Article

Improving Concrete Infrastructure Projects Conditions by Mitigating Alkali-Silica Reactivity of Fine Aggregates

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Abstract: Alkali-silica reactivity (ASR) is one of multiple reactions responsible for premature loss in concrete infrastructure service life. ASR is a deleterious reaction initiated when highly reactive silicious content of aggregates reacts with alkali hydroxides content within portland cement in the presence of moisture. ASR results in the formation of expansive, white-colored gel-like material which results in internal stresses within hardened concrete. ASR induced stresses result in concrete cracking, spalling, and increased reinforcement steel corrosion rates. The main objective of this research is to improve the conditions of concrete infrastructure projects conditions by mitigating ASR damaging effect. The expansion of accelerated mortar bars poured using fine aggregates collected from different sources is measured versus time to evaluate aggregate's reactivity. Different percentages of supplementary cementitious materials (SCMs) including class c fly ash, micro-silica, were used in remixing mortar bars to evaluate the efficiency of different types of SCMs in mitigating mortar bar expansion. Research findings showed that SCMs can mitigate ASR, thus, decrease the mortar bar expansion. The efficiency of SCMs in ASR mitigation is highly dependent on the incorporated SCM percentage and particle fineness. Silica fume, having the least particle size, displayed higher rates of ASR mitigation followed by fly ash, respectively. The outcomes of this research will assist design engineers in avoiding future losses due to ASR cracking in concrete infrastructure projects, and reduce the excessive need to maintenance, repair, and replacement activities.

Keywords: ASR, Aggregates, Moisture, Mortar bas test, Supplementary cementitious materials

1. Introduction

Alkali-silica reaction (ASR) is a common form of alkali-aggregate reaction (AAR) that naturally occurs in concrete structures. ASR is responsible for premature loss in concrete infrastructure projects service life. ASR was first identified in California in the 1940s. ASR is a deleterious chemical reaction initiated when reactive silica content (SiO_2) within the aggregates reacts with the alkali hydroxide content within portland cement in the presence of relatively high moisture. ASR results in the formation of white expansive gel-like material within hardened concrete which adds internal tensile stresses to the concrete structure as it ages. Thus, ASR cracks are developed, and concrete structures deteriorate. ASR mechanism can be viewed as a two-step chemical reaction that takes up to 10 years to mature, according to the following equation:

$$\text{Alkali (Cement)} + \text{Reactive Silica (Aggregates)} \longrightarrow \text{Alkali-Silica Gel} \quad [1]$$

$$\text{Alkali-Silica Gel} + \text{Moisture} \longrightarrow \text{Expansive Gel} \quad [2]$$

In 1956, ASR were reported in 17 states. In 1993, the Strategic Highway Research Program (SHRP) conducted a nationwide survey [1] to investigate ASR impact on the national highway network. The SHRP survey received a positive response from 19 states, negative response from 18 states, and no response from 5 states, as shown in Figure 1.

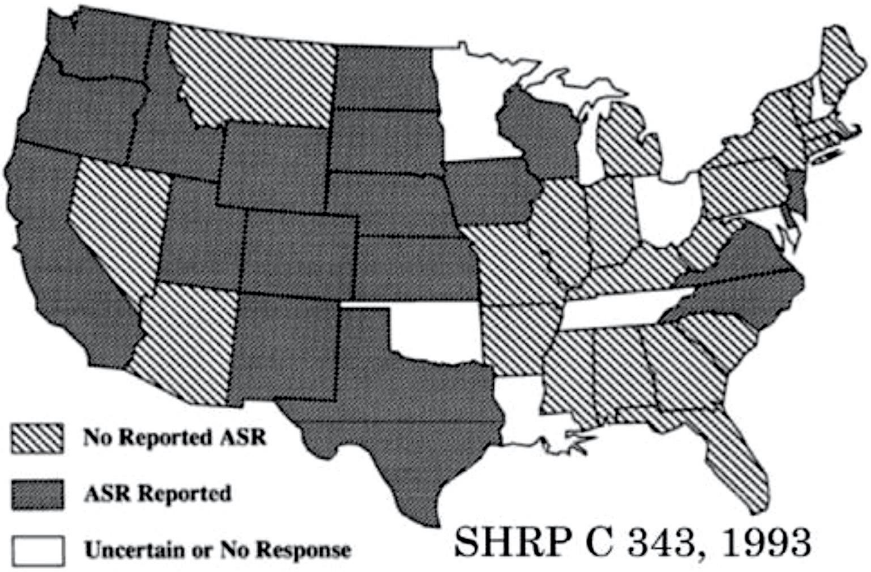

Figure 1. ASR survey results (Stark 1993)

The number and severity of ASR reported cases and the impact of ASR deleterious effect depends on concrete mix proportions, air content, exposure to moisture, and the type and percentage of reactive silica in the mix. The presence of gel does not necessarily indicate destructive ASR, as some gels have low tendency to expand. Low-swelling gels will not create ASR problems. High-swelling gels, once formed, tend to react with free moisture within a hardened concrete structure to expand and may cause tensile stress that exceeds concrete strength, which results in premature cracking of concrete structures. By year 2003, more than 40 state Department of Transportation (DOT) have reported a significant damage in infrastructure due to ASR. States with reported ASR cases are shown in **Figure 2**. The national loss due to ASR on state DOTs projects is estimated by several hundreds of millions of dollars.

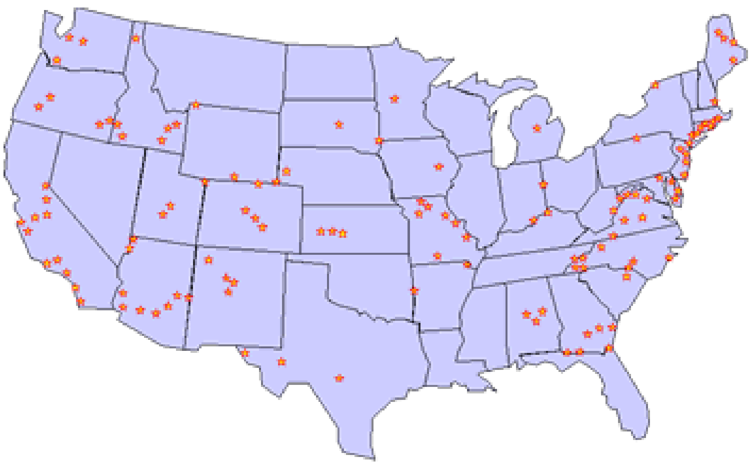

Figure 2. States with ASR reported cases [2]

2. Literature Review

Early deterioration and premature failure of concrete structures due to ASR was first explained in the United States in the 1940s [3]. Based on Stanton's discovery, several deteriorate concrete structures were investigated, and ASR was found responsible for the premature deterioration of concrete. The amount of expansive gel responsible for concrete damage varies according to the type of reactive silica, alkali hydroxide content concentration in concrete pore solution. Exact gel composition varies; however, it will always contain alkali, silica, calcium, and water [4]. Aggregates with large surface area for reaction, poor crystalline, with many lattice defects are more susceptible to ASR reaction [5,6]. ASR white expansive gel, shown in Figure 3, results in cracking once the resulting tensile stresses exceed the hardened concrete tensile strength. Initially, hair cracks are formed; as the structure ages and expansive gel volume increases, hair cracks increase in number and unite to form larger size cracks. Larger cracks reduce the concrete structure serviceability and results in deterioration in project conditions.

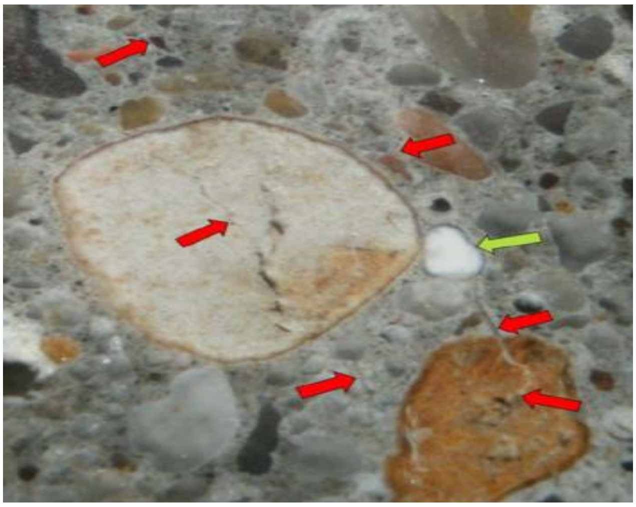

Figure 3: Expansive white gel-like substance formed as a result of ASR

Several research studies provided further explanation to ASR and how it is initiated. During concrete mixing, the aggregate content including limestone, gravel, crushed granite, and fine sand is encapsulated with hydrated cement paste with high alkalinity (pH value may exceed 13.0). Once hydration process is concluded, free moisture within the hardened concrete dissipates through concrete pores as a high alkaline solution that reacts with specific silicious content within the aggregates [7-10]. The alkali-silica reaction tends to form the expansive gel that results in ASR damaging effect. Similarly, the alkaline solution may attack specific carbonates present in the aggregate to form a damaging alkali-carbonate reaction (ACR). Both ASR and ACR reactions are extremely damaging and may cause premature failure to concrete structures. ASR and ACR damages are similar to other types of deterioration due to weathering, effect of de-icing salts on concrete structures, and freeze-thaw cycles.

In order to differentiate between ASR and other types of concrete damages, a petrographic analysis of concrete specimens is required to identify the nature of the reaction causing deterioration. In a typical petrographic testing, a concrete core is drilled in the structure, and the obtained sample is shipped to the lab, where reagents are applied on the concrete surface under consideration, as shown in **Figure 4**. Based on the reagent reaction outcomes, ASR could be confirmed or denied.

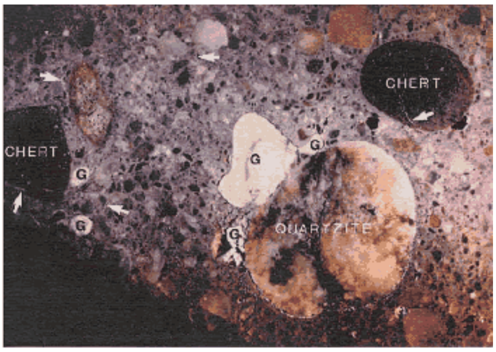

Figure 4. ASR damage as detected by petrographic analysis (Fournier et al. 2010)

Internal stresses resulting from the expansion of formed del is directly proportional to the amount of gel formation, the rate of gel expansion upon reacting with free moisture within hardened concrete, and the surface area of concrete structure exposed to external environmental conditions, and excessive moisture. ASR is responsible for significant deterioration of hardened concrete structures, mainly infrastructure projects as roadways, tunnels, bridges, roadway barriers, and earth retaining structures due to their large-exposed surface and possible moisture ingress through rain, thawing of snow, and underground water tables [12-18]. Examples of ASR damage in infrastructure projects are shown in **Figure 5**.

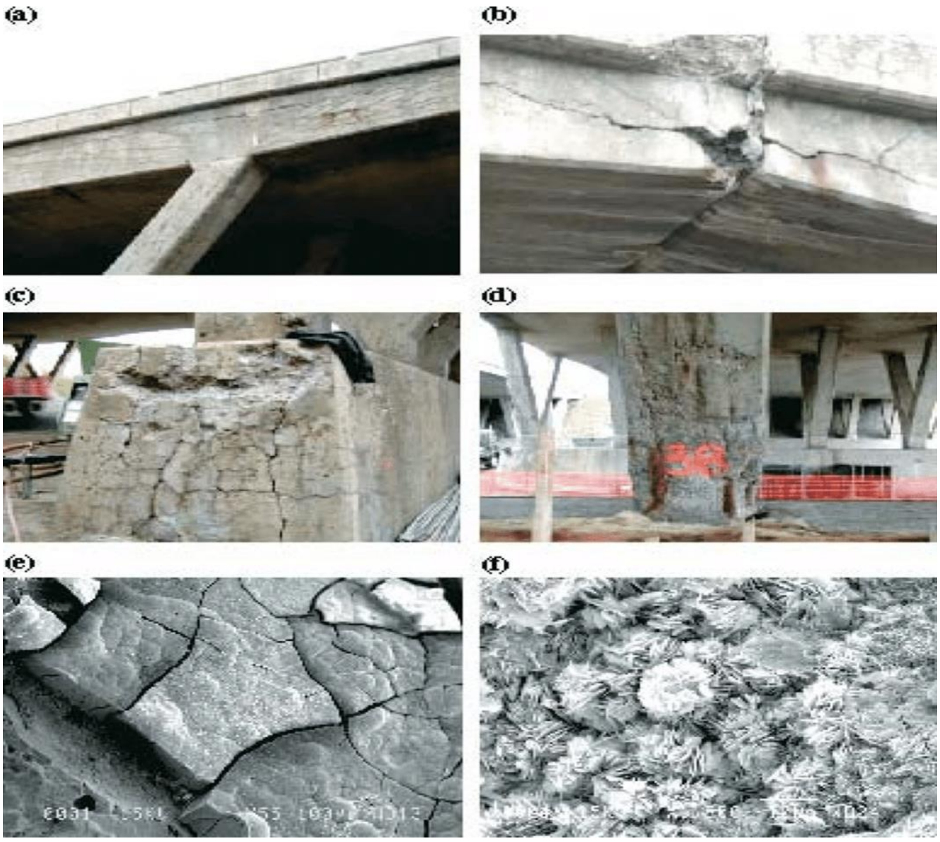

Figure 5. Alkali-silica reaction damage to infrastructure projects [19]

The infrastructure project damage due to ASR is classified as low, medium, or high. These ratings adopted by the Federal Highway Administration (FHWA) are based upon the extent of the damage, and its diagnostic. **Table 1** provides the extent of different damage features associated with different ASR condition rating [20].

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Table 1. Nature and extent of damage for different ASR condition rating

ASR Damage Rating	Nature and Extent of Damage Features
Low	• No ASR gel formation (or only present in few air voids) • Extremely limited cracking within the aggregate particles that may/may not extend to cement paste • Absence of other destruction indicative features
Moderate	• Presence of damp patches on core surfaces • Presence of reactive rocks • Moderate cracks extending the cement paste • Darkening of cement paste around reactive aggregate particles
High	• Extensive signs of ASR reaction as measure expansion and extensive cracking • Presence of expansive gel in cracks • Possible concrete surface spalling

Recent studies investigated the possibility of ASR early detection prior to the start of construction activities. Proactive measures include the detection of potentially reactive aggregates available at local sources. Expedited testing for ASR and relevant standards are developed for early detection of ASR [21-24]. ASR Laboratory evaluation measures has average reliability due to the difference between lab conditions and the environmental conditions a concrete member is subjected to during its service life [25-29]. Other ASR detection methods includes the development of field exposure site to predict ASR through full scale expansion testing of hardened concrete members [30, 31]. Finally, potential ASR could be assessed using petrographic analysis using SEMs. ASR detection by petrography provides accurate detection of ASR [32, 33], however, it is laborious, expensive, and destructive. Also, petrography testing is conducted in limited labs across the United States.

Several ASR mitigation techniques are being utilized to mitigate, or possibly eliminate, its damaging effect including (1) the use of chemical admixtures as lithium salts to halt ASR [34-41], (2) the use of mineral admixtures, also known as supplementary cementitious materials (SCMs), as silica fume, quartz flour, fly ash, blast furnace slag, metakaolin, and multi-wall carbon nanotubes [42-47], and (3) the use of chemical and latex surface painting to prevent the moisture ingress into hardened concrete surface [48-50].

The main objective of this research is to investigate the potential reactivity of fine aggregates received from different sources, and evaluate the efficiency of different percentages of SCMs in mitigating alkali silica deleterious reaction impact on hardened concrete. ASR mitigation efficiency is evaluated by measuring the reduction in concrete expansion due to the incorporation of SCMs in concrete mix design. The research objectives are attained through the following methodology:

1. Local sources of fine aggregates are surveyed, and samples are obtained for ASR detection
2. Accelerated mortar bar test for ASR detection of fine aggregates are conducted. Expansion of mortar bars is measured and compared with permissible limits
3. Different percentages of SCMs, including micro-silica and class c fly ash are used to pour additional mortar bars for expansion measurements
4. Efficiency of SCMs in ASR mitigation is quantified through the decrease in bars expansion
5.

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3. Experimental Investigation

Three different types of fine aggregate is obtained from local sources. Fine aggregate, denoted as F1, F2, and F3, are selected due to their inclusion in the Department of Transportation concrete infrastructure projects. The experimental investigation includes 2 phases:

Phase 1: Evaluate the reactivity of the different types of fine aggregate using the accelerated mortar bar test (AMBT)

Phase 2: Evaluate the efficiency of different percentage of SCMs in mitigating potential ASR

Phase 1: Accelerated Mortar Bar Test (AMBT) for ASR of Fine Aggregates

AMBT was originally developed in South Africa in the 1980s as an accelerated method to identify potentially reactive fine aggregates, and evaluate the possible mitigation of ASR expansion using SCMs. The AMBT, currently adopted by different codes and specifications as *the Canadian Specifications*, *AASHTO, ASTM International*, and *PCA*, uses a standard prism mold of 2.5 x 2.5 x 28.5 cm. (1.0 x 1.0 x 11.25 in.) to pour mortar bars using fine aggregates and SCMs to be investigated. The prism mold has 2 studs (one stud per end) to be embedded in the poured mortar bar to measure the length change versus time. AMBT mortar molds and poured prisms are shown in **Figure 6.**

Figure 6. AMBT molds and mortar bars pour for AMBT test

The AMBT spans for 16 days before the potential reactivity of fine aggregates or the efficiency of SCMs in expansion mitigation are evaluated. According to ASTM International, average expansion of 3 mortar bars poured using the same mix should be calculated. A total expansion less than 0.1% of the initial bar length indicates low reactivity. The reduction in expansion measured when SCMs are incorporated in the concrete mix design is indicative of the SCMs efficiency in mitigating ASR possible damage.

Mortar Bar Preparation

Mortar bars were poured according to ASTM International guidelines. The following procedures were followed in the preparation of test specimens:

1. Type I/II portland cement was used in pouring AMBT specimens. The same cement batch is used in the preparation of all specimens to ensure the consistency of test results
2. Fine aggregate specimens (F1, F2, and F3) were used to pour the mortar bars. Three bars were poured using the same aggregate sample
3. SCM-free AMBT were poured using high energy paddle mixer using a cement-to-aggregate ratio of 1 : 2.25 by weight
4. SCMs including micro-silica, class c fly ash, were used to pour additional mortar bars. SCMs are used in stepwise replacement of portland cement using a 1 : 1 weight ratio. Mortar bars design combinations are shown in **Table 2**.

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Table 2. Mortar bar design combinations (based on fine aggregate and SCM type and content)

Specimen	Aggregate	Silica Fume	Class c fly ash
F1-SF(0%)-FA(0%)	Fine Aggregate (F1)	0%	
F1-SF(15%)-FA(0%)		15%	0%
F1-SF(30%)-FA(0%)		30%	0%
F1-SF(0%)-FA(15%)		0%	15%
F1-SF(0%)-FA(30%)		0%	30%
F2-SF(0%)-FA(0%)	Fine Aggregate (F2)	0%	
F2-SF(15%)-FA(0%)		15%	0%
F3-SF(30%)-FA(0%)		30%	0%
F4-SF(0%)-FA(15%)		0%	15%
F5-SF(0%)-FA(30%)		0%	30%
F3-SF(0%)-FA(0%)	Fine Aggregate (F3)	0%	
F3-SF(15%)-FA(0%)		15%	0%
F3-SF(30%)-FA(0%)		30%	0%
F3-SF(0%)-FA(15%)		0%	15%
F3-SF(0%)-FA(30%)		0%	30%

Mortar Bar Fabrication, Storage, and Expansion Measurements

Mortar bars are poured, consolidated, and left to harden for a 24-hour duration. When removed from molds, bars are initially stored initially stored for 24 ± 2 hours in a relative humidity greater than 95% and a temperature of 73.4 ± 3 F., as shown in Figure 7.

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Figure 7. Mortar bar storage for AMBT testing

After initial storage, mortar bars were removed from their sealed containers, and initial AMBT readings were measured and recorded. The readings calculate the difference between the mortar bar length and a fixed length comparator bar. Initial readings recorded at 48-hour age are considered the base for measuring length changes during the duration of the experimental investigation (16 days). According to ASTM standard specifications, expansion measurement measured included the average of 3 readings for every design combination (S1 through S15). Lab measuring device for mortar bar extension and measuring process are shown in Figure 8.

Figure 8: Mortar bar expansion measurement (using standard metal bar comparator)

During the 2-week AMBT duration, specimens are stored in a solution of 1 M NaOH at a temperature of 176 $\pm$ 3.6 F. Specimens are required to be stored at these harsh conditions to induce the potential ASR in a short period of time. Bars expansion was measured and recorded according along the test duration, as shown in **Table 3**.

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Table 3: AMBT expansion results versus time

Specimen	Day 1	Day 4	Day 7	Day 10	Day 13	Day 16
F1-SF(0%)-FA(0%)	0.000	0.025	0.043	0.079	0.092	0.110
F1-SF(15%)-FA(0%)	0.000	0.049	0.056	0.060	0.061	0.062
F1-SF(30%)-FA(0%)	0.000	0.042	0.044	0.046	0.046	0.047
F1-SF(0%)-FA(15%)	0.000	0.066	0.074	0.079	0.079	0.080
F1-SF(0%)-FA(30%)	0.000	0.062	0.065	0.066	0.067	0.069
F2-SF(0%)-FA(0%)	0.000	0.061	0.066	0.072	0.086	0.101
F2-SF(15%)-FA(0%)	0.000	0.051	0.057	0.058	0.059	0.060
F2-SF(30%)-FA(0%)	0.000	0.040	0.041	0.042	0.043	0.045
F2-SF(0%)-FA(15%)	0.000	0.057	0.058	0.061	0.062	0.064
F2-SF(0%)-FA(30%)	0.000	0.057	0.058	0.060	0.065	0.068
F3-SF(0%)-FA(0%)	0.000	0.041	0.051	0.059	0.081	0.094
F3-SF(15%)-FA(0%)	0.000	0.029	0.038	0.046	0.048	0.050
F3-SF(30%)-FA(0%)	0.000	0.020	0.037	0.043	0.044	0.045
F3-SF(0%)-FA(15%)	0.000	0.050	0.052	0.056	0.057	0.059
F3-SF(0%)-FA(30%)	0.000	0.051	0.053	0.055	0.056	0.060

Fine Aggregates Reactivity

Mortar bars fabricated using fine aggregates displayed potential reactivity based on the AMBT measurements. The average expansion of mortar bars at 16 days exceeded 0.1% for bars fabricated using fine aggregates F1 and F2. On the contrary, mortar bars fabricated using fine aggregate F3 had a 16-day expansion slightly lower than 0.1%. Average bars expansion are shown in **Figure 9**.

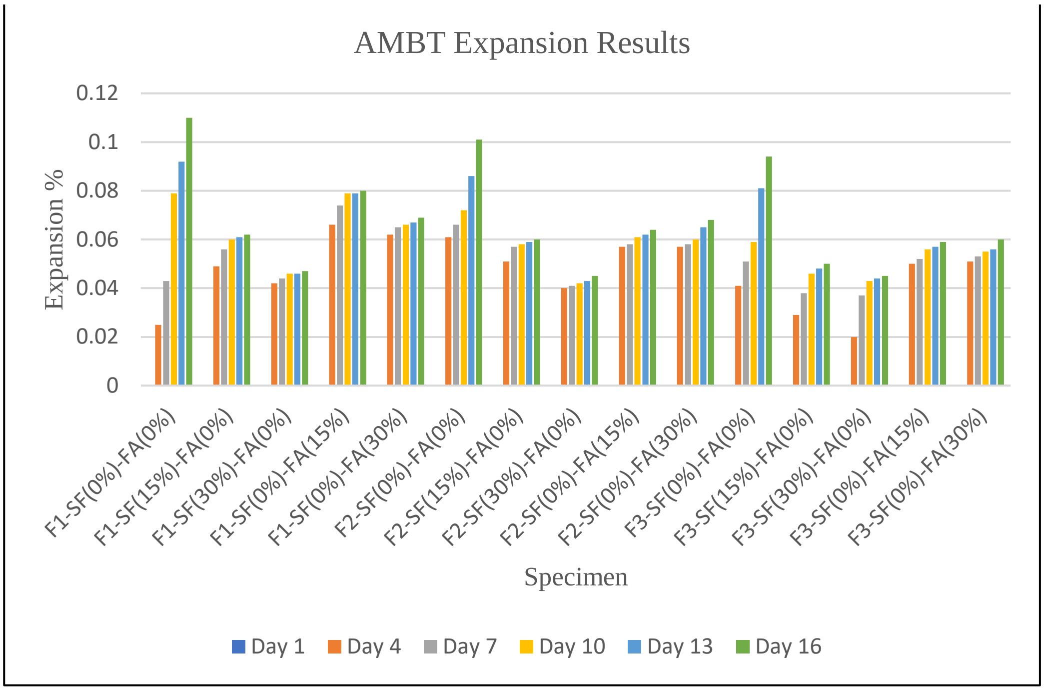

Figure 9. Average mortar bar expansion for fine aggregates F1, F2, and F3

Phase II: Impact of Supplementary Cementitious Materials on ASR Expansion

Mortar bars expansion was re-calculated after SCMs were incorporated in the concrete mix design used in bars' fabrication. In this research, micro-silica and class c fly ash were added to concrete mix design. Two ratios were selected for the SCMs content in replacement of 15% and 30% of portland cement by weight. The efficiency of SCMs in mitigating ASR is attributed to the following:

1. SCMs have a fine particle size as compared to all granular mix constituents. The fine particle size results in an improved packing order of the mix constituents and a decreased void's ratio. This lowers the rate of moisture ingress and reduces the rate of reactivity
2. SCMs result in a lower cement content, which reduce the alkaline content of the mix, and significantly reduce the alkali-silica reactivity within the mix
3. The incorporation of SCMs in concrete mix binds the alkaline content during the cement hydration process which reduces the pH value of the mix and slow down the deleterious ASR

According to the research findings, both micro-silica, with an average particle size of 0.5 μm (0.0002 in.), and class c fly ash, with an average particle size ranging from 10 to 100 μm (0.0004 to 0.004 in.) lowered the final measured mortar bar expansion, which indicates efficient mitigation of ASR. Micro-silica, with finer particle size, was more efficient in reducing mortar bar expansion. The percentage of reduction in bars expansion due to SCMs incorporation is shown in Figure 10.

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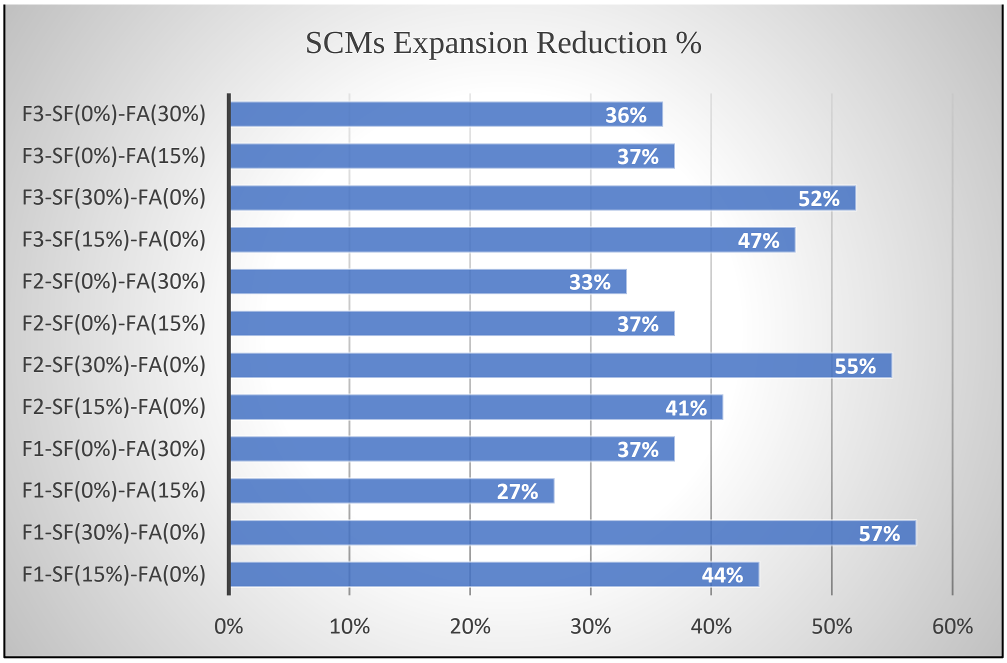

Figure 10. Percentage of AMBT expansion reduction due to SCMs

The average reduction in AMBT expansion due to the incorporation of different types and weights of silica fume and fly ash on different fine aggregate specimens (F1, F2, and F3) is shown in **Figure 11.** The incorporation of 30% of silica fume by weight resulted in maximum expansion reduction of 55% versus 34% reduction in expansion when 15% of class C fly ash is incorporated in the mix.

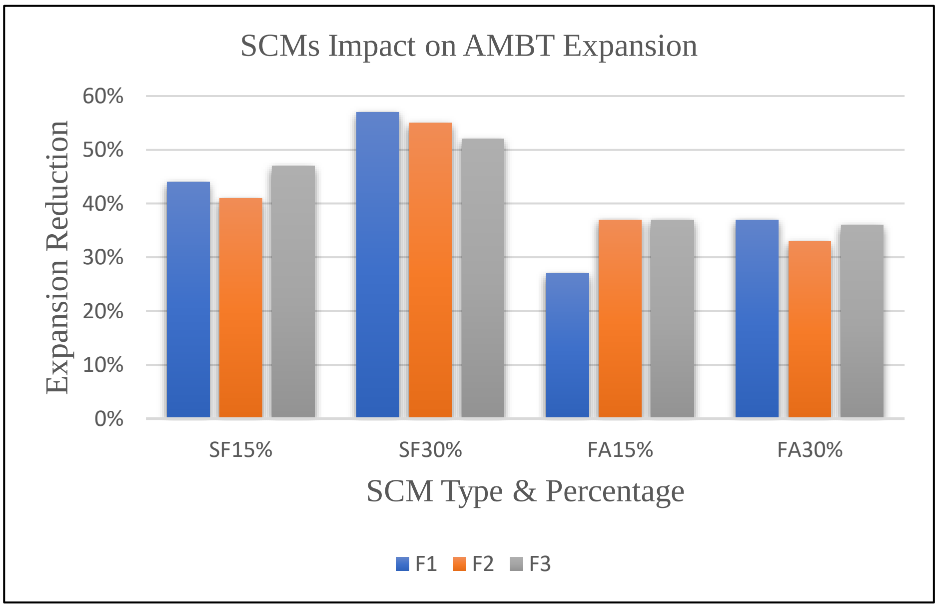

Figure 11. Percentage of AMBT expansion reduction versus SCMs incorporation

4. SUMMARY AND CONCLUSIONS

Alkali-silica reactivity has been identified as a main cause of infrastructure projects deterioration by different State DOTs. ASR impact on infrastructure project is attributed to the large exposure surface of infrastructure projects to environmental conditions, and the high rate of moisture ingress as a result of ground water table, rain, and ice formation.

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The free moisture catalyze the deleterious reaction between cement alkaline content and specific reactive silica available in aggregates.

Different testing techniques are currently used to investigate the potential reactivity of different types of aggregates. In this research, the AMBT is used to test three different types of fine aggregate specimens used in DOT projects. The outcome of the AMBT showed that two fine aggregate specimens represents a potentially reactive aggregate (with AMBT final expansion in excess of 0.1% of the bar original length). In an effort to mitigate the potential aggregate reactivity, silica fume and fly ash are incorporated in the mix with a minimum percentage of 15% and a maximum percentage of 30% by weight. The inclusion of SCMs with a fine particle size reduce the permeability of hardened concrete, thus the ingress of moisture is decreased. In addition, SCMs results in a lowered cement content, which reduces the alkalinity of the mix. Finally, SCMs bind the cement alkalinity, which mitigates the alkali-silica reactivity.

The outcomes of this research showed that the incorporation of 30% of silica fume in partial replacement of cement content results in a 55% reduction of bars final expansion. A minimum expansion reduction of 34% was attained when 15% of portland cement was replaced by class C fly ash. The successful detection of reactive aggregates and the possible mitigation of ASR through SCM incorporation will reduce the damaging effect of ASR, minimize the need to frequent maintenance, and result in improved infrastructure project conditions.

5. Recommendations for Future Research

ASR results in concrete deterioration and reduces the service life of concrete infrastructure projects resulting in major economic losses to the construction sector. Current methods of testing for ASR assist material engineers and project managers in selecting constituents with lower reactivity. More reliable testing techniques should be developed to predict ASR with higher accuracy. In addition, the efficiency of finer SCMs including nano-silica and multi-wall carbon nano tubes (MWCNTs) in ASR mitigation should be investigated, despite the high material cost of nano SCMs.

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