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Improving Concrete Infrastructure Project 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 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 by mitigating ASR's damaging effect. The expansion of accelerated mortar bars poured using fine aggregates collected from different sources is measured versus time to evaluate the aggregates' reactivity. Different percentages of supplementary cementitious materials (SCMs), including class C fly ash and microsilica, were used in remixing mortar bars to evaluate the efficiency of different types of SCMs in mitigating mortar bar expansion. The research findings showed that SCMs can mitigate ASR, thus decreasing 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 smallest particle size, displayed higher rates of ASR mitigation, followed by fly ash. 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 for maintenance, repair, and replacement activities.

Keywords: ASR; aggregates; mortar bar test; supplementary cementitious materials

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Citation: Akhnoukh, A.K. Improving Concrete Infrastructure Project Conditions by Mitigating Alkali–Silica Reactivity of Fine Aggregates. *Constr. Mater.* **2023**, *3*, 233–243. https://doi.org/10.3390/constrmater3020015

Received: 12 February 2023
Revised: 24 April 2023
Accepted: 11 May 2023
Published: 1 June 2023

1. Introduction

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. The ASR mechanism can be viewed as a two-step chemical reaction that takes up to 10 years to mature, according to the following equation:

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

$$\text{Alkali-Silica Gel} + \text{Moisture} \rightarrow \text{Expansive Gel} \quad (2)$$

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

The number and severity of ASR reported cases and the impact of ASR's 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 a low tendency to expand. Low-swelling gels do 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 the concrete's strength, which results in premature cracking of concrete structures. By the year 2003, more than 40 state Departments of Transportation (DOTs) had reported significant damage in infrastructure due to ASR. States with reported ASR cases are shown in Figure 1. The national loss due to ASR on state DOT projects is estimated to be hundreds of millions of dollars.

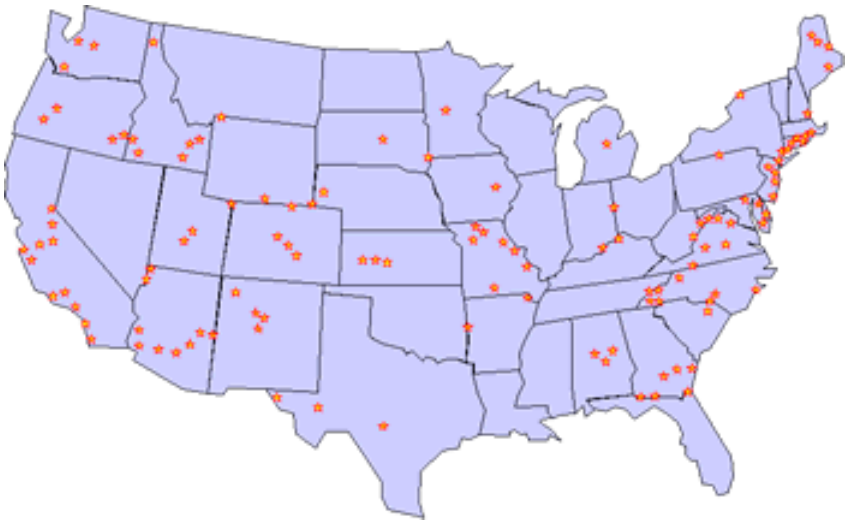

Figure 1. States with reported ASR cases [2].

2. Literature Review

The early deterioration and premature failure of concrete structures due to ASR were first explained in the United States in the 1940s [3]. Based on Stanton's discovery, several deteriorated concrete structures were investigated, and ASR was found to be responsible for the premature deterioration of concrete. The amount of expansive gel responsible for concrete damage varies according to the type of reactive silica and the alkali hydroxide content concentration in the concrete pore solution. The exact gel composition varies; however, it always contains alkali, silica, calcium, and water [4]. Aggregates with a large surface area for reaction, poor crystalline structure, and many lattice defects are more susceptible to ASR reactions [5,6]. White expansive gel that forms due to ASR, shown in Figure 2, results in cracking once the resulting tensile stresses exceed the hardened concrete tensile strength. Initially, hair cracks are formed; as the structure ages and the expansive gel volume increases, the hair cracks increase in number and unite to form larger cracks. Larger cracks reduce the concrete structure's serviceability and result in deterioration in project conditions.

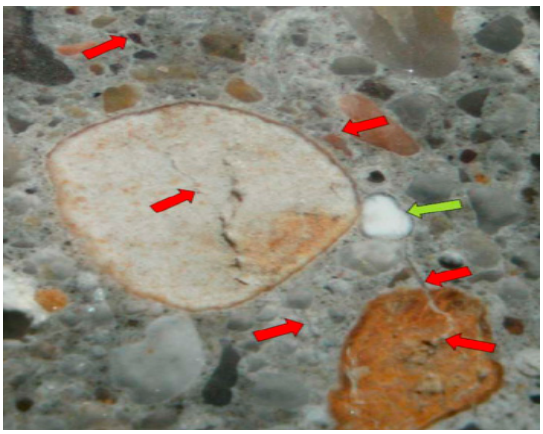

Figure 2. Expansive white gel-like substance formed as a result of ASR. Reprinted from ref. [7].

Several research studies provided further explanation of 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 (the pH value may exceed 13.0). Once the 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 [8–12]. The alkali–silica reaction tends to form an expansive gel that results in the damaging effect of ASR. Similarly, the alkaline solution may attack specific carbonates present in the aggregate to form a damaging alkali–carbonate reaction (ACR). Both the 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, the effect of deicing 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. Based on the reagent reaction outcomes, ASR can be confirmed or denied.

Internal stresses resulting from ASR-formed gel depend on the type and amount of reactive silica within the aggregates, the rate of gel expansion upon reacting with free moisture within hardened concrete, and the amount of free moisture available to catalyze the ASR. Due to the internal stress development, ASR is responsible for the expedited deterioration of hardened concrete structures. Deterioration starts when fine hair cracks are internally generated. These cracks increase in number and unite to form a smaller number of larger cracks, which result in concrete spalling and premature structural failure [13–18]. Examples of ASR damage in infrastructure projects are shown in Figure 3.

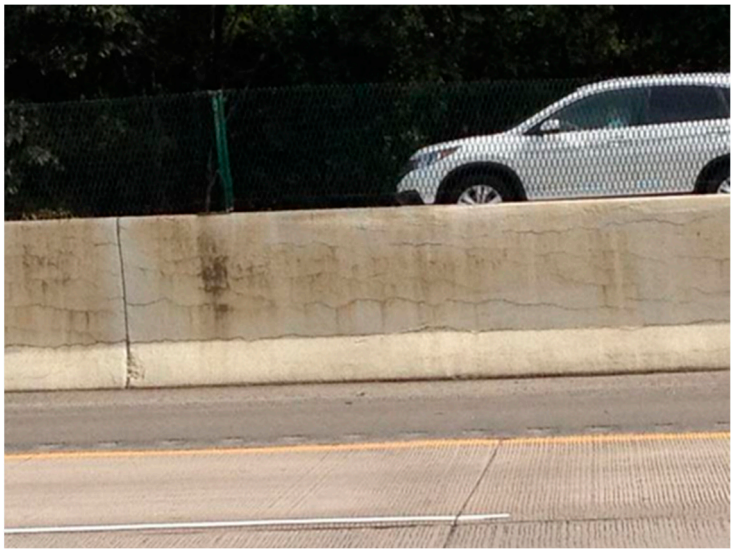

Figure 3. Alkali–silica reaction damage to infrastructure projects [19].

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 diagnostics. Table 1 provides the extent of different damage features associated with different ASR condition ratings [20].

Table 1. Nature and extent of damage for different ASR condition ratings [20].

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 indicative features of destruction
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 measured by expansion and extensive cracking • Presence of expansive gel in cracks • Possible concrete surface spalling

Recent studies have investigated the possibility of early detection of ASR 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 being developed for early detection of ASR [21–24]. ASR laboratory evaluation measures have 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 include the development of field exposure sites 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 using petrography provides accurate detection of ASR [32,33]; however, it is laborious, expensive, and destructive. In addition, petrography testing is conducted in a limited number of 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 such as lithium salts to halt ASR [34–41]; (2) the use of mineral admixtures, also known as supplementary cementitious materials (SCMs), such as silica fume, quartz flour, fly ash, blast furnace slag, metakaolin, and multiwall carbon nanotubes [42–46]; and (3) the use of chemical and latex surface painting to prevent moisture ingress into hardened concrete surfaces [47–49].

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

1. Local sources of fine aggregates were surveyed, and samples were obtained for ASR detection.
2. Accelerated mortar bar tests for ASR detection in fine aggregates were conducted. The expansion of mortar bars was measured and compared with the permissible limits.
3. Different percentages of SCMs, including microsilica and class C fly ash, were used to pour additional mortar bars for expansion measurements.
4. The efficiency of SCMs in ASR mitigation was quantified through the decrease in bar expansion.

In this research effort, market surveys focused on locating aggregate sources with potential ASR problems. Larger number of specimens (multiple sets of AMBT) were poured to conduct ASR testing for statistical validation of test results. The curing of ASR specimens

was conducted under strict lab supervision to simulate harsh environmental conditions as per relevant ASTM standards.

3. Experimental Investigation

Three different types of fine aggregate were obtained from local sources. Fine aggregates, denoted as F1, F2, and F3, were selected due to their inclusion in the Department of Transportation's concrete infrastructure projects. Selected fine aggregate samples were made of C33 sand of river origin. The experimental investigation included 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 percentages 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 × 2.5 × 28.5 cm (1.0 × 1.0 × 11.25 in) to pour mortar bars using fine aggregates and SCMs to be investigated. The prism mold has two 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 4.

Figure 4. AMBT molds and mortar bars poured for AMBT test. Reprinted from ref. [7].

The AMBT spans 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 possible ASR 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 was 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 was poured using high-energy paddle mixer using a cement-to-aggregate ratio of 1:2.25 by weight. Water-to-cement ratio of 0.5:1 was used to fabricate the AMBT.
4. SCMs including microsilica and class C fly ash were used to pour additional mortar bars. Silica fume and class C fly ash were selected due to their availability in the local market, and due to their incorporation in standard DOT mixes. SCMs were used in

stepwise replacement of portland cement using a 1:1 weight ratio. Mortar bar design combinations are shown in Table 2.

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 were poured, consolidated, and left to harden for a 24 h duration. When removed from molds, bars were initially stored for 24 ± 2 h at a relative humidity greater than 95% and a temperature of 73.4 ± 3 F., as shown in Figure 5.

Figure 5. Mortar bar storage for AMBT testing. Reprinted from ref. [7].

After initial storage, mortar bars were removed from their sealed containers, and initial AMBT readings were measured and recorded. The readings calculated the difference between the mortar bar length and a fixed-length comparator bar. Initial readings recorded at 48 h were 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).

During the 2-week AMBT duration, specimens were stored in a solution of 1 M NaOH at a temperature of 176 ± 3.6 F. Specimens were required to be stored in these harsh conditions to induce potential ASR in a short period of time. Bar expansion was measured and recorded throughout the test duration, as shown in Table 3.

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 Aggregate 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 bar expansion results are shown in Figure 6.

Phase 2: Impact of Supplementary Cementitious Materials on ASR Expansion

Mortar bar expansion was recalculated after SCMs were incorporated in the concrete mix design used in bars' fabrication. In this research, microsilica and class C fly ash were added to concrete mix design. Two ratios were selected for the SCM content in replacements of 15% and 30% of portland cement by weight. The aforementioned percentages were selected as they are generally used in the DOT mix to enhance concrete's mechanical properties. The efficiency of SCMs in mitigating ASR is attributed to the following:

1. SCMs have a fine particle size as compared with all granular mix constituents. The fine particle size results in an improved packing order of the mix constituents and a decreased void ratio. This lowers the rate of moisture ingress and reduces the rate of reactivity.
2. SCMs result in a lower cement content, which reduces the alkaline content of the mix, and significantly reduces 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 slows down deleterious ASR.

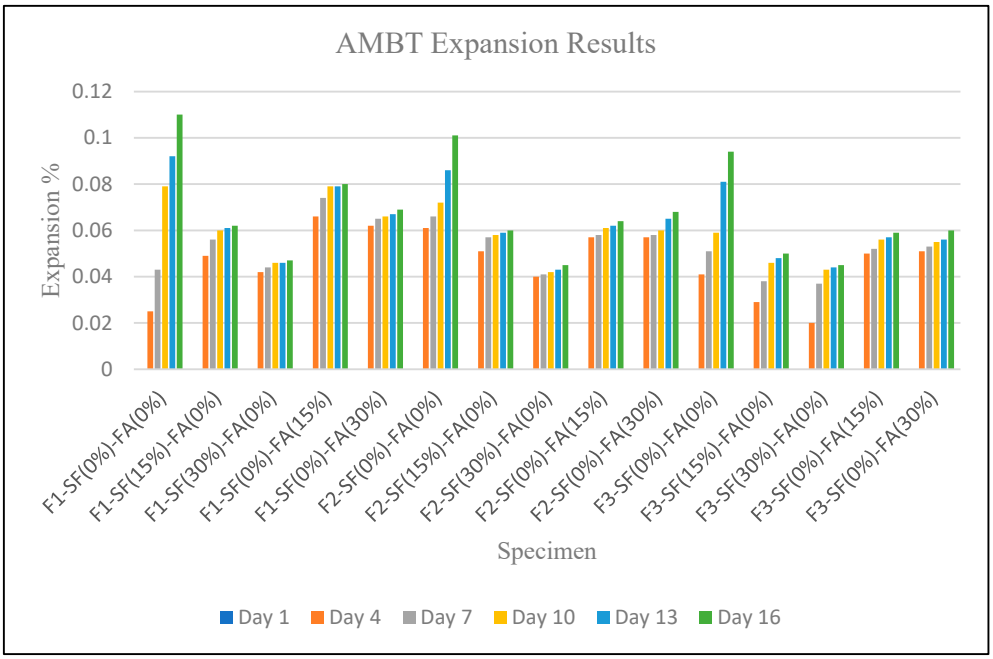

Figure 6. Average mortar bar expansion for fine aggregates F1, F2, and F3.

According to the research findings, both microsilica, 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. Microsilica, with finer particle size, was more efficient in reducing mortar bar expansion. The percentage of reduction in bar expansion due to incorporation of SCMs is shown in Figure 7.

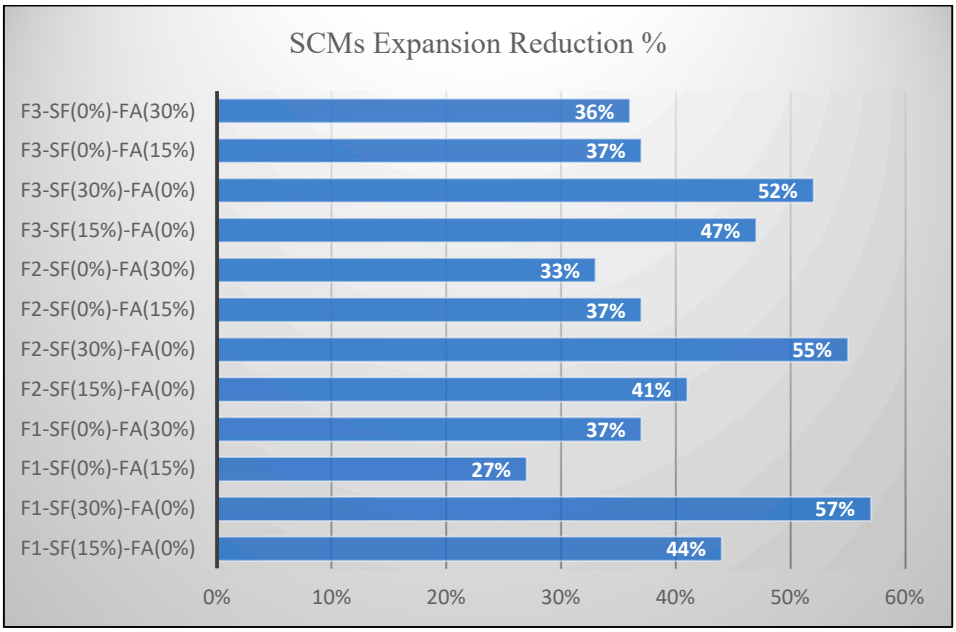

Figure 7. Percentage of AMBT expansion reduction due to SCMs.

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 8. 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 was incorporated in the mix.

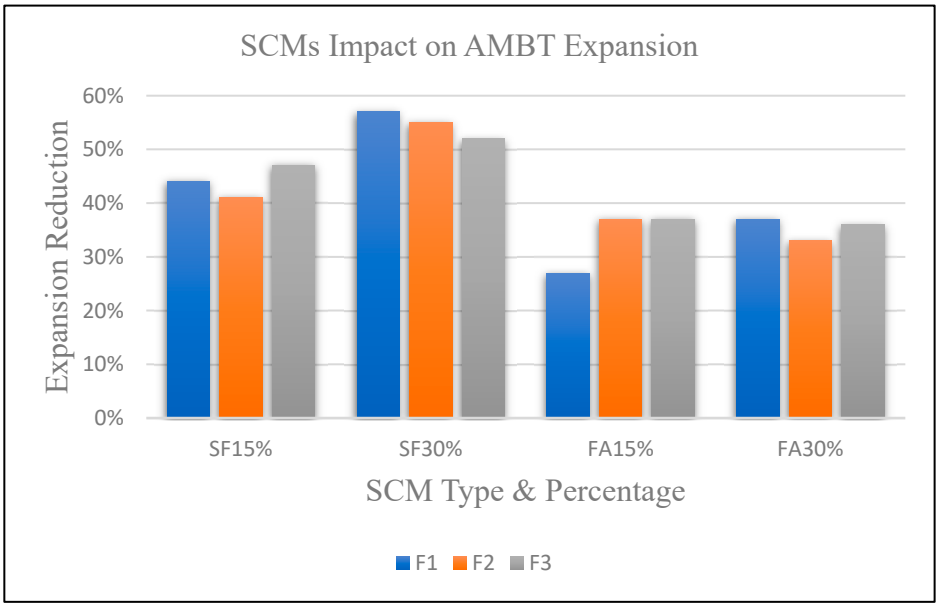

Figure 8. Percentage of AMBT expansion reduction versus SCM incorporation.

4. Summary and Conclusions

Alkali–silica reactivity has been identified as a main cause of infrastructure project deterioration by different state DOTs. The impact of ASR on infrastructure projects is attributed to the large exposure surface of infrastructure projects to environmental conditions, and the high rate of moisture ingress as a result of the ground water table, rain, and ice formation. The free moisture catalyzes a deleterious reaction between cement's 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 was 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 represented a potentially reactive aggregate (with AMBT final expansion in excess of 0.1% of the bar's original length). In an effort to mitigate the potential aggregate reactivity, silica fume and fly ash were 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 reduced the permeability of hardened concrete; thus, the ingress of moisture was decreased. In addition, SCMs resulted in a lowered cement content, which reduced the alkalinity of the mix. Finally, SCMs bound the cement's alkalinity, which mitigated alkali–silica reactivity.

The outcomes of this research show that the incorporation of 30% of silica fume in the partial replacement of cement content results in a 55% reduction in final bar 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 reduce the damaging effect of ASR, minimize the need for frequent maintenance, and result in improved infrastructure project conditions.

5. Recommendations for Future Research

The AMBT test results need to be validated in future research by developing ASR field exposure sites to investigate the reactivity of selected fine aggregates and the efficiency of selected SCMs under normal environmental conditions. The results of field exposure testing should be compared with AMBT lab results for additional validation.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Conflicts of Interest: The author declare no conflict of interest.

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