

Correlation of Alkali Silica Reaction with Petrographic Examination

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Abstract—The alkali-silica reaction, more commonly known as "concrete cancer", 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 many common aggregates in the presence of sufficient moisture.

This reaction causes the expansion of the altered aggregate by the formation of a soluble and viscous gel of sodium silicate [$\text{Na}_2\text{SiO}_3 \cdot n \text{H}_2\text{O}$, or $\text{Na}_2\text{H}_2\text{SiO}_4 \cdot n \text{H}_2\text{O}$, or N-S-H (sodium silicate hydrate)]. This hygroscopic gel swells and increases in volume after absorbing water, it exerts an expansive pressure inside the siliceous aggregate, causing spalling and loss of strength of the concrete, finally leading to its failure.

ASR can lead to serious cracking in concrete, resulting in critical structural problems that can even force the demolition of a particular structure. The expansion of concrete through reaction between cement and aggregates was first studied by Thomas E. Stanton in California during the 1930s with his founding publication in 1940.

In many parts of the world, precautions must be taken to avoid excessive expansion due to alkali-aggregate reactivity (AAR) in many types of concrete construction. AAR may involve siliceous aggregates (alkali-silica reactivity, ASR) or carbonate aggregates (alkali-carbonate reactivity, ACR) and failure to take precautions may result in progressive deterioration, requiring costly repair and rehabilitation of concrete structures to maintain their intended function.

The correlation between the results of ASR and petrographic examination has been presented in this paper.

Keywords: Alkali silica reaction, distress, petrographic examination, alkali carbonate reaction, siliceous aggregate, carbonate aggregate, hygroscopic gel, concrete cancer.

I. INTRODUCTION

Alkali-silica reactivity (ASR) was first recognized in concrete pavement in California by Stanton in 1940 & 1942. Stanton's early laboratory work demonstrated that expansion and cracking resulted when certain combinations of high alkali cement and aggregate were combined in mortar bars stored in containers at very high relative humidity. Two important conclusions were drawn from his work. First, expansions resulting from ASR in damp mortar bars were negligible when alkali levels in cement were less than 0.60 percent expressed as equivalent sodium oxide (percent $\text{Na}_2\text{O}_e = \text{percent Na}_2\text{O} + 0.658 \times \text{percent K}_2\text{O}$). A second conclusion was that the partial replacement of high alkali cement with a suitable pozzolanic material prevented

excessive expansions. Based on Stanton's work, Meissner in 1941 in the U.S. Bureau of Reclamation conducted investigations of abnormal cracking in concrete dams. Meissner's findings generally corroborated those of Stanton and lent further credence to the importance of cement alkali level, aggregate composition and environmental requirements in the development of expansion due to ASR.

Alkali-carbonate reactivity (ACR) was identified as causing a type of progressive deterioration of carbonate by Swenson in 1957 in Canada. He found that an alkali-carbonate reaction had developed in concrete containing argillaceous calcitic dolomite aggregate that appeared to be different than the alkali-silica reaction.

II. MANIFESTATIONS OF DISTRESS DUE TO ALKALI-SILICA REACTIVITY

The most evident manifestations of deleterious ASR in a concrete structure are concrete cracking, displacement of structural members due to internal expansion of the concrete. Cracking in concrete is essentially the result of the presence of excessive tensile stress within the concrete, which can be caused by external forces such as load, or by development of a differential volume change within the concrete. Early contraction, too large thermal gradients during curing of the concrete, corrosion of embedded reinforcement, freezing & thawing and internal & external sulfate attack are some of the mechanism that also can lead to the formation of cracks in concrete.

Diagnosing ASR-related cracking requires the additional identification of ASR reaction product in the concrete and most importantly requires positive indications that this product has led to the generation of tensile stresses sufficiently large that the tensile strength of the concrete was exceeded. Figure 1 is a sketch of the surface and a cross section of a concrete slab undergoing ASR. These cracks tend to occur in a polygonal pattern that is the basis for the term map-cracking.

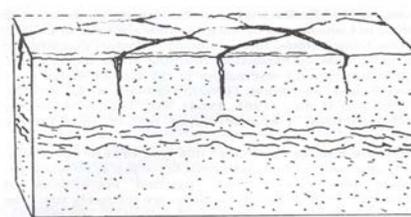


Figure 1: Sketch showing typical features of surface map-cracking and sub-parallel cracks in concrete with ASR. Stresses due to ASR grades from horizontal tension near the surface to horizontal compression and vertical tensions with depth

III. ALKALI SILICA REACTIVITY MECHANISMS

Three basic conditions must exist for ASR to proceed in concrete. These conditions include high pH, moisture and reactive silica. The rate of the reaction is influenced by the temperature.

Cement alkali levels - Early investigators recognized that the alkali content of portland cement had a direct influence on potential expansion. The two alkali constituents are reported from chemical analysis as sodium and potassium oxide. A limit of 0.60 percent on the Na₂O equivalent alkali content of portland cement has been made in the IS code to minimize the deterioration of concrete when reactive aggregates are used.

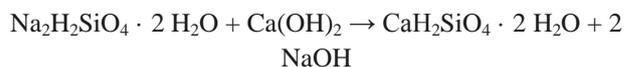
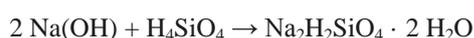
Moisture - Moisture must be available for ASR to proceed and below about 80 percent internal relative humidity, the reaction will cease. For ordinary concrete, some portion of the original mixing water is usually available for a long period even in the dry service conditions. However, for low water to cementitious ratio mixtures the water may be used up by hydration of cement.

Reactive Silica - Researchers first believed there was a limited group of susceptible aggregate constituents such as opal, chert containing chalcedony and some glassy volcanic rocks. It is now recognized that ASR can occur with a wider range of siliceous aggregate constituents. Various other metastable forms of silica can be involved. Reactivity depends not only on the mineralogy but also on the mechanics of formation of the aggregate material and the degree of deformation of quartz.

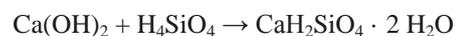
Temperature - As temperature increases, the rate of ASR increases. With given concrete materials and proportions, the reaction will take place more rapidly under warmer conditions. While this factor has not been quantified, it should be kept in mind when considering approaches to prevent ASR.

ASR by NaOH or KOH

The ASR reaction significantly differs from the pozzolanic reaction by the fact that it is catalysed by soluble alkali hydroxides (NaOH / KOH) at very high pH. It can be represented as follows using the classical geochemical notation for fully hydrated dissolved silica (Si(OH)₄ or silicic acid: H₄SiO₄), but an older industrial notation also exists (H₂SiO₃, hemihydrated silica (does not exist), by analogy with carbonic acid):



The sum, or the combination, of the two above mentioned reactions gives a general reaction resembling the pozzolanic reaction, but it is important to keep in mind that this reaction is catalysed by the undesirable presence in cement, or other concrete components, of soluble alkaline hydroxydes (NaOH / KOH) responsible for the dissolution of the silicic acid at high pH:



Without the presence of NaOH or KOH responsible for a high pH (~13.5), the amorphous silica would not be dissolved and the reaction would not evolve. Moreover, the soluble sodium or potassium silicate is very hygroscopic and swells when it absorbs water. When the sodium silicate gel forms and swells inside a porous siliceous aggregate, it first expands and occupies the free porosity. When this latter is completely filled, if the soluble but very viscous gel cannot be easily expelled from the silica network, the hydraulic pressure raises inside the attacked aggregate and leads to its fracture. It is the hydro-mechanical expansion of the damaged siliceous aggregate surrounded by calcium-rich hardened cement paste which is responsible for the development of a network of cracks in concrete. When the sodium silicate expelled from the aggregate encounters grains of portlandite present in the hardened cement paste, an exchange between sodium and calcium cations occurs and hydrated calcium silicate (C-S-H) precipitates with a concomitant release of NaOH. In its turn, the regenerated NaOH can react with the amorphous silica aggregate leading to an increased production of soluble sodium silicate. When a continuous rim of C-S-H completely envelops the external surface of the attacked siliceous aggregate, it behaves as a semi-permeable barrier and hinders the expulsion of the viscous sodium silicate while allowing the NaOH / KOH to diffuse from the hardened cement paste inside the aggregate. This selective barrier of C-S-H contributes to increase the hydraulic pressure inside the aggregate and aggravates the cracking process. It is the expansion of the aggregates which damages concrete in the alkali-silica reaction.

Portlandite (Ca(OH)₂) represents the reserve of OH⁻ anions in the solid phase. As long as portlandite, or the siliceous aggregates, has not become completely exhausted, the ASR reaction will continue. The alkali hydroxides are continuously regenerated by the reaction of the sodium silicate with portlandite and thus represent the transmission belt of the ASR reaction driving it to completeness. It is thus impossible to interrupt the ASR reaction. The only way to avoid ASR in the presence of siliceous aggregates and water is to maintain the concentration of soluble alkali (NaOH and KOH) at the lowest possible level in concrete, so that the catalysis mechanism becomes negligible.

IV. PERTOGRAPHY OF ALKALI-SILICA REACTIVE AGGREGATE

The alkali-silica reactive aggregate constituents can be classified in two broad categories: 1) naturally occurring forms of essentially pure silica, into which minerals, mineraloids and volcanic glasses are grouped and 2) synthetic or artificial siliceous materials. The reactivity of an aggregate depends on the composition, geologic origin and textural characteristics of the rocks from which the aggregate is derived.

Potentially Reactive Natural Silica Constituents

Opal – Opal either alone or as a component in a rock is probably the most alkali-silica reactive natural material. As per ASTM C 294, opal is a hydrous form of silica ($\text{SiO}_2 \cdot n\text{H}_2\text{O}$) that occurs without characteristic form or internal crystalline arrangement.

Chalcedony–As per ASTM C 294, Chalcedony is a fibrous, microcrystalline form of silica. Chalcedony has been considered both as a distinct mineral and a variety of quartz. It occurs in massive form as cavity fillings, cementing material and replacement material for fossils. It is often a major constituent for chert.

Quartz–Coarse megascopically-crystalline quartz is normally not reactive. However, there have been indications that megascopic unstrained (undeformed) quartz may with certain irregularities or of inclusions present be slowly reactive and expansive over a sufficient period of time under alkaline condition. Highly fractured quartz in quartzite and gneisses and strained quartz are alkali reactive.

Volcanic Glasses–Volcanic glasses occur in virtually all volcanic rocks. Igneous rocks are described as acidic if they contain more than 66% silica, intermediate when silica contents range from 52 to 66% and basic when silica contents are less than 52%. Acid and intermediate glasses tend to be alkali reactive with reactivity decreasing as the amount of silica decreases. Thus, high silica glasses of rhyolites, dacites and andesites are more reactive while basaltic glasses are less reactive.

Chert–Chert is a general term applied to variously coloured, fine grained siliceous rocks composed of microcrystalline or cryptocrystalline quartz, chalcedony, opal or mixtures of these constituents. Cherts can be dense or porous and chalky. Most cherts are alkali-silica reactive. The degree of reactivity is dependent on several factors including the mineralogic composition and internal structure of the chert, the amount of reactive chert relative to that of the total aggregate and the particle size distribution.

Volcanic Rocks – Acidic and intermediate volcanic rocks that are alkali-silica reactive include some rhyolites, dacites,

latites and andesites. The reactivity of these rocks can be attributed to the texture and composition of glassy or partially glassy ground mass. Some basic volcanic glasses and rocks are also alkali-silica reactive. Basalts containing highly siliceous interstitial glasses are slowly alkali-silica reactive and produce the expansion and map cracking typical of ASR in concrete.

V. MEASURES TO PREVENT ALKALI SILICA REACTIVITY

ASR and subsequent expansion of concrete occur only when the following conditions are present:

- Concrete is sufficiently moist in service.
- Concrete contains aggregates with siliceous constituents that are alkali-silica reactive. These constituents may include inter-layer silicate minerals, which may cause expansion in some cases, by react at a slower rate.
- A source of sufficient alkalis, i.e. sodium and potassium, is available that can
- Raise the pH of the pore fluid by allowing more hydroxyl ions to remain in solution, and
- React with the dissolved silica to form alkali silica gel

Strategies to prevent ASR expansion focus on controlling one or more of the three preceding conditions, that is:

- Control the available moisture
- Control the type and amount of potentially reactive siliceous constituents in the aggregate or in the concrete
- Lower the pH of the concrete pore fluid in order to decrease the solubility of the silica in the pore fluid.

VI. METHODS TO EVALUATE POTENTIAL FOR EXPANSIVE ALKALI-SILICA REACTIVITY

Several information research papers have been published on methods to evaluate the potential deleterious ASR. Standard organizations such as ASTM and BIS supply detailed methodologies for evaluating potential ASR of aggregates, concrete and cement-aggregate combinations.

Common Tests to Evaluate Potential Alkali-Silica Reactivity of Aggregates

Several tests are commonly used to evaluate whether an aggregate or cement-aggregate combination is potentially deleterious alkali-reactive. These tests are usually done to pre-screen new aggregate sources before use as concrete aggregate.

Petrographic Examination of Aggregate

Potentially reactive components of an aggregate can be identified and quantified through petrographic examination. A petrographic examination can be done on samples from

undeveloped quarries, operating quarries, undeveloped sand & gravel deposits and operating sand and gravel deposits. The petrographic examination is a useful screening procedure that can be done early in the development and testing of a new aggregate source and as a periodic check of operating deposits to verify consistency of composition. The petrographic examination shows that siliceous rock types that contain more than 20% strained quartz having an undulatory extinction angle (an optical property indicating deformed crystals) greater than 15 degrees, then the aggregate is considered potentially reactive and is to be tested for deleterious expansion as per IS: 383-2016.

Mortar-Bar Expansion Test

One of the most commonly used tests to determine whether a cement-aggregate combination is potentially alkali-silica reactive is the mortar-bar expansion test described in detail in ASTM C 227. An average length change (for three mortar bars) greater than 0.05% at 3 months and greater than 0.10% at 6 months is considered to be excessive and indicative of potentially deleterious ASR. Specimens exhibiting expansions greater than 0.05% at 3 months but less than 0.10% at 6 months are not considered to be deleterious expansive by ASTM C 33. This test is considered an accurate indicator of a highly reactive siliceous aggregate's potential for deleterious reactivity with alkalis in concrete.

Accelerated Mortar-Bar Expansion Test

This test is modification of ASTM C 227. As the bar size is smaller, the aggregate sizes are different than the mortar-bar expansion test. The test conditions are more severe than most field service environments. After 22days, if the average expansion is less than or equal to 0.10%, the cement-aggregate combination is considered non-reactive. If the average expansion is greater than 0.10%, the aggregate is considered deleteriously reactive. The accelerated mortar-bar test is quick, reliable and can characterize the potential reactivity of slowly as well as rapidly reactive rock types.

Concrete Prism Test

The concrete prism test is similar to the mortar bar expansion test, except that it uses concrete prism rather than mortar bars and alkali is added to the fresh concrete mixture to reach a certain level within the concrete. The prism test has been adopted as ASTM C 1293, IS: 2386-1963 (Part VII a) and CSA A23.2-14A.

The criteria for expansions are 0.03% at 6 months and 0.04% at one year. If the expansion is more the aggregate is considered to be potentially deleterious. In critical structure such as those used for nuclear containment or large dams, a lower expansion limit may be required.

VII. TESTING PROGRAMME

The coarse aggregate from different hydro electric projects have been tested by accelerated mortar bar expansion test and also petrographic examination of all samples have been conducted.

VIII. RESULTS AND DISCUSSIONS

The results of six coarse aggregate samples from different hydro electric projects have been presented in figures 2 & 3.

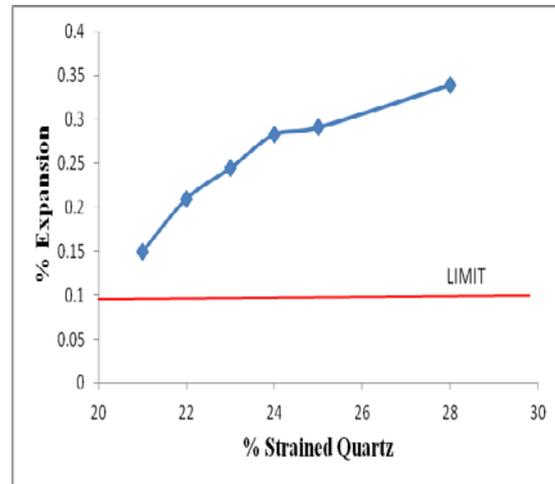


Figure 2: Relation of % Expansion with % Strained Quartz

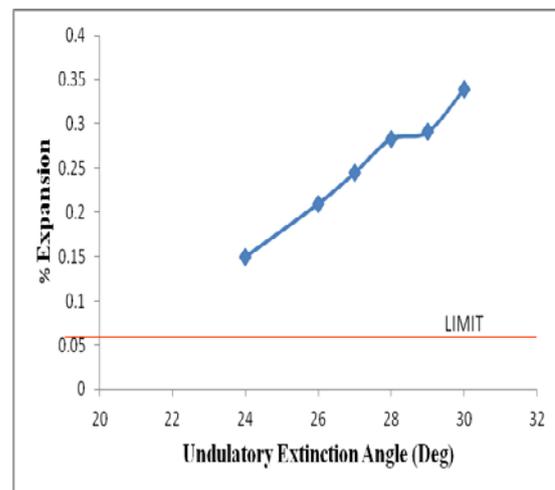


Figure 3: Relation of % Expansion with Undulatory Extinction Angle

IX. CONCLUSIONS

Alkali-aggregate reaction causes significant damage to concrete structures worldwide. This harmful reaction can occur if the alkali content of the cement and the aggregate are high and enough moisture is present to sustain the reaction. Under some conditions, the reaction may result in slow but progressive expansion and cracking of the concrete.

From the study, it can be revealed that % expansion of concrete bar due to AAR has definite relation with the results of petrographic examination i.e. % strained quartz and undulatory extinction angle. It can be concluded that

petrographic examination, being faster than AAR tests, can reveal the expansion behaviour of the coarse aggregates.

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