

A Critical Assessment to the Performance of Alkali-Silica Reaction (ASR) in Concrete

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Received: June 4, 2013 Revised: October 10, 2013 Accepted: October 12, 2013 Published: October 13, 2013

Abstract: Alkali-silica reaction is one of the most recognized deleterious phenomenon in concrete that results in excessive expansion, cracks, loss in mechanical properties and serviceability problems. This paper reports overview of alkali-silica reactivity (ASR) in concrete including background, chemistry behind ASR, factors affecting ASR, and symptoms of ASR. The aggregates susceptible to ASR were evaluated using field performance, petrographic analysis, aggregate mineralogy and the standard and modified methods of ASTM C 1260 and C 1293, and their modifications. Aggregate classifications into innocuous and reactive based on the stated mineralogy tests, and the expansion limits of the standard methods and their modifications were compared. The study demonstrated that none of the single method is an ideal approach to evaluate the alkali-silica reactivity of an aggregate, and a suitable combination of various methods can be utilized to better predict the potential ASR reactivity of an aggregate.

Keywords: Alkali-Silica Reactivity, Aggregate Mineralogy, Petro Graphic Analysis, Field Performance, Mortar Bars, Prisms, Expansion Limits

1. INTRODUCTION

The fast growth of the world population and increased urbanization during the 20th and 21st centuries has generated a high demand of new construction work. The abundance, availability and economy of materials used in cement-based concrete are a great concern for future construction. Since the end of the 19th century, a tremendous number of investigations have been conducted throughout the world on cement-based concrete and its characteristics in order to improve the strength and serviceability qualities of the materials used in concrete construction.

In the present day, concrete is the most widely-used construction material in the world [1]. It consists of particles of aggregate, water, and a binding agent (cement and other cementitious materials). The reactions between aggregates and binding agents are extremely complex. Many natural aggregates contain a quantity of amorphous silica and carbonate, which both react with the alkalis (Na and K) of the mixture,

which mainly come from cementitious materials). This interaction is widely known as the alkali-aggregate reaction (AAR). Depending on which minerals are involved, AAR is subdivided into alkali-silica reaction which is called ASR and alkali-carbonate reaction, which is known as ACR. ASR develops by the aggregates containing reactive silica minerals. On the other hand, ACR develops due to the composition of aggregates, such as in dolomite. ASR is a common form of AAR while ACR is very rare [2].

In the United States, many concrete structures built from the late 1920's to the early 1940's failed due to overall cracking throughout the structures. The destruction manifested at the concrete surface as extensive map cracking, surface pop-outs, spalling and gel exudation [3]. In 1940, T. Stanton of the California Division of Highways identified the phenomenon and called it alkali-silica reactivity (ASR). From that time, it has been a subject of intense research.

A large number of researches have been conducted to investigate both the fundamental and practical aspects of AAR. Diamond (1992) [4] provided an excellent overview of the literature pertaining to alkali-aggregate reactions from 1940 to 1991, and the result is shown in Figure 1. It has been shown that the number of published papers has been increasing substantially over the three decades of 1970 to 1990 (Figure 1). Nearly one thousand of published papers concerning AAR-related issues have been appended during the last two decades to the web of knowledge database, which is a premier research platform for information in the sciences, social sciences, humanities and arts. This proves an intense awareness of concrete durability problems as related to AAR.

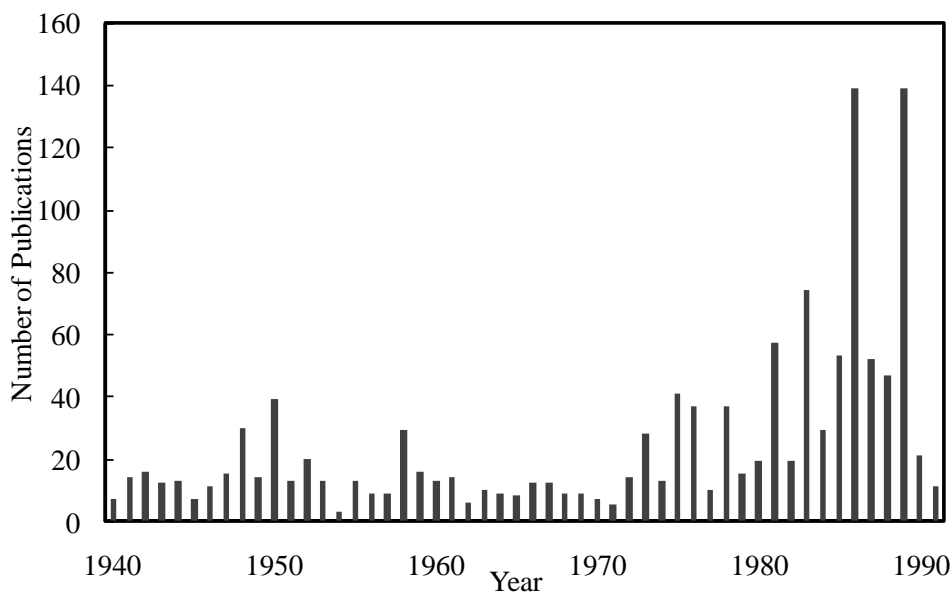
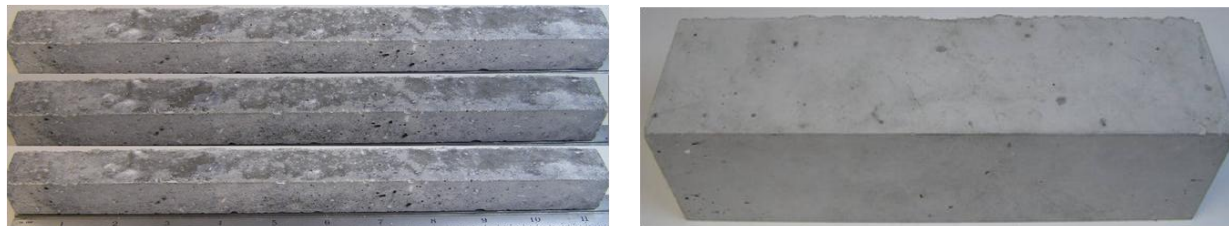


Figure 1: Number of publications concerning alkali-aggregate reactivity over time (Data retrieved from [4])

The deterioration caused by alkali-silica reaction is fairly slow but progressive [5-7]. The ASR reaction leads to concrete expansion, loss of strength, and stiffness, and tends to deform the structures and disturb the internal forces [5-8]. The long term durability, serviceability, and the safety of the structures can be damaged by the alkali-silica reaction [9, 10].

2. CHEMISTRY BEHIND ALKALI-SILICA REACTION

The chemical reaction of ASR is a multi-stage process [8]. The process starts with the reactive silica on the surface area of the aggregate in a high alkaline (high pH) solution. The hydroxyl ions (OH^-) attack the stronger siloxane bridge (Si-O-Si) as it forms a poor crystallized silica network. The silanol bonds

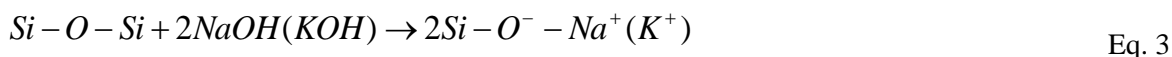


a) Mortar Bars ($25.4 \times 25.4 \times 254$ mm)

b) Prisms ($75 \times 75 \times 250$ mm)

Figure 2. Specimens prepared with innocuous aggregate [14, 15]

replace broken Siloxane bonds as shown in Equations 1 and 2. The positively charged alkali ions, such as Na^+ or K^+ balance the negative charge created by the breakdown as shown in Equation 3.



The alkali-silica reaction produces two types of component gel [11] non-swelling calcium-alkali-silicate-hydrate [C-N(K)-S-H] and swelling alkali-silica-hydrate [N(K)-S-H] gels. When the alkali-silica reaction occurs in concrete, some non-swelling C-N(K)-S-H component are produced. The presence of non-swelling gel does not coincide with distress, and thus, does not necessarily indicate destructive ASR. Only when the both types of ASR gels form the damages due to alkali-silica reactivity only occur. The occurrence of reaction products (swelling gel) is the main diagnostic symptom of ASR.

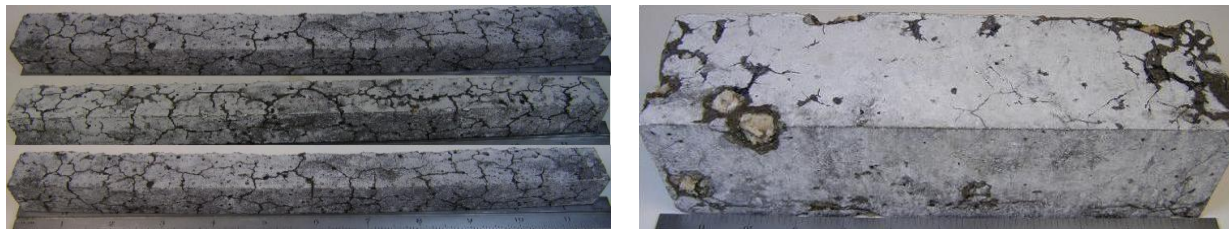
The alkali-silicate gel absorbs water from surroundings and increases in volume. Once the pressure is larger than the tensile strength of concrete, cracks occur and lead to additional water permeation through migration and gel swelling. Extensive expansion and severe cracking are caused by high-swelling gel. The rate of the expansion depends on the chemical composition and the available alkali content of the cement matrix [12]

3. Symptoms of ASR

As the alkali-silica reaction starts to take place, some cracks develop at the outer zone of the reactive aggregate due to the tension created by ASR gel. As the reaction takes place, the reactive particles are dissolved in the inner part of the aggregate, and an alkali gel is formed within the grains. The reaction processes depend on the level of reactivity of the aggregates [8]. Common symptoms of ASR-affected structures are map cracks, longitudinal cracks, exudation, pop out, buckling and spalling [13]. Figures 2 and 3 show the specimens prepared with innocuous and reactive aggregates, respectively. As can be seen, the mortar and prism specimens prepared with innocuous aggregates showed no ASR-related cracks even at the extended test duration of 13 weeks (Figure 2), whereas those containing reactive aggregates

experienced severe cracks (map cracks) and aggregate pop out, as shown in Figure 3.

ASR cracks in reinforced concrete develop in the direction of the main reinforcing bars [16]. Fewer cracks occur in the perpendicular direction because compressive stress is developed in the concrete as a result of restraint from expansion by the reinforcing bar. For the concrete with little/no reinforcement (i.e. at the free end of a beam or abutment, on the surface of a sea defense structures or in a concrete block, etc.), the ASR caused crack pattern is irregular or map-like. Concrete section exposed to rain has more cracks than the sheltered part of the same structure. The regions of the cracks are determined by the area on the aggregates with reacting silica and the availability of the OH⁻ vicinity.



a) Mortar Bars ($25.4 \times 25.4 \times 254$ mm)

b) Prisms ($75 \times 75 \times 250$ mm)

Figure 3. Specimens prepared with innocuous aggregate [14, 15]

4. FACTORS AFFECTING ASR

It is widely accepted that three main components are essential for ASR-induced damages in concrete structures: (i) reactive silica in aggregates, (ii) sufficient alkalis, and (iii) presence of moisture. The ongoing process of ASR simply brings to an end when one of the reacting substances is used up.

4.1 Reactive Forms of Silica in Aggregates

Reactive aggregates exposed to a highly alkaline pore solution tend to break down, which creates silica. Subsequently, the reaction between alkali hydroxides and reactive silica occurs to produce ASR gel in concrete. The probable reactivity of aggregates depends on numerous factors, such as chemical composition, level of crystallinity, and solubility of the silica in alkaline (high-pH) concrete pore solution [17]. Additionally, the aggregate's internal grain size is inversely correlated to the surface area of the silica accessible for alkali attack. Therefore, fine aggregates are more susceptible to ASR because of their higher surface area [18, 19]. The porosity of the aggregate also increases the rate and ASR reactivity [13, 20].

As a result of deficiency in ordered pattern, amorphous silica has holes (porous) in the network where electrical neutrality is unsatisfied. This situation creates a large surface area for the alkali-silica reactions to take place [21]. The extent of ASR-related reactions is proportional to the amount of amorphous silica present in an aggregate [22]. Certain volcanic aggregates have glassy materials produced by the brisk cooling of melted silica that prevents it from crystallization, and renders it very reactive [23].

Table 1 shows the rocks and reactive minerals that are susceptible to alkali-silica reaction. Table 1 highlights two groups of rocks, and their main differences in the crystalline structure of mineral constituents. The first set of rocks has a lack of minerals with a crystalline structure. The structures of these rocks are in disorder, resulting in holes and channels. As such, reactive ion can easily migrate in a larger surface area of these rocks and more ASR reactions can take place [21]. The rocks of this category are extremely reactive [24]. The second category of rocks contains minerals with a crystalline structure.

The level of ASR of this group of rocks ranges from mild to very. However, it is highly recommended that the rocks or minerals shown in Table 1 are always susceptible to ASR or the other rocks and minerals not listed in the table are completely immune from the adverse effects of ASR.

A wide range of rock types used as aggregates in concrete construction. Table 2 outlines a summary of findings on major rock types susceptible to alkali-silica reaction. Based on the findings in Tables 1 and 2, andesite, basalt, decite, dolomitic-limestone, chert, opal, pyrex glass, quartz, rhyolite, and silicious rocks are prone to alkali-silica reactions. On the other hand, the mono-minerals dolomite and limestone rocks, which often do not contain reactive minerals, are not susceptible to alkali-silica reaction [25].

Table 1. Minerals and rocks susceptible to ASR [24]

Category (1)	Alkali-reactive poorly crystalline or metastable silica minerals, and volcanic or artificial glasses (Classical alkali-silica reaction)
Reactants	Opal, tridymite, cristobalite; volcanic glasses; artificial glasses, beekite
Rocks	Opal such as shales, sandstones, silicified carbonate rocks, some cherts, flints, and diatomite Volcanic rocks, such as rhyolites, dacites, latites, andesites, and their tuffs, perlites, obsidians; some basalts
Category (2)	Alkali-reactive quartz-bearing rocks
Reactants	Chalcedony; cryptocrystalline to microcrystalline quartz; quartz with deformed crystal lattice, rich in inclusions, intensively fractured or granulated; poorly crystalline quartz at grain boundaries; quartz cement overgrowths (in sandstones)
Rocks	Cherts, flints, quartz veins, quartzites, quartz-arenites, quartzitic sandstones which contain microcrystalline to cryptocrystalline quartz and/or chalcedony Volcanic rocks such as that in category (1) but with devitrified, cryptocrystalline to microcrystalline groundmass Micro-granular to macro-granular silicate rocks of various origins which contain microcrystalline to cryptocrystalline quartz: a) Metamorphic rocks: gneisses, quartz-mica schists, quartzites, hornfelses, phyllites, argillites, slates; b) Igneous rocks: granites, granodiorites, charnockites; c) Sedimentary rocks: sandstones, greywackes, siltstones, shales, siliceous limestones, arenites, arkoses; Sedimentary rocks (sandstones) with epitax

The amount of reactive silica is the most crucial factors for alkali-silica reaction. A small amount of reactive silica can produce ASR-induced effects [8], and the quantity varies on the rock types and reactive minerals [40]. An aggregate used in concrete might contain a small proportion of reactive silica as an original, primary or secondary constituent, which may not be determined by the chemical compositions. As such, the deleterious effects cannot be estimated from the knowledge of the quantities of the reactive materials used in the concrete alone. The structure of silica decides whether a siliceous aggregate acts as reactive or not. Broekmans (1999) demonstrated that the type, size, and the amount of reactive silica also

influence ASR-related damages in concrete [41]. In order to provide a better understanding of alkali-silica reactions, the structures of silica need to be discussed.

The basic structure of silicate is silicon tetrahedron, as shown in Figure 4, which consists of one center silicon atom bonded with four oxygen atoms, one in each corner of the silicate [27]. The tetrahedron can be formed singularly or in multiples with rings, chains, sheets or frameworks. A crystalline silicate structure can be formed by the repetition of the silicon tetrahedron in an oriented manner of three-dimensional space [27, 42].

Table 2. Summary of findings on major rock types susceptible to ASR [6]

Rock Types	Research Investigations	ASR Type
Andesite	[26], [8], [27], [28], [13], [29]	Reactive
Basalt	[30], [28], [31]	Reactive
Chert	[25], [30], [27]	Reactive
Dacite	[8],[24], [32], [26], [27], [13]	Reactive
Dolomite	[33], [25]	Innocuous
Dolomitic-limestone	[34], [30]	Reactive
Limestone	[25], [35], [27]	Innocuous
Opal	[36], [24]	Reactive
Pyrex glass	[37], [33], [30]	Reactive
Quartz	[27], [25], [30], [28]	Reactive
Rhyolite	[27], [28]	Reactive
Silicious aggregate	[33], [38], [39]	Reactive

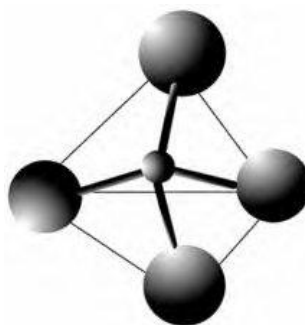


Figure 4: Silicon tetrahedron [27]

Figure 5 show a quartz (SiO_2) structure, where the silica is completely crystalline. Each silicon tetrahedron is linked by oxygen ions, and each oxygen ion is tied with two silicon ions in order to achieve electrical neutrality. On the surface, however, unsatisfied negative charges develop because the structure is linked with three oxygen atoms instead of four oxygen atoms. Such structures are chemically and mechanically stable, impervious, and react only on the outside.

When the ASR reaction proceeds, alkali hydroxides penetrate into the siliceous particle, thus loosening the lattice structure. In a well-crystallized silica (such as quartz), the breakdown of the lattice

structure by alkali hydroxides is almost impossible. On the contrary, crypto-crystalline and amorphous silica are more susceptible to ASR attack because of an untied and disordered lattice structure and increased surface area. In the case of a non-reactive quartz, the alkali ions cannot penetrate the well-ordered crystal lattice [23].

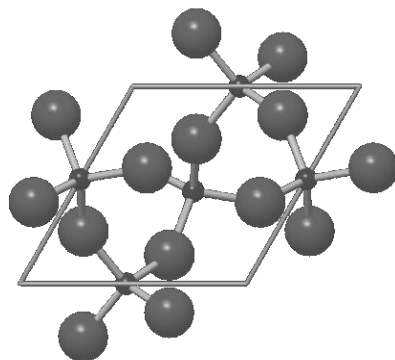


Figure 5: Quartz (silica) structure [27]

4.2 SUFFICIENT ALKALIS

Concrete consists of infinite pores that are often filled with a solution containing alkalis (Na^+ , K^+) and hydroxyl (OH^-) ions. The amount of alkalis in concrete is expressed by sodium oxide equivalent as the percent of Na_2O plus 0.658 times the percent of K_2O . An effective way of preventing ASR-induced damages is not only to control cement alkalis, but also the total alkali content of the concrete mixture [43].

Among all ingredients of concrete contributing the total alkalis in concrete, Portland cement contributes the largest amount of alkalis. Alkalis in the Portland cement varies from 0.2 to 1.1 percent [43] and produce an inherently high pH (normally from 13.2 to 14) in the pore solution by associating hydroxyl ion (OH^-) concentration [44]. ASR-induced expansion increases with an increase in cement alkali [6, 27, 45]. Limiting cement alkalis below 0.60% $\text{Na}_2\text{O}_{\text{eq}}$ is unlikely to prevent the occurrence of ASR. Additionally, the lowest cement alkali of $1.8 \text{ kg/m}^3 \text{ Na}_2\text{O}_{\text{eq}}$ is recommended for the structures with a relatively high risk level of alkali-silica reaction to ensuring a safety factor from the potential contribution of alkalis [46]. However, cement alkali substance did not considerably affect the expansion of the mortar bars made with the moderately reactive aggregate, but tended to have a significant effect on the expansion of the mortar bar having highly reactive aggregates [6, 27]. The fineness of Portland cement plays an important role on the alkali content. The finer cement releases alkalis rapidly, thus, inducing expansion faster [47].

Pozzolanic materials, such as fly ash, silica fume and ground granulated blast furnace slag (GGBFS), are used as cement replacement or a part of cementitious material to modify or improve concrete properties, and occasionally used for economical consideration. They react with lime produced from cement hydration, forming a compound possessing binding properties. Addition of pozzolans to concrete results in a reduction of alkali content which yields reducing ASR expansion [48]. A pozzolanic reaction reduces the permeability of concrete and absorbs some alkali ions [48]. Thus, the concrete is protected from the reaction between alkalis and aggregates.

Some aggregates can release alkalis, thus increasing the alkali content of the mixture [49, 50]. For an example, aggregate containing feldspars, mica, glass, and glass rock release alkalis in concrete. For certain aggregates, the amount of released alkalis is equivalent to 10 percent of Portland cement alkalis

under severe conditions [43]. A significant amount of alkalis can also be supplied to concrete pore solution with time by feldspar-rich aggregates, such as granite, which are often used in concrete [51]. Additionally, if sea-dredged aggregates are utilized in the mixture, the additional alkalis lead to the concrete mixture resulting in ASR expansion.

Some of the admixtures (accelerators, water reducers, super plasticizers, retarders, and air-entraining) contain sodium and potassium compounds that also contribute to the alkalis in concrete. The total alkali content of a given mixture may also be increased from the external sources, such as seawater, ground water, and water from industrial process. Nixon and Sims (1992) [52] confirmed that seawater increases the OH⁻ concentration in the pore solution. This resulted in high ASR-induced expansion.

4.3 SUFFICIENT MOISTURE

Alkali-silica reactivity requires water to initiate the reaction. Water is an essential for the 'carrier' of alkali cations and hydroxyl ions. Water is absorbed by the gel which is the essential element in developing pressures to crack the concrete. Sufficient moisture is necessary to induce pressure on gels. These gels are formed by the alkali-silica reaction that leads to expansion and cracking of the aggregate in surrounding paste. Concrete mixtures involved in highly reactive aggregates and high-alkali cements have exposed little or no expansion in a dry environment. Likewise, the concrete structure with a large amount of local moisture typically results in more expansion.

The effects of alkali-silica reaction vary directly with the relative humidity (RH) of the concrete. The swelling of the gel takes place at a RH higher than 80%, although it can be formed in a lower humidity [53, 54]. Moreover, Swamy (1992) [8] and Pedneault (1996) [54] suggested that limiting moisture content to less than 70 and 80% RH does not undergo significant expansion and severity of ASR distress, respectively. Applying a protective coating over concrete is another solution to minimize contact with moisture through the procedure can be costly.

Reducing the permeability of concrete is also a feasible approach to decline the deleterious effects of ASR [40]. In concrete, the decrease of the water-to-cement ratio results in high alkali content and a reduction of pore space. It affects the expansion rate [40, 45, 49]. As such, one approach of suppressing ASR-related damages is to add silica fume or other supplementary cementitious materials to the concrete mixture.

5. STANDARD TESTS FOR ALKALI-SILICA REACTIVITY

A number of standard tests have been used in assessing alkali-silica reactions and their potential for deleterious expansion in concrete. Among them, the three most popular methods are described below:

5.1 ASTM C 295 (Petrographic examination of aggregates)

Petrographic examination of aggregates is one of the most reliable indicators of the potential for deleterious ASR. Petrographic evaluation provides valuable information about the types and quantities of minerals present in an aggregate. It can be used to identify a wide range of reactive components. This test is highly recommended for use in combination with other tests and field performance evaluations. It is recommended that petrographic examination together with ASTM C 1260 [55] jointly appear to the most reliable indicators of potential for deleterious ASR.

ASTM C 289 is a very quick method and its findings greatly depend on the experience and capabilities of the petrography examiners of the aggregate. While conducting the test, a small amount of certain important components can readily be missed, especially with an aggregate such as opal [52]. A

few aggregates, on the other hand, can be classified as deleterious reactive even with a good service record, because they contain minerals that have been known to be reactive in other situations [27].

5.2 ASTM C 1260 (Accelerated mortar bar test)

The accelerated mortar bar test (AMBT) is a recommended test method for assessing alkali-silica reaction. This is recognized as a very rigorous test method because of the intense test conditions such as highly alkaline storage solution and high temperature. The test requires only 16 days in deciding the level of reactivity, compared to one year for the concrete prism test [56]. As the specimens are exposed to the 1N NaOH solution, the quantity of alkali in the cement is not an important factor in affecting expansion [55].

Most researchers agree that the 14-day expansion of ASTM C 1260 under the 1N NaOH solution of less than 0.10% is an indication of innocuous aggregate. On the other hand, more than 0.20% is regarded as highly reactive aggregates. The expansion between 0.1% and 0.2% is either slowly reactive or inconclusive. It is more likely depends on concrete prism test, aggregate type or field performance. Aggregates found innocuous by the 14-day failure limit of ASTM C 1260 are very likely to perform well in the field. Some studies showed that the 14-day expansion limit of 0.10% was incapable of assessing the actual ASR evaluation of some aggregates [43, 57, 58]. To minimize the associated problems, additional expansion limits of 0.33% at 28 days and 0.48% at 56 days were proposed by Hooton [32], Rogers and Hooton [33]. Islam and Ghafoori [14, 15] recently proposed that the aggregates producing the 2-, 4- and 8-week mortar expansions of 0.10, 0.28 and 0.47%, respectively, are considered reactive. Moreover, those producing the expansions of less than the above-mentioned three proposed limits can be classified as innocuous. Recently, kinetic based model was also utilized to explain the expansion characteristic of AMBT, and to better evaluate the reactivity of aggregates [15, 59].

5.3 ASTM C 1293 (Concrete prism test)

Among the ASR assessing standard test methods, the concrete prism test is considered to be more representative of field performance. It is due to concrete specimen and curing environment. The method is normally considered the most precise and suitable test method in predicting the site performance of aggregates. The concrete prism test is less conservative than the AMBT test. It is more likely for assessing slow reacting and suspicious aggregates. To supplement these tests, a petrographic evaluation [60] is also suggested, but not required.

The only disadvantage of ASTM C 1293 [56] is that it takes one year to determine the alkali-silica reactivity of an aggregate. In order to improve this drawback, research studies have been conducted in changing the solution type and/or solution strength, and altering curing environment and test duration. It is done to show the equivalent results of ASTM C 1293 in a shorter span of time. A non-standard method of the concrete prisms immersed in the 1N NaOH at 80°C (1293M1) experimentally proved that the test can reliably predict the alkali-silica reactivity of an aggregate source (Stark, 2006). The proposed failure criteria of alkali-cured prism of 0.04% at 4 weeks, recommended by Fournier *et al.* [3], had been proved to be unreliable for assessing the potential alkali-silica reactivity of some aggregates [17, 27]. However, the prisms cured in the 1N NaOH solution at 80°C exceeding the 4-week expansions of 0.080% were considered highly reactive [17, 27]. Islam and Ghafoori (2013) [14,15] proposed that the failure limits of alkali-cured prisms of 0.052% at 4 weeks, 0.100% at 8 weeks and 0.150% at 13 weeks proved to produce more consistent results than those generated at the early immersion age of 4 weeks.

5.4 ASR EVALUATIONS OF AGGREGATES

The following data of each aggregate group has been obtained from the research investigation conducted by Touma *et al.* [27]. In this section, the alkali-silica reactivity of nine aggregate groups was evaluated based on aggregate's field performance, petrographic analysis, aggregate mineralogy and the expansion limits of ASTM C 1260, ASTM C 1293 and the modified ASTM C 1293 (prisms submerged in 1N NaOH at 80°C). The ASR classification of each aggregate is shown in Table 3. Based on aggregate's mineralogy, as shown in Tables 1 and 2, D2-IL (dolomite) aggregate group was innocuous, and the remaining eight aggregate groups of A1-WY (rhyolite), A9-NE (quartz), B4-VA (quartz), C2-SD (quartz), E2-IA (opal), E4-NV (natural siliceous), E6-IN (natural siliceous) and E8-NM (rhyolite) were considered reactive.

Table 3: ASR classifications of aggregates based on field performance, petrographic analysis, aggregate mineralogy, the expansion limits of ASTM C 1260 and ASTM C 1293, and modified ASTM C 1293 (data retrieved from [27])

Agg. ID	Field Performance	Petro-graphic Analysis	Aggregate's mineralogy	ASTM C 1260			ASTM C 1293	Modified ASTM C 1293 ^f				
				14 Days	28 Days	56 Days	1-Year	4 Weeks	8 Weeks	13 weeks		
				0.10% ^a	0.15% ^b	0.33% ^b	0.48% ^b	0.040 ^c	0.04% ^d	0.052% ^e	0.100% ^e	0.150% ^e
A1-WY	R	R	R	0.24 (R)	0.24 (R)	0.35 (R)	0.48 (R)	0.073 (R)	0.037 (I)	0.037 (I)	0.074 (I)	0.109 (I)
A9-NE	R	R	R	0.21 (R)	0.21 (R)	0.37 (R)	0.56 (R)	0.051 (R)	0.209 (R)	0.209 (R)	0.330 (R)	0.418 (R)
B4-VA	R	I	R	0.12 (R)	0.12 (I)	0.26 (I)	0.46 (I)	0.040 (R)	0.097 (R)	0.097 (R)	0.119 (R)	0.192 (R)
C2-SD	R	I	R	0.13 (R)	0.13 (I)	0.26 (I)	0.48 (R)	0.053 (R)	0.148 (R)	0.148 (R)	0.209 (R)	0.266 (R)
D2-IL	I	I	I	0.02 (I)	0.02 (I)	0.03 (I)	0.05 (I)	0.022 (I)	0.006 (I)	0.006 (I)	0.016 (I)	0.019 (I)
E2-IA	I	I	R	0.47 (R)	0.47 (R)	0.65 (R)	0.85 (R)	0.025 (I)	0.207 (R)	0.207 (R)	0.276 (R)	0.315 (R)
E4-NV	I	R	R	0.30 (R)	0.30 (R)	0.66 (R)	1.35 (R)	0.060 (R)	0.189 (R)	0.189 (R)	0.332 (R)	0.478 (R)
E6-IN	I	I	R	0.23 (R)	0.23 (R)	0.43 (R)	0.67 (R)	0.022 (I)	0.068 (R)	0.068 (R)	0.109 (R)	0.154 (R)
E8-NM	R	R	R	0.40 (R)	0.40 (R)	0.53 (R)	0.71 (R)	0.063 (R)	0.176 (R)	0.176 (R)	0.230 (R)	0.279 (R)

I: Innocuous; R: Reactive

^afailure limit recommended by ASTM C 1260 [55]; ^bfailure limits proposed by Hooton (1991) [32], and Rogers and Hooton (1993) [33]; ^cfailure limit recommended by ASTM C 1293 [56]; ^dexpansion limits of alkali-cured prisms recommended by Fournier *et al.* [3]; ^eexpansion limits of alkali-cured prisms suggested by Islam and Ghafoori [14].

Table 3 shows that the 14-day expansion limit of mortar bars of 0.10% resulted in an identical agreement on aggregate classifications with that obtained by the aggregate mineralogy and the expansion limits of alkali-cured prisms at 4, 8 and 13 weeks with an exception of A1-WY aggregate group. The early age failure limit of mortar bars, recommended by ASTM C 1260, produced more conservative result as compared to the findings obtained by the 14-, 28- and 56-day expansion limits of mortar bars suggested by Hooton (1991) [32], and Rogers and Hooton (1993) [33].

The concrete prism test showed a good correlation with the findings obtained by the petrographic test. However, it did not show a good agreement with the outcome generated by field performance and aggregate mineralogy. The expansion limits of alkali-cured concrete prisms at the ages of 4, 8 and 13 weeks were unable to produce consistent results with the results obtained by the standard concrete prism test. Among all, the ASR evaluation tests stated in Table 3, aggregate mineralogy and early age expansion limit of mortar bar resulted in more conservative approach followed by the expansion limits of alkali-cured prisms. Compared to other test methods, the concrete prism test might yield the most accurate ASR evaluation since the specimens are more likely to be exposed to the actual field conditions. On the other hand,

ASR classifications of the aggregates based on the field performance were not as expected. The possible reasons might be variations in the exposure conditions (relative humidity and the presence of OH⁻ concentrations) and the mixture design on the ASR in concrete structures prepared with respective aggregate group.

6. CONCLUSIONS

Alkali-silica reaction in concrete is a complex chemical reaction that depends on numerous factors. The reaction causes huge expansions and cracks, loss in mechanical properties of concrete and eventually damages the structures. As such, by early detection of ASR, engineers and builders can save millions of dollars in repair and rehabilitation costs, and increase the service life of existing structures through maintenance programs. Though various test methods are available in assessing ASR, none of them is an ideal approach to evaluate the alkali-silica reactivity of an aggregate. To predict the potential alkali-silica reactivity, suitable combination of various methods can be used as indicators.

It is highly recommended not to use the aggregate type as the primary method to evaluate aggregate reactivity. Though pure dolomite and limestone rocks can be considered as innocuous, and andesite, basalt, decite, dolomitic-limestone, chert, opal, pyrex glass, quartz, rhyolite, and silicious rocks are prone to alkali-silica reactions. An aggregate used in concrete might contain a small fraction of reactive silica as any forms of original, primary or secondary constituent, which may not be determined by the chemical compositions. Moreover, the mineralogy of aggregate is quite unable to offer the extent of ASR reactivity. Evaluation by the standard tests of ASTM 1260 and 1293 is required to reassure the extent of reactivity of the aggregates as obtained from the initial petrographic test and rock mineralogy. The amount of reactive silica, the chemical and physical properties of silica and aggregate mineralogy play an important role in alkali-silica reactivity. The alkali content of cement has a little influence on the expansion of mortar bars, and limiting cement alkalis below 0.6%Na₂O_{eq} does not arrest ASR below the prescribed expansion limits. However, blending appropriate amount of pozzolans like fly ash, silica fume and slag in concrete mixture not only improves concrete properties but also reduces the ASR-related damages. This approach is occasionally used for the economical consideration and reduction of green house gas emission to the atmosphere.

ACKNOWLEDGEMENT

This research has been conducted with the collaboration of Research Interface-Bangladesh (RIN-BD).

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The authors declare no conflict of interest

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