International Journal of Engineering Science Invention (IJESI)
ISSN (Online): 2319 – 6734, ISSN (Print): 2319 – 6726
www.ijesi.org ||Volume 8 Issue 02 Series. I || Feb 2019 || *PP 34-40*

A Critical Review on Mitigation of Alkali-Silica Reaction in Concrete

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Abstract: *The biggest problem with concrete is its deterioration over time and there are various factors responsible for this. One of the major reason for the deterioration of concrete is alkali-silica reaction (ASR). ASR is a reaction that takes place between alkali of the cement and silica of reactive aggregates and when this reaction comes in contact with water it expands and therefore leads to cracks in the concrete structure. This review paper discuss about different tests, materials and methods available to reduce the effect of alkali-silica reaction (ASR) in concrete. Researchers used various materials in concrete to reduce the effect of ASR such as fly ash, rice husk ash, metakaolin, glass fibers and glass powder as supplementary cementitious materials (SCM's). Studies showed that these materials are very effective in mitigating the alkali-silica reaction (ASR). Mitigation of alkali-silica reaction (ASR) can also be checked by changing the grading of aggregates either towards finer side or coarser side from the standard grading. Alkali-silica reaction (ASR) expansion was also reduced by different types of fine light weight aggregates (FLWA's) such as expanded shale, expanded slate and clay in concrete.*
Keyword: *ASR, Concrete,FLAW's,Grading, SCM's.*

Date of Submission: 24-01-2019 Date of acceptance: 08-02-2019

I. Introduction

Concrete is the most widely used construction material in the world. There are various reasons behind the popularity of concrete as the first choice of building material, such as durability, low relative cost, low maintenance and high fire resistance[1]. However, exposure to an aggressive environmental condition for an extended period of time can cause deterioration of concrete. The lifespan of concrete can be reduced by various factors, such as reinforcement corrosion, alkali-silica reaction (ASR), carbonation and leaching [1]. Among all the concrete damage mechanisms, ASR is one of the severe durability related issues that may cause extensive damage to concrete structures [2-11].

The alkali–silica reaction (ASR), more commonly known as "concrete cancer" [12], is a swelling reaction that occurs over time in concrete between the highly alkaline cement paste and the reactive non-crystalline (amorphous) silica found in aggregates, in the presence of sufficient moisture [13].
The ASR mechanism consists of three major stages of chemical reaction as shown inEqs. (1)– (3)[1].

$$\equiv \mathrm{Si-O-Si+OH+\ R^{+}\ \rightarrow \equiv Si-O-R+H-O-Si\ \equiv} \quad (1)$$

$$\equiv \mathrm{Si-O-H+OH^{-}+R^{+}\rightarrow \equiv Si-O-R+H_2O} \quad (2)$$

$$\equiv \mathrm{Si-O-R+nH_2O\ \rightarrow \equiv Si-O^{-}-(H_2O)_n+R^{+}} \quad (3)$$

At the initial stage of ASR, the hydroxyl ions undergo reaction with Si-O-Si bonds of amorphous silica to produce silicic acid (Si-OH) and alkali silicate (Si-O-R), where $\mathrm{R^{+}}$ represents the alkali metal ions. Then the silicic acid reacts with the hydroxyl ions ($\mathrm{OH^{-}}$) and metal alkali that forms alkali silicate hydrate by liberating water. Finally, the expansion occurs due to hydration of the alkali silicate gel [1]. Later, the hydrated alkali-silicate gel gets defused from aggregate to cement paste and undergoes reaction with the calcium ions $\mathrm{Ca^{2+}}$. This generates alkali-calcium-silicate hydrate gel. These products absorb moisture from the surroundings and expand in volume. Excessive expansion can cause cracking of aggregate and cement paste to initiate degradation of concrete [1].

The alkali silica reaction (ASR), leads to the formation of a gel. This ASR gel is considered harmless but its water absorbing property can be problematic for concrete. Gel expands in the presence of moisture and exerts pressure on the surrounding concrete leading to excessive cracking. Normally, presence of alkalis in the pore solution, reactive aggregates and moisture are considered as essential factors for ASR to initiate [14].
The proportion and the size of a particular type of reactive aggregate have also been found to largely influence the expansive behavior of ASR affected concrete, which are generally observed as pessimum effects [15-20].

The conditions required for ASR to occur are [21]:

a) A sufficiently high alkali content of the cement (or alkali from other sources)
b) A reactive aggregate
c) Water - ASR will not occur if there is no available water in the concrete, since alkali-silica gel formation requires water.

II. Test Method to Evaluate Alkali-Silica Reaction (ASR)

There are a number of standard test methods to evaluate the potential reactivity of aggregates and aggregate-cement combinations that have been developed over the years since its discovery by Stanton(1940) [22].These methods include chemical tests, microscopic, visual examination and tests for cementitious materials-aggregate combinations in mortar or concrete.

2.1 Mortar Bar Test (MBT)

To determine whether an aggregate is potentially reactive or not, ASTM C1260[23], standard test method for potential alkali reactivity of aggregates (Mortar-Bar Method) is often used as a screening test. A similar test, ASTM C1567[24], standard test method for determining the potential alkali-silica reactivity of combinations of cementitious materials and aggregate (Accelerated Mortar-Bar Method), is used to evaluate the efficacy of mitigation using hydraulic cement and supplementary cementitious materials (SCM) combinations. In the ASTM C1260/C1567/accelerated mortar bar test (AMBT), aggregate with a specified gradation is used in making 25 mm × 25 mm × 285 mm (1 in. × 1 in. × 11.25 in.) mortar bars that are cured for 48 hours, and then stored in a 1M NaOH solution at 80°C (176°F). In ASTM C1260 [23] testing, bars that expand in this harsh environment by more than 0.20% after 14 days of soaking are considered to be made with aggregates that are potentially ASR-reactive. Bars that expand between 0.10% and 0.20% include aggregates that are known to be both innocuous and deleterious in field performance.Expansions of less than 0.10% at 14 days are generally indicative of innocuous aggregate, using ASTM C1260 [23], or of effective mitigation using ASTM C1567 [24].

2.2 Concrete Prism Test (CPT)

ASTM C1293[25], standard test method for determination of length change of concrete due to alkali-silica reaction (also known as the concrete prism test or CPT), to be the best test method for evaluating deleterious ASR potential in terms of providing the strongest correlation to field performance. During the testing method, samples are exposed at 38º C at 95% RH for a period of 1 year [25].However, ASTM C1293 [25] takes 1 year to perform when evaluating aggregate reactivity, or 2 years when evaluating the efficacy of SCMs to mitigate deleterious expansion. The expansion value for CPT is 0.04%, if the expansion goes above that means there are reactive aggregates available to induce ASR expansion and if it is below 0.04% than it could be concluded that ASR expansion has not taken place. In addition, ASTM C1293 [25] suggests that if an aggregate exhibited expansion exceeding the allowable limit in AMBT but the expansion was lower than the allowable limit in CPT, the aggregate can be used in concrete constructions.

2.3 Scanning Electron Microscopy Test (SEM)

Scanning Electron Microscopy (SEM) is a test process that scans a sample with an electron beam to produce a magnified image for analysis. The method is also known as SEM analysis and SEM microscopy, and is used very effectively in microanalysis and failure analysis of solid inorganic materials. Electron microscopy is performed at high magnifications, generates high-resolution images and precisely measures very small features and objects.

Scanning Electron Microscopy uses a focused beam of high-energy electrons to generate a variety of signals at the surface of solid specimens. In most SEM microscopy applications, data is collected over a selected area of the surface of the sample and a two-dimensional image is generated that displays spatial variations in properties including chemical characterization, texture and orientation of materials. The SEM is also capable of performing analyses of selected point locations on the sample. This approach is especially useful in qualitatively or semi-quantitatively determining chemical compositions, crystalline structure and crystal orientations.
This test is very useful for determining the cracks present in the concrete specimen, and also the amount of ASR gel forming in the microstructure of the concrete.

2.4 X-ray diffraction test (XRD)

The X-ray diffraction test (XRD) is a technique used to determine the crystalline phases present in the concrete such as calcium hydroxide (Portlandite). This technique is also being extended to determine the early hydration reactions of cement. However, the identification of cement phases present in concrete is more complicated because hydration phases of concrete are mostly amorphous, which results in weak diffraction peaks. In addition, the peaks from aggregate minerals may also interfere in XRD analysis of concrete.

III. Different Measures To Reduce The Effect Of Alkali-Silica Reaction (ASR)

There are various methods and materials available to reduce the effect of ASR in concrete, which have been studied by various researchers [26-35] such as:

3.1 Materials

3.1.1 Fly Ash (FA)

Various studies have been carried out for the mitigation of ASR using the fly ash in different forms and percentages as Supplementary Cementitious Materials(SCM) in the concrete[1, 36-38].

Shi et al. 2018 [36]found the optimum proportion of fly ash required as SCM to mitigate alkali-silica reaction (ASR). Study represented that fly ash was capable to bring the expansion below the specified limit of 0.1% as given by ASTM C1260 [23] after 14 days of exposer.The optimum proportion of fly ash was found to be 30% [36].Up to this proportion the alkali-silica reaction (ASR) expansion decreased and above this proportion the ASR expansion begin to rise again.It concluded that replacement level of fly ash should not go above 30%to reduce ASR expansion [36].

Turk et al. 2017 [37]presented the effect of F-Class fly ash as supplementary cementitious materials (SCM) to reduce the alkali-silica reaction (ASR)in concrete. The bars containing 10%, 20% and 30% fly ash (FA) showed reduced expansion of 4%, 11% and 15% compared to that of control mix at 14 days expansion [37]. It was evident thatwith increase in FA content the ASR expansiondecreased.Scanning electron microscopic (SEM) images of mortar barsindicated that number of cracks in the bars decreased with the increase in concentration of fly ash (FA), and cracks were not even noticeable at higher magnification [37]. Therefore as the content of FA increased, the cracking due to ASR decreased. Replacement of 30% of Portland cement with F-class fly ash had better performance on limiting alkali-silica reaction (ASR) expansion for 14 days compared to other mortars with binary blends of F-class fly ash.

Shehata et al. 2000 [38] demonstrated the effect on alkali-silica reaction (ASR) expansion by using different types of fly ash (FA) and reactive aggregates. A total of 18 different types of fly ashes were used and 42 mixes were cast using various replacement levels. Concrete prism test (CPT) was used according to ASTM C1293 [25] for determine the expansion of the samples incorporating fly ashes at different replacement levels [38]. High calcium fly ashes reduced the expansion compared to the control [38], but it was not sufficient to prevent the damages that were caused due to expansion.It was concluded that all the fly ashes reduced the expansion of concrete prisms [25] compared with control concretes [38].In all cases, as the level of replacement of fly ash increased,the expansion due to ASR reduced. For reducing the expansion to < 0.04% at 2 years certain amount of fly ash replacement was required. That amount of fly ash replacement increased with the increase of calcium or alkali content in fly ashand decreased with decrease of silica content in fly ash [38].The variation in performance of different fly ashes was dependent on pore solution analysis which means the fly ashes that brought down the level of alkalinity in pore solution were also capable to reduce the effect of alkali-silica reaction (ASR) expansion [38].

In addition to that the studies also suggest the dosage of class C fly ash to be 50% to mitigate ASR expansion [39-45].

3.1.2 Metakaolin (MK)

Metakaolin is also considered as Supplementary Cementitious Materials (SCM) along with fly ash (FA) for the mitigation of alkali-silica reaction (ASR) expansion in the concrete [36, 46].

Shi et al. 2018 [36]showed that mortars containing MK decreased the expansion with increased amount of metakaolin (MK). Results showed that MK was more effective in mitigating ASR than fly ash when the replacement levels were at 10%. The case was not same when it reached 30% replacement level [36]. Similarly, the mass gain of the mortars decreased with the increased amount of metakaolin.This was similar to trend observed for ASR expansion as the expansion was completely suppressed when the slag was replaced by 70% MK.

Reddy et al. 2018 [46]used metakaolin, fly ash and brick powder (BP) as partial replacement from 0-20% by weight of cement. Compressive strength of the samples increased up to 10% of combined replacement for 7 and 28 days [46].Ultrasonic pulse velocity (UPV)manifested the results to be in excellent category for both individual MK and combined replacement. This demonstrated that there were less cracks in the concrete structure due to mitigation of ASR [46]. The resultsshowed that the 10% replacement with MK was most optimum replacement as it enhances the concrete's compressive strength at all ages. Therefore it can be concluded that other than mitigating ASR, metakaolin (MK) can also improve the basic quality of concrete.

3.1.3Rice Husk Ash (RHA)

Rice Husk ash is available in abundance at places where there are power plants. These power plants use rice husk as the fuel, after it burns about 20% of this is converted to the RHA [14].These ashes are then dumped at power plants in millions of units and not being used for any other purpose causing environmental pollution. From the various studies it has been found that RHA can be used as supplementary cementitious material(SCM) in concrete to mitigate alkali-silica reaction (ASR) [14, 26, 47].

Le et al. 2018 [47] used different sizes of rice husk ash (RHA) such as 5.7µm, 7.7µm and 15.6µm. The study said that finer RHA (5.7µm) had higher pozzolanic activity than the coarser one (15.6µm). Since the finer RHA containing mortar bars exhibited better refinement of pores than the coarser RHA modified bars [47].Therefore the finer RHA was better at reducing the effect of ASR on concrete than the coarser RHA.

Ahsan et al. 2018 [26]used different percentages (0, 10 and 20%) of three rice husk ash (RHA) samples of nominal sizes 600µm (RHA-1), 150µm (RHA-2) and 44µm (RHA-3).Class C fly ash was also incorporated for comparative analysis with RHA modified concrete specimen [26]. Expansion of the control mix was found within the range of 0.1–0.2%, indicating a possibility of the presence of reactive aggregate. RHA-1 and RHA-2 being the coarser particles exhibited higher expansion than control mix. On the other hand, RHA-3 and class C fly ash (CFA) being the finer particles were found quite effective in mitigating ASR expansion [26]. Mortar bars with 10% and 20% replacement of RHA-3 had reduced the ASR expansion as compared to control by 81% and 40% respectively. RHA-3 hadproduced sufficient C-S-H gel to react with alkali cations and thus reduced alkali to silica ratio. Therefore it concluded that44-RHA (RHA-3)was best among all three samples[26]in mitigating ASR expansion.

Abbas et al. 2017 [14]used rice husk ash (RHA) for mitigation of alkali-silica reaction (ASR) at replacement levels of 0-40% by weight of OPC. The results displayed reduction in mortar bar expansion of up to 50% compared to control specimen at a replacement level of 40%. Scanning electron microscopy (SEM) images displayed no cracks in specimen containing RHA [14]. While cracks were found in control specimen.Rice husk ash (RHA) due to its pozzolanic reaction helps in binding alkalis leading to reduced alkali content and subsequently decreased the ASR expansion.Therefore it was concluded that the optimum replacement of 40% of rice husk ash (RHA) was suitable for the reduction of alkali-silica reaction (ASR) in concrete.

3.1.4 Glass fibers and powder

Another supplementary cementitious material (SCM) which is very popularly used as partial replacement to mitigate ASR is glass powder or fibers. There are various studies supporting this claim [48-50].

Dehghan et al. 2017 [48]extracted glass fibers from waste glass fibers reinforced polymers (GFRPs). These fibershad the potential to provide some of the same benefits achieved by conventional fiber additions. The compressive strength results demonstrated maximum strength for control mix among all the samples [48].Accelerated mortar bar test (AMBT) [24]displayed that the expansion was well below the specified limits of 0.1% for all the mixes. Concrete prism test (CPT) [25] also revealed that expansion values were well below the expansion limits of 0.04% for all the mixes [48]. X-Ray diffraction test (XRD) images displayed no alkali-silica reaction (ASR) related cracking for any of the mixes. Therefore it was concluded that these fibers were able to control the effect of alkali-silica reaction (ASR) on concrete.

Guo et al. 2017 [49] observed ASR in the recycled glass mortar by using supplementary cementitious material (SCMs) like recycled glass powder and class F fly ash (CFA). For this purpose different samples were prepared.Expansion test at the end of 14 days exhibited that the samples prepared with glass powder having high alumina contentexhibited expansion values below 0.1% [49]. The microscopic study alsodisplayed that the samples having high alumina content and class F fly ashexhibited very less alkali-silica reaction (ASR) damage.Scanning electron microscopy(SEM) images revealed that ASR damage mainly happened inside the reactive glass aggregate instead of glass cement paste interface [49]. The ASR expansion cracks remained inside the glass aggregate and therefore these cracks were not harmful for concrete because of the added supplementary cementitious material(SCMs).

Dezfouli et al. 2017 [50]demonstrated the usage of ground glass fiber in mitigating the effect of alkali-silica reaction(ASR) in concrete. Three different materials such as ground glass fiber (GGF), ground bottle glass (GLP)at replacement levels of 10%, 20% and 30%, and metakaolin (MK)at replacement level of 10% and 20% were used. Strength activity index (SAI) displayed highest SAI value for metakaolin (MK) [50].Accelerated mortar bar test (AMBT) [23]at 14 days presented that only MK and GGF had expansion values below 0.1% showing mitigation of ASR. According to MCPT test the expansion value should be 0.02% at 56 days which was obtained by GGF-30 sample, exhibiting reduced ASR expansion [50]. The scanning electronic microscopy (SEM) images revealed many cracks in the mortar bar of control mix. The images of GLP-30 exhibited the formation of ASR gel within paste matrix and at the interface of glass aggregate and cement paste but it was less than the ASR gel of control mix. In the case of MK-10 and GGF-30 samples, SEM images displayed no cracks and no formation of alkali-silica reaction (ASR) gel. Therefore it was concluded that using GGF at 30% replacement level can successfully be used to mitigate the effect of ASR in concrete.

3.2 Method:

3.2.1 Aggregate Grading and types of Aggregate

Generally for the reduction of alkali-silica reaction (ASR) various supplementary cementitious materials (SCM's) are being used in the concrete and they are most likely successful in reducing ASR effect [50]. There can be other methods to reduce the ASR by either changing the grades of aggregates for concrete preparationor by usingdifferent types of aggregates [51, 52].

Gautam et al. 2017 [51]in the study demonstrated effect of deviation ofcoarse aggregate grading on the alkali-silica reaction (ASR). Three grading i) standard grading (mix S) ii) a fine dominant grading having 10% more of finer fraction and 10% less of coarser fraction than standard (mix F) iii) a coarse dominant grading having 10% less of finer fraction and 10% more of coarser fraction than standard (mix C) were used [51]. Expansion results in the studyexhibited that mix F had greater expansion than mix S by approx. 50% at all ages. The expansion of mix C was greater than mix S by 2-15%. It was suggested that the alkali-silica reaction (ASR) expansion of the concrete having grading other than the control grading washigh. After the initiation of ASR the values of modulus of elasticity decreased for the all the three mixes i.e., mix F, C and S [51]. Any deviation in grading of coarse aggregate even by 10% towards finer size resulted in 50% deviation in expansion measurement compared to standard mix. DRI resultsdemonstrated that any deviation from standard grading increases the damage due to alkali-silica reaction (ASR) [51].

Li et al. 2017 [52]used three types of fine light weight aggregates (FLWAs) such as expanded slate, shale and clay for the mitigation of alkali-silica reaction (ASR). The accelerated mortar bar test(AMBT) [24] and concrete prism test(CPT) [25] resultsdemonstrated that expanded clay was most effective in reducing the expansion caused by ASR [52]. Pore solution analysisdisplayed that FLWAs especially expanded shale and clay can reduce the alkalinity and increase aluminum content in pore solution. Which will reduce alkali content available for ASR reaction [52]. Scanning electron microscopy (SEM) analysis revealed that infilling reaction products formed in the pores of FLWAs. These products reduced the cracks developed due to ASR.

IV. Concluding Remark

The studies suggested thatalkali-silica reaction (ASR) can be mitigated using various supplementary cementitious materials and by changing aggregates grading or types, the following concluding remarks can be drawn from the studies reported by several researchers [14, 26, 36-38, 46-52]:

1) The study showing inclusion of fly ash gave us the optimum amount which was 30% for low calcium fly ash and F-class fly ash. Up to which all the parameters leading to alkali-silica reaction (ASR) decreased but above that those parameters started to increase back. While using different types of fly ashes, the replacement level was dependent on pore solution analysis but all the fly ashes were capable in reducing alkali-silica reaction (ASR).Therefore fly ash can be used as partial replacement but only up to some replacement levels.
2) The usage of metakaolingave the optimum dosage required to mitigate alkali-silica reaction (ASR) which was at 10% replacement level. Along with reducing alkali-silica reaction (ASR) it also helped in maintaining the strength of concrete in specified limits and also kept the value of expansion well below limits.
3) The inclusion of rice husk ash showed the mitigation of alkali-silica reaction (ASR) for a replacement level of 40% and more effective results were obtained with incorporating of fine rice husk ash in the concrete. Class C fly ash along with rice husk ash also showed a positive effect on mitigating alkali-silica reaction (ASR) from the concrete.
4) The inclusion of glass powder or fibers were proved to be helpful in mitigating the effect of alkali-silica reaction (ASR), and not only the virgin fibers but even the fibers collected from waste glass fibers were capable in mitigating the alkali-silica reaction (ASR) in concrete.
5) The change in grading of aggregate showed that any deviation from standard grading either towards finer side or coarser side increased the expansion by 50%. Using fine light weight aggregates such as expanded slate, shale and clay also reduced the effect of alkali-silica reaction (ASR) in concrete.

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Hardik S Parmar" A Critical Review on Mitigation of Alkali-Silica Reaction in Concrete" International Journal Of Engineering Science Invention (Ijesi), Vol. 08, No. 02, 2019, Pp 34-40