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Impact of Supplementary Cementitious Materials on Alkali-Silica Reactivity of Concrete

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Alkali-silica reactivity (ASR) is a deleterious reaction initiated in hardened concrete when aggregates silica reacts with alkali hydroxide in portland cement in the presence of high moisture. The ASR results in the formation of expansive gel which induce internal stresses in hardened concrete, and may lead to concrete cracking, spalling, and possibly structure failure. The main objective of this research is to investigate the impact of supplementary cementitious materials (SCMs) on the gel-formation, and the possible use of SCMs in mitigating ASR damage on hardened concrete. In this research, different types of aggregates were used to pour ASR test specimens, and ASR mortar bar tests were conducted according to relevant ASTM standard specifications. Additional concrete specimens were poured using different percentages of SCMs, mainly silica fume, class c fly ash, and ASR testing was repeated to assess the SCMs impact on ASR. The research outcomes showed that fine SCM particles used in concrete mixes can halt the concrete expansion due to ASR. SCMs efficiency in mitigating ASR is directly proportional to the SCM particle size. The successful use of SCMs in mixing concrete will reduce the rate of hardened concrete deterioration, limit the need to maintenance and repair, and reduce the life cycle cost of concrete construction projects.

Key Words: Alkali-Silica Reactivity, ASR, Silica Fume, Fly Ash, Aggregates, Mortar Bar Test

Introduction

Alkali-silica reactivity (ASR) was first identified as a possible cause for hardened concrete deterioration in California in the 1940s. ASR is a deleterious chemical reaction which start when active silica found in specific types of aggregates reacts with the alkaline hydroxide of portland cement. The deleterious ASR is catalyzed by the presence of moisture content within hardened concrete. As a result of ASR, expansive, white-colored gel-like substance is formed within concrete, which adds internal tensile stress to the hardened concrete as it ages. The white gel-formation could be detected using petrographic analysis of hardened concrete specimens obtained by core drilling (ASTM C 295), as shown in Figure 1.

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Figure 1. ASR expansive gel as shown in petrographic analysis of hardened concrete (courtesy of FHWA labs)

The ASR mechanism can be explained as a two-step chemical reaction, as per the following equations:

Alkali hydroxides (in portland cement) + Reactive silica (in aggregates) → ASR gel [1]

ASR gel + Moisture (within hardened concrete) → Gel expansion (internal stresses) [2]

The internal stresses generated due to the expansion of formed gel induces escalating internal stresses as the concrete ages. The rate of stress increase is proportional to the amount of reactive silica present in the concrete aggregates content, the moisture content within hardened concrete, and the surface area of the concrete structure exposed to air. ASR is known to result in significant deterioration of concrete infrastructure projects, as shown in Figure 2, due to their large-exposed surfaces, and the possible ingress of moisture.

Figure 2. ASR damage in highway barrier (Deschenes Jr., 2017)

Literature Review

ASR destructive effect to hardened concrete and the premature failure of concrete sections were first explained in the Unites States in the 1940s (Stanton, 1940). Based on Stanton discovery, multiple concrete structures failures were investigated, and ASR was found responsible for the premature distress including hydraulic plant premature failure in Virginia (Kammer and Carlson, 1941). In order for ASR mechanism to work, coarse and/or fine aggregate used should contain reactive silica to react with portland cement alkaline content. Sufficient moisture resulting from mixing water (that didn't react with cement during hydration) or external moisture ingress to hardened concrete through concrete voids is required to catalyze the reaction as the concrete ages. ASR components are shown in Figure 3.

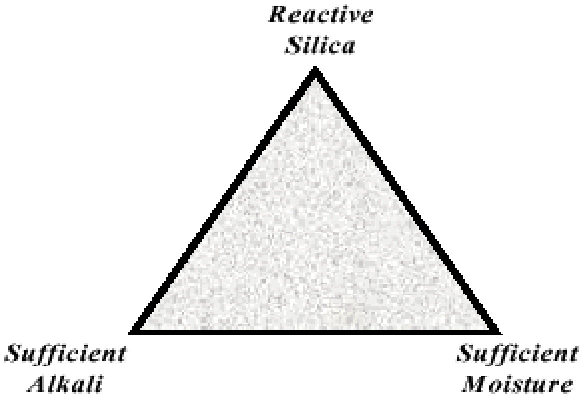

Figure 3. Components required to initiate destructive ASR (Thomas et al., 2007)

Recent studies provided detailed explanation for ASR (Akhnoukh and Mallu, 2022, Wang et al., 2022, Fanijo et al., 2021, Abd-Elssamd et al., 2021 and 2020, and Akhnoukh et al., 2016). During concrete mixing, the aggregate content (gravel, limestone, sand, or crushed granite) is encapsulated with hydrated portland cement with high alkaline content (pH value of hydrated cement may reach 13.5). When cement hydration is concluded and the concrete hardens, the remaining (unused) mixing water and moisture dissipating through hardened concrete voids forms a strong alkaline solution which is capable of dissolving particular silicious content within the aggregate to form the white gel particles. As the hardened concrete ages, the formed gel reacts with moisture to expand, and internal stresses are applied to hardened concrete. The magnitude of ASR damage to concrete depends on (1) the type and quantity of reactive silicious content; (2) the amount of free moisture resulted from the unused mixing water; and (3) the ingress of moisture through the hardened concrete capillary voids (concrete voids ratio and permeability).

Several research projects investigated different alternatives to reduce ASR and/or mitigate its destructive impact on hardened concrete. Proposed ASR mitigation techniques include (1) the use of chemical admixtures (lithium salts) to halt ASR (Carles-Gibergues et al., 2007); (2) the use mineral admixtures, also known as supplementary cementitious materials (SCMs) as silica fume, quartz flour, fly ash, blast furnace slags, metakaolin, and multi-wall carbon nanotubes (MWCNTs) (Chihaoui et al., 2022, Luo et al., 2022, Akhnoukh and Buckhalter 2021, Akhnoukh, 2020, 2018, and 2016, Figueira et al., 2019, Kawabata and Yamada, 2017, and Elia et al. 2017); and (3) the use of chemical and latex surface painting to prevent the moisture dissipation in hardened concrete (Deschenes et al., 2017). The main objective of this research is to investigate the possibility of ASR mitigation using class C fly ash, silica fume. In order to attain the research objective, accelerated mortar bar testing for concrete specimen is conducted, and specimen expansion is measured. Measured expansion is evaluated according to ASTM C1293-20 standard specifications, and is used to assess the reactivity of aggregates and the effectiveness of SCMs in mitigating ASR impact on hardened concrete.

Experimental Investigations

The accelerated mortar bar test (AMBT) developed in South Africa in the 1980s is used to identify possible reactivity of different aggregates. The AMBT adopted by multiple specifications as ASTM International, AASHTO, Canadian Standard Specification, and Portland Cement Association (PCA) is conducted using a standard prism mold of 1x1x11.25 in. (2.5 x 2.5 x 28.1 cm.) to fabricate mortar bars using the aggregate to be tested. The AMBT spans for 16 days before the potential reactivity or the impact of SCMs on ASR is reported. Length changes of fabricated bars are measured and reported during the test duration (ASTM C 1293). A total expansion less than 0.1% of the original bar length is acceptable as the used aggregate is considered non-reactive. In addition, the reduction in expansion when different SCMs are used is an indicator of SCMs efficiency in mitigating ASR in hardened concrete members.

In this research, fine aggregates were obtained from 3 different queries to investigate aggregate reactivity, and the efficiency of silica fume and class C fly ash in mitigating ASR. Fifteen AMBT specimens were fabricated using the aggregates obtained from the three different sources, denoted as aggregates A, B, and C. Five different specimen mix designs were fabricated using each aggregate source (a total of 15 different material designs). Mix designs were selected based on aggregate source and SCMs content, as shown in Table 1.

Table 1.

Accelerated mortar bar specimen constituent combination (based on aggregate source and SCM content)

Sample	Aggregate	Silica Fume	Class C Fly Ash
Control – A	Fine aggregate (A)	0% SCMs	
A15SF		15%	0%
A30SF		30%	0%
A15FA		0%	15%
A30FA		0%	30%
Control – B	Fine aggregate (B)	0% SCMs	
B15SF		15%	0%
B30SF		30%	0%
B15FA		0%	15%
B30FA		0%	30%
Control – C	Fine aggregate (C)	0% SCMs	
C15SF		15%	0%
C30SF		30%	0%
C15FA		0%	15%
C30SF		0%	30%

Three mortar bars were fabricated for each AMBT specimen mix designs. The average expansion for the three bars is recorded at day 1 (original length), and at days 4, 7, 10, 13, and 16 to calculate bars expansion. During the 16-day duration of the AMBT test, specimens were stored in a sodium hydroxide solution at a temperature of 176 ± 3.6 F. Specimens are stored in this harsh environment to expedite potential ASR in a short period of time as sodium hydroxide solution serves as a catalyst to ASR. Accelerated Mortar bar specimens and measurement of specimens' expansion are shown in Figure 4.

(a) (b)

Figure 4. (a) AMBT specimens, and (b) Expansion testing for fabricated specimens

The average expansion of control specimens for aggregates A, B, and C is measured to evaluate the potential aggregate reactivity. Measured expansion for control specimens (A, B. and C) as a percent of the original length of the mortar bars at 16-day age were 0.082%, 0.07%, 0.06%. Detailed result for mortar bar expansions during different testing days is shown in Figure 5. According to ASTM C1293, silica content in the three aggregate sources is considered non-reactive (final expansion < 0.1%).

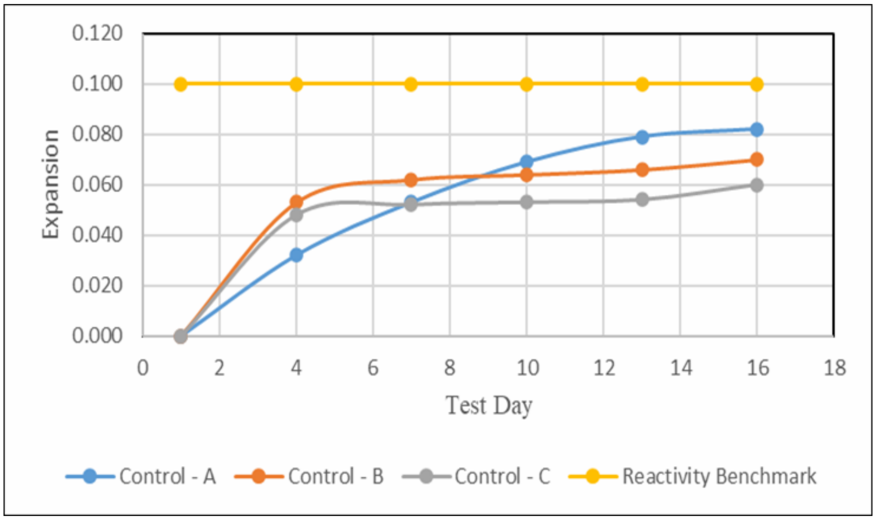

Figure 5. Expansion of control specimens (16-day results)

In order to investigate the efficiency of SCMs in mitigating ASR, the decrease in bars expansion after 16 days of measurement for specimens fabricated using class C fly ash and silica fume is calculated as a percent of the control specimen expansion. Test results showed that SCMs successfully reduce concrete expansion due to ASR. Silica fume displayed higher ability to reduce the final expansion. The effect of SCMs is directly proportional to their percentage in the concrete mix. Detailed results are shown in Figure 6.

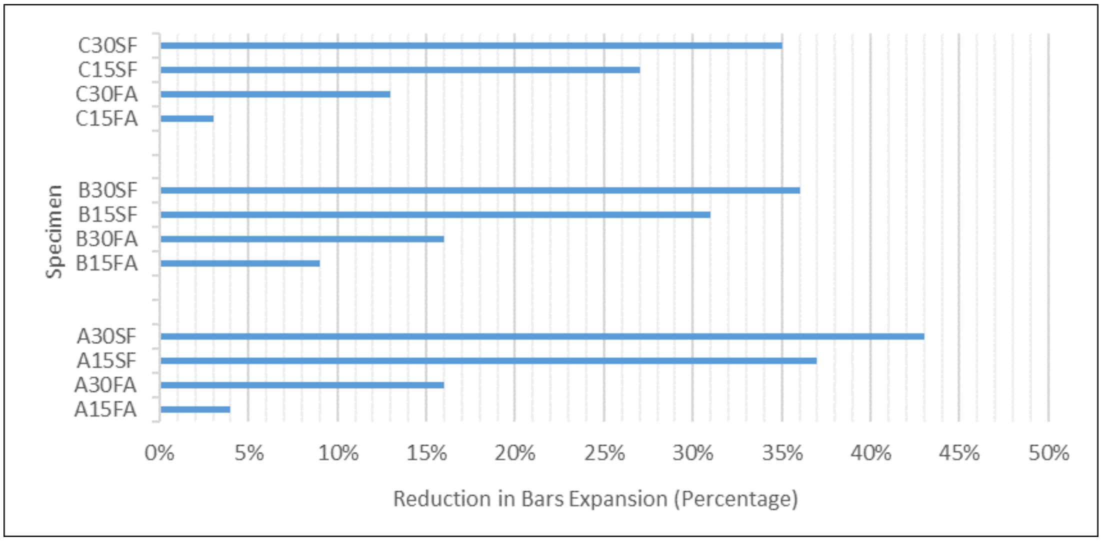

Figure 6. Reduction in mortar bars expansion vs. SCMs type and percentage

Conclusions

ASR is a deleterious effect that results in concrete project deterioration. ASR could be detected through different testing techniques including petrographic analysis of concrete cores, and accelerated mortar bar testing (AMBT) for laboratory-fabricated specimens. In this research, aggregates obtained from three different sources were evaluated for ASR using AMBT. Control specimens fabricated using the three aggregates, and no SCMs, were tested for 16-day expansion. Test results showed that the three sources resulted in mortar bars expansion less than 0.1%, which indicates that aggregates tested are non-reactive. AMBT was conducted for different specimens fabricated using different percentages of class c fly ash and silica fume to assess their potential impact on hardened concrete expansion. The following conclusions are made based on SCM incorporated specimens' tests outcomes:

- SCM incorporation in concrete mixes results in reducing the hardened concrete expansion as calculated by AMBT. This indicates that SCMs can be used in concrete mix designs to mitigate ASR of aggregates with high reactivity
- Silica fume is more efficient in mitigating ASR. This could be attributed to the smaller particle size of silica fume, which reduces concrete porosity; thus slow the ingress of moisture required to catalyze the ASR
- SCMs ability to reduce ASR is proportional with their percentage of incorporation in the concrete mix. The decrease in bars expansion is more sensitive to the increase in fly ash content as compared to silica fume

- Portland cement replacement by 15% silica fume or 30% fly ash (by weight) results in a significant decrease in ASR. The percentage of expansion decrease due to SCMs incorporation is associated with comparable compressive strength increase as a result of SCMs incorporation in concrete mix design (Akhnoukh and Elia 2020, Akhnoukh 2019 and 2008, Zackary et al., 2018, and Graybeal and Hartman, 2008)

The successful mitigation of ASR in concrete construction projects in general, and transportation infrastructure in particular, will significantly improve projects conditions, increase their service life, and reduce the need to maintenance and/or repair activities during the life span of the project.

Recommendations for Future Research

The petrographic analysis of hardened concrete and the lab experimental investigation is labor intensive and may result in injuries for researchers, lab personnel, and labors while conducting their ASR testing. Specific safety measures for ASR testing should be developed and enforced to ensure safety of conducted site and lab work.

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