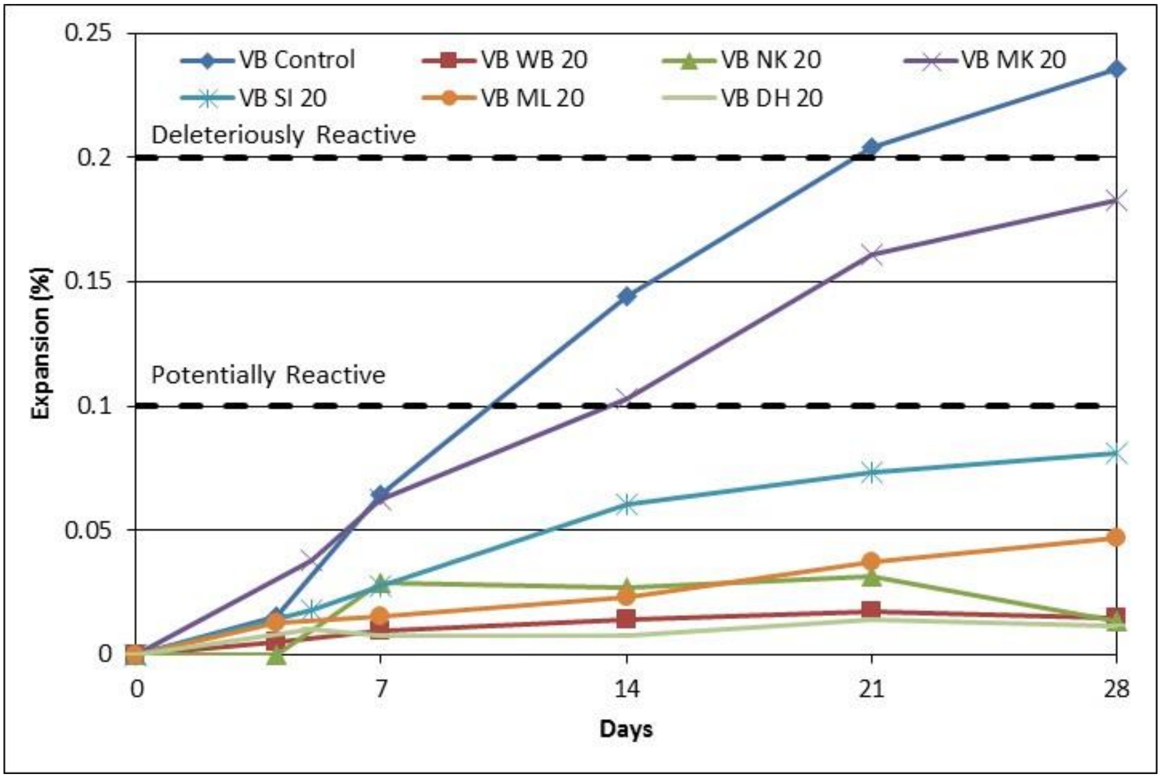

Figure 4.1 - 20% Fly Ash Replacement Rate with Arkansas River Sand

Shown in Figure 4.2 is the expansion data for all the mixtures containing 30% fly ash. At the 30 percent replacement rate, the addition of fly ash, all sources and types, reduced the expansion. For five of the six fly ashes, 30 percent percent fly ash reduced the 28 day expansion by over 75 percent when compared to the control mixture`. With the 30 percent addition of these fly ashes, the aggregate would be classified as non-reactive when used in conjunction with five of the six fly ashes. As with the 20 percent replacement rate, the only fly ash that did not reduce expansion to the same degree as the others was the Class C fly ash from Muskogee (VB MK 30). There was very little difference between the performance of the Class C and Class F fly ashes when mixed with the fine aggregate from the Arkansas River. Therefore, based on ASTM C1567, 30 percent fly ash (either Class C or Class F) would be effective in preventing ASR in mixtures containing fine aggregate from the Arkansas River as long as the fly ash had an MgO content less than 5.0 percent.

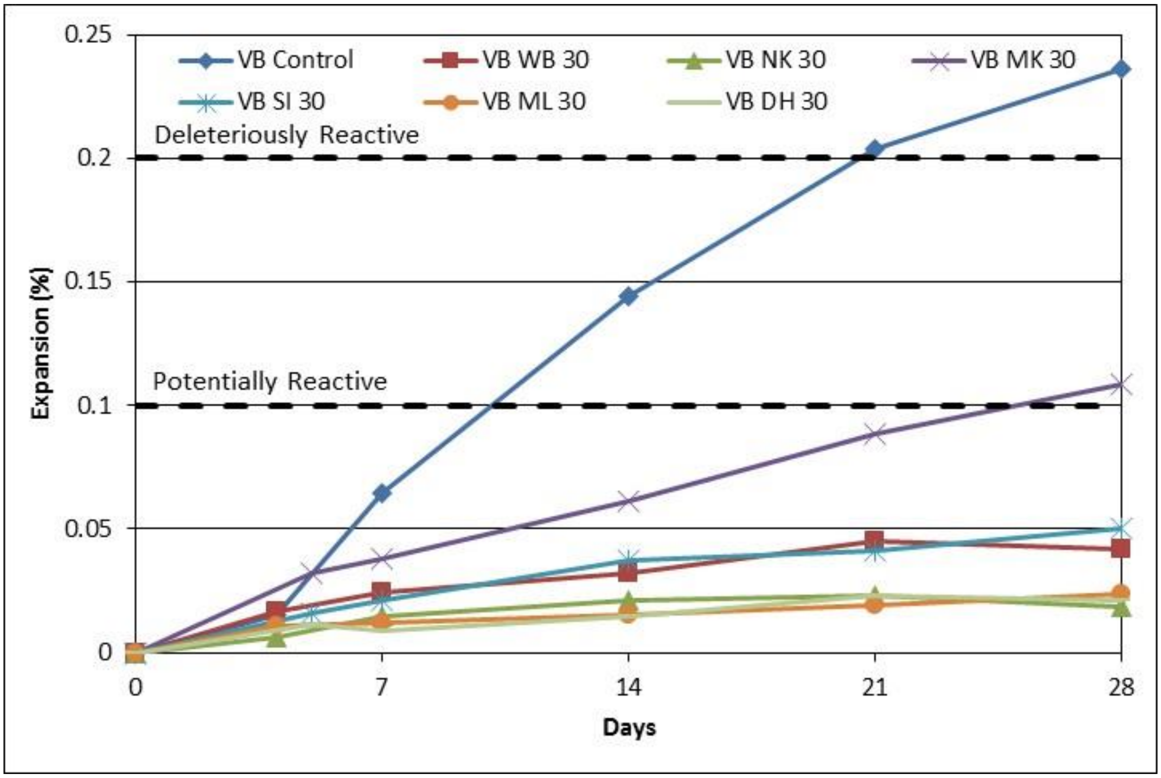

Figure 4.2 - 30% Fly Ash Replacement Rate with Arkansas River Sand

Shown in Figure 4.3 is the expansion data for all the mixtures containing 40 percent fly ash. At the 40 percent replacement rate, the addition of fly ash, all sources and types, reduced the expansion. For all fly ashes, 40 percent fly ash reduced the 28 day expansion by over 75 percent. With the 40 percent addition of any of the fly ashes included in the study, the aggregate would be classified as non-reactive. At this replacement rate, there was almost no difference between the Class C and Class F fly ashes. Therefore, based on ASTM C1567, 40 percent fly ash (either Class C or Class F) would be effective in preventing ASR in mixtures containing this specific fine aggregate.

Regarding the replacement rates, expansion decreased as the replacement rate increased for each specific fly ash when the replacement rate increased from 20 to 30 percent. Excluding the Muskogee (MK), Class C fly ash, there was little change when the replacement rate increased from 30 to 40%. As mentioned earlier, the Muskogee, Class C fly ash contained over 5.0 percent MgO and this could have affected its ability to prevent ASR.

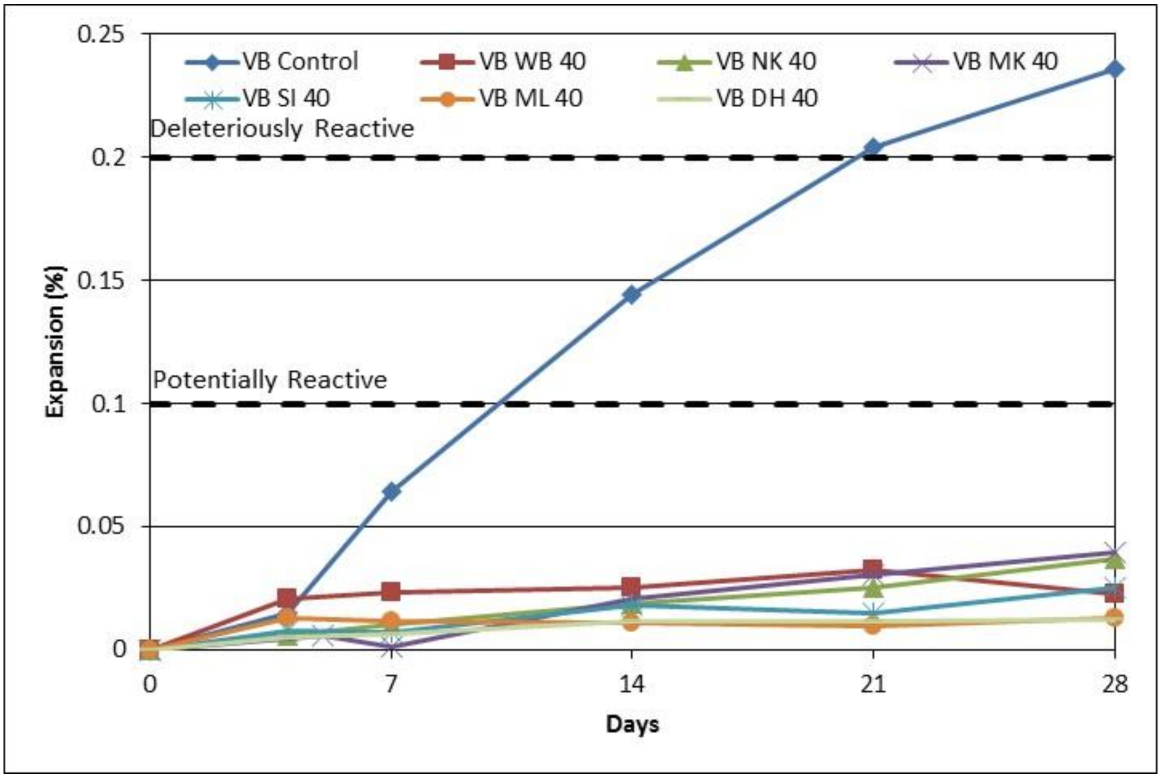

Figure 4.3 – 40% Fly Ash Replacement Rate with Arkansas River Sand

4.2.2 AMBT WITH JOBE-NEWMAN

The second phase of the AMBT examined the effectiveness of the fly ash in mitigating ASR when the mortar contains a highly reactive aggregate. As described in Chapter 3, 40 percent of the fine aggregate (Arkansas River sand) was replaced with Jobe-Newman aggregate. This aggregate has been documented as a highly reactive aggregate and has been used in many research projects. In this second phase of AMBT, the ability of each fly ash (excluding the Class C fly ash from Muskogee) to prevent expansion due to ASR was examined. Due to the

Muskogee fly ash's poor performance in the first phase of the AMBT, it was not included in the second phase of AMBT.

The AMBT results for mortar bars containing 20 percent fly ash and 40 percent Jobe-Newman aggregate are shown in Figure 4.4. When compared to the control mixture shown in Figures 4.1 to 4.3, the effect of the Jobe-Newman aggregate is evident. The control mixtures have an expansion of 0.50 percent at 28 days which is more than twice the expansion observed in the mixtures containing only fine aggregate from the Arkansas River. At a fly ash content of 20 percent, only mixtures containing the Class F fly ashes were classified as potentially reactive while all of the Class C fly ashes were classified as deleteriously reactive.

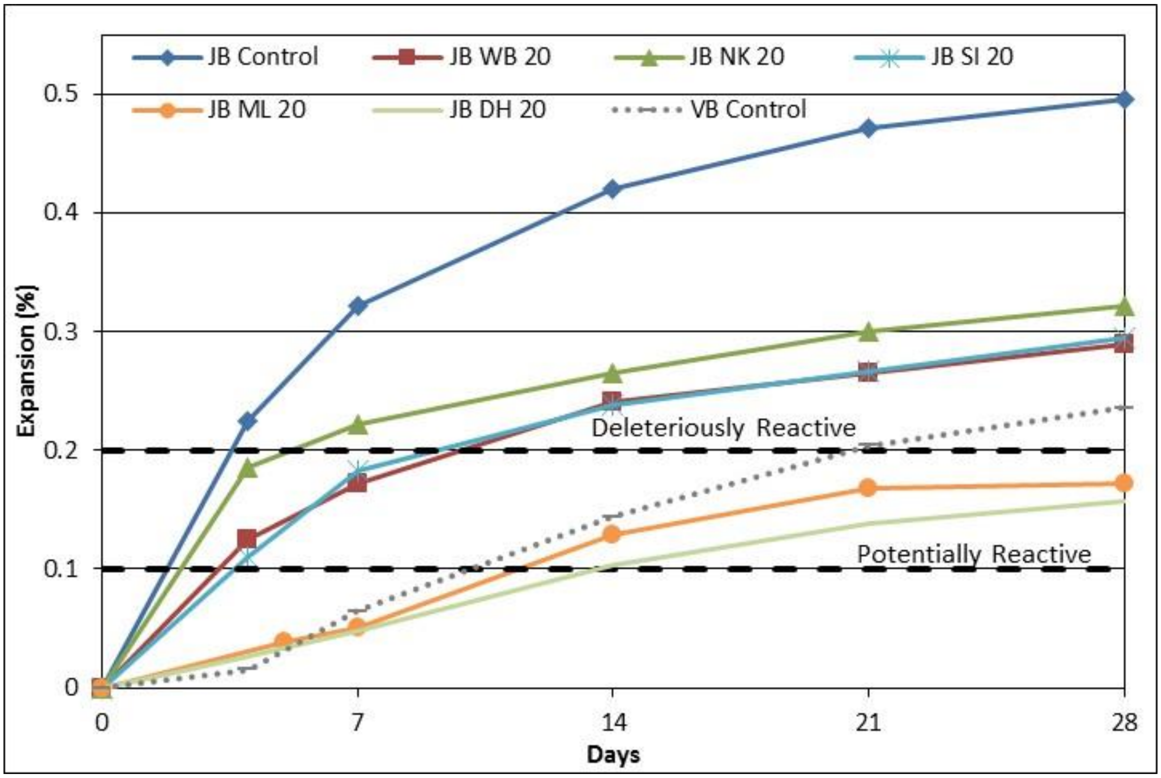

Figure 4.4 – 20% Fly Ash Replacement Rate with Jobe-Newman & Arkansas River Sand

The AMBT results for mortar bars containing 30 percent fly ash and 40 percent Jobe-Newman aggregate are shown in Figure 4.5. At the 30 percent replacement rate, only the mortar bars containing Class F fly ash (JB ML 30 and JB DH 30) were classified as non-reactive. The mortar bars containing Sikeston Class C fly ash were potentially reactive, and the mortar bars containing Newark and White Bluff Class C fly ashes were still considered deleteriously reactive.

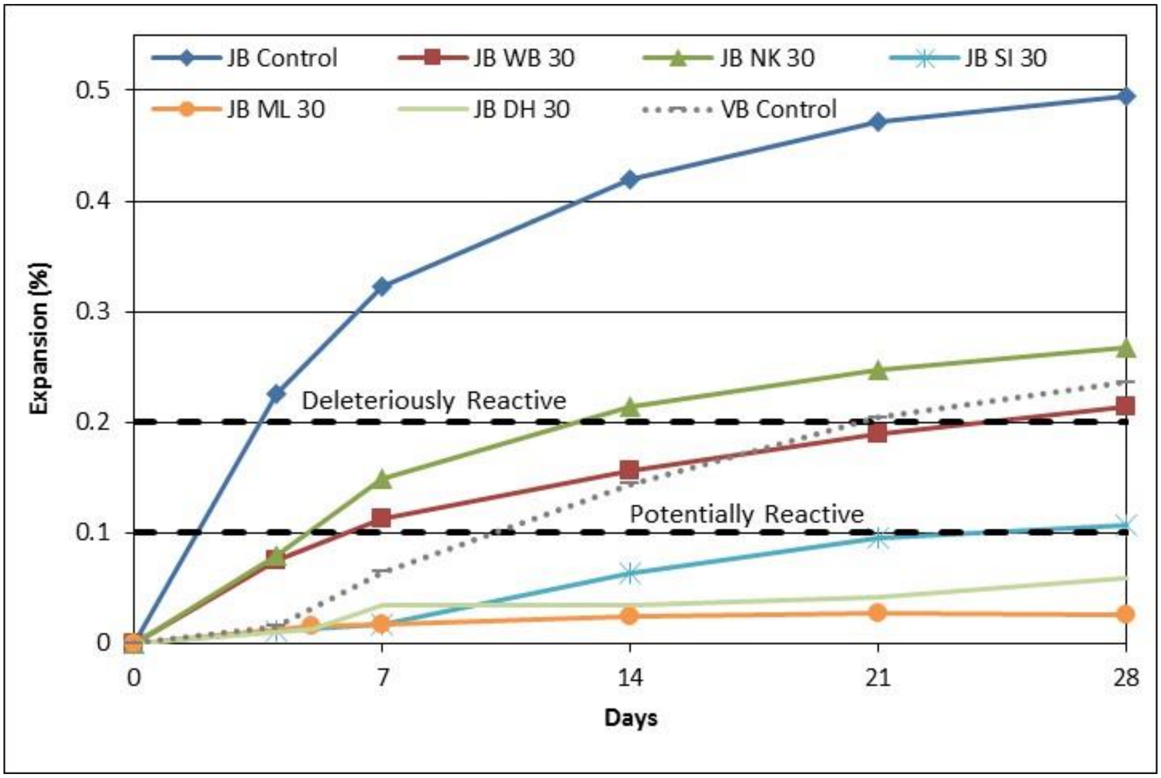

Figure 4.5 – 30% Fly Ash Replacement Rate with Jobe-Newman & Arkansas River Sand

The AMBT results for mortar bars containing 40 percent fly ash and 40 percent Jobe-Newman aggregate are shown in Figure 4.6. At the 40 percent replacement rate, the aggregate would be classified as non-reactive no matter the type of fly ash (Class C or F). The two mortar bars containing Class F fly ash had the lowest expansion of approximately 0.03 and 0.04 percent. The mortar bars containing Class C fly ash had an expansion of 0.05 to 0.08 percent.

When highly reactive aggregates are used, the benefit of Class F fly ash was observed in the results. The previous results showed that 30 percent Class F fly ash was needed to reduce to the expansion to less than 0.10 percent. Whereas, 40 percent Class C fly ash was needed to reduce the expansion below 0.10 percent.

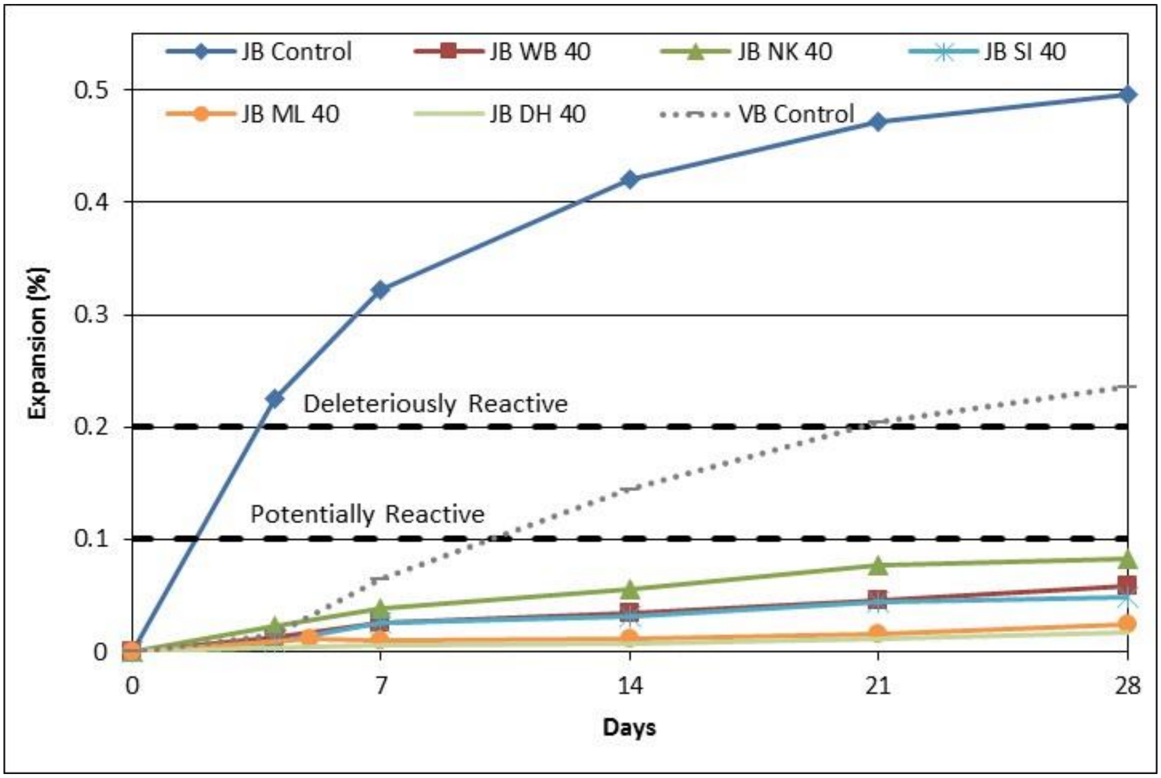

Figure 4.6 – 40% Fly Ash Replacement Rate with Jobe-Newman & Arkansas River Sand

4.3 AMBT CHEMICAL ANALYSIS

Researchers have shown that the chemical composition of the fly ash affects its ability to prevent ASR (Malvar 2006). The chemical composition of all the fly ash used in the study was shown in Tables 3.2 and 3.3 in Chapter 3. In the following figures (Figures 4.7 to 4.11), the expansion was plotted versus various chemical compositions of the fly ashes.

4.3.1 AMBT CHEMICAL ANALYSIS WITH ARKANSAS RIVER SAND

This section investigates the effect of the chemical composition of the concrete on the expansion rate of mortar mixtures cast with fine aggregate from the Arkansas River. The first chemical composition examined was the ratio of CaO to SiO_2 (CaO/SiO_2). The expansion (as measured by the AMBT) versus CaO/SiO_2 was plotted in Figure 4.7. There were three data points for each fly ash with each point representing one of the fly ash contents (20, 30, or 40 percent). The CaO/SiO_2 ratio was based on the total CaO and total SiO_2 in a concrete mixture. The CaO/SiO_2 for the White Bluff, Class C fly ash (WB) was approximately 1.77, 2.1, and 2.4. The CaO content for the White Bluff fly ash was 22.70 percent and the SiO_2 content was 36.73 percent. To calculate the 1.77, for a fly ash content of 40 percent, the total CaO content for the fly ash portion was 0.40 percent x 22.7 percent which was 9.08 percent. The mixture was 60 percent portland cement and the CaO content of the cement was 63.5 percent (0.6 percent x 63.5 percent = 38.1 percent). Therefore, the total CaO content for the 40% White Bluff fly ash mixture was 47.18 percent. A similar calculation can be made for the SiO_2 content (0.4 percent x 36.73 percent = 14.69 percent for the fly ash and 0.6 percent x 19.88 percent = 11.93 percent for the portland cement and the total was 26.62 percent). So, for the mixture containing 40% White Bluff fly ash, the CaO/SiO2 was 1.77 which was 47.18 percent/26.62 percent. This calculation was performed for all fly ashes and for all replacement rates. For all fly ashes, the first point represents the 40 percent fly ash content followed by the 30 percent content and then the 20 percent replacement rate. All the ratios are shown Figure 4.7.

Based upon Figure 4.7 when the CaO/SiO_2 was less than 2.1, the mortar bar expansion (as measured by ASTM 1567) was considered non-reactive for all fly ashes and replacement rates. At a CaO/SiO2 ratio greater than 2.1, the mortar bars containing the Muskogee, Class C fly ash were potentially reactive. These results are similar to the results show in Figures 4.1 through 4.3. Based on the AMBT, the fine aggregate from the Arkansas River was potentially reactive, and the level of expansion was reduced to non-reactive for any mixture containing fly ash (excluding the Muskogee Class C fly ash). For this level of reactivity, the CaO/SiO_2 had little effect on the amount of expansion. For example, the amount of expansion increased as the CaO/SiO_2 increased for some fly ashes, and the expansion decreased for other fly ashes. This is reflected in the R^2 value for the trend line shown in Figure 4.7. The closer the R^2 value is to 1.00, the more accurate the trend line while a R^2 value nearing 0.00 has no correlation to the trend line plotted. For this data set, the R^2 value was 0.51 and therefore there was little correlation between the CaO/SiO_2 to expansion.

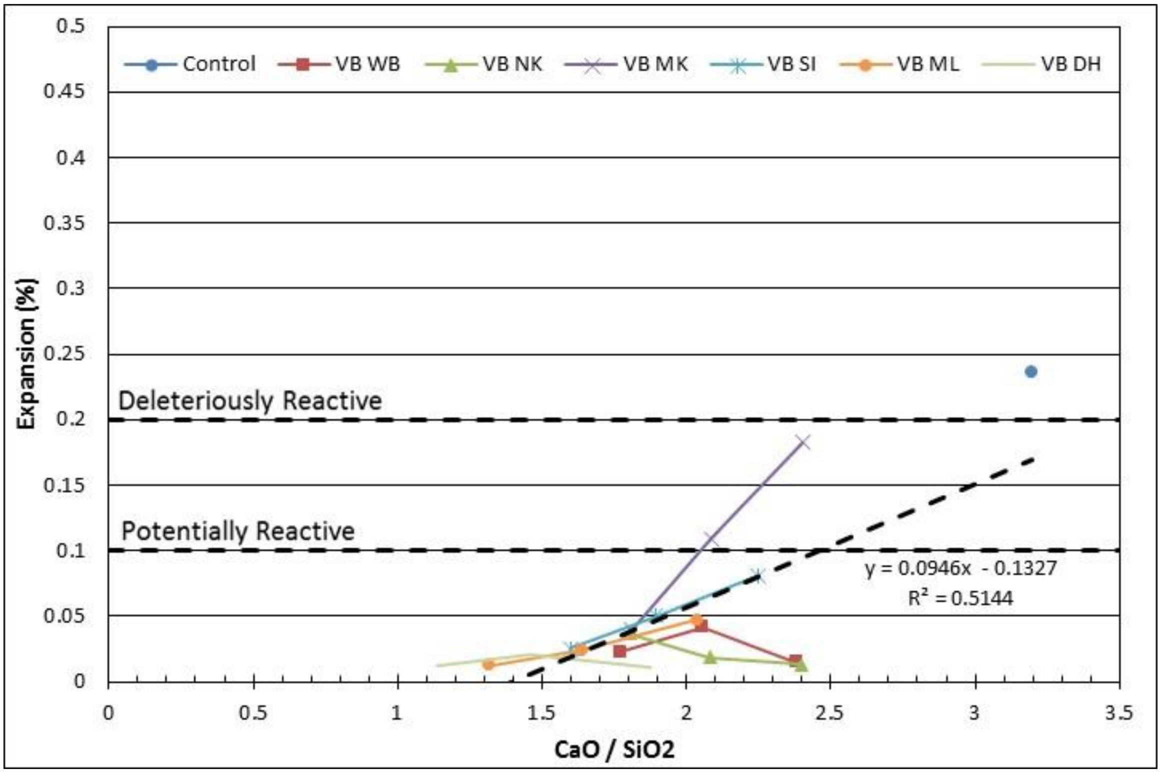

Figure 4.7 – Calcium Oxide to Silicon Dioxide Ratio and Arkansas River Sand, AMBT

The CaO content was the next chemical composition examined. For each fly ash, there are three data points which represent 20, 30, and 40 percent fly ash content. The CaO content was determined by multiplying the fly ash content by its CaO content. For example, the CaO content of the Martin Lake fly ash (shown in Figure 4.8) was approximately 42, 47, and 53 percent. As shown in Table 3.2, the Martin Lake fly ash has a CaO content of 10.46 percent and the portland cement has a CaO content of 63.50 percent. So, for a 40 percent fly ash replacement rate, the total CaO content was 42.28 percent (0.40 x 10.46 percent plus 0.60 x 63.50 percent).

For all fly ashes, the first point represents a 40 percent replacement rate followed by the 30 percent and then 20 percent replacement rates.

The data in Figure 4.8 show that the CaO content did not directly influence the expansion rate for all fly ashes except for the Muskogee fly ash. Mortar bars cast with five of the six fly ashes experienced expansions less than 0.1 and were classified as non-reactive. For some mortar bars, expansion increased as CaO content increased and for other mortar bars, expansion decreased. This was most likely due to the reactivity of the fine aggregate from the Arkansas River. Researchers (Thomas et al. 2000) have suggested using the CaO content as a means to predict the ability of the fly ash to prevent ASR. If a more reactive aggregate were used (which will be discussed in the following section), it is expected that expansion will increase as the CaO content increases. Finally, the R^2 value was 0.46 and therefore there was little correlation between the CaO/SiO_2 to expansion.

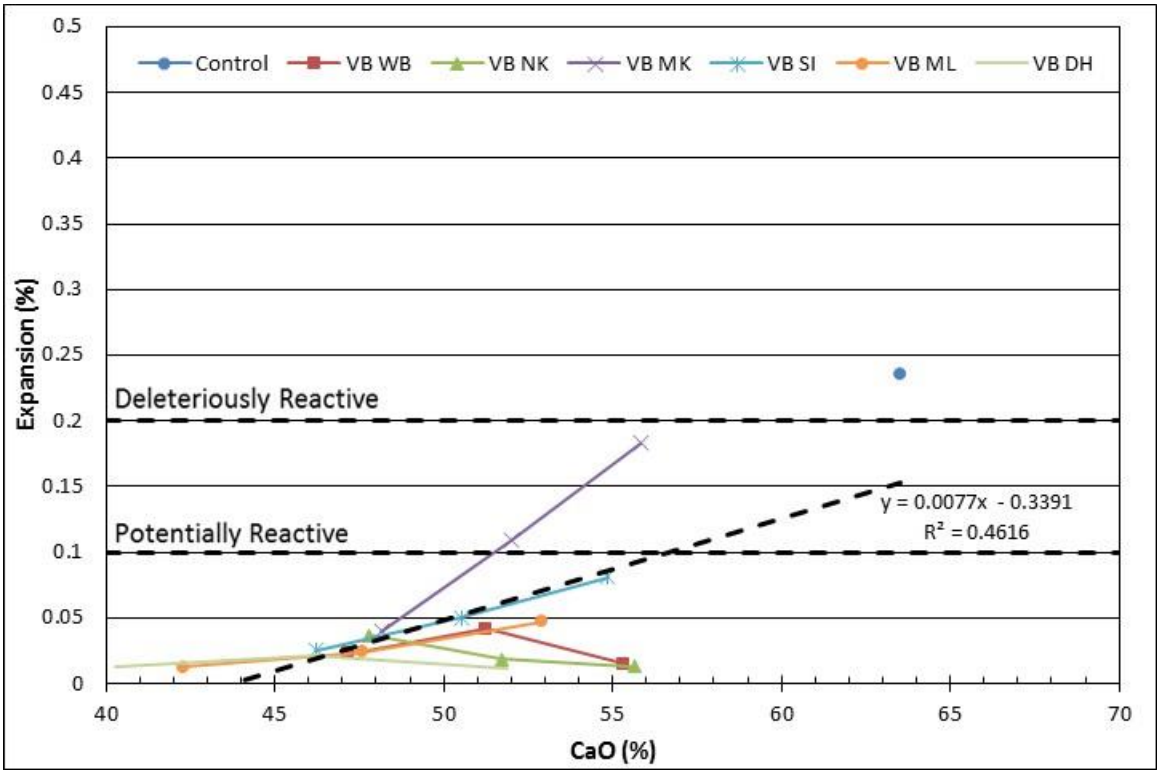

Figure 4.8 – Calcium Oxide and Arkansas River Sand, AMBT

The expansion as measured by the AMBT was plotted versus the SiO_2 content for each fly ash and fly ash content in Figure 4.9. The SiO_2 content was calculated in the same manner as the CaO content. For each fly ash, there are three points which represents the three fly ash contents. For the SiO_2, the first point represents a fly ash content of 20 percent and then followed by the 30 percent and then 40 percent contents. The data shown in Figure 4.9 follow a general trend of a decrease in expansion as the SiO_2 content increases. This trend has been documented in the literature (Malvar 2006). As with the CaO/SiO_2 and CaO content, the fine aggregate from the Arkansas River would be classified as non-reactive for five of the six fly ashes (excluding the Muskogee fly ash). If a more reactive aggregate were used (which will be discussed in the following section), it is expected that expansion would decrease as the SiO_2 content increases and that the trend would be more apparent. The R^2 value was 0.35 and therefore there was little correlation between the SiO_2 content and expansion.

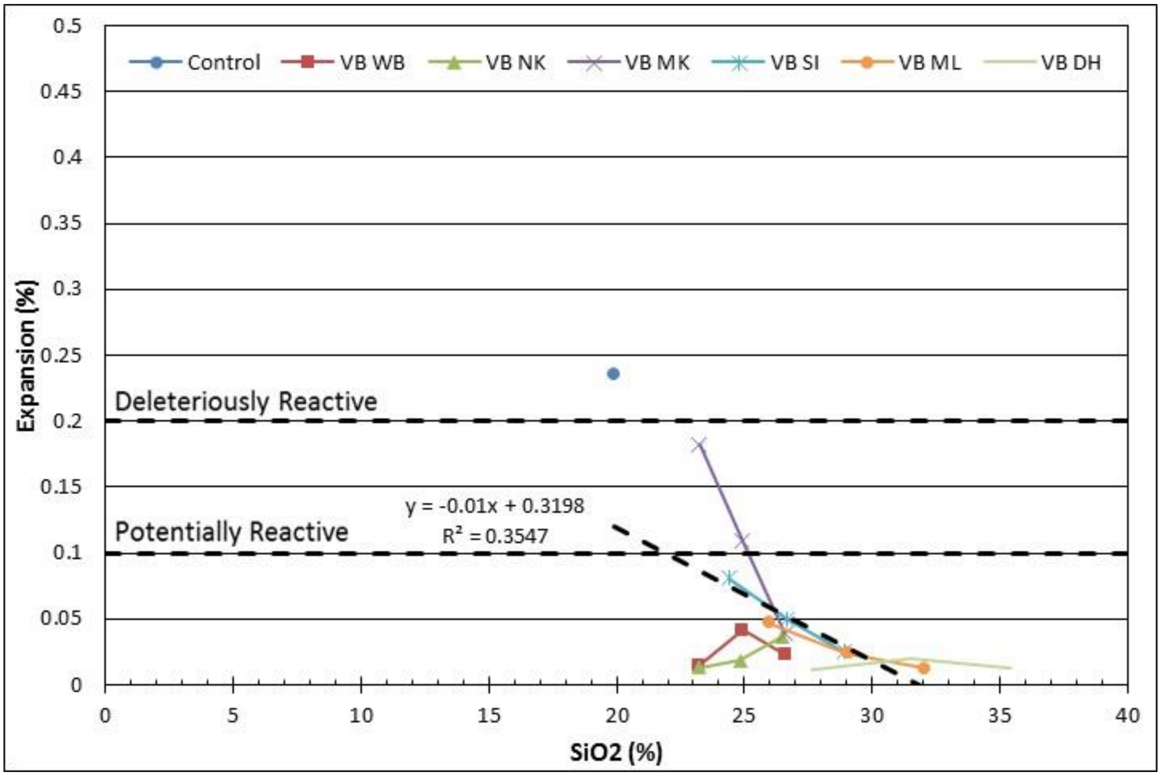

Figure 4.9 – Silicon Dioxide and Arkansas River Sand, AMBT

The expansion versus the sum of the alkalis to the sum of the oxides (Σalkalis/Σoxides) was plotted in Figure 4.10. The total alkali content and total oxide content was calculated in the same manner as the previous chemical contents. For each fly ash, there are three points which represents the three fly ash contents. For the Σalkalis/Σoxides, the first point represents a fly ash content of 40 percent and then followed by the 30 percent and then 20 percent contents. The data shown in Figure 4.10 do not follow any general trend. This was most likely due to the low reactivity of the fine aggregate from the Arkansas River. For five of the six fly ashes (excluding the Muskogee fly ash), the expansion was below 0.10 which would be classified as non-reactive. This was true for a Σalkalis/Σoxides of 0.84 (Dolet Hills Class F fly ash) and was also true for a ratio 1.77 (Newark Class C fly ash). If a more reactive aggregate were used (which will be discussed in the following section), it is expected that expansion would decrease as the Σalkalis/Σoxides content increases and that the trend would be more apparent. The R^2 value was 0.54 and therefore there was little correlation between the Σalkalis/Σoxides and expansion.

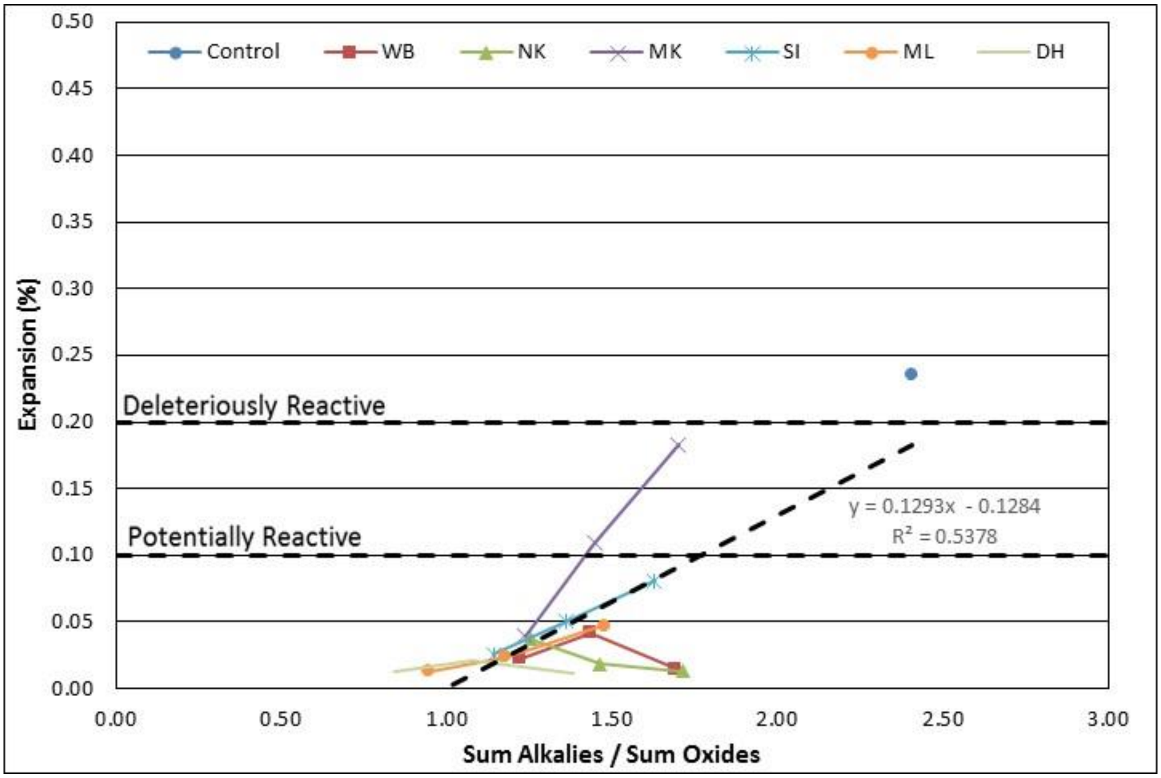

Figure 4.10 – Total Alkalis to Total Oxides Ratio and Arkansas River Sand, AMBT

In Figure 4.11, the mortar bar expansion data were plotted against the total alkali content of the mortar. This included the alkali content of the cement and the alkali content of the fly ash. As in the previous figures, the total alkali content was determined by multiplying the fly ash content by its alkali content. This calculation was repeated for the cement. For each fly ash, there are three data points. Each data point represents the fly ash content. The first point was represents a fly ash content of 40 percent followed by 30 percent and then 20 percent.

The data in Figure 4.11 show that the total alkali content did not directly influence the expansion rate for all fly ashes except for the Muskogee fly ash. Mortar bars cast with five of the six fly ashes and at all replacement rates experienced expansions less than 0.1 and were classified as non-reactive. For some mortar bars, expansion increased as total alkali content increased as Malvar’s results found and for other mortar bars, expansion decreased (2006). This was most likely due to the reactivity of the fine aggregate from the Arkansas River. If a more reactive aggregate were used (which will be discussed in the following section), it is expected that expansion will increase as the CaO content increases. Finally, the R^2 value was 0.44 and therefore there was little correlation between the total alkali content to expansion.

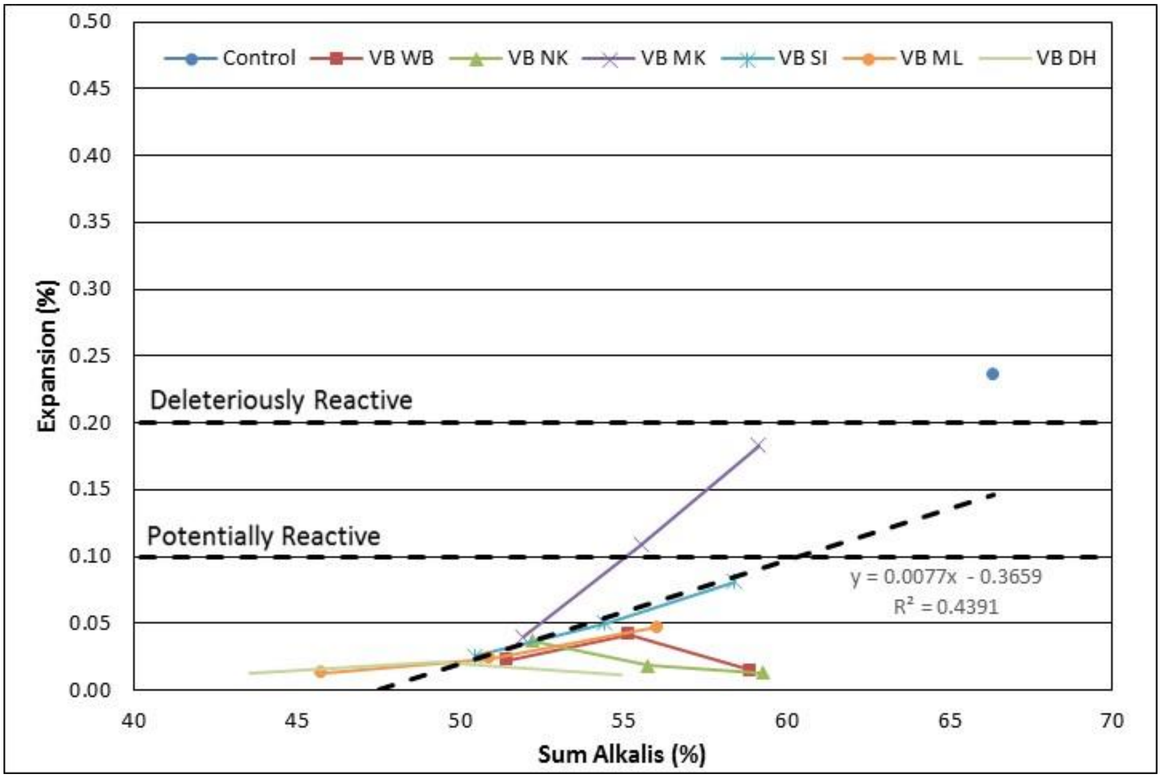

Figure 4.11 – Total Alkalis and Arkansas River Fine Aggregate, AMBT

In Figure 4.12, the mortar bar expansion data were plotted against the total oxide content of the mortar. This included the oxide content of the cement and the oxide content of the fly ash. As in the previous figures, the total oxide content was determined by multiplying the fly ash content by its oxide content. This calculation was repeated for the cement. For each fly ash, there are three data points. Each data point represents the fly ash content. The first point represents a fly ash content of 20 percent followed by 30 percent and then 40 percent.

The data in Figure 4.12 show that total oxide content did not directly influence the expansion rate for all fly ashes except for the Muskogee fly ash. Mortar bars cast with five of the six fly ashes and at all replacement rates experienced expansions less than 0.1 and were classified as non-reactive. For some mortar bars, expansion increased as total oxide content increased and for other mortar bars, expansion decreased. This was most likely due to the reactivity of the fine aggregate from the Arkansas River. If a more reactive aggregate were used (which will be discussed in the following section), it is expected that expansion will increase as the oxide content increases. Finally, the R^2 value was 0.42 and therefore there was little correlation between the total alkali content to expansion.

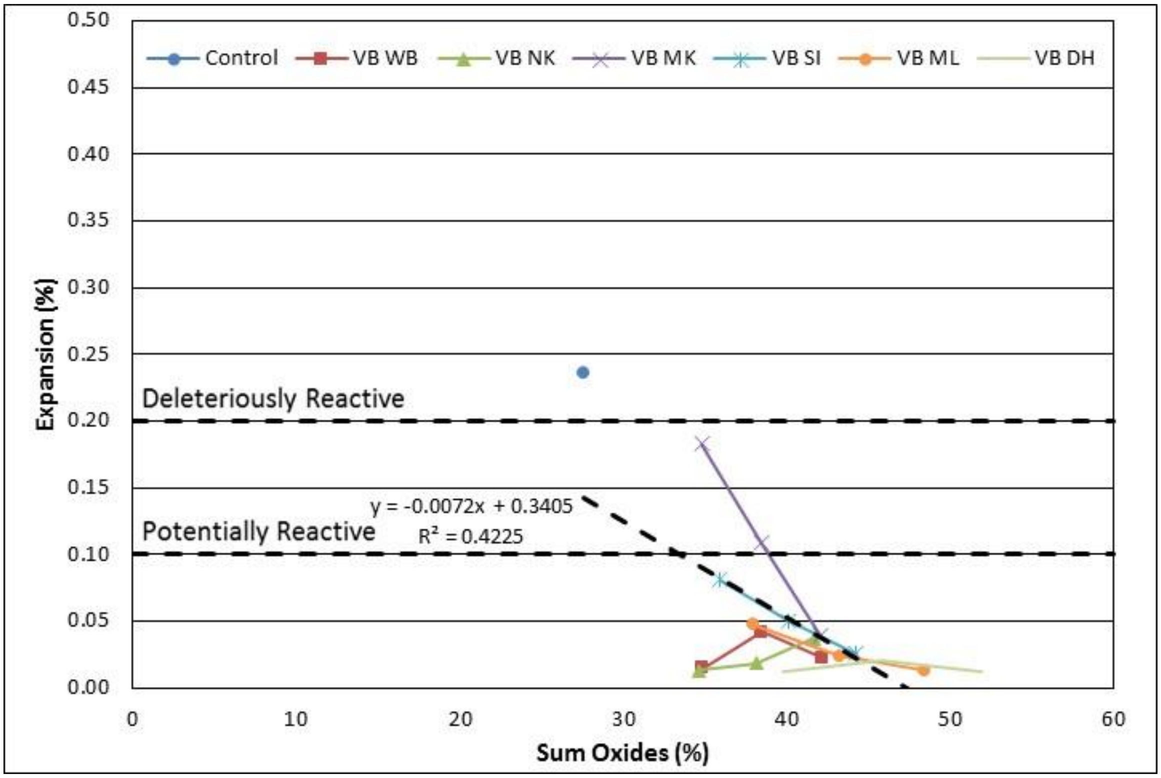

Figure 4.12 – Total Oxides and Arkansas River Sand, AMBT

4.3.2 AMBT CHEMICAL ANALYSIS WITH JOBE NEWMAN AGGREGATE

This section investigates the effect of the chemical composition of the fly ash and cement on the expansion rate of mortar mixtures containing the Jobe-Newman fine aggregate. As mentioned in Chapter 3, the Jobe-Newman aggregate is highly reactive and has been used to initiate ASR in many research projects.

The first chemical composition examined was the ratio of CaO to SiO_2 (CaO/SiO_2). The expansion (as measured by the AMBT) versus CaO/SiO2 was plotted in Figure 4.13. The procedure to calculate this ratio was discussed earlier in Section 4.2.1. There were three data points for each fly ash with each point representing one of the fly ash contents (20, 30, or 40 percent). For all fly ashes, the first point represents the 40 percent fly ash content followed by the 30 percent replacement rate and then the 20 percent replacement rate.

Figure 4.13 shows that if the CaO/SiO_2 was less than 1.7, the mortar bar expansion (as measured by AMBT ASTM 1567) was considered non-reactive for all fly ashes and replacement rates. At a CaO/SiO_2 ratio greater than 1.7, mortar mixtures containing the Class C fly ashes and Class F fly ash from Martin Lake (ML) were potentially reactive. At a CaO/SiO_2 greater than 1.6, the mortar mixture containing Class F fly ash from Dolet Hills was potentially reactive. These results are similar to the results shown in Figures 4.1 through 4.3. Contrary to the mortar mixtures containing only fine aggregate from the Arkansas River, the amount of expansion increased as the CaO/SiO_2 increased for all fly ashes. This was reflected in the R^2 value for the trend line shown in Figure 4.13. The accuracy of the trend line for each figure was compared to the data set to obtain a linear regression value (R^2). For this data set, the R^2 value was 0.91 and therefore there was a strong correlation between the CaO/SiO_2 to expansion.

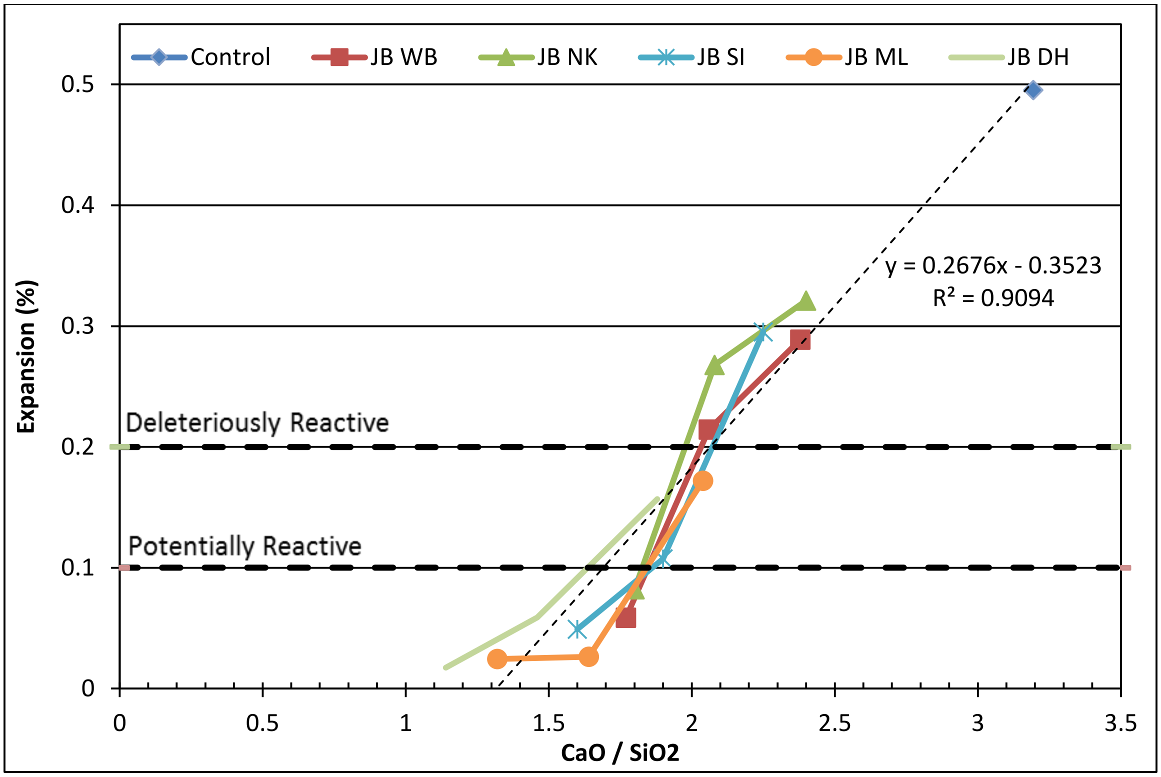

Figure 4.13 – Calcium Oxide to Silicon Dioxide Ratio for Jobe-Newman Aggregate, AMBT

The data in Figure 4.14 show that the CaO content did directly influence the expansion rate for all fly ashes used in the test. The first point represents a 40 percent replacement rate followed by the 30 percent and then 20 percent replacement rates. For all mortar bars, expansion increased as CaO content increased. Researchers (Thomas et al. 2000) have suggested using the CaO content as a means to predict their ability to prevent ASR. Class F fly ash contains a CaO content less than 8 percent. While Class C fly ash has a CaO content between 8 and 20 percent. Finally Thomas stated Class C high reactivity (CH) fly ash was classified as having CaO percent higher than 20 percent of the chemical composition. Using a highly reactive fly ash is more likely to have expansion due to the increased CaO content. For this study, once the CaO content surpassed 47 to 50%, the mortar bars were classified as potentially reactive. The R^2 value was 0.88 and therefore there was a strong correlation between the CaO/SiO_2 to expansion.

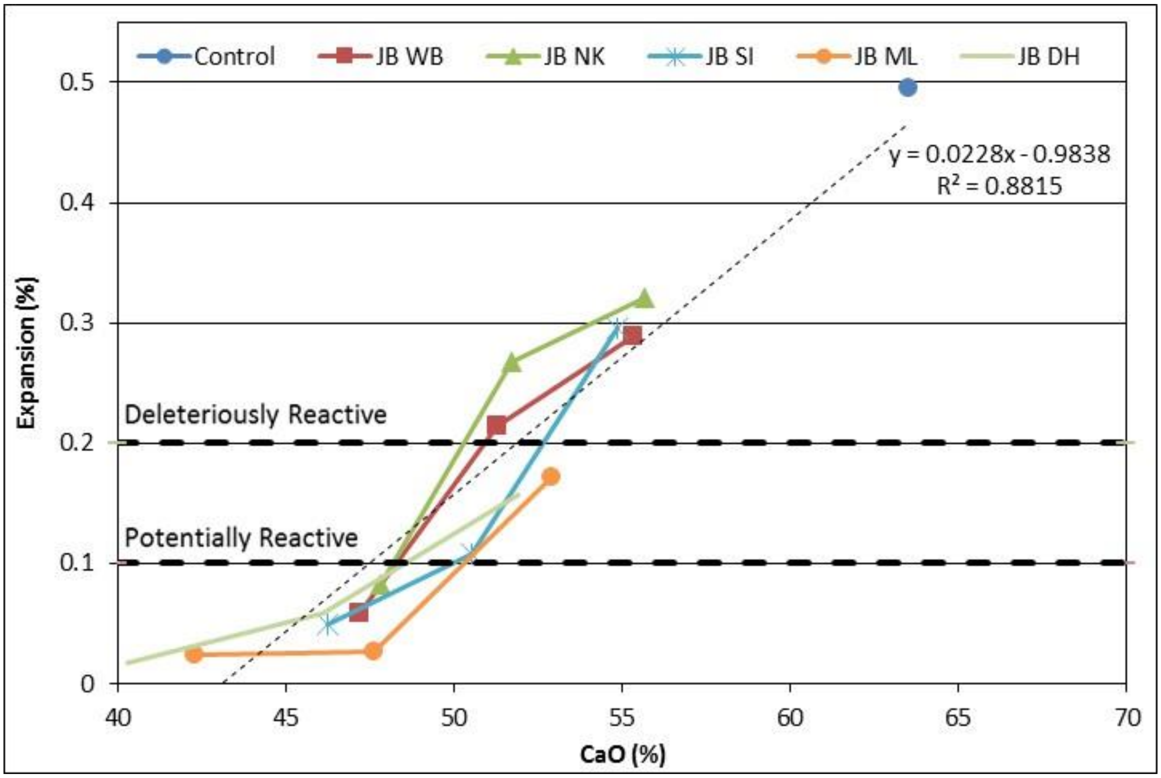

Figure 4.14 – Calcium Oxide Percentage for Jobe-Newman Aggregate, AMBT

The expansion as measured by the AMBT was plotted versus the SiO_2 content for each fly ash and fly ash content in Figure 4.15. The SiO_2 content was calculated in the same manner as the previously calculations. For each fly ash, there are three points which represents the three fly ash contents. For the SiO_2, the first point represents a fly ash content of 20 percent and then followed by the 30 percent and then 40 percent contents. The data shown in Figure 4.15 follow a general trend of a decrease in expansion as the SiO_2 content increases. This trend has been documented in the literature (Malvar 2006). To ensure the expansion remains less than 0.1 percent, the SiO_2 content should be greater than approximately 30 percent. However, there are some fly ashes, such as Class C fly ash from White Bluff or the Class C fly ash from Newark, where the SiO_2 content can be as low as 26 percent before expansion exceeds 0.1 percent. The

R^2 value was 0.76 and therefore there was a somewhat strong correlation between the SiO_2 content and expansion compared to Figure 4.9 where the R^2 value was 0.35.

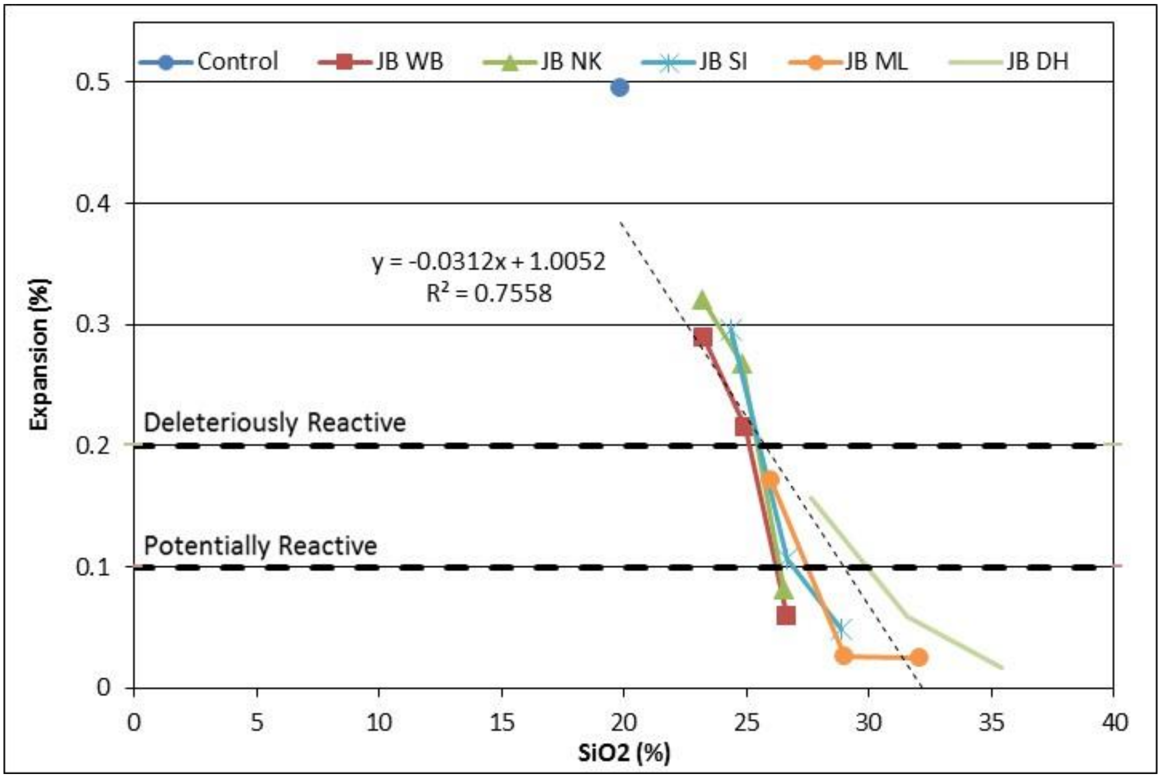

Figure 4.15 – Silicon Dioxide Percentage for Jobe-Newman Aggregate, AMBT

The expansion versus the total alkali content to the total oxide content (Σalkalis/Σoxides) was plotted in Figure 4.16. The total alkali content and total oxide content were calculated in the same manner as the previous chemical contents. For each fly ash, there are three points which represents the three fly ash contents. For the Σalkalis/Σoxides, the first point from left to right represents a fly ash content of 40 percent and then followed by the 30 percent and then 20 percent contents. The data shown in Figure 4.16 show an increase in expansion (as measured by the AMBT) as the Σalkalis/Σoxides increased. The expansion increased as the Σalkalis/Σoxides content increased. If the Σalkalis/Σoxides remained below approximately 1.20, the expansion was less than 0.1 percent. As shown in Figure 4.16, there was a noticeable trend in expansion as the Σalkalis/Σoxides increased. The R^2 value was 0.91 and therefore there was strong correlation between the Σalkalis/Σoxides and expansion.

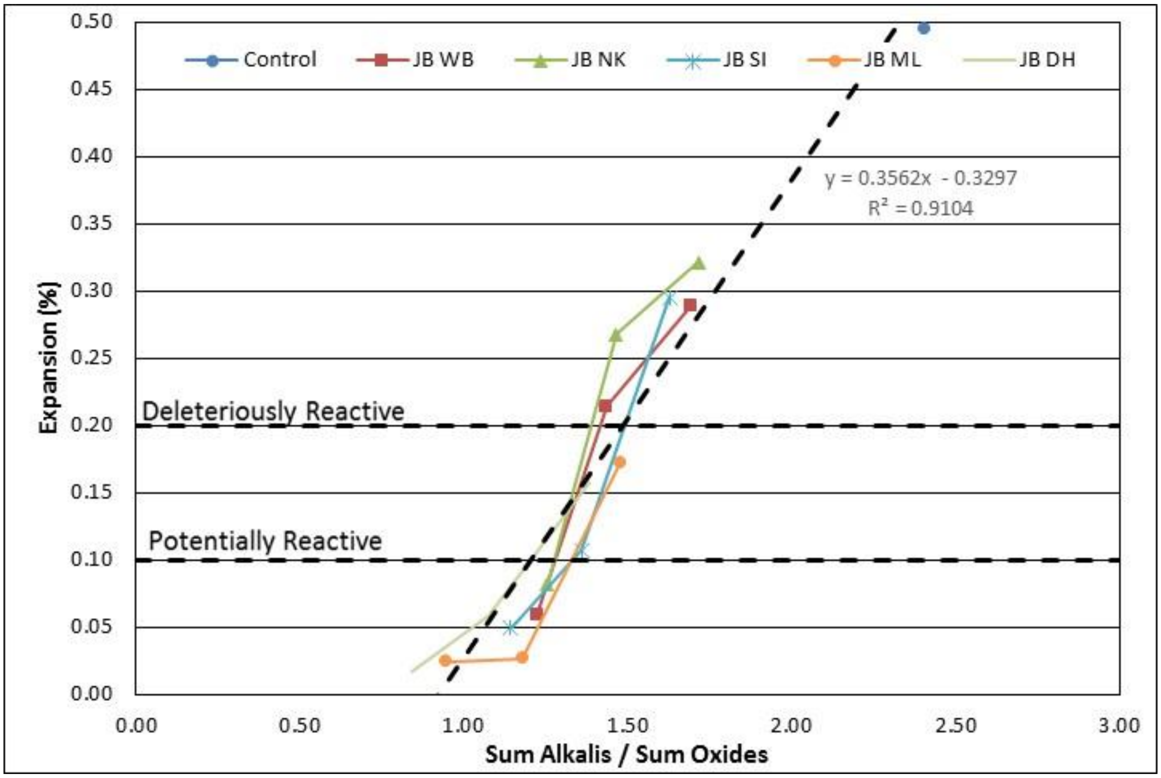

Figure 4.16 – Total Alkalis to Total Oxides for Jobe-Newman Aggregate, AMBT

In Figure 4.17, the mortar bar expansion data were plotted against the total alkali content of the mortar. This included the alkali content of the cement and the alkali content of the fly ash. As in the previous figures, the total alkali content was determined by multiplying the fly ash and cement content by their respective alkali content. For each fly ash, there are three data points. Each data point represents the fly ash content. The first point represents a fly ash content of 40 percent followed by 30 percent and then 20 percent.

The data in Figure 4.17 shows that the total alkali content did directly influence the expansion rate for all fly ashes. Mortar bars cast with five fly ashes at 40 percent replacement rate experienced expansions less than 0.1 and were classified as non-reactive. The expansion increased as the alkali content increased. An alkali limit of 51 percent in the cement and fly ash would sufficiently impede the ASR from occurring. For some fly ashes, both Class C and F, the alkali content limit could be increased. Finally, the R^2 value was 0.87 and therefore there was strong correlation between the total alkali content to expansion.

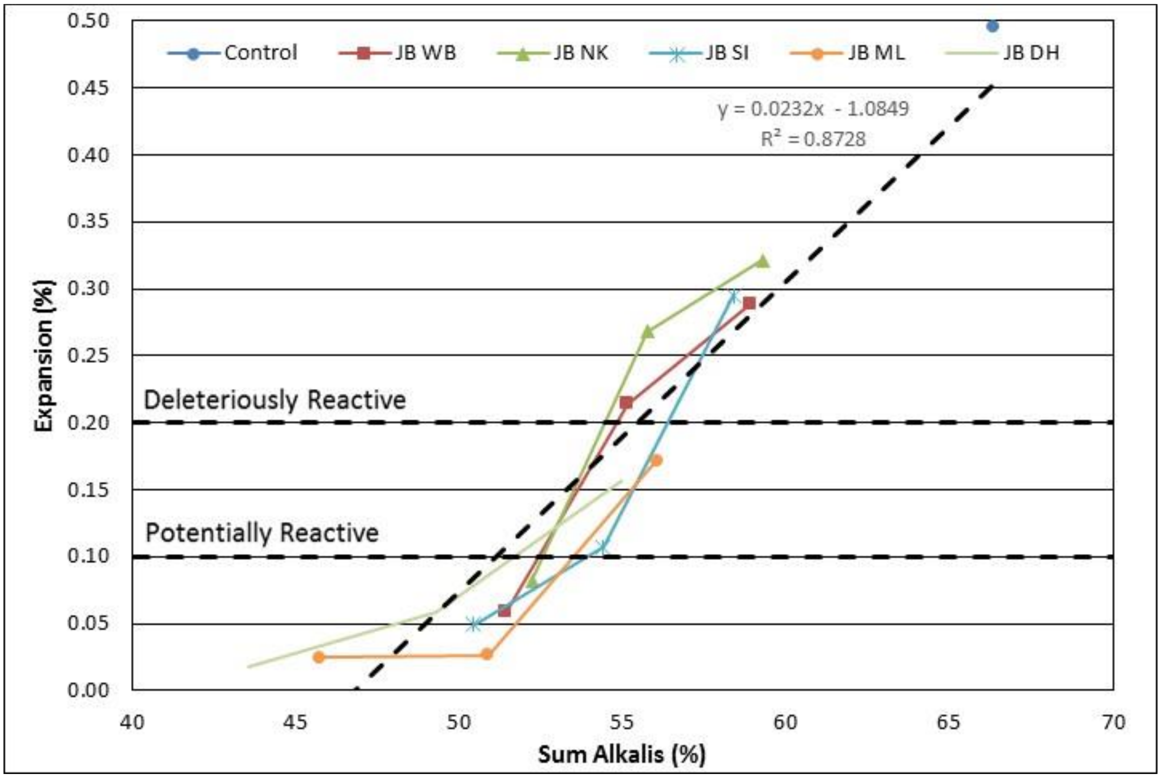

Figure 4.17 – Total Alkalis for Jobe-Newman Aggregate, AMBT

In Figure 4.18, the mortar bar expansion data were plotted against the total oxide content of the mortar. This included the oxide content of the cement and the oxide content of the fly ash. As in the previous figures, the total oxide content was determined by multiplying the fly ash content by its oxide content. This calculation was repeated for the cement. For each fly ash, there are three data points. Each data point represents the fly ash content. The first point was from left to right represents fly ash contents of 20 percent followed by 30 percent and then 40 percent.

The data in Figure 4.18 show that total oxide content did directly influence the expansion rate for all fly ashes. Mortar bars cast with the five fly ashes and at 40% replacement rates experienced expansions less than 0.1 and were classified as non-reactive. For all mortar bars, expansion decreased as the total oxide content increased. Based on the data shown in Figure 4.18, an oxide content greater than 40 percent would prevent ASR damage from occurring based on the materials included in the study. Finally, the R^2 value was 0.86 and therefore there was strong correlation between the total alkali content to expansion. The oxide content in a mixture to prevent ASR should be greater than 41 percent for five of the fly ashes and greater than 45 percent for the Dolet Hills fly ash.

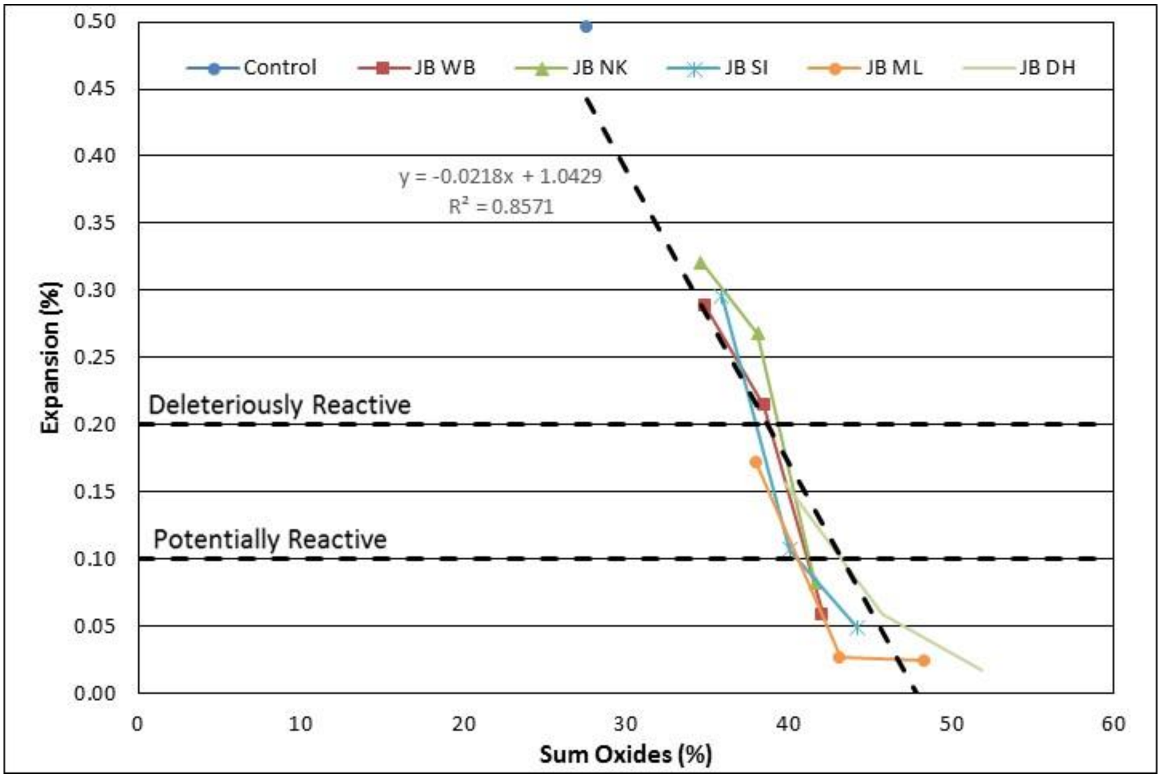

Figure 4.18 – Total Oxides for Jobe-Newman Aggregate, AMBT

4.4 CPT INTRODUCTION

This section presents the results from the CPT. Many researchers recommend using the CPT to determine the potential for ASR in concrete mixtures. This section of the research program determined the amount of Class C fly ash that was necessary to prevent ASR in concrete mixtures containing locally available materials according to ASTM C1293.

4.4.1 CPT DATA

CPTs are typically tested for one year (ASTM C1293), however when using high volume fly ash contents, the test is typically run for two years due to the SCMs slowing hydration (ASTM C1293). To date, 6 months of data have been collected and the tests are 25% complete. Even though the tests are not complete, there is enough data to determine if trends are apparent.

Shown below in Figure 4.19 is the CPT data for all fly ash sources. These specimens were cast with the fine aggregate from the Arkansas River. The AMBT results classified this fine aggregate as potentially reactive. In order for the aggregate to be classified as deleteriously reactive by the CPT, prism expansion must be greater than 0.04% at either 1 or 2 years of age. With the current results, the control specimen (containing no fly ash) has an expansion of 0.015% at 180 days of age. If the control specimen continued to expand at the same rate for the next year, the expansion would be 0.03% which is less than the limit of 0.04%. Therefore the aggregate would be classified as non-reactive. However, the expansion rate could change over the duration of the testing period. It is possible that the ASR gel that has formed is enough to fill only the entrapped air voids. Once the air voids are filled, the expansion rate could increase.

Based on the current expansion rates and the measured expansion at 180 days, none of the mixtures would be classified reactive. Also, based on the current data, the addition of 40 percent fly ash (Class C or Class F) reduced the 180 day expansion for all mixtures except for the concrete containing the Class C fly ash from Newark. Also shown in Figure 4.19 is the contraction (negative values) of the prisms containing Class C fly ash from White Bluff (VB WB 1 and VB WB 2). Two sets of prisms were cast with the White Bluff fly ash to confirm the trend. Specimens from both mixtures contracted for the first 28 days after casting, and then began to expand. There were no noticeable differences in the chemical composition between the White Bluff fly ash and the other Class C fly ashes. Also the fineness of all the Class C fly ashes was similar.

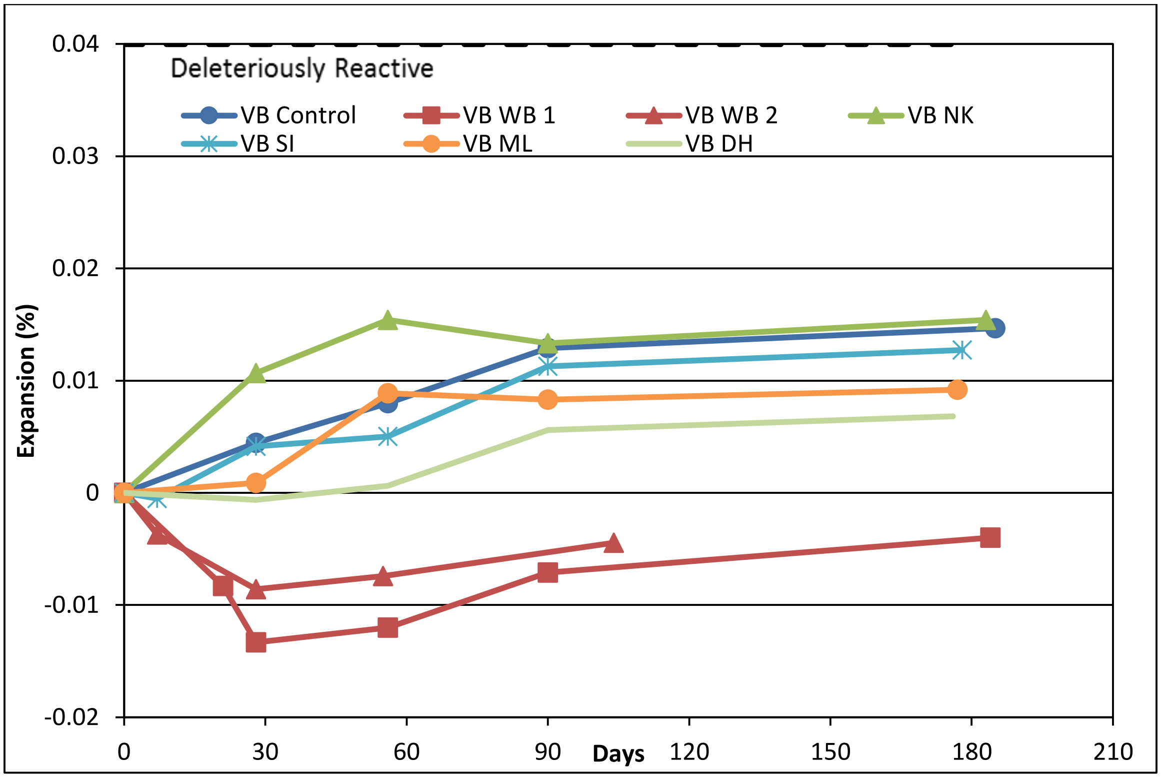

Figure 4.19 – CPT Data with Arkansas River Sand

Shown below in Figure 4.20 are the CPT results for the concrete prisms containing 40 percent fly ash that were cast with the Jobe-Newman fine aggregate. The 180 day expansion for the control specimen cast with Jobe-Newman fine aggregate was 0.06 percent which would be classified as reactive. When 40 percent fly ash (either Class C or Class F) was added to the concrete, the expansion decreased from 0.06 percent to less than 0.015 percent. All mixtures containing fly ash would be classified as non-reactive.

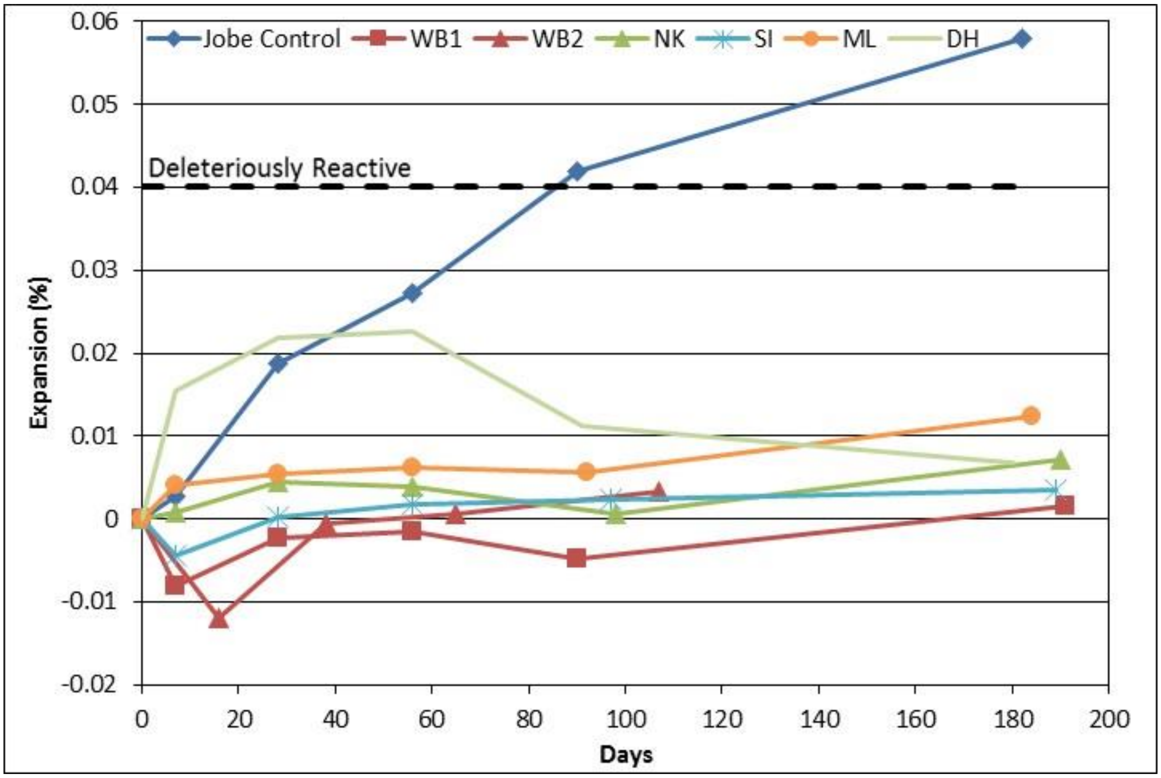

Figure 4.20 – Concrete Prism Test Data with Jobe-Newman Aggregate

4.4.2 CPT CHEMICAL ANALYSIS WITH ARKANSAS RIVER SAND

This section investigates the effect of the chemical composition of the fly ash and cement on the expansion rate of concrete mixtures containing only fine aggregate from the Arkansas River. The correlation of the chemical compositions of the fly ashes and cement to the expansion of the prisms containing only fine aggregate from the Arkansas River, was similar to the AMBT results presented in section 4.2.1. Due to the limited reactivity of the fine aggregate, there was little correlation between the expansion values and the chemical compositions.

The same chemical compositions that were examined in the AMBT section were also investigated in this section. The chemical compositions included CaO/SiO_2, CaO content, SiO_2 content, Σalkalis/Σoxides, total alkali content, and the total oxide content. The limited, if not nonexistent, correlation can be seen in Figures 4.21 through 4.26. For R^2 value for this data ranged from 0.10 to 0.14. Therefore there was no correlation between any of the chemical compositions and expansion due to ASR. There was a possibility if two years of data were available (instead of six months), trends in the data might be observed. However it was likely the data at 2 years would be similar to the AMBT data (Figures 4.7 to 4.12) which also show no correlation between the chemical composition and expansion. Also, trends are more likely to occur when a more reactive aggregate was used in the concrete mixture.

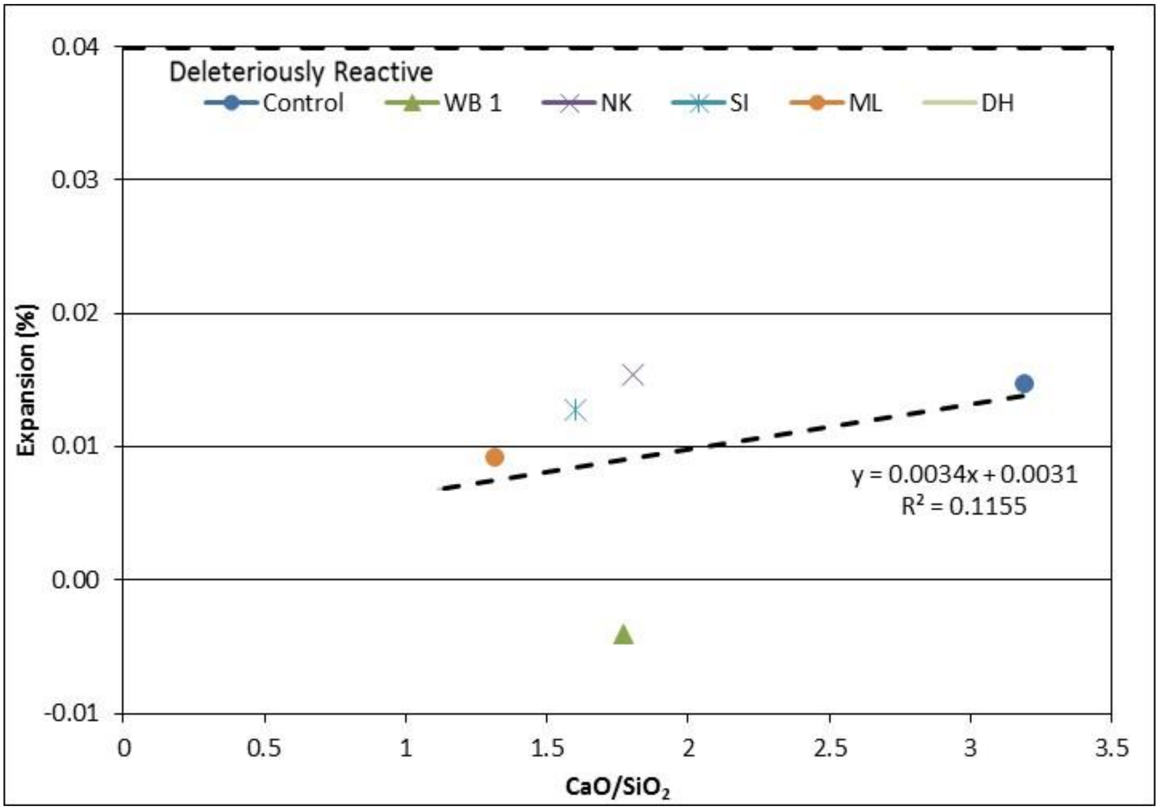

Figure 4.21 – Calcium Oxide to Silicon Dioxide Ratio Percentage with Arkansas River Sand

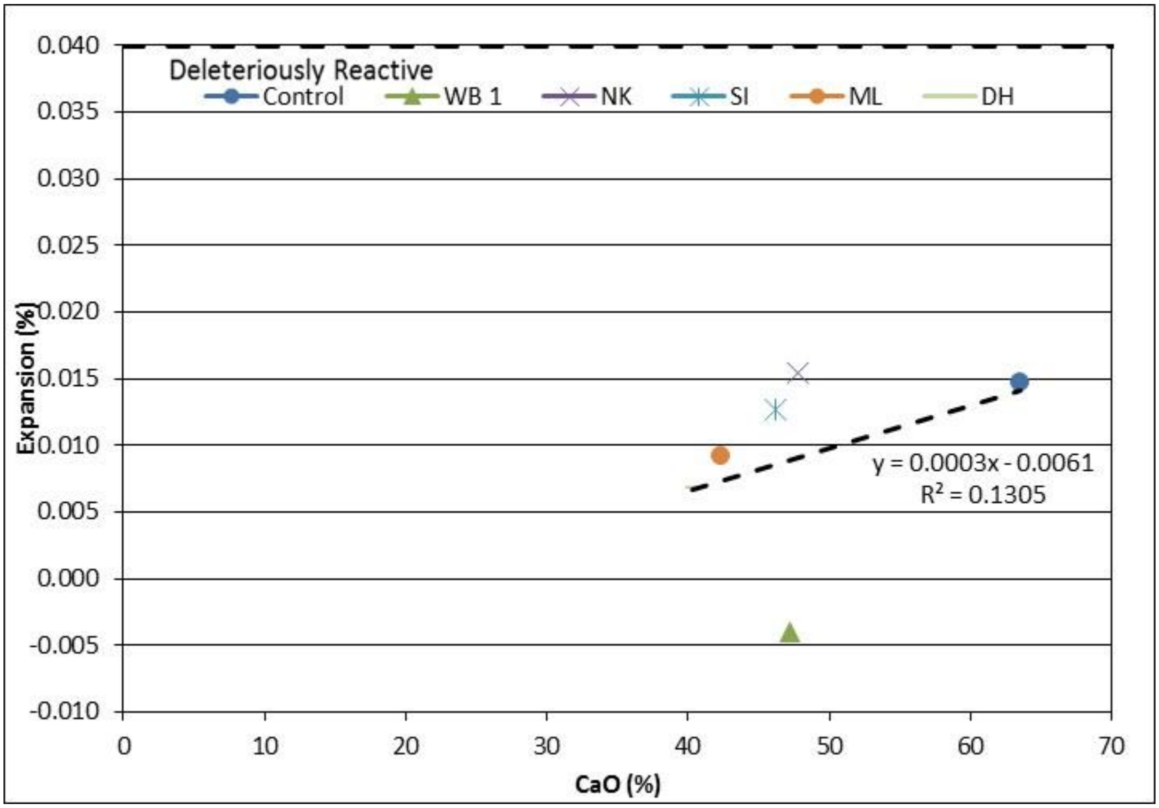

Figure 4.22 – Calcium Oxide Percentage with Arkansas River Sand

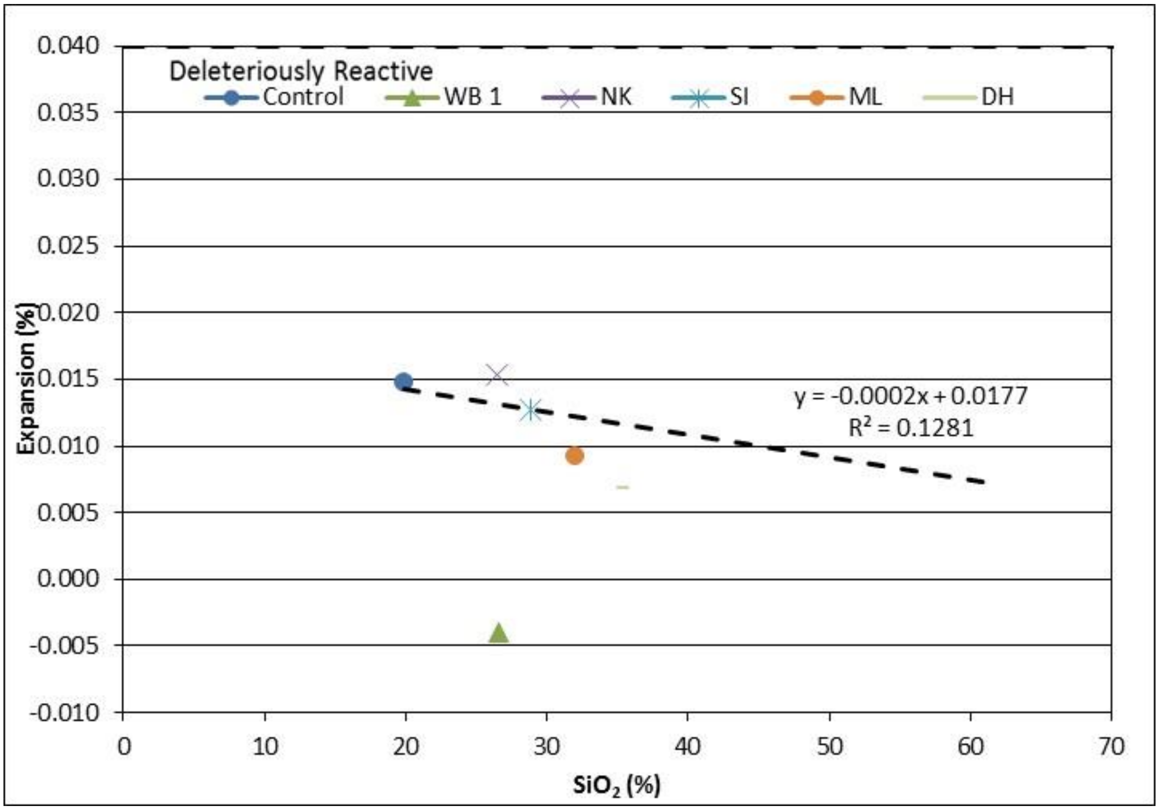

Figure 4.23 –Silicon Dioxide Percentage with Arkansas River Sand

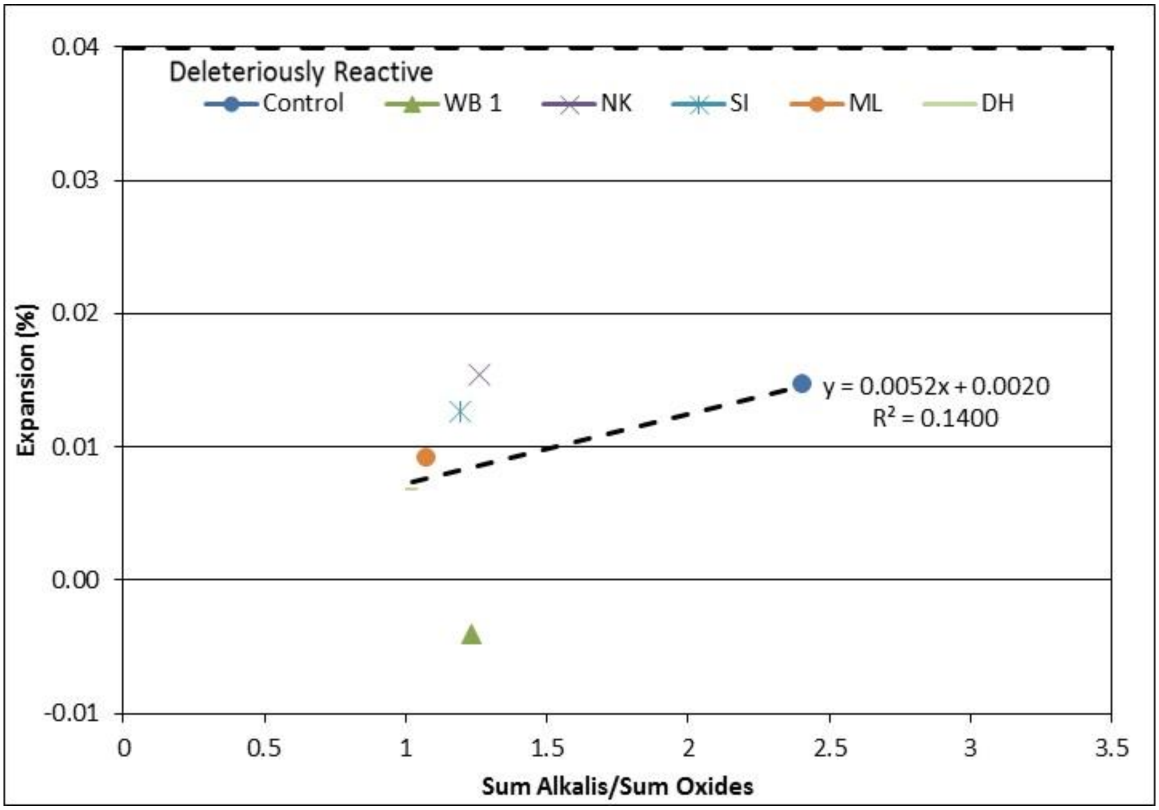

Figure 4.24 – Sum Alkalis to Sum Oxide Ratio Percentage with Arkansas River Sand

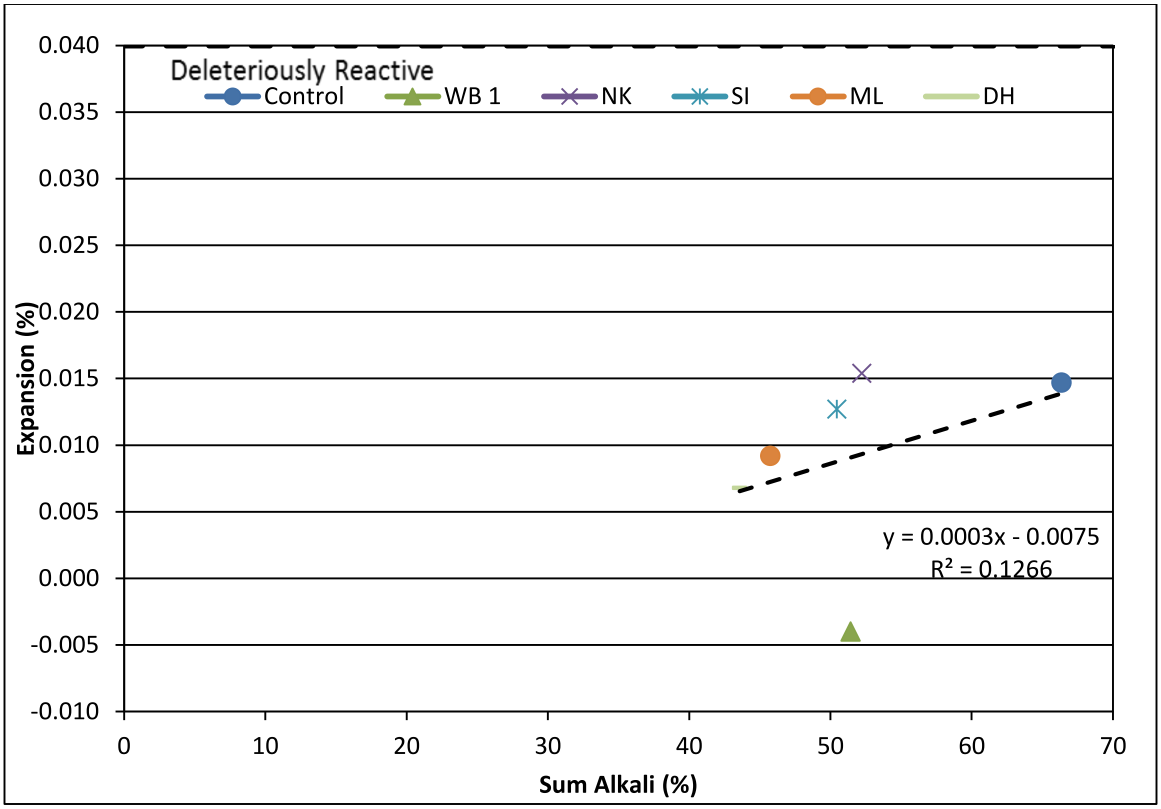

Figure 4.25 – Sum Alkali Percentage with Arkansas River Sand

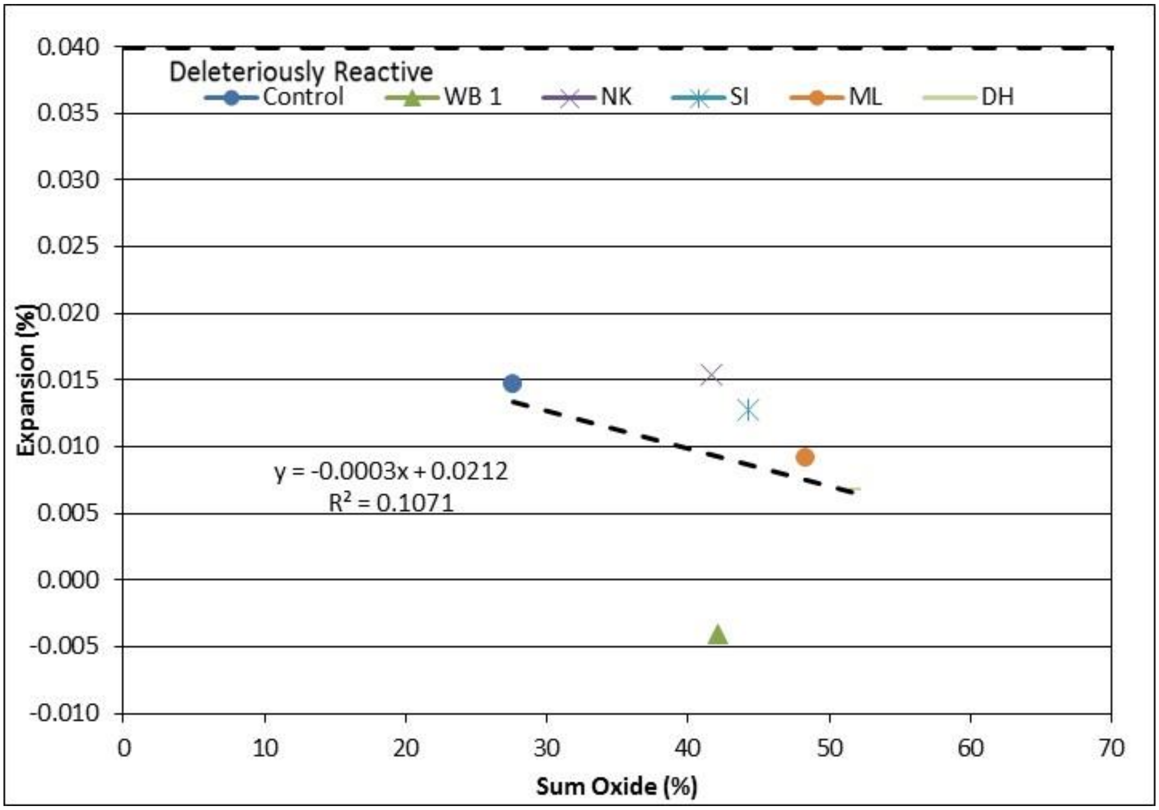

Figure 4.26 – Sum Oxide Percentage with Arkansas River Sand

4.4.3 CPT CHEMICAL ANALYSIS WITH JOBE-NEWMAN AGGREGATE

As discussed in the previous section, there was little to no trends apparent in the expansion data when the fine aggregate was composed of only fine aggregate from the Arkansas River. However, when the mortar mixtures contained 40 percent Jobe-Newman fine aggregate, trends became apparent. In this section of the research, concrete mixtures containing 40 percent Jobe-Newman were cast and subjected to the CPT. To date, the CPT was approximately 25 percent complete (6 months), but due to the reactivity of the Jobe-Newman fine aggregate, some trends related to the chemical composition of the fly ash and cement and expansion should be apparent.

Shown below in Figure 4.27 is the expansion data for the CPTs versus the CaO/SiO_2. The trend line provides a R^2 of 0.79 and based on that trend line, expansion increases as the CaO/SiO_2 increases. It should be noted, that the expansion data is 25 percent complete (24 month test and 6 months of data have been collected) and more expansion is expected. At this completion level, all fly ashes at a 40 percent cement replacement rate have expansion less than 0.04 percent. Based on the trend line, if the CaO/SiO2 is less than 2.75, the aggregate would be classified as non-reactive.

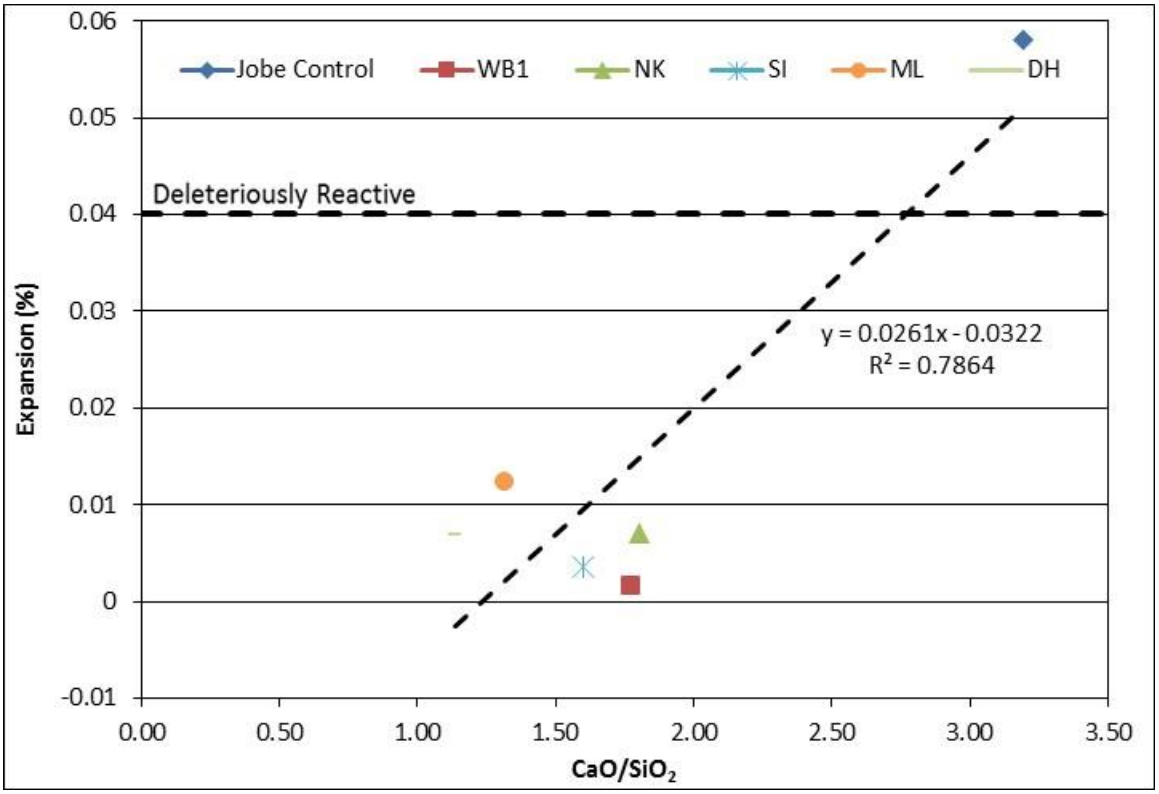

Figure 4.27 – Calcium Oxide to Silicon Dioxide Ratio Percentage with Jobe Newman

The expansion data versus the CaO content is plotted in Figure 4.28. The data show that the CaO content did influence the expansion rate of the concrete prisms. While there was some variability in the expansion data of the prisms containing fly ash, there was a trend that showed the increase in expansion as CaO content increased. At 6 months of age, the concrete prisms cast with the five fly ashes tested experienced expansions less than 0.04 and were classified as non-reactive. Based on the trend line, if the CaO content is less than approximately 58 percent, the aggregate would be classified as non-reactive.

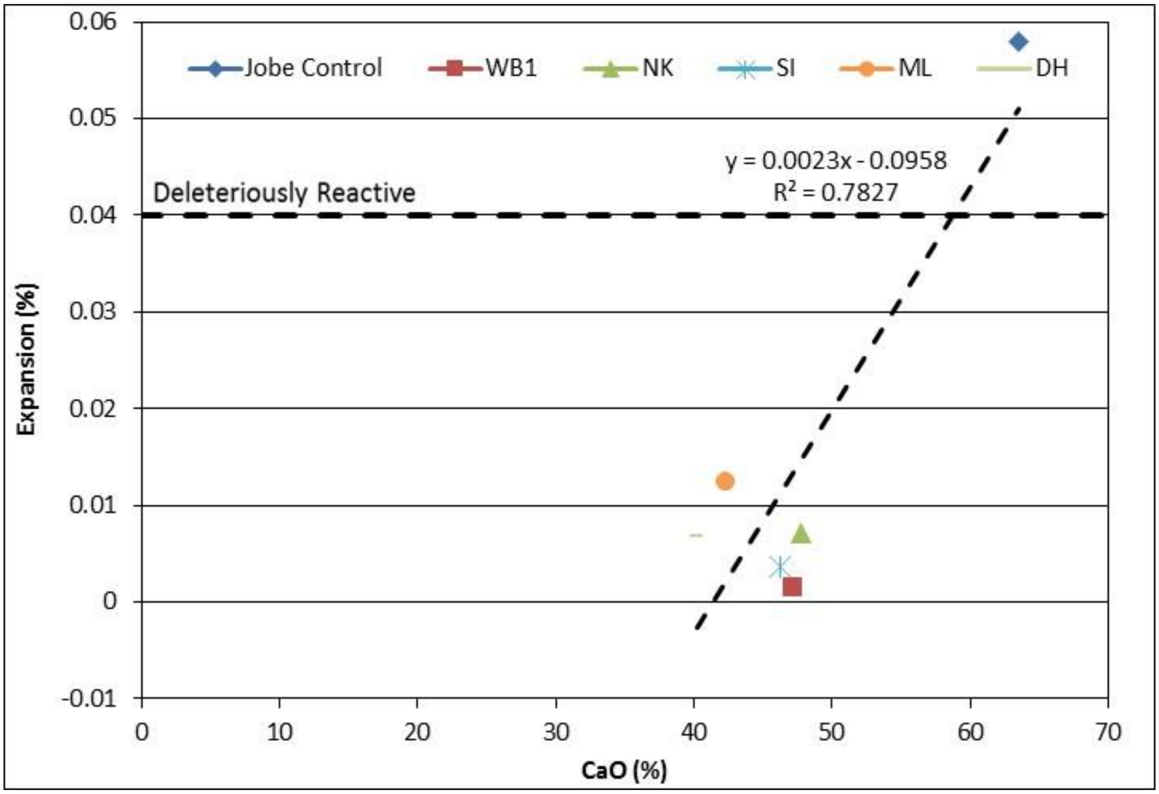

Figure 4.28 – Calcium Oxide Percentage with Jobe-Newman

The expansion as measured by the CPT was plotted versus the SiO_2 content for each fly ash in Figure 4.29. The SiO_2 content was calculated in the same manner as the previously calculations. The data shown in Figure 4.29 follow a general trend of a decrease in expansion as the SiO_2 content increases. This trend has been documented in the literature (Malvar 2006). As with the CaO/SiO_2 and CaO content, the fine aggregate mix of 40 percent Jobe-Newman and 60 percent Arkansas River sand would be classified as non-reactive for concrete mixtures containing any of the five fly ashes tested. The R^2 value was 0.49 and therefore there was some correlation between the SiO_2 content and expansion, however the correlation was one of weakest of the chemical compositions investigated.

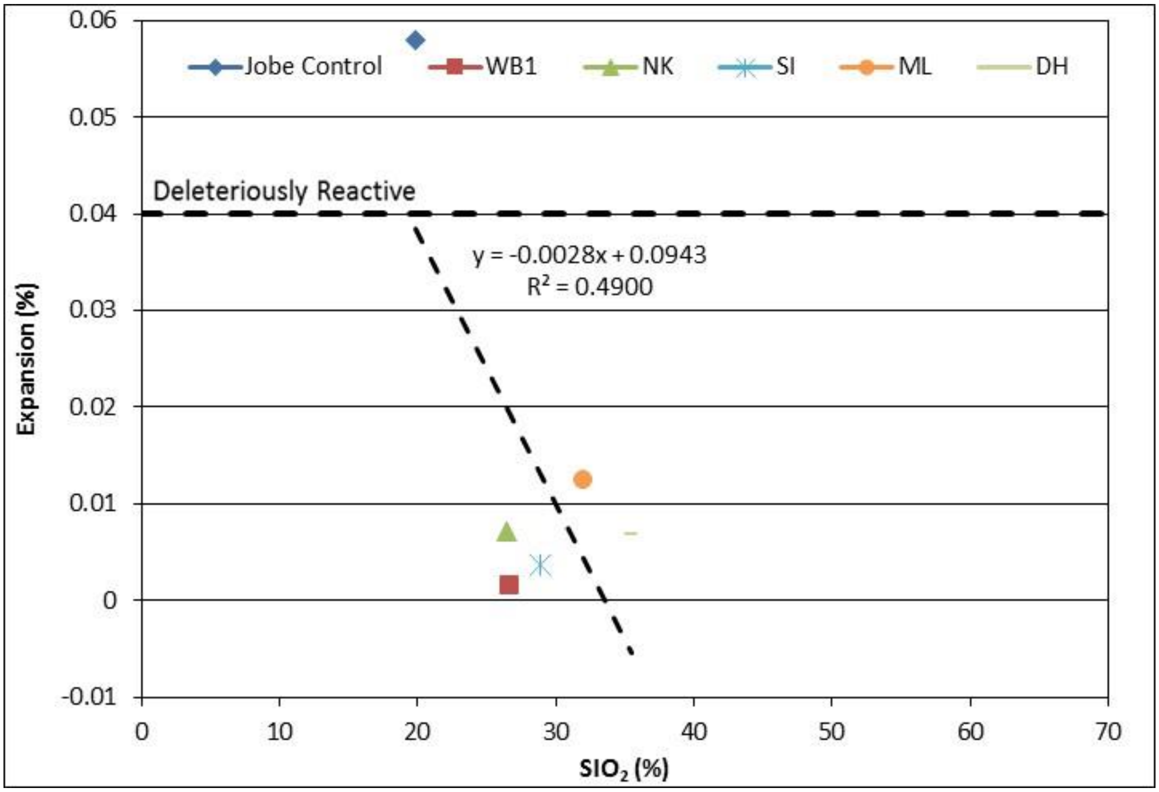

Figure 4.29 –Silicon Dioxide Percentage with Jobe-Newman

The expansion versus the ratio of the sum of the alkalis to the sum of the oxides (Σalkalis/Σoxides) was plotted in Figure 4.30. Figure 4.30 has the most accurate trend with an R^2 value of 0.91. At 6 months of age, concrete prisms containing any of the fly ashes had an expansion that was less than 0.015 and the mixture would be classified as non-reactive. For the 6 month data, the Σalkalis/Σoxides should be less than 2.15 to be classified as non-reactive based on the trend line.

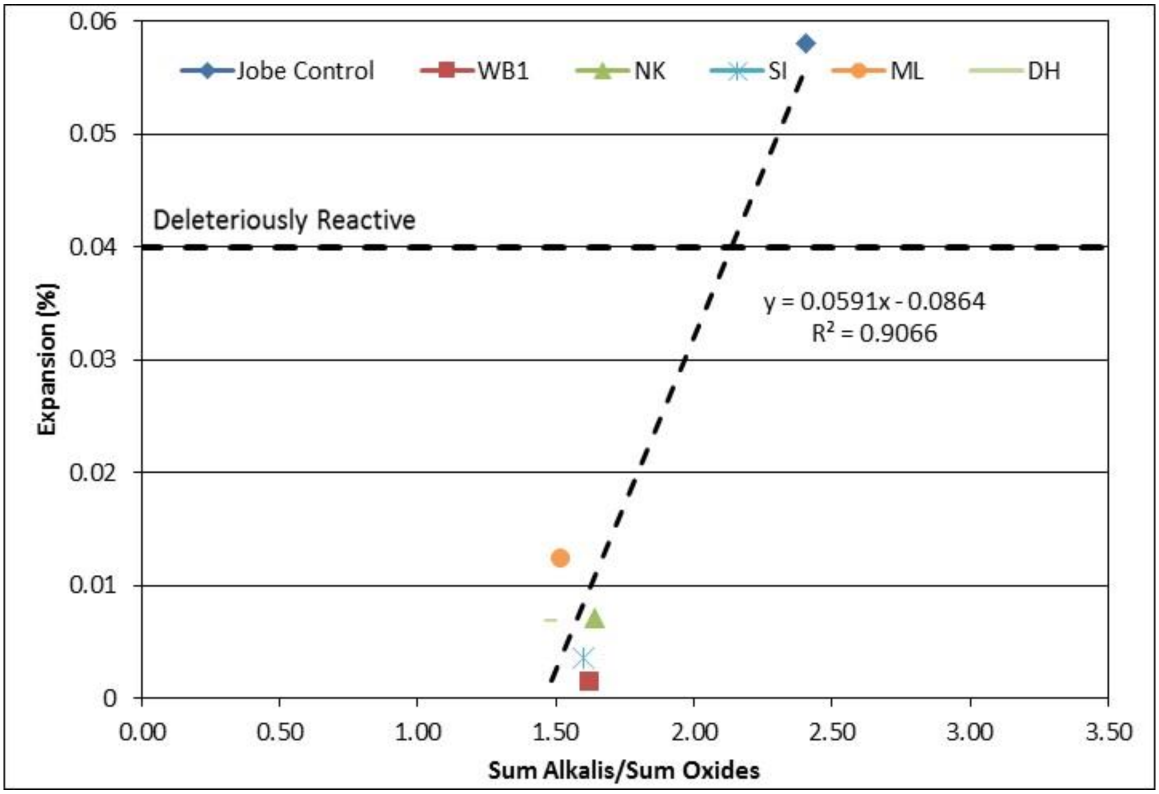

Figure 4.30 – Sum Alkali to Sum Oxide Ratio Percentage with Jobe Newman

The concrete prism expansion data were plotted against the total alkali content of the concrete in Figure 4.31. This included the alkali content of the cement and the alkali content of the fly ash. As in the previous figures, the total alkali content was determined by multiplying the fly ash and cement content by their respective alkali content. For each fly ash, there was one data point. Each data point represents the 40 percent fly ash content.

The data in Figure 4.31 shows that the total alkali content did directly influence the expansion rate for the mixtures tested. Concrete prisms cast the five fly ashes at the 40 percent replacement rate were classified as non-reactive. For all concrete prisms, expansion increased as total alkali content increased. Based on the trend line, if the alkali content is below approximately 63 percent, the aggregate would be classified as non-reactive. Finally, the R^2 value was 0.72 and therefore there was mildly strong correlation between the total alkali content to expansion.

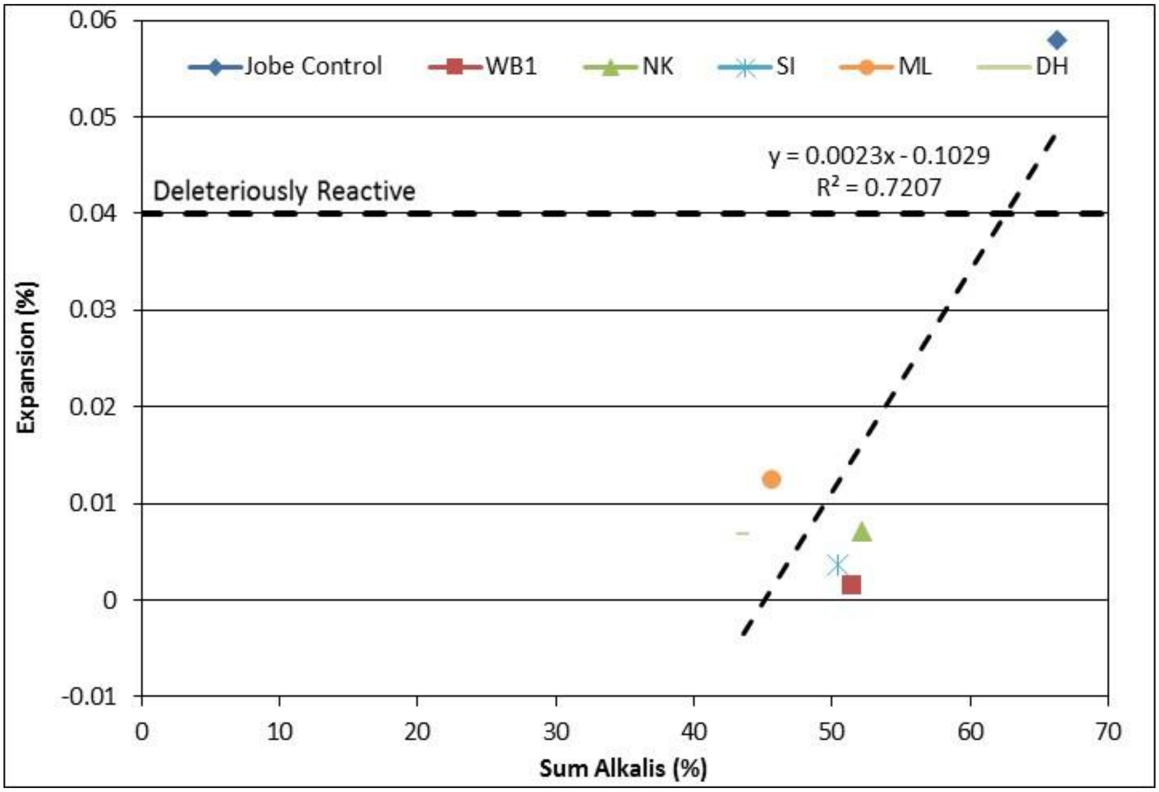

Figure 4.31 – Sum Alkali Percentage for Jobe with Jobe-Newman

In Figure 4.32, the mortar bar expansion data were plotted against the total oxide content of the concrete. This included the oxide content of the cement and the oxide content of the fly ash. As in the previous figures, the total oxide content was determined by multiplying the fly ash content by its oxide content and adding it to the oxide content of the cement multiplied by the percentage content of the cement. For each fly ash, there was one data point. Each data point represents the 40 percent fly ash content.

The trend line in Figure 4.32 shows that there is a relationship between the total oxide content and the expansion. However, at 6 months of age, concrete prisms cast with five fly ashes experienced expansions less than 0.04 and were classified as non-reactive. For all concrete prisms, expansion decreased as total oxide content increased. Based on the trend line, if the total oxide content is greater than 30 percent, the aggregate would be classified as non-reactive. Finally, the R^2 value was 0.69 and therefore there was mild correlation between the total alkali content to expansion.

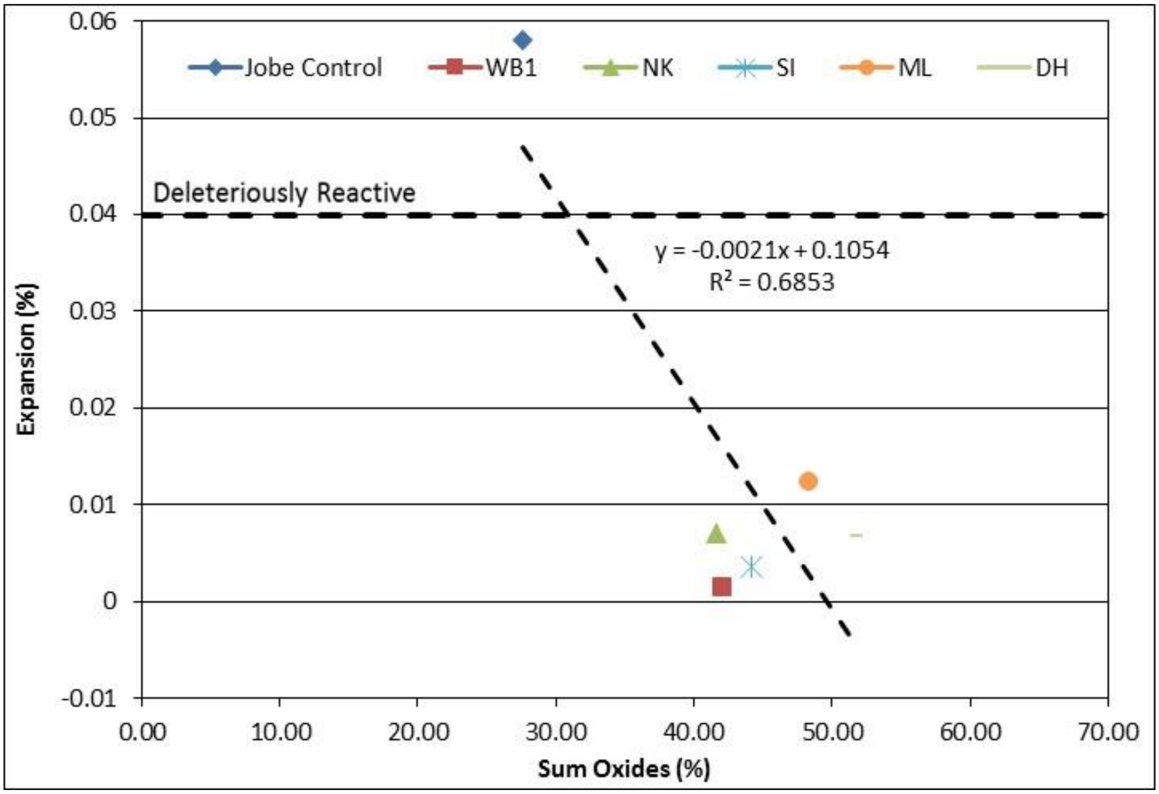

Figure 4.32 – Sum Oxide Percentage with Jobe-Newman

Chapter 5: CONCLUSIONS

5.1 INTRODUCTION

The objective of the research project was to prevent future occurrences of ASR in Arkansas through the addition of Class C fly ash in concrete. To achieve this objective, six locally available fly ashes were examined at cement replacement rates of 0 to 40 percent. To initiate ASR, two reactive aggregates were included in the study. The accelerated mortar bar test (ASTM C1260 and C1567) and preliminary results from the concrete prism test (ASTM C1293) were used to examine the effectiveness of the fly ash in preventing ASR. The concrete prism test (CPT) has a testing duration of two years, and therefore only six months of results were shown for that particular test.

5.2 CONCLUSIONS

The results show that Class C fly ash can effectively impede ASR expansion for mixtures containing fine aggregate from the Arkansas River and for mixtures with 40 percent of the fine aggregate replaced with Jobe-Newman fine aggregate. The results show that for all fly ashes tested, except for the Muskogee fly ash, a replacement rate of 20 percent would classify the mixture (according to the AMBT – ASTM C1260 and C1567) as being non-reactive when the fine aggregate from the Arkansas River was used. There was little to no difference in the performance between the Class C and Class F fly ashes when the mortar mixtures contained only fine aggregate from the Arkansas River. When the mortar contained Jobe-Newman aggregate, a Class F fly ash content of 30 percent or a Class C fly ash content of 40 percent was necessary to reduce the expansion to below 0.10 percent and therefore classify the aggregate as non-reactive (according to ASTM C1260 and C1567). For all fly ashes tested, expansion decreased as the fly ash content increased.

The effect of the chemical composition of the fly ash and cement on the expansion as measured by the AMBT was also examined. When the mixtures contained only fine aggregate from the Arkansas River, there were no apparent trends in the expansion data. However, when the mixtures contained the Jobe-Newman fine aggregates, several trends were obvious. Those conclusions are summarized below.

1. Expansion increased as the CaO/SiO_2 increased. For mortar mixtures containing any of the Class C fly ashes tested or the Class F fly ash from Martin Lake, the CaO/SiO_2 ratio should be less than 1.7 in order to be classified as non-reactive. For the Class F fly ash from Dolet Hills, the ratio should be less than 1.6.
2. Expansion increased as the CaO content increased in most cases. To ensure the mortar mixtures were classified as non-reactive, the CaO content should be limited to 47 to 50% depending on the fly ash type.
3. Expansion increased as the SiO_2 content decreased. To ensure the expansion remains less than 0.1 percent, the SiO_2 content should be greater than approximately 30 percent. However, there are some fly ashes, such as Class C fly ash from White Bluff or the Class C fly ash from Newark, where the SiO_2 content can be as low as 26 percent before expansion exceeds 0.1 percent.
4. Expansion increased as the Σalkalis/Σoxides increased. If the Σalkalis/Σoxides remained below approximately 1.20, the expansion was less than 0.1 percent.

5. Expansion increased as the total alkali content increased. An alkali limit of 51 percent in the cement and fly ash would sufficiently impede the ASR to stop potential concrete damage.
6. Expansion increased as the oxide content decreased. In order to prevent ASR, the oxide content in a mixture should be greater than 43 percent for five of the fly ashes and greater than 45 percent for Dolet Hills fly ash.

The Concrete Prism Test (CPT) was also used to determine the effectiveness of the fly ashes in preventing ASR. At six months of age, there was little difference in the expansion of the concrete prisms cast with four of the five fly ashes for concrete containing only fine aggregate from the Arkansas River. The difference in expansion was due to the addition of the White Bluff Class C fly ash which contracted during the first 28 days of testing. The mixture was tested twice and both times the mixture contracted during the first 28 days and then began to expand.

For mixtures containing Jobe-Newman fine aggregate, the addition of fly ash reduced expansion when compared to the control specimens at 6 months of age. At the 40 percent replacement rate, there was little difference between the effectiveness of the Class C fly ashes versus the Class F fly ashes. As discussed in Chapter 4, with six months of data, there are no conclusions that can be determined from the CPT tests in relation to the chemical composition of the fly ashes.

5.3 RECOMMENDATIONS

The following recommendations are based on the results from the research project. The recommendations are limited to the materials tested and tests that were performed in this research project.

1. Expansion increased as fly ash content decreased. A minimum fly ash content of 20% for the fly ashes tested other than Muskogee fly ash which requires a 40% replacement rate to be used in Arkansas to prevent ASR. While the trends aren't as accurate for analyzing the use of fly ashes the test results have shown that all fly ashes except Muskogee to have been nonreactive with a 20% replacement rate. This replacement rate was based off the low reactivity of the Arkansas River Sand and the rigorous testing of AMBTs in the high temperature alkali saturated water bath.
2. ASTM C618 was shown to be inaccurate using only oxide content to analyze expansion. ASTM C618 should be updated to using a ∑alkalis/∑oxides ratio.
3. ASTM C618 maximum of MgO of 5.0% should remain in effect as the Muskogee fly ash showed an increase in deleterious expansion due to MgO.
4. The concrete prism tests have been tested to 6 months out of 2 year test period required per ASTM C1293. The CPT data collecting should continue until the ASTM C1293 specified two year testing length is complete.
5. Fly ash replacement rates tested include 0, 20, 30, and 40 for the AMBT. Testing fly ash replacement rates for AMBTs should expand to include 5, 10, and 15 % replacement rates to determine potential pessimum effects.
6. Also, due to the Muskogee fly ash having similar chemical composition, other than the high MgO content, to the other Class C fly ashes and higher expansion than the

other fly ashes it should be retested to verify the results. The Muskogee fly ash tested did have a higher MgO content than specified by ASTM C618 and the higher reactivity was explained by Diamond's findings saying high MgO content can cause unsoundness of the aggregate in the concrete via the MgO reacting and becoming $Mg(OH)_2$ (Diamond 1981).

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