

## Microscopic and Chemical Methods of Diagnosis of Alkali-Aggregate Reactions in Concrete

[Extracted from PCA R&D Serial No. 2071b By James A. Farny and Beatrix Kerkhoff, [http://www.cement.org/docs/default-source/fc\\_concrete\\_technology/is413-02---diagnosis-and-control-of-alkali-aggregate-reactions-in-concrete.pdf](http://www.cement.org/docs/default-source/fc_concrete_technology/is413-02---diagnosis-and-control-of-alkali-aggregate-reactions-in-concrete.pdf)]

### 1.0 Introduction

Aggregates containing certain constituents can react with alkali hydroxides in concrete. The reactivity is potentially harmful only when it produces significant expansion. This alkali-aggregate reactivity (AAR) has two forms—alkali-silica reaction (ASR) and alkali-carbonate reaction (ACR, sometimes called alkali-carbonate rock reaction, or ACRR). ASR is more often a concern than ACR because the occurrence of aggregates containing reactive silica minerals is more common. Alkali-reactive carbonate aggregates have a specific composition that is not very common.

Alkali-silica reactivity has been recognized as a potential source of distress in concrete since the late 1930s. Even though potentially reactive aggregates exist throughout the country, ASR distress in structural concrete is not common. There are a number of reasons for this:

- Most aggregates are chemically stable in hydraulic-cement concrete.
- Aggregates with good service records are abundant in many areas.
- The concrete in service is dry enough to inhibit ASR.
- The use of certain pozzolans or ground granulated blast-furnace slags controls ASR.
- In many concrete mixtures, the alkali content of the concrete is low enough to control harmful ASR.
- Some forms of ASR do not produce significant deleterious expansion.

Concrete deterioration caused by alkali-aggregate reaction is generally slow, but progressive. Cracking due to alkali aggregate reaction generally becomes visible when concrete is 5 to 10 years old. The cracks facilitate the entry of deleterious substances solutions that may cause corrosion of the reinforcing steel, thereby accelerating deterioration and weakening a structure.

### 2.0 Alkali-Silica Reaction

#### 2.1 Mechanism of ASR

Concrete consists of aggregates—stone or gravel and sand, in a matrix of cement paste. The cement paste contains interconnected microscopic pores through which water or ions in solution can migrate. The pore water in concrete is an alkaline solution; the measure of alkalinity is pH. The alkali-silica reaction forms a gel (Fig. 1) that swells as it draws water from the surrounding cement paste.

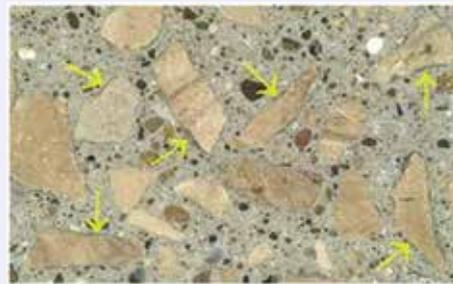


Fig. 1: The gel formation around the aggregates

Reaction products from ASR have a great affinity for moisture. In absorbing water, these gels can induce pressure, expansion, and cracking of the aggregate and surrounding paste. The reaction can be visualized as a two-step process:

- Alkali + reactive silica → alkali-silica gel
- Alkali-silica gel + moisture → expansion

The presence of gel does not necessarily indicate destructive ASR. Some gels expand very little or not at all. If a gel is low swelling, it will not create problems. High-swelling gel may cause pressures exceeding the tensile strength of concrete, which results in cracking of the concrete. Rate of migration of pore fluids to the reaction site and temperature also influence swelling pressures. Consequently, the presence of gel must be linked to destructive cracking for a positive identification of harmful expansive ASR.

#### 2.2 Factors Affecting ASR

For alkali-silica reaction to occur, three conditions must be present:

- Reactive forms of silica in the aggregate
- High-alkali (pH) pore solution
- Sufficient moisture

The amount of gel formed in the concrete depends on the amount and type of reactive silica, and the alkali hydroxide concentration in the concrete pore solution. Natural aggregates contain various forms of silica minerals, which have varying reactivities—measures of the readiness of the silica to react with alkali. Internal sources of alkali (sodium and potassium) can come from the cement, pozzolans, aggregates, admixtures, and mix water. When the alkali and silica react, they form the gel reaction product. External alkalies can come from a number of sources, but the predominant source is anti-icing or deicing chemicals. Exact composition will vary, but the gel always contains alkali, calcium, silica, and water.

##### 2.2.1 Reactive Silica in the Aggregate

Reactivity is a function of the type and form of constituents composing the aggregate. Silica minerals in aggregates are generally stable if crystalline and

reactive if amorphous, but there are exceptions. For instance, there are a few common crystalline forms of silicon dioxide: quartz, tridymite, and cristobalite. Quartz, unless it is microcrystalline or highly strained, is stable. Tridymite and cristobalite are crystalline also, but are low density, porous materials, and are susceptible to attack from alkali hydroxides. An aggregate that presents a large surface area for reaction—poorly crystalline, many lattice defects, amorphous, glassy, micro-porous—is susceptible to reaction.

The constituent minerals of an aggregate are obtained from a petrographic analysis. The following rock types contain critical amounts of potentially reactive forms of silica: chert and flint containing chalcedony; acidic and intermediate volcanic rocks, such as rhyolite, dacite, latite, and andesite, and the associated porphyries and tuffs; shale and slate; sandstone, siltstone, and quartzite; siliceous carbonate rocks; graywackes; argillites; phyllites; granites and granodiorites; granite and granodiorite gneisses.

The list is not all inclusive, and many aggregates listed will perform adequately in concrete that contains more than enough alkali to promote ASR. Fine and coarse aggregate containing more than the following quantities of constituents as given below are considered potentially reactive:

- Opal—more than 0.5% by mass
- Chert or chalcedony—more than 3.0%
- Tridymite or cristobalite—more than 1.0%
- Optically strained or microcrystalline quartz— more than 5.0% (as found in granites, granite gneiss, graywackes, argillites, phyllites, siltstones, and some natural sands and gravels)
- Natural volcanic glasses—more than 3.0%

## 2.2.2 High-alkali-content Pore Solution

Alkali hydroxides in solution will react readily with reactive forms of silica in aggregate. As the aggregate reactivity increases, gel reaction products can be formed with lesser concentrations of alkali. That is why use of low-alkali cements alone may not be sufficient to control ASR with highly reactive aggregates.

As the pH, or alkalinity, of the pore solution increases, potential for the alkali-silica reaction increases. At higher concentrations of alkali hydroxides, even the more stable forms of silica are susceptible to attack. If the alkali concentration is great enough, the alkali hydroxides break stronger silicon bonds found in less reactive aggregates to form the gel reaction product. This explains why aggregates thought to be nonreactive sometimes exhibit ASR.

Repeated cycles of wetting and drying can create high localized concentrations of alkalies. As moisture travels through concrete, dissolved alkalies move in solution, remaining when the moisture evaporates from the concrete

surface. This process, known as alkali migration, can cause high alkali concentrations at an evaporative surface even when the overall concrete alkali content is low.

## 2.2.3 Sufficient Moisture

Moisture allows migration of alkali ions to reaction sites, and the resulting gel absorbs moisture, leading to expansion. For this reason, deleterious ASR does not occur in concrete that are dry in service. Research has shown that expansive ASR can occur in concrete having a relative humidity above 80%. However, it is possible for well cured concrete in arid regions to have a relative humidity constantly at or above 80% just beneath its surface, even after several decades.

Any reduction in permeability, by using a low water-cement ratio, supplementary cementitious materials (SCMs), or other means, reduces movement of moisture and alkalies into and within the concrete.

It has been found that sealed lower water-cement ratio (0.35) concrete expanded less than higher water-cement ratio concrete at ages up to 19 months.

## 2.2.4 Concrete Alkali Content

The potential for ASR increases as the alkali content of concrete increases. Using field performance as a guide, alkali limits are established in concrete to control ASR.

The approach is most applicable with concrete using Portland cement as the sole cementitious material. However, it can also be applicable, with refinement, to concrete containing supplementary cementitious materials.

## 2.2.5 External Alkalies

External alkalies may increase expansion due to ASR, especially when concrete is cracked or is highly permeable. Common sources of external alkalies are seawater, groundwater, and water from industrial processes. Seawater can provide virtually unlimited amounts of alkali.

Immersing concrete prisms containing reactive aggregates in a sodium chloride solution has demonstrated increases in expansion and deterioration of the concrete, especially at elevated temperatures. There are ways to reduce the ingress of external alkalies. In addition to proper handling, placing, and curing of concrete, the use of supplementary cementitious materials and a low water-cementitious materials ratio will reduce concrete permeability, slow the entrance of external alkalies, and reduce potential ASR expansion. Protective coatings and sealers provide a barrier to seawater and other alkali sources. In some cases, regular cleaning of the structure might be worthwhile so that unwanted salts are carried away before they have a chance to enter the concrete and contribute to reaction.

## 2.2.6 Wetting and Drying

Dry exposures reduce potential for expansive cracking due to alkali-silica reactivity. Indoor concrete is usually drier than exterior concrete. Concrete that has high initial water content, however, may maintain a high internal relative humidity if not permitted to dry. High humidity can sustain the ASR reaction. It's unknown whether continuous saturation or cycles of wetting and drying cause more damage. It is known, however, that alkali migration can occur with alternate wetting and drying, concentrating alkalis near the drying zone and inducing reaction there. It is desirable to minimize both available moisture and wet-dry cycles by providing good drainage.

## 2.2.7 Temperature

Structures in warmer exposures are more susceptible to ASR than those in colder exposures because the ASR rate usually increases with increasing temperature. For the majority of aggregates, higher temperatures also mean larger ultimate expansions. However, there are studies showing that lower temperatures, 13°C and 20°C compared to 38°C, resulted in significantly larger ultimate expansions with certain aggregates. The effect of high or low temperatures on ultimate expansion is aggregate dependent, with most aggregates reacting more at higher temperatures.

## 2.3 Visual Symptoms of Expansive ASR

Harmful ASR expansion does not occur without reaction products. But reaction products can occur without harmful ASR expansion. Since ASR products have been observed in good quality undamaged concrete and the presence of reaction products does not necessarily indicate that destructive ASR is occurring, a cause-and-effect relationship must link the presence of reaction products to harmful expansion.

The British Cement Association and Soil & Materials Research Station, New Delhi outline procedure for diagnosing ASR and assessing its impact on a structure.

The procedure includes the following steps:

(a) Site inspection and testing, (b) sampling, (c) laboratory investigation, (d) evaluation, and (e) risk assessment of future reaction. Visual observation of the structure is a major component of this program.

### 2.3.1 Expansion

Typical indicators of ASR presence are longitudinal cracks, map (random pattern) cracking, and in advanced cases, closed joints, spalled concrete surfaces, or relative displacements of different portions of a structure. Because ASR deterioration is slow, the risk of catastrophic failure is low. ASR can cause serviceability problems and can exacerbate other deterioration mechanisms such as those that occur in freeze-thaw, deicer, or sulfate exposures. For

instance, a concrete pavement might experience map cracking, and with subsequent freeze-thaw damage, begin to break apart. Likewise, cracking from other mechanisms can allow an ingress of alkalis and/or moisture, which then exacerbates ASR. Some of the more serious concerns regarding in-service concrete expansion relate to hydro-electric dams. High-speed rotating equipment requires that strict tolerances be maintained between the machinery and the concrete to which it is anchored.

### 2.3.2 Cracking

Concrete deleteriously affected by expansive ASR is characterized by a network of cracks (Figs. 2 & 3). A visual inspection should note the location, length, width, apparent depth, and continuity of cracks, and whether the cracks go through or around the aggregate. Any other associations with stress directions, reinforcement, restraint conditions, or discolourations should also be made in order to accurately describe the cracking. The wide cracks are easy to see. Fine cracks aren't always visible, but they may be easier to see on a wet concrete surface that is beginning to dry.



Fig. 2: Longitudinal cracks induced by ASR in a pavement



Fig. 3: Close-up view of well developed cracking in a pavement, a typical pattern associated with ASR.

Drying occurs unevenly and provides a contrast that makes fine cracks more prominent. For this reason, some inspectors prefer to examine a concrete structure as it is drying, such as after a rainfall. Expansive ASR begins with the formation of gel either in or on a reactive aggregate particle within the concrete. As the gel absorbs water, it can exert a fairly uniform pressure up to 10 MPa or more in all directions. This pressure exceeds the tensile strength of conventional concretes, which is generally about 10% of compressive strength.

The concrete cracks in a 3- or 4-pronged star pattern.

This cracking is usually enough to relieve the pressure and accommodate the resulting volume increase. As more particles react, cracks radiating from these “stars” join with others to form a pattern resembling a map (Fig. 4).



Fig. 4: Map pattern cracking due to ASR

### 2.3.3 Pavement and Slabs on Grade

In pavements and slabs on grade, cracking from expansive ASR often begins near free edges and joints where moisture is abundant. The ASR cracks are usually perpendicular to transverse joints, and parallel to free edges along the roadside, and against asphalt pavement, where there is less restraint. These cracks often progress to a map pattern. Continuously reinforced pavements will typically have ASR cracks parallel to the reinforcement. Traffic loads aggravate crack formation.

ASR continues until the silica is depleted, until the alkali ion concentration or pH is sufficiently reduced, or until sufficient drying occurs to stem the formation and swelling of gel. The process represented by this three-step model can be temporarily or indefinitely interrupted, for instance, during periods of dry weather. However, if conditions again become conducive to ASR, the reaction will resume.

### 2.3.4 Other Structures

Observed cracking is usually most strongly developed in areas of structures where the concrete has a constantly renewable supply of moisture, such as close to the waterline in piers, from the ground behind retaining walls, beneath pavement slabs, or by wick action in piers or columns.

### 2.3.5 Surface Deposits (Efflorescence)

Deposits of ASR gel or calcium carbonate (from carbonated pore solution) can be found along cracks in concrete, leaving a deposit on the surface ranging in colour from white (Fig. 5) to dark gray. These deposits are sometimes called efflorescence (Fig. 5) or exudations.

The material exuding from the cracks can be white, yellowish, or colourless, and viscous, fluid, waxy, rubbery, or hard. Surface deposits may or may not accompany expansive ASR. However, their presence is not indicative of ASR, as other mechanisms (such as frost action) or the transmission of water through concrete can also cause efflorescence (without the presence of ASR gel). It is good investigative practice during a site survey, however, to

record the extent and location of surface deposits along with their color, texture, dampness, and hardness. A chemical analysis is also helpful to determine if ASR gel is present in the deposit.



Fig. 5: Efflorescence due to ASR patterns

### 2.3.6 Popouts

A popout (Fig. 6) is caused by a fragment breaking out of the surface of the concrete, leaving a hole that may vary in size, but is usually 25 mm to 50 mm wide. Popouts caused by sand-sized particles can be much smaller. A fractured aggregate particle can be found at the bottom of the hole. The number, size, and location of popouts provide valuable information about the quality of aggregates in a concrete. Most commonly a popout is caused by the expansion and contraction of porous aggregate during freezing and thawing cycles. Another cause of popouts is expansive ASR: popouts occur to relieve pressure created by gel formed just beneath the concrete surface. Locating gel at the site of a popout is a strong indication of ASR.



Fig. 6: Popouts due to ASR

Floor coverings may play a role in development of ASR popouts at later ages. Especially on slabs placed over wet cohesive soils, condensation can occur under the covering to develop popouts. Examination of the aggregate at the bottom of the resulting pit can usually explain the cause of the popout. The presence of ASR-induced popouts is not necessarily an indication that the concrete structure will expand and have map cracking or other signs of ASR distress.

### 2.3.7 Colour Change

Surface discolouration is common in conjunction with cracking. Darkened or blotchy areas are often associated with ASR. Areas along cracks may be bleached, pinkish, or brownish in colour, extending several millimeters from the crack.

### 2.4 Methods for Identifying ASR Distress

It is important to distinguish between the ASR reaction and damage resulting from the reaction. In the diagnosis of concrete deterioration, it is most likely that a gel product will be identified. In some cases, significant amounts of gel are formed without causing damage to concrete. It is therefore important that in analysis of deteriorated concrete, signs of distress, such as microcracks and separation of aggregate from the paste, be accurately attributed to ASR gel formation if the damage is to be associated with ASR. Other causes of distress should not be precluded. To pinpoint ASR as the cause of damage, the presence of ASR gel must be verified. However, other characteristics of the concrete should be studied, as ASR may only be a result of other concrete distress. A site of expansive reaction can be defined as an aggregate particle that is recognizably reactive or potentially reactive and is at least partially replaced by gel (Fig. 7).

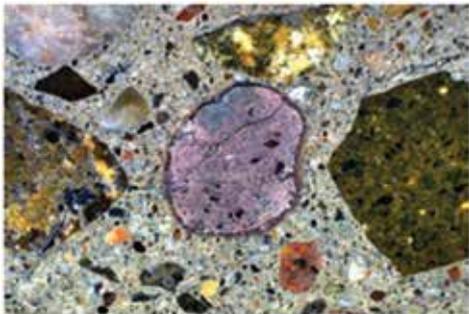


Fig. 7: Reacted particles are identified by dark areas that indicate ASR gel (either inside the particle, or along edges of particles)

ASR-affected coarse aggregates usually exhibit internal fracturing, with cracks extending into the surrounding concrete matrix. If only fine aggregate is reacting, cracks can form in the matrix without affecting coarse aggregate particles. Gel can be present in cracks and voids and may also be present in the area around aggregate particle edges. A network of internal cracks connecting reacted aggregate particles is a strong indication that ASR is responsible for cracking.

### 2.5 Control of ASR in New Concrete

The best way to avoid ASR is to take appropriate precautions before concrete is placed. Standard concrete specifications may require modification to address ASR. These modifications should be carefully tailored to avoid unnecessarily limiting specifiers' options. This requires careful analysis of cementitious materials and aggregates

and choosing a control strategy that optimizes effectiveness and economic selection of materials. Because different geographic regions have different needs and materials available, a guide specification for concrete subject to alkali-silica reactions is needed. The various specifications and guidelines can be referred as given below:

#### 2.5.1 Monograph of Central Soil & Materials Research Station (CSMRS), New Delhi

Soil & Materials Research Station, New Delhi has published booklet in year 2008 "Monograph on alkali-aggregate reaction in concrete for dealing with alkali- aggregate reactions whose website reference is given below. <http://csmrs.nic.in/Monograph%20on%20Alkali%20Aggregate%20Reaction%20in%20Concrete.pdf>

#### 2.5.2 AASHTO Guide Specification

The American Association of State Highway and Transportation Officials (AASHTO) has also developed guidelines and technologies for treating and preventing ASR. Available is a Transition Plan (<http://leadstates.transportation.org/asr/transition/>).

### 2.6 Identification of Potentially Reactive Aggregate

Field performance history is the best method of evaluating the susceptibility of an aggregate to ASR. When evaluating past field performance, the following should be determined: (i) are the cement content of the concrete, the alkali content of the cement, and the water-cement ratio of the concrete similar to that proposed for future use, (ii) is the field concrete at least 15 years old, (iii) are the exposure conditions for the field concrete at least as severe as anticipated for new construction, and (iv) are pozzolans or slags used in the field concrete and are content and properties similar to those proposed for future use? In addition, the current aggregate supply should be examined petrographically to be sure that it is representative of that used in the field concrete. When field history is not available, laboratory tests can be used to evaluate the potential reactivity of aggregate. Several tests to identify potentially reactive cement-aggregate combinations were developed in the 1940s and 1950s, while newer tests were developed in the 1990s. Each test has advantages and disadvantages, as well as limitations.

Two types of diagnostic methods are considered: one relating to the selection of aggregates before a concrete construction is taken up and the second relating to diagnosis of causes of distress in a concrete structure while in service. With regard to the selection of aggregates, the following test methods are used to assess the potential alkali-aggregate reactivity of aggregates:

- Petrographic Examination
- Rapid Chemical Test
- Mortar Bar Test
- Concrete Prism Test
- Rock Cylinder Test

By and large, the above tests have proved suitable for detecting potentially deleterious reactive aggregates containing conventional alkali-reactive minerals or involving alkali-carbonate reaction. However, for evaluation of the deleterious expansion potential due to the presence of strained quartz in the aggregates, the following tests apart from the petrographic examination are of relevance:

- Accelerated Tests
- Scanning Electron Microscopy (SEM), and Infra Red Spectroscopy (IR)

Many concrete surfaces in large dams and their appurtenant works will inevitably be in direct contact with water. Considering that concrete has perviousness in the order of  $10^{-6}$  to  $10^{-7}$  cm per second, there appears very little that can be done to protect the near surface interior concrete from small amounts of moisture.

Although there are many methods for potential reactivity of aggregates but most ideal methods such as the chemical and petrographic test methods are only discussed herewith.

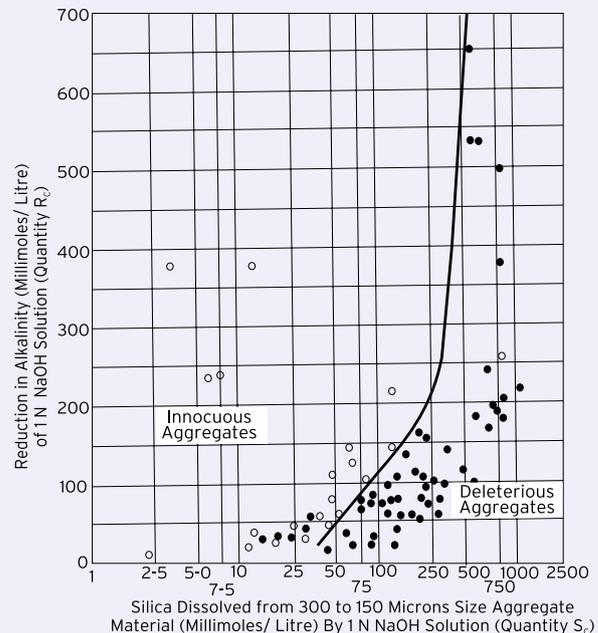
### 2.6.1 Chemical Method

The Test Method for Potential Reactivity of Aggregates (Chemical Method), ASTM C 289, commonly called the quick chemical test, estimates the potential reactivity of siliceous aggregate. Indian Standards IS: 2386-1963, (Reaffirmed 2002) "Methods of Test for Aggregates for Concrete", Part VII for Alkali Aggregate Reactivity by chemical method can also be referred (Fig. 8).



**Fig. 8:** Setup of Alkali Aggregate Reactivity Test for Aggregates by Chemical Method

An aggregate is crushed and sieved to pass 300 micron IS sieve and retained on 150 micron IS sieve to yield three samples of 25 grams each. This material is then reacted with an alkaline solution (1 N sodium hydroxide) at 80°C. At 24 hours, the amount of dissolved silica ( $S_c$ ) from the aggregate and the reduction in alkalinity ( $R_c$ ) of the solution are measured. By plotting these data against a provided curve as given in Fig. 9, it's possible to estimate reaction potential.



**Fig. 9:** Illustration of division between innocuous and deleterious aggregates on bases of reduction in alkalinity

- Aggregates causing mortar expansion more than 0.1 percent in a year when used with a cement containing 1.38 percent alkalis.
- Aggregates causing mortar expansion less than 0.1 percent in a year under same conditions.
- ⊗ Aggregates for which mortar expansion data are not available but which are indicated to be deleterious by Petrographic examination.
- ⊙ Aggregates for which mortar expansion data are not available but which are indicated to be innocuous by Petrographic examination.
- Boundary line between innocuous and deleterious aggregates.

The values of  $S_c$  and  $R_c$  are plotted on a graph and compared with data in Fig. 9 as given in Indian Standards IS: 2386-1963, (Reaffirmed 2002) by which the aggregate can be classified as innocuous, potentially deleterious or deleterious. The results falling on the right side of the boundary line given in Fig. 9 indicate deleterious aggregate. This test and the threshold values were established with results of mortar bar tests on aggregates which were classic examples of reactive aggregates. This test has serious limitations in the sense that it can indicate the presence of only conventional reactive minerals. Also, a positive result does not always indicate that those minerals are present in the aggregate in such proportions as to cause expansion in concrete. The test while being useful is by no means infallible. Another serious draw-back of this method is that in case of aggregates containing strained quartz, in view of slow alkali-silica reaction, the validity and applicability of the

above boundary line is questionable for 24 hours reaction between 1N sodium hydroxide solution and the aggregate. There is, therefore, a school of thought that for strained quartz, a regime of longer period of reaction say 3 to 7 days, may be warranted. However, the final word on this is far from being available.

The aggregate falls into one of three ranges: innocuous, deleterious, or potentially deleterious. ASTM C 289 identifies highly reactive aggregates fairly reliably; however, it fails to identify slowly reactive aggregates. Also, certain aggregates have high amounts of soluble silica present, but produce only small expansions in service. Thus, the test does not always give reliable results. The method also is usually not applicable for testing carbonate aggregates. This test is a helpful research tool and may be useful for initial screening of aggregate; however, other tests should be relied upon to better define which aggregates are potentially reactive.

## 2.6.2 Petrographic Examination

Mineral composition is a good indicator of potential aggregate reactivity. The Guide for Petrographic Examination of Aggregates for Concrete, ASTM C 295, is used to determine mineral composition. Indian Standards IS: 2386-1963, (Reaffirmed 2002) "Methods of Test for Aggregates for Concrete", Part VIII for petrographic method can also be referred.

Petrographic examination should be used as a screening method for aggregates. It gives quick results to help predict possible aggregate reactivity but can't give quantitative information about the aggregate's actual behaviour in concrete.

A petrographic evaluation of an aggregate sample, by an experienced petrographer, will identify potentially reactive minerals in an aggregate sample. The ASTM practice provides guidance on megascopic and microscopic methods of analyzing an aggregate sample. Descriptive nomenclature for minerals is found in ASTM C 294.

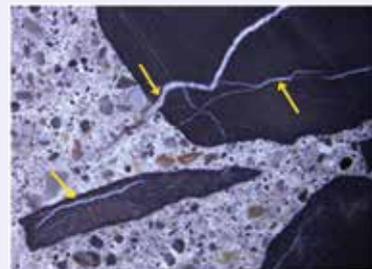
In a megascopic analysis, the aggregate sample is separated into groups of similar rock types. Potentially reactive rock types are quantified on the basis of the total aggregate sample.

A microscopic analysis is a more involved and time-consuming procedure. Hence this analysis will typically use a smaller aggregate sample. A petrographic microscope is most commonly used, and thin sections of aggregates are evaluated under polarized light. Refractive index and specific gravity of powdered aggregate samples are also evaluated. More exotic types of electron microscopes, such as a transmission electron microscope (TEM) and scanning electron microscope (SEM), can also be used to characterize the mineral composition of an aggregate sample. Analytical techniques, like X-ray diffraction and infrared spectroscopy,

may be used to characterize the crystalline form of silica in the aggregate particles.

A petrographic analysis of aggregates can be time consuming. Since small samples are evaluated, precautions must be taken to ensure the sample is representative of the product source. Correlating the results of a petrographic analysis with service record of the aggregate in concrete is very useful. The results of a petrographic analysis will not reveal whether an aggregate will cause deleterious expansion in concrete; this needs to be evaluated using other test methods.

A petrographic examination (ASTM C 856 or AASHTO T 299) is the most positive method for identifying ASR distress in concrete. Prepared sections of concrete are examined under a microscope by an experienced petrographer to determine the presence and location of reactive aggregates (Fig. 10) and gel (Fig. 7). Silica gel appears as a darkened area in the aggregate particle or around its edges (Fig. 7). Petrography, when used to study a known reacted concrete, can confirm the presence of reaction products and verify ASR as an underlying cause of deterioration.



**Fig. 10:** Stereo-optical photo-micrograph of polished concrete specimen showing alkali-silica reaction (ASR) gel filled cracks extending from reactive aggregate into the cement paste

## 2.7 Designing Mixtures to Control ASR

Most concrete is not affected by ASR and special requirements are not needed. However, if historical experience or the tests discussed above demonstrate that ASR is a potential concern, then concrete mixtures must be specifically designed to control ASR. The concrete mixture should be designed with a safe and economic combination of locally available materials. Historical guidance or tests must be used to establish the ASR resistance of selected material combinations. When pozzolans, slags, or blended cements are used to control ASR expansion, their effectiveness must be determined. The limits on expansion referenced in ASTM C 595 (AASHTO M 240), ASTM C 989 (AASHTO M 302), and ASTM C 1157 may not be applicable. The tests do not use job aggregate, and the limits may be more restrictive than is necessary or achievable. An alternative comparative procedure is described in

ASTM C 311, where using the ASTM C 441 test procedure—expansions of fly ash and natural pozzolan are compared to a control mixture with low-alkali Portland cement. Where possible, different amounts of pozzolan or slag should be tested to determine the optimum dosage. Some materials exhibit a “pessimum” effect: dosages that are too low may actually result in higher ASR-related expansions than if no pozzolan or slag were used.

### 2.7.1 Materials and Methods to Inhibit ASR

A variety of locally available materials can be used to control ASR. Using the various tests where applicable to demonstrate effectiveness in controlling ASR, the supplementary cementitious materials listed can be included either as a concrete ingredient added at batching or as a component of a blended hydraulic cement, or both. Blended hydraulic cements should conform to ASTM C 595 (AASHTO M 240) or ASTM C 1157 SCMs added directly to concrete are governed by ASTM C 618 or AASHTO M 295 (fly ash and natural pozzolans), ASTM C 989 or AASHTO M 302 (slag), or ASTM C 1240 or AASHTO M 307 (silica fume). Specifiers should invoke the optional physical and chemical ASR requirements in these standards. The following options are not listed in priority and can be used in combination with one another.

### 2.7.2 Fly Ash

Decades of laboratory and field research demonstrate that certain fly ashes can control ASR. Generally, this works through one (or more) of the following three mechanisms:

- Reduction of concrete permeability and diffusivity due to the pozzolanic reaction of the fly ash with the calcium hydroxide produced by the hydration of the cement
- Removal of some of the alkalis from the pore solution by binding them into the low CaO/SiO ratio hydration products
- Dilution of the cement alkalis by a fly ash with a lower alkali content, or at least a lower available alkali content

The type of ash, its alkali content, chemical composition, and dosage all affect how effectively it will control expansion. In general, Class F fly ashes work better than Class C ashes. Class F ashes have higher silicon dioxide contents and lower lime contents, properties that increase the ability to control expansive reactivity.

In general, ASR expansion decreases as the ash content increases. Ashes require different dosages depending on their chemical composition, the alkali content of the concrete, and the reactivity of the aggregate. Laboratory results show that certain high-alkali/high-calcium fly ashes are not effective at normal dosages to control ASR. Some of these materials may even exacerbate ASR expansion when used at lower amounts (pessimum effect). Generally, the amount of fly ash required to control ASR will increase as any of the following parameters increase: (1) lime or alkali

content of the fly ash Slag. In some parts of the country it is common to control ASR by using slag cement (ground granulated blast-furnace slag). Slag is usually used at higher dosages (25% to 50%) than fly ash to be effective. In one concrete mixture, for example, about 50% slag might be needed to control expansion in concrete with highly reactive aggregate, while only 25% to 35% slag may be required to control expansion in concrete with moderately reactive aggregate. Generally, the amount of slag required to control expansion increases as either the reactivity of the aggregate or the amount of alkali in the mixture increases.

Fly ash with an available alkali content of less than 1.5 % showed an increasing beneficial effect with increase in the amount of cement replaced. On the other hand fly ash with available alkali content greater than 1.5 % needed a minimum percentage of cement replaced to be effective; small additions of this fly ash had caused larger expansions than those of a mixture without fly ash.

### 2.7.3 Silica Fume

Silica fume is also an effective supplementary cementitious material for controlling ASR. Compared to fly ash and slag, only small dosages of silica fume are needed. However, the amount of silica fume required to control expansion with a highly reactive aggregate is around 10% or more. This amount of silica fume is higher than that typically used in concrete and can lead to problems with placing and finishing. The use of silica fume is perhaps most beneficial and practical when used as part of a ternary system.

### 2.7.4 Natural Pozzolans

Raw or calcined natural pozzolans are sometimes used to control ASR highly reactive calcined clay, is almost as effective as silica fume in controlling ASR. It typically requires a replacement level of somewhere between 10 to 15% to control expansion.

### 2.7.5 Ternary Systems

Laboratory data show the beneficial effect of silica fume in combination with fly ash or slag to control ASR. Also, combining two or more supplementary cementitious materials may reduce the quantities needed to control ASR compared to using the materials individually. For example, 4% to 6% silica fume combined with moderate levels of slag (20% to 35%) or fly ash (Class F or Class C), were found to be very effective in controlling the expansion of highly reactive aggregates.

### 2.7.6 Low-alkali Portland Cement

Low-alkali Portland cement (ASTM C 150 or AASHTO M 85), with an alkali content not exceeding 0.60%  $\text{Na}_2\text{O}_{\text{eq}}$ , can be used to reduce ASR. Its use has been successful with slightly reactive to moderately reactive aggregates.

Higher alkali levels (between 0.65% and 0.80%) also have been safely used with certain moderately reactive aggregates.

However, low-alkali cements are not available in all areas. Also, deleterious reactivity has been observed with certain highly reactive glassy volcanic aggregates, especially andesite and rhyolite rocks, even when low-alkali cements (alkali contents of 0.35% to 0.60%) were used. Thus, the use of locally available cements in combination with pozzolans, slags, or blended cements is preferable for controlling ASR.

### 2.7.7 Limiting Concrete Alkalies

Canadian experience indicates that deleterious expansion usually does not take place when reactive aggregates are used in concrete containing less than 3 kg of alkali/m<sup>3</sup> in mixtures containing 100 % Portland cement as the cementitious material. In Canada, CSA Standard A23.2-27A, Alkali-Aggregate Reaction, dictates the requirements for supplementary cementitious materials used to control ASR. A supplementary cementitious material may be used to control ASR provided it meets two criteria: (1) it must conform to certain chemical requirements and (2) it must be used at or above the minimum dosage specified. If less than the required minimum amounts are to be used, the concrete prism expansion test (CSA Test Method A23.2-14A) or the mortar-bar accelerated expansion test (CSA Test Method A23.2-25A) is conducted to verify the material's effectiveness in controlling expansion. Per the chemical requirements, blast-furnace slag can have a maximum 1.0% total alkali content (as Na<sub>2</sub>O<sub>eq</sub>). Fly ash can have a maximum total alkali content of between 3.0% and 4.5%, and silica fume can have a maximum total alkali content of 1.0%. A minimum SCM dosage is required depending on the reactivity of the aggregate, the service life and size of the structural element, the exposure environment, and the composition of the fly ash or slag. The minimum silica fume dosage is calculated based on total alkali content of the concrete.

### 2.7.8 ASR-inhibiting Compounds

Certain chemical admixtures or cement additives can control ASR. For example, lithium compounds can effectively reduce ASR expansion in concrete. When lithium hydroxide or lithium nitrate is added to concrete, a lithium-bearing ASR gel is formed. Lithium-bearing gels have a greatly reduced potential for expansion; some are even non-expansive. Also, less gel is formed in the presence of lithium.

The degree to which lithium compounds suppress expansive ASR depends on two factors: aggregate reactivity and concrete alkali content. In one of the study it was seen that the optimum level of lithium hydroxide monohydrate to control expansive ASR appears to be equal to that of the equivalent alkali content of the cement. It has been shown

that insufficient quantities of certain lithium compounds may actually increase expansion.

This is related to the increased hydroxyl ion concentration in the pore solution, as many lithium compounds combine with calcium hydroxide, producing insoluble calcium salt and lithium hydroxide. Lithium nitrate does not behave in this manner due to the high solubility of calcium nitrate. The efficient molar ratio [Li] / [Na+K] to suppress expansion may vary from as low as 0.56 to over 1.11 depending on the aggregate source. The Federal Highway Administration (FHWA) has published Interim Recommendations for the Use of Lithium to Mitigate or Prevent Alkali-Silica Reaction (ASR) which provides information and guidance to test, specify, and use lithium compounds in new concrete construction.

Neither ASTM C 1260 (AASHTO T 303) nor ASTM C 1567 should be used to test the effectiveness of lithium compounds. ASTM C 1293, with test duration of two years, should be used to assess lithium compounds.

### 2.7.9 Aggregate Selection and Beneficiation

Using a nonreactive aggregate is ideal but not always practical. The surest way of predicting aggregate performance is a good service record, but this information is not always available. Instead, it is frequently necessary to investigate aggregate quality through the tests that measure potential reactivity.

It may be possible to improve aggregate quality by selective processing known as beneficiation. Processes that have been used are heavy media separation, jigging, rising-current classification, and crushing. In some cases, one of these steps may be able to remove a large portion of the reactive aggregate, but also may remove some of the good aggregate.

It may be possible to blend reactive aggregate with nonreactive aggregate to mitigate the effects of ASR.

This blending sometimes occurs as part of the quarrying process, when only small amounts of reactive aggregate are present. Nonreactive aggregates can be purposefully blended with known reactive aggregates.

In some cases, this means of diluting aggregates can adequately control expansive ASR. An example of this method is limestone sweetening.

Limestone sweetening, or replacing up to 30% of a reactive sand-gravel aggregate with crushed limestone, is effective in preventing deterioration in some sand-gravel aggregate concretes. The resulting combination of materials should be tested in accordance with ASTM C 227, ASTM C 1260 (AASHTO T 303), ASTM C 1567, or ASTM C 1293 to verify control of deleterious expansion.

### 2.7.10 Controlling Existing ASR

Lithium salts have also been applied topically to treat ASR in existing concrete. Laboratory studies show that treating small samples with lithium can reduce expansion. In the field however, lithium may not penetrate sufficiently into the structure to mitigate the reaction below the surface, allowing continuous deterioration. Some researchers have found out that insufficient amounts of lithium penetration into hardened concrete may even enhance ASR expansion. Methods of driving lithium ions into the concrete using electrical fields or vacuum impregnation are being studied to improve penetration.

FHWA has published guidance for selecting ASR-affected structures for lithium treatment. They identify ideal structures for lithium treatment as those for which, (1) ASR has been confirmed as the principal cause for deterioration; (2) the deterioration has reached a certain severity, and (3) laboratory testing or in-situ monitoring indicates a potential for significant further expansion if the structure is left untreated.

### 2.8 Recycled Concrete as Aggregate

When recycled concrete is used as coarse aggregate in new concrete, it should be evaluated in the same manner as virgin aggregate. Recycling concrete for use as coarse aggregate in new construction can be economical, saving disposal costs of old concrete and reducing the need for virgin aggregate. Increased environmental concerns and diminishing quarry resources may make recycling even more popular in the future.

There are two main uses for recycled aggregate in new pavement construction: as a granular subbase material and as coarse aggregate for the new concrete pavement.

Research was undertaken to study expansion of new concrete made with recycled ASR-affected concrete as aggregate. It was determined that potential for ASR in the new concrete is affected by the old concrete's original alkali level, extent of expansion, and the remaining potential reactivity of the aggregate. Also, the alkali content of new concrete had a significant effect on subsequent expansions due to ASR. The use of a low-lime Class F fly ash greatly reduced expansions due to ASR in new concrete.

The research demonstrated that with appropriate selection of cementitious materials, even recycled concrete containing highly reactive aggregate can be used safely. The engineer must know the ASR potential of the recycled aggregate. If information is not available about the cementitious materials and aggregates contained in the old concrete, even if the old concrete has not experienced ASR deterioration, its ASR potential should be petrographically evaluated prior to recycling. Laboratory expansion tests may also be helpful.

## 3.0 Alkali-Carbonate Reaction

### 3.1 Mechanism of ACR

Reactions observed with certain dolomitic rocks are associated with alkali-carbonate reaction (ACR). Reactive rocks usually contain larger crystals of dolomite scattered in and surrounded by a fine-grained matrix of calcite and clay. Calcite is one of the mineral forms of calcium carbonate; dolomite is the common name for calcium-magnesium carbonate. ACR is relatively rare because aggregates susceptible to this reaction are usually unsuitable for use in concrete for other reasons—strength potential, etc.

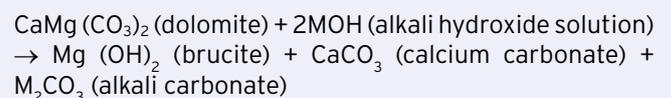
Argillaceous dolomitic limestone contains calcite and dolomite with appreciable amounts of clay and can contain small amounts of reactive silica. Alkali reactivity of carbonate rocks is not usually dependent on clay mineral composition. Aggregates have potential for expansive ACR if the following lithological characteristics exist:

- Clay content, or insoluble residue content, in the range of 5% to 25%
- Dolomite content (percentage in carbonate fraction) in the range of 40% to 60%
- Interlocking dolomite grains (late expansion)
- Small size (25 to 30  $\mu\text{m}$ ), discrete dolomite crystals (rhombs) suspended in a clay matrix

### 3.2 Factors Affecting ACR

#### 3.2.1 Dedolomitization

Dedolomitization, or the breaking down of dolomite, is normally associated with expansive ACR. Concrete that contains dolomite and has expanded also contains brucite (magnesium hydroxide,  $\text{Mg}(\text{OH})_2$ ), which is formed by dedolomitization. Dedolomitization proceeds according to the following equation:



Where, M represents an alkali element, such as potassium, sodium, or lithium.

Expansion may be due to a combination of migration of alkali ions and water molecules into the restricted space of the fine-grained matrix surrounding the dolomite rhomb, migration of these materials into the rhomb, and the growth and rearrangement of the dedolomitization products, especially brucite, which exerts pressures as it crystallizes.

#### 3.2.2 Other Factors

The nominal maximum size of the reactive aggregate influences the amount and extent of reaction. Testing done with a particular ACR rock and high-alkali cement showed

that both the rate and degree of expansion decreased with a decrease in nominal maximum aggregate size. Concrete can contain a certain percentage of carbonate reactive aggregates without experiencing detrimental expansion. Alkali-carbonate reaction is also affected by pore solution alkalinity.

ACR can occur in a solution with a relatively low pH. As the pH of the pore solution increases, potential for the alkali-carbonate reaction increases. During ACR, calcium hydroxide produced by Portland cement hydration can combine with the alkali carbonate produced in the initial reaction to regenerate alkali hydroxide and calcium carbonate. This reaction not only regenerates alkali, but also reduces the concentration of carbonate ions and aggravates the dedolomitization reaction. Low-alkali cements and supplementary cementitious materials—even at high levels—are thus ineffective at reducing ACR to acceptable limits.

### 3.3 Visual Symptoms of Expansive ACR

ACR, like ASR, is a chemical process that can induce physical damage— expansion and cracking of concrete (Fig. 11). Information obtained from a site inspection should be evaluated along with testing to determine the destructive mechanism.

ACR-affected concrete does not exhibit telltale features to distinctly identify alkali-carbonate reaction as the cause of cracking. The crack pattern will be influenced by restraint conditions and moisture availability. In slabs, decks, and footings, when a top-to-bottom or side to-side moisture gradient exists, map cracking is likely to occur. This growth can cause closed joints, misalignment of adjoining members, crushed concrete, and pavement blowups. Because low levels of alkali can initiate ACR and higher levels can exacerbate it, the use of deicer salts that contain alkalis can increase damage.



Fig. 11: Map cracking pattern caused by ACR

### 3.4 Test Methods for Identifying ACR Distress

Brucite is usually formed during destructive ACR and is evident in expanded concrete. Its presence must be determined through petrographic or other analysis. The concrete and carbonate rocks must be examined petrographically in accordance with ASTM C 856 and C 295

respectively. Physical expansion tests, such as ASTM C 586, performed in a laboratory are also helpful to verify the presence of ACR.

### 3.5 Test Methods for Identifying Potentially Reactive Aggregate

ACR is rather uncommon because the carbonate rocks containing proportions of dolomite, calcite, and insoluble material that will lead to dedolomitization do not often compose a major portion of the aggregate supply. The test commonly used to identify potentially alkali-carbonate reactive aggregate are described below:

#### 3.5.1 Petrographic Examination (ASTM C 295)

Petrographic examination, ASTM C 295, can be used to establish the character of rock. Potentially alkali-carbonate reactive aggregates (Fig. 12) have a characteristic lithology that makes them easy to identify. The rock is considered to be reactive if the physical make-up is a fine grained matrix of calcite and clay surrounding rhombic crystals of dolomite. With no known exceptions, all rocks with the characteristic lithology have expanded in an alkaline environment, and all rocks in concrete that have expanded due to ACR exhibit the characteristic lithology. Petrographic testing identifies ACR-susceptible rocks.

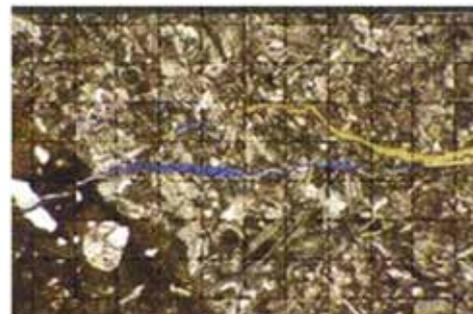


Fig. 12: Microscopic view of alkali-carbonate reactive aggregates

### 3.6 Control of Alkali-Carbonate Reaction

ACR-susceptible aggregate has a specific composition that is readily identified by petrographic testing. If a rock indicates ACR-susceptibility, preventive measures must be taken. It's difficult to arrest alkali-carbonate reaction once expansion has begun.

#### 3.6.1 Selective Quarrying

Quarries are routinely mapped and tested to define the rock groupings and stratification. Reactive rock may be naturally isolated in layers or by other physical features. In this case, selective quarrying can be used to completely avoid the reactive strata. Small portions of reactive aggregate may become naturally diluted when the rock is processed.

### 3.6.2 Blended Aggregate

Another option is blending reactive aggregate with aggregate proven by testing—and service record, if possible—to be nonreactive. This can mitigate the reactive aggregate's detrimental effects on concrete.

Accordingly, the Appendix in ASTM C 1105 limits the safe proportion of reactive aggregate to 20% for either the coarse or fine sizes when used alone, or a limit of 15% total when used in combination. Test the resulting diluted or blended aggregate using ASTM C 1105 to be certain it is acceptable for use in Portland cement concrete.

### 3.6.3 Aggregate Size

Limiting the nominal maximum size of aggregate is another way to minimize expansion due to ACR. Use the smallest practical nominal maximum size of aggregate to minimize detrimental expansion.

### 3.6.4 Low-Alkali Cement

Low-alkali cement is not generally effective in controlling expansive ACR. Even cements with alkali levels as low as 0.40% can produce pore solutions with sufficient alkalinity to initiate reaction. Due to the chemistry of the alkali-carbonate reactions, alkalis are regenerated rather than consumed. They undergo a series of reactions with aggregates and are then available to react again with more aggregate. The cement alkali level is of less concern than the alkali content of concrete, which should be kept as low as possible when using alkali-carbonate reactive aggregate.

### 3.6.5 Pozzolans

Supplementary cementitious materials are not very effective in controlling ACR. Pozzolans tie up alkalis by reacting with them, but ACR can be initiated with low levels of alkali, and pozzolans may not consume enough alkalis to limit the reaction. Pozzolans do reduce paste porosity, which helps limit the moisture available for reaction. The reduced concrete porosity is beneficial, but concrete in most environments contains enough moisture to sustain alkali-carbonate reaction. Larger amounts of pozzolans could possibly control ACR, but these amounts are generally too high to be practical. ACR is more effectively controlled by processing the aggregate to minimize particle size or the amount of reactive aggregate in the concrete.

### 3.6.6 ACR-inhibiting Compounds

While some researchers have found that lithium compounds appear to control ACR, others found that lithium hydroxide and lithium carbonate increase expansion of alkali-carbonate reactive rock.

## 4.0 Conclusion

When assessing the potential for the concrete to suffer damage from AAR, two basic questions need to be answered:

- Is the aggregate potentially deleterious?
- How much alkali will be brought into the system by each of the materials to be used?

Aggregates and other concrete constituents should be tested in accordance with the specified methods before a concrete construction is taken up.

A concrete mixture is proportioned to have a number of properties including strength and durability against attack from weathering, water, etc. Unfortunately, parameters such as low water-cement ratios and higher cement contents which enhance the defense against external aggressive agents, are likely to produce concrete with a high alkali content which is more, rather than less, susceptible to damage from AAR if the aggregates are potentially reactive. It is difficult to envisage any circumstance where it would be justified to compromise the general durability and strength of concrete to ensure that damage from AAR does not occur. The correct approach should always be to use the mixture required to satisfy other criteria, and then select materials which will avoid the danger of damage from AAR.

After the concrete has been placed and properly cured, there is nothing further which can be done to reduce the severity of damage from AAR, except possibly to limit the supply of water. Everything should be done, in both design and construction, to reduce unnecessary contact between moisture and the concrete. This would include providing adequate slopes to prevent water standing on horizontal surfaces, giving attention to the design, construction and maintenance of joints to prevent leakage, and providing adequate copings and other weathering details to protect vertical surfaces from rainfall.

It might be possible, though often not practicable, to enclose buildings in an impermeable coating, but this is impossible with dams and retaining walls where water can enter the concrete via the foundations. It is also doubtful whether any coating can be considered permanently impermeable.

The expansion due to AAR not only causes cracks but also leads to the closing of joints, jamming of gates and misalignment of machinery. Adequate provision for such movements in design, wherever possible, would reduce the problems caused by expansion of the concrete. For most structures there is little that can be done during the design and detailing or construction to prevent or reduce the effects of AAR should it occur beyond that which should be expected of good practice in any case. The primary defense must always be to ensure that the materials and concrete mixtures used in the construction will not lead to expansion or damage due to AAR.