



ALKALI-SILICA REACTIVITY IN SOUTHWESTERN ONTARIO AGGREGATES

Ahmed, R. Suleiman
Ph.D. Candidate, Western University, Canada

Aaron, Jobst
M.Eng, Western University, Canada

Moncef, Nehdi
Ph.D., P.Eng. Western University, Canada.

ABSTRACT

Alkali-silica reaction (ASR) occurs between alkalis in concrete and reactive silica in aggregates. This reaction results in the formation of alkali-silica gel, which fills the pore space in the cementitious matrix, leading to expansion and damage. Reactive aggregates that can cause this type of damage were identified in different locations in Southwestern Ontario. X-Ray diffraction and petrographic analysis were used to investigate the type of reactive minerals in such aggregates. In addition, the effect of using different types of cement replacement-materials, including crushed limestone powder, fly ash, silica fume, and nano-silica on ASR were investigated in cement mortars incorporating the reactive aggregates. Results indicate that the expansion of mortar bars due to alkali-silica reaction can be controlled using an adequate type and substitution level of cement replacement materials.

Keywords: Alkali-silica reaction; Crushed limestone; Nano-silica; Fly ash; Silica fume; Petrographic analysis.

1. INTRODUCTION

Alkali-silica reactivity (ASR) in concrete can be defined as a chemical reaction between the hydroxyl ions in the pore solution and reactive silica in the aggregate. The product of this reaction is an alkali-silica gel that forms within and around the aggregates. This gel, when exposed to moisture, has the capability to absorb water and expand, causing distress within the concrete matrix (Yurtdas, et al. 2013; Latifee, et al. 2014). The expansion due to ASR can result in extensive cracking and lead to premature deterioration, loss of serviceability and damages beyond repair.

The result of the alkali-silica reaction is the formation of two different types of gel products: a non-swelling calcium-alkali-silica-hydrate gel {C-N-S-H or C-K-S-H} and a swelling alkali-silica-hydrate gel {N-S-H or K-S-H}. According to Islam and Akhtar (2013), alkali-silica reaction can only cause damage when both gels form, since the presence of the swelling gel is what produces expansion. The expansion excreted by the alkali-silica gel depends on the moisture from pore water in the concrete, air humidity, or other sources of water. Once the pressure from the expansion exceeds the tensile strength of the concrete, cracks occur (Rajabipour et al. 2015). The expansion and cracking of the concrete due to ASR are dependent upon the type of gels formed (Farny and Kerkhoff, 2007). Extensive expansion and severe cracking correspond to a high-swelling alkali-silica gel while moderate expansion and minor cracking correspond to a mild-swelling gel. Silica in aggregates can take two different basic forms (crystalline and amorphous). For the most part, silica is innocuous and unreactive if it is in crystalline form, and reactive if it is amorphous (Farny and Kerkhoff, 2007). When reactive silica is exposed to a highly alkaline solution, the structure is broken down, thereby creating the alkali-silica gel product. The reactivity of a rock or mineral depends on various factors including its chemical composition, level of crystallinity, and solubility of the silica phase in the alkaline solution (Islam and Akhtar, 2013).

A wide variety of potentially reactive silica bearing rocks and minerals are known to exist in Ontario. Rogers, et al. (2000) reported that chert, a potentially reactive form of silica, can be found in sand and gravel pits and bedrock quarries throughout southwestern Ontario. In this study, natural aggregates located at different locations in Southwestern Ontario and intended to be used for concrete construction purposes were investigated.

2. RESEARCH SIGNIFICANCE

The objective of this study is to investigate the alkali-silica reactivity (ASR) of fine aggregate samples retrieved from different locations in Southwestern Ontario. X-Ray diffraction and petrographic analysis were used to identify the different types of minerals that can lead to alkali-silica reactivity. The results could provide guidance to avoiding the potential damage to new structures due to alkali-silica reactivity.

3. EXPERIMENTAL PROGRAM

3.1 Accelerated Mortar Bar Test Procedure

The potential of ASR of all fine aggregates collected from different locations in Southwestern Ontario was investigated according to CSA A23.2-25A (Test method for detection of alkali-silica reactive aggregate by accelerated expansion of mortar bars).

3.2 X-Ray diffraction Analysis

X-ray diffraction (XRD- Bruker D8 diffractometer) was carried out on all fine aggregate samples. All samples were dried and grounded to pass the 200 μm sieve before testing. Cu-K α radiation with a wavelength of 1.54 \AA was conducted at a voltage of 40 kV. The scanning speed was 2 $^\circ$ /min at a current of 35 mA.

3.3 Petrographic Analysis

Petrographic analysis according to CSA A23.2-15A (Petrographic examination of aggregates) was carried out on different aggregate samples using a petrographic microscope in order to quantify the various rock and mineral constituents present. The samples were separated into five thin sections, which correspond to sieve numbers 8, 16, 30, 50, and 100, and were examined in plane polarized light (PPL) and cross-polarized light (XPL).

4. MITIGATION TECHNIQUES

Tables 1, 2, and 3 list properties of the materials used in this study. Several different materials were used either in combination or as partial substitution for cement in the mortar mixtures in conjunction with the reactive aggregate samples to evaluate and compare the effectiveness of different ASR mitigation techniques. The mortar bars were prepared according to a CSA A23.2-25A and the results were compared to that of the control mortar bars containing 100 % portland cement. Table 4 shows the mixture proportions for the mortar bars. One set of mixtures explores the use of different proportions of fly ash as partial substitution for cement to mitigate ASR expansion. Another set investigates the differences between various dosages of silica fume as partial substitution for cement. Similarly, the third set of mixtures contains an equal percentage of silica to the second set; however, nano-silica was used as partial replacement for silica fume. Finally, the last mixture contains a portion of the expansive aggregate diluted with non-reactive limestone powder to compare its effectiveness versus the addition of pozzolanic materials.

Table 1: Properties of nano-silica used in this study

Particle Diameter(nm)	Density (g/cm 3)	Purity (%)
5-10	< 0.15	>99.8

Table 2: Physical and chemical properties of OPC, Fly ash, and Silica fume

Components /Property	OPC	Silica Fume	Fly ash
Calcium oxide (CaO) (%)	61.50	0.49	16
Sulfur trioxide (SO ₃) (%)	3.50	0.24	2.4
Loss on ignition (%)	1.90	1.99	1.6
Insoluble residue (%)	0.44	-	-
Equivalent alkalis (%)	0.7	-	-
Tricalcium silicate (C ₃ S) (%)	55	-	-
Dicalcium silicate (C ₂ S) (%)	15	-	-
Tricalcium aluminate (C ₃ A) (%)	7	-	-
Tetracalcium aluminoferrite (C ₄ AF) (%)	10	-	-
Autoclave expansion (%)	0.09	-	-
Compressive strength 28 days (MPa)	40.9	-	-
Specific gravity	3.15	2.58	2.60
Time of setting (min) Vicat Initial	104	-	-

Table 3: Properties of limestone powder used in this study

Particle Size(μm)	Specific Gravity	Absorption (%)
300	2.61	1.58

Table 4: Mixture proportions for tested mortars

Mixture ID	Ingredient (%)										
	Cementitious Materials					Aggregate					
	OPC	FA	SF	NS	Sieve #	Sieve #	Sieve #	Sieve #	Sieve #	LS	w/c
					8	16	30	50	100		
FA-15	85	15	-	-	10	25	25	25	15	-	0.44
FA-25	75	25	-	-	10	25	25	25	15	-	0.44
FA-35	65	35	-	-	10	25	25	25	15	-	0.44
SF-3	97	-	3	-	10	25	25	25	15	-	0.44
SF-5	95	-	5	-	10	25	25	25	15	-	0.44
SF-8	92	-	8	-	10	25	25	25	15	-	0.44
NS-1	97	-	2	1	10	25	25	25	15	-	0.44
NS-2	95	-	3	2	10	25	25	25	15	-	0.44
LSP	100	-	-	-	7.5	18.75	18.75	18.75	11.25	25	0.44

5. RESULTS AND DISCUSSION

5.1 Accelerated Mortar Bar Test Results for Fine Aggregates from Different Locations in Southwestern Ontario

Figure 1 shows the results at 14 days of the accelerated mortar bar test for the fine aggregates collected from different locations in Southwestern Ontario. As shown in Figure 1, the expansion of the mortar bars exceeded the CSA A23.2-25A recommended expansion limit of 0.15% indicating potential alkali-silica reactivity. This indicates that all tested aggregates are highly reactive.

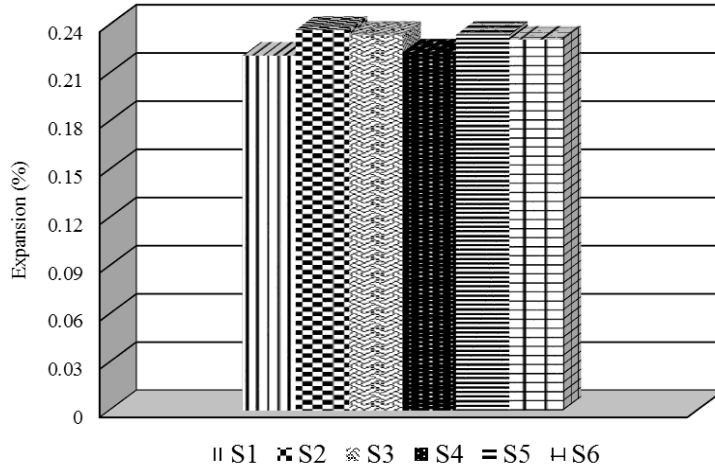


Figure 1: Results of accelerated mortar bar tests at 14 days for fine aggregates retrieved from different locations in Southwestern Ontario.

5.2 X-Ray diffraction and Petrographic Analysis

Figure 2 shows XRD analysis for a fine aggregate sample that led to exceeding the recommended expansion limit in the mortar bar test. Results show that the tested aggregate contains feldspar and mica. Both feldspar and mica release alkalis and increase the alkali content of the mixture leading to larger expansion (Islam and Akhtar, 2013). Table 4 and Figures 3, 4, and 5 show the results of the petrographic analysis. Reactive minerals such as volcanic glass and chert were found in the tested aggregate. These minerals are susceptible to alkali-silica reaction. Previous study by Rogers, et al. (2000) reported that cherts are found in sands and gravels and in some quarries located in Southwestern Ontario. The current study also documented the presence of volcanic glass among the reactive minerals that can be found in Southwestern Ontario.

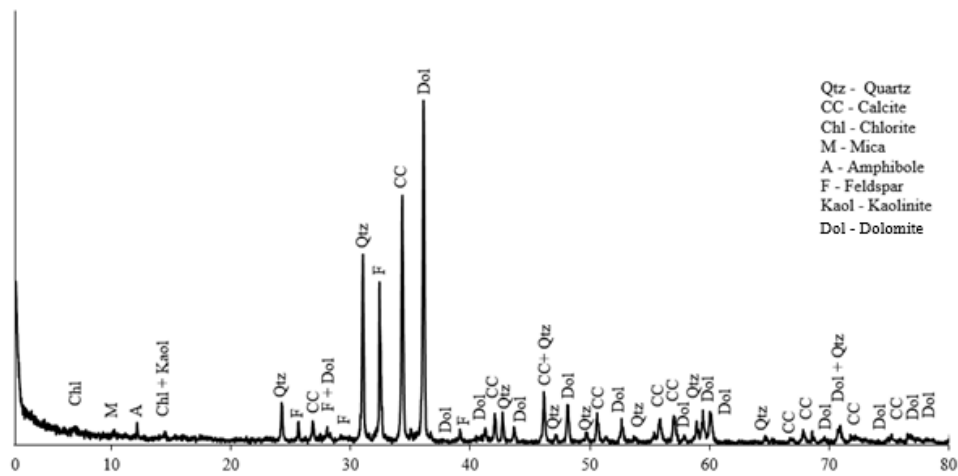


Figure 2: XRD pattern for fine aggregate.

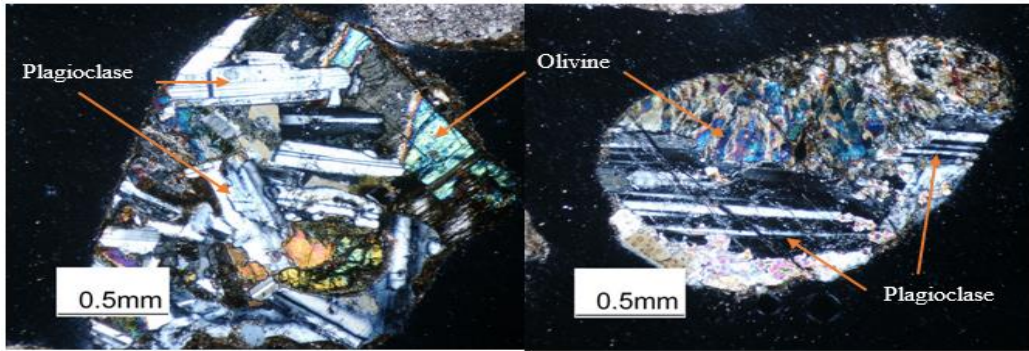


Figure 3: Two volcanic glass/plutonic fragments from sieve number 16 in XPL.

Table 4: Results of particle count for the tested fine aggregate

Constituents	Sieve no. 8		Sieve no. 16		Sieve no. 30		Sieve no. 50		4 - sieve no. 100	
	No. of particles	%	No. of particles	%	No. of particles	%	No. of particles	%	No. of particles	%
Carbonate	14	37.8	53	52	201	50.2	183	45.8	163	40.8
Sandy/silty carbonate	5	13.5	6	5.9	35	8.8	32	8	17	4.2
Chert/cherty carbonate	1	2.7	8	7.8	14	3.5	6	1.5	8	2
Micrite	6	16.2	15	14.7	20	5	34	8.5	11	2.8
Lithic fragments	5	13.5	6	5.9	29	7.3	15	3.8	20	5
Volcanic-glass/plutonic fragments	6	16.2	11	10.8	52	13	13	3.3	4	1
Plagioclase feldspar	-	-	2	2	7	1.8	13	3.3	22	5.5
Quartz	-	-	1	1	42	10.5	104	26	117	29.3
Potassium feldspar	-	-	-	-	-	-	-	-	3	0.8
Hornblende	-	-	-	-	-	-	-	-	18	4.5
Garnet	-	-	-	-	-	-	-	-	10	2.5
Epidote	-	-	-	-	-	-	-	-	7	1.7
Totals	37	100	102	100	400	100	400	100	400	100

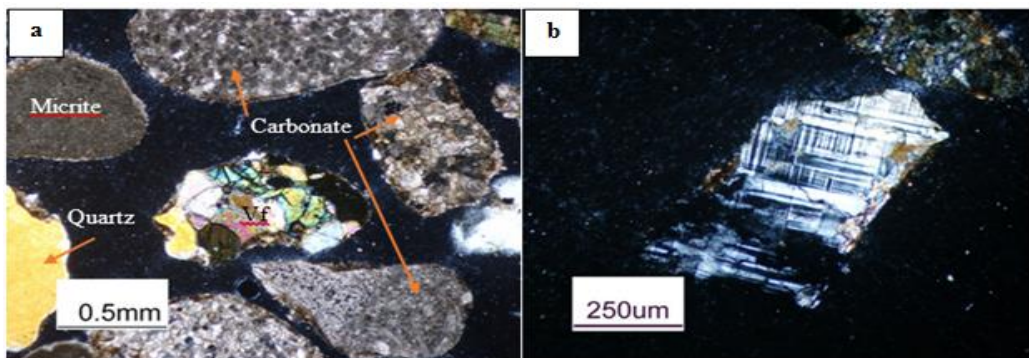


Figure 4: (a) XPL image of a volcanic/plutonic fragment surrounded by carbonate grains and two quartz grains from sieve number 30. (b) XPL image of volcanic glass/plutonic fragment.

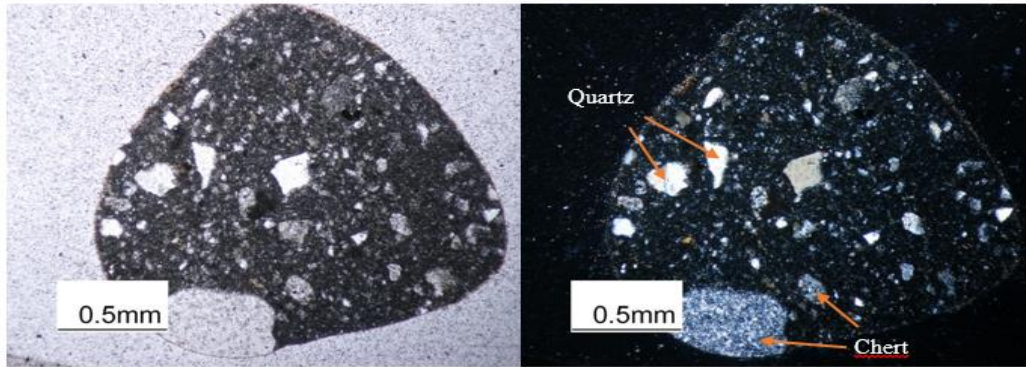


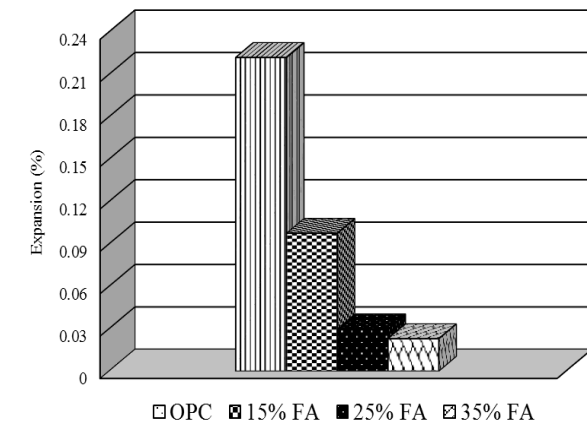
Figure 5: Lithic fragment from sieve number 8 in PPL (left) and XPL (right). The grains are composed of quartz and chert fragments.

5.3 Mitigation Techniques

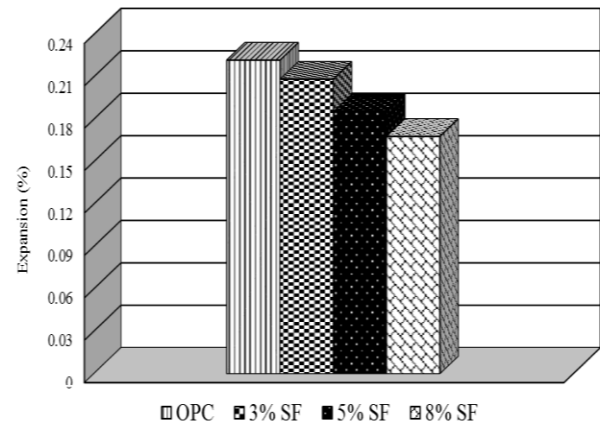
Figure 6 shows the results at 14 days of the accelerated mortar bar test for mortar specimens incorporating different proportions of fly ash, silica fume, nano-silica, and limestone filler. The results indicate that the expansion of the mortar bar specimens had a strong correlation with the amounts of fly ash used as a replacement of cementitious material. The higher the fly ash content, the lower was the mortar bar expansion. It was observed that 15% fly replacement was able to lower the expansion down to slightly over the unreactive threshold of 0.1%. The specimens containing 25% and 35% reduced expansion below the 14 day limit of 0.1%. It can be deduced that addition of the used fly ash in excess of 25% supplied marginal decrease of ASR expansion. This also conforms to current recommendations of a minimum fly ash requirement of 25% replacement to control ASR (Malvar et al. 2002; Shehata and Thomas, 2000). Thus, fly ash used as a mitigation technique can be an efficient method to alleviate the expansion due to ASR.

Partially replacing the cement with silica fume up to 8% did not control the ASR expansion. In addition, using 2% of nano-silica in combination with 3% of silica fume reduced the expansion of the mortar bar compared to the control mixture, but failed to adequately control the overall expansion. It was observed that the expansion of the bars exceeded the CSA-recommended expansion limit of 0.15%, indicating potential alkali-silica reactivity. Different factors can affect the expansion of the accelerated mortar bar test when silica fume is used as a supplementary cementitious material. For instance, a study by Andrew et al. (2007) showed that some agglomerated particles of silica fume may actually act as alkali-silica reactive aggregates and participate in ASR. Thus, these type of particles can increase the expansion rather than reducing it. Another study by Boddy et al. (2000) investigated different product forms of silica fume such as densified, compacted, and slurried under ASR. It was reported that using undensified and slurried silica fume significantly controlled the expansion of a reactive aggregate more than using densified or pelletized silica fume. In the current study, densified silica fume was used. Overall, in order to sufficiently affect the expansion from ASR, silica fume must be effectively dispersed and agglomeration should be prevented. Since higher dosages of silica fume also tend to drastically decrease workability, the best use of silica fume as a mitigation strategy for ASR may be in a ternary system with fly ash.

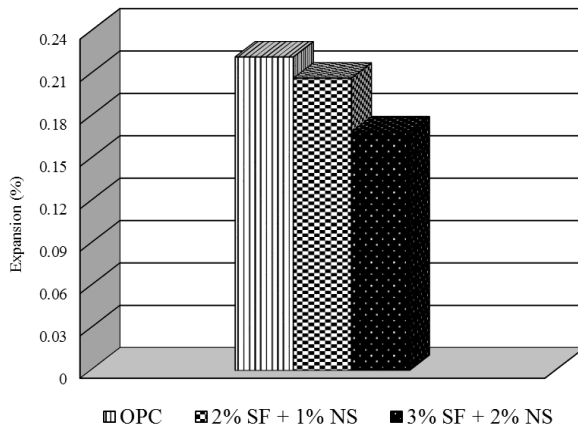
The addition of crushed limestone was ineffective in controlling the expansion due to ASR. The replacement of 25% of the reactive aggregate was explored as a means to dilute the source of aggregate susceptible to ASR reaction known as limestone sweetening. By reducing the concentration of reactive siliceous aggregate, it was expected to result in the production of fewer ASR gel products and decreasing the overall expansion. Although the addition of crushed limestone powder resulted in a minor reduction in mortar bar expansion, it appeared that the effect of the limestone had only caused a delay in the expansion. The expansion rate of the bars with limestone had appeared to slow significantly for the first two days, at which point the expansion began to proceed at a similar rate of the control mixture. This lag resulted in a minor decrease in expansion at 14 days but was not significant enough to reduce the ASR expansion below the deleterious limit.



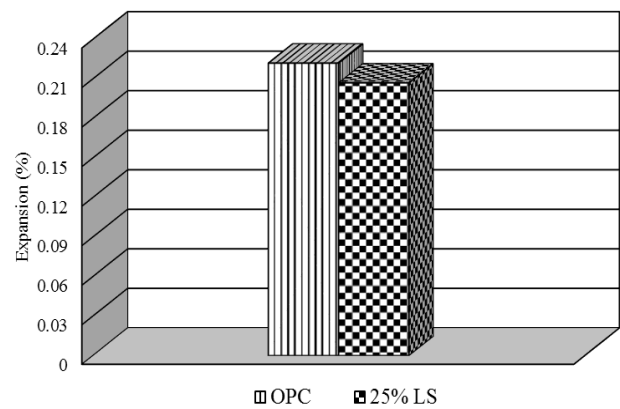
(a)



(b)



(c)



(d)

Figure 6: Results of accelerated mortar bar test at 14 days for specimens with (a) fly ash, (b) silica fume, (c) silica fume + nano-silica, and (d) limestone powder.

6. CONCLUSIONS

In this study, fine aggregate retrieved from different locations in Southwestern Ontario was investigated for alkali silica reactivity. Several conclusions can be drawn based on the experimental results:

1. Reactive minerals such as volcanic glass and chert were found in all tested specimens. In addition, feldspar and mica that can increase the potential of alkali-silica reactivity were also identified at these locations.
2. It was found that partial replacement of cement by fly ash in excess of 25% could effectively control the expansion of the mortar bars incorporating the reactive aggregates.
3. Dosages of up to 8% were not sufficient to control expansions due to ASR. This is likely due to inadequate dispersion of silica fume and its agglomeration.

4. The replacement of 25% of reactive aggregate by crushed limestone powder was unable to effectively control mortar bar expansion. The effect of limestone appeared to have only caused a short delay in the rate of expansion.

ACKNOWLEDGMENTS

The authors would like to thank Centre for Environment and Sustainability at Western University for the technical support in performing the petrographic analysis. In particular, the authors would like to extend their gratitude to Dr. Patricia Corcoran and Carolyn Hill.

REFERENCES

- Andrew, J. M. Jason, H. I. and Maria C. G. J. 2007. Alkali Silica Reactivity of Agglomerated Silica Fume. *Cement and Concrete Research*, 37 (2): 166-174.
- Boddy, A. M. Hooton, R. D. and Thomas M. D. A. 2000. The Effect of Product Form of Silica Fume on Its Ability to Control Alkali Silica Reaction. *Cement and Concrete Research*, 30 (7) 1139-1150.
- CSA A23.2-25A. 2009. Test Method for Detection of Alkali-Silica Reactive Aggregate by Accelerated Expansion of Mortar Bars. *Canadian Standard Association*, 359-365.
- CSA A23.2-15A. 2009. Petrographic Examination of Aggregate. *Canadian Standard Association*, 297-328.
- Farny, J. A. and Kerkhoff, B. 2007. Diagnosis and Control of Alkali-Aggregate Reactions in Concrete. *Portland Cement Association*, Skokie, Illinois, USA, 26 pages.
- Islam, M. S. and Akhtar, S. 2013. A critical Assessment to the Performance of Alkali-Silica Reaction (ASR) in Concrete. *Canadian Chemical Transactions*, 4 (1): 253-266.
- Latifee, E. R. and Rangaraju, P. R. 2014. Miniature Concrete Prism Test: Rapid Test Method for Evaluating Alkali-Silica Reactivity of Aggregates. *Journal of Materials in Civil Engineering*, 27 (7): 04014215.
- Malvar, L. Cline, D. Burke, D. Rollings, R. Sherman, T. and Greene, J. 2002. Alkali-Silica Reaction Mitigation: State of the Art and Recommendations. *ACI Materials Journal*, 99 (5): 480-489.
- Rajabipour, F. Giannini, E. Dunant, C. Ideker, J. and Thomas, M. 2015. Alkali-Silica Reaction: Current Understanding of the Reaction Mechanisms and the Knowledge Gaps. *Cement and Concrete Research*, 76: 130-146.
- Rogers, C. Grattan-Bellew, P. E. Hooton, D. R. Ryell, J. and Thomas, M. D. A. 2000. Alkali-Aggregate Reactions in Ontario. *Canadian Journal of Civil Engineering*, 27 (2): 246-260.
- Shehata, M. H. and Thomas, M. D. 2000. The Effect of Fly Ash Composition on the Expansion of Concrete Due to Alkali-Silica Reaction. *Cement and Concrete Research*, 30 (7): 1063-1072.
- Yurtdas, I. Chen, D. Hu, D. W. and Shao, J.F. 2013. Influence of Alkali Silica Reaction (ASR) on Mechanical Properties of Mortar. *Construction and Building Materials*. 47: 165-174.