World Academy of Science, Engineering and Technology
International Journal of Civil and Environmental Engineering
Vol:10, No:2, 2016

Alkali Silica Reaction Mitigation and Prevention Measures for Arkansas Local Aggregates

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Abstract**—**The objective of this research is to mitigate and prevent the alkali silica reactivity (ASR) in highway construction projects. ASR is a deleterious reaction initiated when the silica content of the aggregate reacts with alkali hydroxides in cement in the presence of relatively high moisture content. The ASR results in the formation of an expansive white colored gel-like material which forms the destructive tensile stresses inside hardened concrete.

In this research, different types of local aggregates available in the State of Arkansas were mixed and mortar bars were poured according to the ASTM specifications. Mortar bars expansion was measured versus time and aggregates with potential ASR problems were detected. Different types of supplementary cementitious materials (SCMs) were used in remixing mortar bars with highly reactive aggregates. Length changes for remixed bars proved that different types of SCMs can be successfully used in reducing the expansive effect of ASR. SCMs percentage by weight is highly dependent on the SCM type. The result of this study will help avoiding future losses due to ASR cracking in construction project and reduce the maintenance, repair, and replacement budgets required for highways network.

Keywords**—**Alkali Silica Reaction, Aggregates, Moisture, Cracks, Mortar Bar Test supplementary cementitious materials.

I. INTRODUCTION AND LITERATURE REVIEW

ASR destructive effect to hardened concrete and the premature failure of a concrete structure was first explained in the USA in the 1940 [1] Based on Stanton discovery, several deteriorated concrete structures were investigated and ASR was found responsible for the premature deterioration of hardened concrete. A notable example for ASR destructive effect was reported in Virginia where a hydroelectric plant had a severe premature deterioration for its hardened concrete [2] According to multiple research programs, the ASR reactions start when specific reactive aggregate types are mixed with cement. The white gel formed as a byproduct of the ASR expands when it reacts with moisture within the concrete. ASR components are shown in Fig. 1.

ASR expansive gel, shown in Fig. 2, adds outward tensile stress on the hardened concrete. Concrete deterioration starts when the tensile stress formed overcome the restraint imposed by hardened concrete [3]. The expansive gel starts as a small accumulation of ASR byproduct. During the aging process of concrete, gel accumulations reacts with moisture infiltrating the hardened concrete to result in concrete hair cracks. Concrete hair cracks increase in number and unite to form a smaller number of larger cracks, which result in concrete degradation.

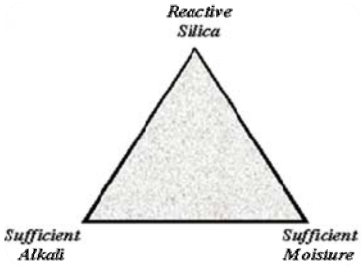

Fig. 1 Components required for ASR reaction

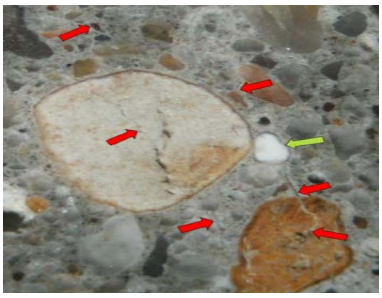

Fig. 2 ASR gel formation in hardened concrete

In recent studies, more detailed explanations for the ASR were presented. During concrete mixing, the aggregate content including gravel, sand, or crushed rocks and granites is encapsulated with the cement paste, which has a high alkaline content (pH value may reach 13.5). When cement hydration process is concluded and the concrete mix hardens, the remaining (unused) mixing water and moisture dissipating through hardened concrete air voids represents a strong alkaline solution which is capable of dissolving particular siliceous particles of the aggregates resulting in the ASR gel, which expands when additional moisture is added to form the ASR damaging effect on hardened concrete. A similar damaging effect is produced when the high alkaline content of the cement paste causes chemical changes in a particular carbonate content of some aggregate types. This damaging reaction is known as alkali-carbonate reaction (ACR). Both ASR and ACR are deleterious reactions, and results in a significant premature deterioration of concrete structures.

ASR and ACR damages are similar to other types of deterioration due to weathering or freeze-thaw cycles. In order to differentiate between ASR and other causes of

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deterioration, a petrographic investigation is required where a core of the damaged concrete is inspected by a petrographer using a special microscope to investigate the cause of concrete deterioration. The petrographic investigation is confirms the ASR damage once the white expansive ASR gel is detected by the microscope, as shown in Fig. 3.

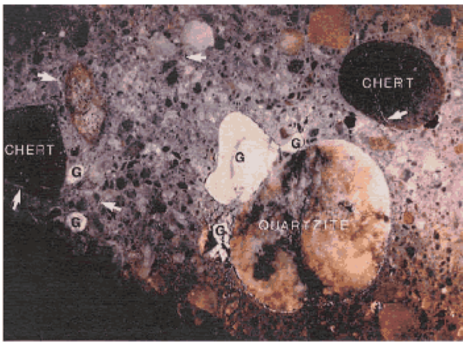

Fig. 3 ASR damage as shown by petrographic test [4]

To date, several research programs are funded by the Federal Highway Administration and State Departments of Transportation (DOTs) to mitigate or prevent the damaging effect of the ASR on highway and bridge network of the United States. Highway projects are highly affected by ASR due to their extreme exposure to environmental changes and the relatively high exposed surface area of highway projects components as bridge decks, concrete pavement, bridge piers, bridge decks, and highway barriers. Most of the afore-mentioned components have a large area of exposure compared to their structural thickness. In addition, the use of salts and de-icing chemicals in northern states result in a quick deterioration to the concrete surface which enables moisture to attack and penetrate the concrete and expedite the ASR damage. Damaged concrete due to ASR may be maintained, treated, or replaced according to the degree of ASR induced damage. Typical ASR damage for reinforced concrete projects are shown in Fig. 4.

Fig. 4 ASR damage in highway projects [4]

Recently, the Arkansas Highway and Transportation Department (AHTD) experienced premature damage to the Arkansas highway concrete pavement and barriers at different locations across the State. The life spans of some damaged highway concrete projects, shown in Fig. 5, were less than 10 years. The short life and rapid deterioration of highway concrete represented a threat to the AHTD due to the anticipated increase in the project life cycle cost.

Fig. 5 Deterioration in Arkansas Highway Projects

The damage in Arkansas highway network due to ASR is attributed to multiple factors. First, the presence of reactive coarse and fine aggregates delivered from some of the aggregates in the State, second, the use of type I/II Portland cement without incorporating SCMs in the highway projects, third, the relatively high moisture in air (relative humidity) which acts as a catalyst to the ASR and expedite the rate of concrete deterioration. Due to the increased maintenance expenditure, the AHTD launched its research project to mitigate and/or prevent the ASR problem and its negative impact on highway projects. The main objectives of this project are: 1) investigate different coarse and fine aggregate sources within the state of Arkansas to locate the potential reactive aggregates, 2) determine the possibility of using SCMs in reducing the rate of ASR damage, 3) determine the possibility of using special types of cement to reduce ASR damaging effect, and 4) determine the most economic standard concrete mix for future highway project with minimal ASR activity.

II. RESEARCH METHODOLOGY

During this research study, samples of fine aggregates were collected from different suppliers within the State of Arkansas. Selected samples were collected from suppliers who provide highway contractors with their fine aggregates. Reactivity was tested using the accelerated mortar bar test, AMBT, which is standardized by the ASTM International. The AMBT was originally developed in South Africa in the 1980s as an accelerated method to identify potentially reactive fine aggregates which may result in destructive ASR when used in a concrete mix. The AMBT was initially used to test fine aggregates reactivity when portland cement is used [5]. Currently, the AMBT is also used in evaluating the possibility of using different types of SCMs to reduce the potential ASR damage. The AMBT, currently adopted by multiple specifications as *Canadian Standard Specifications*, *AASHTO*, and *PCA*, uses a standard prism mold of 1x1x11.25 inch to pour mortar bars using the fine aggregate and/or SCMs to be investigated for potential ASR reactivity. The prism mold has 2 studs at both ends to be embedded in the poured mortar prism and used in measuring the length change versus time. The mortar mold and prisms are shown in Fig. 6.

Fig. 6 AMBT molds and mortar bars

The AMBT spans for 16 days before the potential reactivity of fine aggregates or efficiency of SCMs are reported. The length changes are measured during the test duration and reported at the end of the 16 day period. According to the relevant ASTM specification (ASTM C 1293), a total expansion less than 0.1% of the initial length of the bar is acceptable as the fine aggregate used is considered a non-reactive, or the SCM mix provided is deemed successful is produced a concrete mix with no potential ASR problem.

In this project, three different types of fine aggregates, denoted as aggregates A, B, and C, were tested for their potential reactivity and the effectiveness of two different types of SCMs (type C fly ash and silica fume) were investigated. Different percentages of the SCMs were used to calculate the optimum content required for avoiding the ASR problem. A total of 15 different combinations of fine aggregates and different percentages of silica fume and fly ash were included in the experimental investigation, selected combinations, curing regimen, samples testing, and recorded expansion are explained in details in the following section.

III. EXPERIMENTAL INVESTIGATION

A. Mortar Bars Preparation

The AMBT was conducted at the Concrete Materials Testing Lab at the University of Arkansas at Little Rock. Mortar bars were poured using ASTM Specifications guideline, which includes the following:

1. Type I/II Portland cement is used
2. Aggregates A, B, and C are used alternatively to produce the mortar bars
3. Cement was mixed with aggregates using a paddle mixer with a cement-to-aggregate percentage of 1:2.25 by weight
4. A minimum of three mortar bars were produced for every mix to provide statistical approved results for each mortar bar mix.
5. Fly ash and silica fume was used to step-wisely reduce the cement content of the specimen to investigate SCMs performance in mitigating the ASR. SCMs are used to replace Portland cement by a ratio of 1:1 by weight.
6. Mortar bar specimens were cured using a NaOH solution as per the ASTM specifications.

The afore-mentioned specifications were used to produce the different combinations to be investigated in this research. The main objectives of using the stated mortar bar mix combinations are: 1) Investigate the potential reactivity of aggregates A, B, and C when used in producing Portland cement concrete mixes, 2) Investigate the capability of different types of SCMs in reducing ASR damaging effect, and 3) Calculate the cost of ASR-free mixes based on SCMs incorporation. Different aggregates and SCMs combinations used in this experimental investigation are shown in Table I. A total number of 45 mortar bars were produced (3 bars x 15 combinations). Mortar bars were cured and tested for expansion for a total duration of 16 days to investigate the potential reactivity of each mix.

TABLE I
MORTAR BAR COMBINATIONS (BASED ON AGGREGATE TYPE AND SCM CONTENT)

Sample	Aggregate	Silica fume	Fly ash (class C)
S1	Fine aggregate (A)	0%	
S2		15%	0%
S3		30%	0%
S4		0%	15%
S5		0%	30%
S6	Fine aggregate (B)	0%	
S7		15%	0%
S8		30%	0%
S9		0%	15%
S10		0%	30%
S11	Fine aggregate (C)	0%	
S12		15%	0%
S13		30%	0%
S14		0%	15%
S15		0%	30%

B. Curing, Storage, and Expansion Measurements of Mortar Bars

Mortar bars are poured, consolidated, and left to harden for a total time duration of 24 hours. When removed from the mold, bars are initially stored for 24 ± 2 hours in a relative humidity greater than 95% and a temperature of 73.4 ± 3 F. This is achieved by submerging the mortar bars in sealed containers in the lab oven, as shown in Fig. 7.

Fig. 7 Storage of mortar bars for AMBT test

After initial storage process is included, mortar bars are removed from their sealed containers and readings for the bar is taken and recorded. The recorded reading shows the difference between the mortar bar length and a fixed length metal comparator bar. Readings reported at this age (48 hours after pouring the mortar bars) are considered initial readings (baseline) for length changes when compared to readings measured and recorded for two weeks past the initial readings.

According to the ASTM C1293, a minimum of three readings are required to be taken during the 2-week duration past the initial reading. Lab measurement device and process is shown in Fig. 8.

Fig. 8 Mortar bar length reading (compared to metal comparator)

During the 2-week duration, specimens are stored in a solution of 1 N NaOH at a temperature of 176 ± 3.6 F. Specimens are required to be stored at these harsh conditions to induce the potential ASR in a short period of time. The submerged specimen and added NaOH to stored solution represents a catalyst to expedite the ASR, and provide adequate indication for the potential reactivity of the used aggregate and/or SCM mix based on the measured length changes. The final reading after 14 day of storage (16 days of age) is compared to a 0.1% of expansion. According to standard specifications, a relative expansion of 0.1% or higher indicates a potential for ASR problems during the life span of the structure where the mix is used.

The afore-mentioned procedure was used in preparing, curing, and testing mortar bars poured using local fine aggregates from three different sources in Arkansas. Aggregates were tested in mixes with type I/II Portland cement or a combination of cement and one SCM with different percentages, as shown in Table I. Three mortar bars were tested for each combination indicated in Table I, and specimens average results are presented in the following section.

1. Lab Test Results

Results of fine aggregate (A) when tested for expansion versus time are shown in Table II and Fig. 9. Aggregate (A), being used with Portland cement in concrete mixes, showed expansion results close to the potential reactivity benchmark (sample S1). The addition of SCMs positively reduced the potential reactivity of the specimens. Silica fume proved a higher efficiency in reducing potential ASR compared to class C fly ash.

TABLE II
FINE AGGREGATE (A) SPECIMENS TEST RESULTS

Sample	1st Day	Day 4	Day 7	Day 10	Day 13	Day 16
S1	0.000	0.025	0.053	0.079	0.079	0.082
S2	0.000	0.055	0.056	0.065	0.061	0.052
S3	0.000	0.042	0.057	0.041	0.034	0.047
S4	0.000	0.066	0.074	0.079	0.081	0.079
S5	0.000	0.062	0.065	0.066	0.067	0.069

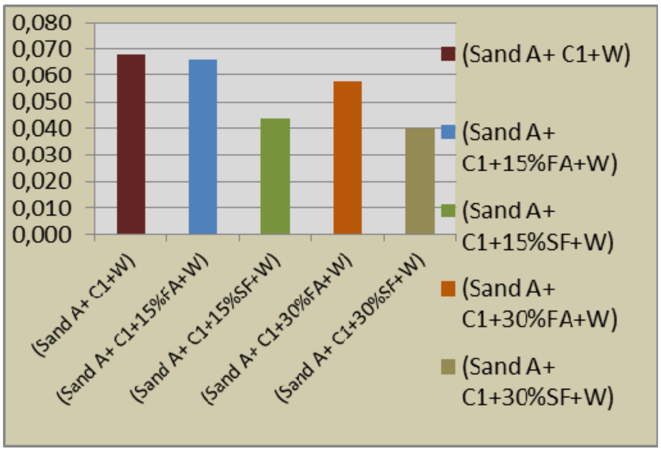

Fig. 9 Fine Aggregate A Results

Lab tests for fine aggregates (B) and (C) displayed similar trends when used with Portland cement only, and when SCMs where added by different percentages. The effect of silica fume and class C fly ash are clear as the particle sizes of either of the SCMs is small compared to cement particles. Smaller particle size enables the SCMs to fill the voids within the cement paste, thus reduce the possibility of water and NaOH particles from percolating inside the mortar bars. It is well noted that the efficiency of silica fume (with particle diameter of 0.5 microns) is higher than class C fly ash (with particle diameter around 10 microns). Hence, SCMs and other fine sized pozzolans are successfully used to reduce the mortar bars expansion. Test results for fine aggregate samples (B) and (C) are shown in Tables III, IV, and Figs. 10 and 11.

TABLE III
FINE AGGREGATE (B) SPECIMENS TEST RESULTS

Sample	1st Day	Day 4	Day 7	Day 10	Day 13	Day 16
S6	0.000	0.061	0.061	0.064	0.066	0.070
S7	0.000	0.051	0.059	0.064	0.056	0.048
S8	0.000	0.048	0.052	0.045	0.043	0.045
S9	0.000	0.059	0.058	0.061	0.055	0.064
S10	0.000	0.057	0.058	0.062	0.065	0.059

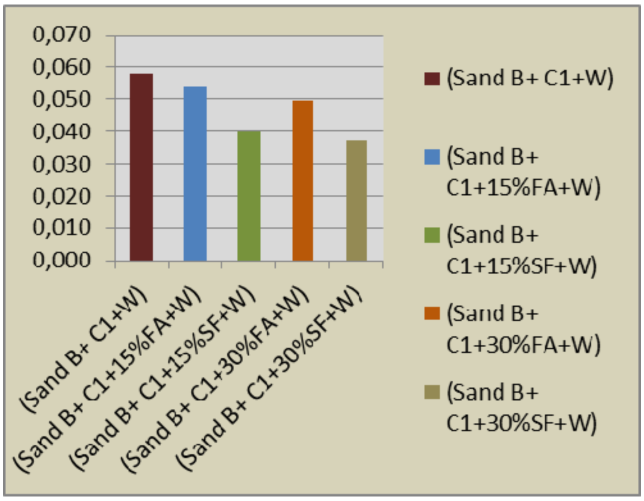

Fig. 10 Fine aggregate (B) specimens test result

TABLE IV
FINE AGGREGATE (C) SPECIMENS TEST RESULTS

Sample	1st Day	Day 4	Day 7	Day 10	Day 13	Day 16
S11	0.000	0.059	0.052	0.053	0.054	0.060
S12	0.000	0.041	0.051	0.057	0.051	0.044
S13	0.000	0.020	0.043	0.044	0.034	0.039
S14	0.000	0.050	0.058	0.053	0.055	0.058
S15	0.000	0.035	0.053	0.055	0.053	0.052

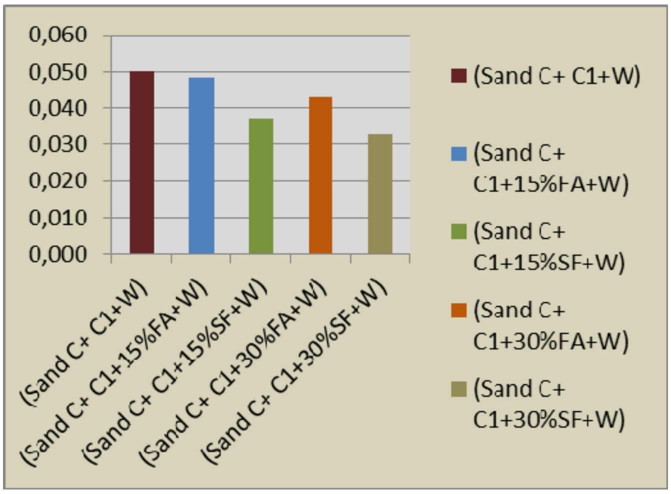

Fig. 11 Fine aggregate (C) specimens test result

The experimental investigation test results for different fine aggregates and SCMs, shown in Tables II-IV shows that different types of aggregates would result in different expansion rates at the test completion. None of the aggregates should a high risk of ASR, however, specific mixes without SCMs were close to being potentially reactive. Detailed conclusions are mentioned in the following section.

IV. CONCLUSIONS

Fine aggregates represents a potential threat for the long term performance of concrete structures due to its siliceous content, which tends to react with the alkali content of Portland cement producing expansive damaging alkali-silica expansive gel. The ASR damaging effect depends on the reactivity of the aggregate and the amount of moisture present in the hardened concrete. ASR can be successfully detected using the AMBT. The research conclusions include the following:

1. Fine aggregates reactivity is highly dependent on the source of the aggregate. Thus, AMBT test has to be done for each individual aggregate source.
2. SCMs can be used to mitigate the ASR effect. The percentage of SCM used depends on its type. According to this research, the following findings were made:

a. A percentage of 15% of silica fume is required to reduce the potential expansion by 50%, which eliminates the ASR threat to hardened concrete.
b. Increasing the silica fume beyond 15% will not result in a proportional reduction of expansion. Given the commercial price of silica fume, it is highly recommended to limit its percentage to produce economic mixes.
c. A minimum percentage of 30% of class C fly ash is required to reduce the potential ASR effect on concrete.

V. RECOMMENDATIONS FOR FUTURE RESEARCH

The authors would like to include additional types of SCMs in AMBT including blast furnace slag and multi-wall carbon nanotubes. It is expected that nanomaterial with lower particle diameter will improve the capability of concrete to resist ASR. In addition, the authors believe that a long-term exposure site for ASR specimens is required to compare the results of the AMBT performed under harsh lab conditions with long-term natural exposure of concrete to site conditions.

VI. ACKNOWLEDGEMENTS

The authors would like to acknowledge the Arkansas Highway and Transportation Department for funding this research project. The authors would like to thank material suppliers for their generous materials donations including Ash Grove, Arkansas River Sand, Pine Bluff Aggregates, and Silica Fume Association. Finally, the author would like to acknowledge the support and the help of undergraduate students and student interns who participated in this project including Mohammed Al-Qadhi Fumonde Yann, and Ian Tramel.

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