MONOGRAPH
ON
ALKALI-AGGREGATE REACTION IN CONCRETE
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The Central Soil and Materials Research Station (CSMRS), under the Ministry of Water Resources, Govt. of India, is a premier institute in the country located at New Delhi deals with field and laboratory investigations, basic and applied research, problems in geo-mechanics and materials of construction relevant to river valley projects and other connected civil engineering structures.

Dissemination of knowledge is our one of the areas. Large number of papers have been published in National, International journals and proceedings of seminars and workshops so far. Monograph on alkali Aggregate Reaction is a first publication of CSMRS.

In recent years, distress due to Alkali -Aggregate Reaction (AAR) in concrete structures has increased. It is well known that the locally available aggregates are mostly reactive and prone to deleterious reaction. The reaction mainly aggravates in moist environment, therefore the water retaining and other related civil engineering structures are mostly affected. It is therefore advisable to carryout detailed investigations during preconstruction stage so as to mitigate the future problems. Also, the health of the existing structures has to be evaluated so as to monitor the serviceability of the structures.

A general understanding of the science of AAR is necessary to engineers who have the responsibility for the design, construction, operation and maintenance of the structures. This monograph mainly contains causes of AAR and its effects, laboratory investigations, diagnosis including case studies.

This monograph is therefore mainly informative and will be of great use to the readers and serve as a template for many investigations.

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ALKALI-AGGREGATE REACTION IN CONCRETE

1.0 INTRODUCTION

It is a well known fact that concrete deterioration may have different causes, alkali-aggregate reaction being only one among many. Some other causes are swelling due to expansion of the cement (from free lime or ettringite) or swelling clay in the aggregate, external factors such as cycles of freezing and thawing or the attack on concrete by water in some forms such as extremely pure water, acidic water, and sulphate-rich water. In many cases, there may be a combination of causes, so that when there is an alkali-aggregate reaction in the concrete for example, the effects of other factors may thereby be aggravated or accelerated.

The alkali aggregate reaction (AAR) in concrete is considered as a great menace to the durability of concrete structures especially the hydraulic structures. The manifestations of this deleterious reaction appear only a few years after construction.

Damage to concrete caused by alkali-aggregate reaction takes a variety of forms, the most common being surface cracking and, sometimes, exudations of gel at the exposed face. Such damage has been reported in many countries, particularly in those with hot-wet climates. The damage first appears varies from a few months to several decades after construction. Cracks usually grow wider with time and site repairs are often found to be quite ineffectual. Alkali-aggregate reaction is a serious form of deterioration and measures need to be taken to minimize it.

Typical indicators of AAR are random map cracking and, in advanced cases, closed joints and attendant spalled concrete. Cracking due to AAR usually appears in areas with a frequent supply of moisture, such as close to the waterline in piers, near the ground behind retaining walls, near joints and free edges in pavements, or in piers or columns subject to wicking action.

Interest in the Alkali-Aggregate Reaction (AAR) in concrete structures has increased in recent times because of the risk for dam safety and the high cost of repairs and replacements. One of the first structures identified as affected by AAR was the Parker Dam (USA) in 1941 and an ICOLD survey in 1985 has shown the worldwide distribution of damaged dams because of AAR.

2.0 WHAT IS ALKALI AGGREGATE REACTION?

Alkali-aggregate reaction is a chemical reaction between certain types of aggregates and hydroxyl ions (OH⁻) associated with alkalis (Sodium Oxide and Potassium Oxide) in the cement. Usually, the alkalis come from the portland cement but they may also come from other ingredients in the concrete or from the environment. Under some conditions, the reaction may result in damaging expansion and cracking of the concrete. 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 de-icing salt solutions that may cause corrosion of the reinforcing steel, thereby accelerating deterioration and weakening a structure.
This alkali-aggregate reaction has two forms:
* Alkali-silica reaction (ASR)
  - Alkali reaction with amorphous silica;
  - Alkali reaction with silicates caused by reactions in polyphase siliceous aggregates (shale, granite, sandstone);
* Alkali-carbonate reaction (ACR).
  - Alkali reaction with dolomitic carbonates.

2.1 Alkali-Silica Reaction

This is the most common form of alkali aggregate reaction and results from the presence of certain siliceous aggregates in the concrete found in some granites, gneisses, volcanic rocks, greywackes, argillites, phyllites, hornfels, tuffs, and siliceous limestones. In ASR, aggregates containing certain forms of silica will react with alkali hydroxide in concrete to form a gel that swells as it adsorbs water from the surrounding cement paste or the environment. These gels can swell and induce enough expansive pressure to damage concrete. The product of the alkali-silica reaction is a gel that absorbs water and increases in volume. Pressure generated by the swelling gel ruptures the aggregate particles and causes cracks to extend into the surrounding concrete. Typically, alkali-silica reaction results in the formation of map-pattern cracking of the concrete.

2.1.1. Alkali Reaction with Amorphous Silica

Amorphous silica is a form of loose arrangement of tetrahedra around a silicon atom bonded to oxygen ions and OH\(^{-}\) ions. When placed in a soda solution, there is first an acid-base reaction between the silanol groups (Si - OH) and the OH\(^{-}\) ions from the alkaline solution, followed by neutralisation of the resultant negative charge by a Na\(^{+}\) ion. (reported by Dent-Glasser and Kataoka)

The next reaction is an attack on the siloxane bridges by the OH\(^{-}\) ions. This leads to disintegration of the structure and the silica enters into solution in the form of protonated ions (H\(_2\)SiO\(_4\)).

Both reactions take place simultaneously and show the importance of the OH\(^{-}\) ions. They eventually lead to the formation of expansive sodium silicate gels.

2.1.2. Alkali reaction with silicates caused by reactions in polyphase siliceous aggregates (shale, granite, sandstone)

Deterioration of polyphase siliceous aggregate appears under the microscope as a dark zone between the aggregate and cement paste and by a white deposit on the aggregate and in cleavage planes. The dark zone is due to an alkaline silicate gel. The white deposit consists of flaky crystals containing Si, K, and Ca. Between the white deposit and the dark zone, there is often an area with an intermediate texture. There thus seems to a tendency for the gel to develop a more
Monograph on Alkali Aggregate Reaction

highly organised structure. A gel whose CaO/SiO$_2$ ratio is lower than in the cement but higher than in the gel in contact with the aggregate is observed in the larger pores in the cement paste (Fig. 1 & 2).

There may also be some gelling of the cement paste around the aggregates. Thus, a low viscosity gel forms and is able to migrate away from the aggregate. Thaumasite and silica-rich ettringite are also present near the aggregate. This is proof of multiple corrosion of the concrete, where the expansive gel produces cracks that provided access for the SO$_4^{2-}$ ions.

2.2 Alkali-Carbonate Reaction

With the alkali-carbonate reaction, certain dolomitic limestone aggregates react with the hydroxyl ions in the cement (or other sources such as de-icing salts) and cause swelling. The swelling of the limestone particles causes the concrete to expand and crack.

Dedolomitisation from reaction of the calcium and magnesium carbonate with an alkaline solution involves the formation of Brucite [Mg (OH)$_2$] and regeneration of the alkaline hydroxide.

The brucite may be isolated from the interface between aggregate and cement paste or in the middle of the aggregate. It can also react with the silica around the aggregate and form magnesium silicate. The porous zone created around the aggregate by extraction of the Mg$^{2+}$ ions weakens the cement-aggregate bond. Cracks appear, although some may heal through precipitation of Ca (OH)$_2$.

Dedolomitisation does not produce an expansive gel. The expansion sometimes observed has been associated with the presence of clays either as inter granular material or as inclusions in the carbonate crystals. These clays cause the concrete to deteriorate by absorbing the OH$^-$ ions.

The deterioration caused by ACR is similar to that caused by ASR; however, ACR is relatively rare because aggregates susceptible to this phenomenon are less common and are usually unsuitable for use in concrete for other reasons. Aggregates susceptible to ACR tend to have a characteristic texture that can be identified by petrographers.

2.3 Mechanism of ASR.

The alkali-silica reaction forms a gel that swells as it draws water from the surrounding cement paste. 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 (Fig. 3). The reaction can be visualized as a two-step process:

- Alkali hydroxide + reactive silica gel → reaction product (alkali-silica gel)
- Gel reaction product + moisture → expansion
The amount of gel formed in the concrete depends on the amount and type of silica and alkali hydroxide concentration. The presence of gel does not always coincide with distress, and thus, gel presence does not necessarily indicate destructive ASR.

3.0 EFFECTS OF ALKALI AGGREGATE REACTION

Typical indicators of ASR might be any of the following: a network of cracks; closed or spalled joints; relative displacements of different parts of a structure; or fragments breaking out of the surface of the concrete (pop outs) (Fig. 4 & 5). Because ASR deterioration is slow, the risk of catastrophic failure is low. However, ASR can cause serviceability problems and can exacerbate other deterioration mechanisms such as those that occur in frost, deicer, or sulphate exposures.

3.1 Typical Cracking due to Alkali- Aggregate Reaction

Relatively equi-dimensional pattern cracking is characteristic of non-reinforced or lightly reinforced concrete affected by alkali-aggregate reaction (Fig. 6 & 7). But when there is a significant amount of reinforcing steel, cracking tends to be more prominent in the direction parallel to the reinforcement (Fig. 8). However, map-cracking can also result from other causes such as drying shrinkage (sometimes referred to as plastic cracking), particularly in slabs on grade that were placed in hot windy weather without proper curing. This type of cracking appears within hours, or days after casting the concrete. In contrast, cracking due to alkali-aggregate reaction usually becomes evident only after 5 to 10 years.

3.2 Swelling of the Concrete due to Alkali-Aggregate Reaction

Both alkali-silica and alkali-carbonate reactions result in swelling of the concrete. The amount of swelling or expansion depends on the reactivity of the aggregates, the alkalinity of the cement solution, and the ambient moisture conditions of the structure. Expansions of over 0.1% are not uncommon. An expansion of 0.1% would result in an increase in length of 1 cm for every 10 m length of an unreinforced structure. In many structures this amount of expansion may not cause problems, but in long sidewalks or median barriers, for example, the expansion may cause compression and heaving. Expansion in large structures like dams, powerhouses and locks can interfere with the operation of the flow gates or turbines.
Monograph on Alkali Aggregate Reaction

Figure-1: showing the gel formation around the aggregates

Figure-2: showing the Structure of gel under Scanning Electron Microscopy
Figure-3: showing the cracks due to AAR passing through aggregates.

Figure-4: showing the spilling of concrete

Figure-5: showing the severe cracking due to AAR
Figure- 6: Typical map-pattern cracking due to alkali-silica reaction
Figure- 7: Map-pattern cracking and extrusion of joint filling material due to expansion of concrete affected by alkali-carbonate reactivity

Figure-8: Prominent cracking runs parallel to reinforcing bars
4.0 FACTORS AFFECTING ALKALI-AGGREGATE REACTION

Concrete deterioration from alkali-aggregate reaction is due to the simultaneous effect of several factors. They may be subdivided into three groups:

* Material properties: Aggregate and Cement
* External influences: Humidity, Temperature and Compressive Stresses
* Time.

4.1 Material Properties

4.1.1 Aggregates

Aggregates used for concrete may come from rock that is used under conditions that are different from those obtaining in its natural state. The rock will have evolved slowly from the time it was first formed, slowly undergoing chemical alteration and weathering until it has reached equilibrium. When it is suddenly put into an environment with an average pH of 12.6 (rising locally to 13.6) which occurs in the pore water within concrete, the constituent minerals will once again start to evolve in an attempt to find a new equilibrium. This new stage of alteration leads to the appearance of a partial solution which tends to form what might become an expansive gel. When it does so, it is known as reactivity.

Reactivity is dependent partly on the minerals and partly on the rocks formed by the combination of minerals. Thus we must distinguish between.

Factors connected with the constituent minerals:

* type
* tectonic and weathering history

Factors connected with the rock:

* structure, grain size, porosity, permeability, specific surface
* composition

4.1.1.1 Mineral-dependent Factors

Type: the most commonly incriminated minerals in structures subject to alkali-aggregate reaction are the siliceous polyphased minerals and a few silicates such as:

* amorphous minerals like opal and volcanic glass
* cryptocrystalline minerals like chalcedony
* crystalline minerals like quartz, feldspar, and phyllosilicates.
**History:** Opal occurs mainly in sedimentary rocks and occasionally in certain basalts, and is the most reactive mineral. The other minerals like quartz, feldspars and the phyllosilicates are noted to be more reactive when they contain imperfections.

These imperfections fall into two categories:

- *a*) Those associated with tectonic stresses which have deformed the crystalline lattice. This is the case with quartz having distortions of the crystal lattice as demonstrated by a microscopic technique referred to as "undulatory extinction" utilizing polarized light. Such quartz is frequent in metamorphic rocks like gneiss and mica schist, but is also found in some magmatic rocks such as granite.

  More than 30% strained quartz in granites, granodiorites and gneisses as by an undulatory extinction angle of 25° or more has been categorized as reactive component. However there is also evidence of the reactivity of aggregates containing more than 20% strained quartz with undulatory extinction angle greater than 15°. Therefore, the criteria for deleterious percentage for strained quartz need more investigations to be carried out.

- *b*) Those associated with chemical alterations. This is the case with the quartz in some igneous rocks, as well as sedimentary sandstone and quartzite, and metamorphic rocks. It is also the case with alkali and calcium alkali feldspars which have greater reactivity when they reach a more advanced state of alteration.

  The alteration of quartz through this corrosive process produces corrosion shapes on a minute scale consisting of nested angles or triangles. Alteration of feldspars is revealed by the existence of clay minerals along the mineral cleavage planes.

  It should be noted that siliceous minerals react to alkalis by the formation of expansive gel through the gradual freeing of silica. Feldspar and micaceous minerals react by: (i) freeing alkalis, tending to increase the available concentration and (ii) yielding (like the siliceous minerals) silica which helps in the development of the gel.

**4.1.1.2 Rock-dependent Factors**

Although it is the minerals which react, they are contained in rock and their reactivity is governed partly by the rock formation. Lists of rocks classified as reactive, which are known to have produced reactions in various countries are a useful guide. The proportion of reactive aggregate causing maximum swelling - the "pessimum content" - is highly variable. In many cases it ranges from 3% to 5% but it can be greater, depending on rock type and how pessimum content is measured.

There are two categories of rock-dependent factors:

* structural factors
* composition factors.
The most readily recognizable structural factor is the grain size. It is generally thought that grained rocks whose grain size is measured in several millimetres are much more susceptible to reactivity than very fine grained rocks. Exceptions are noted—however, as in the case of the Malmesburg group of rocks in South Africa. A coarse-grained texture is often accompanied by severe cracking, and it is therefore important to determine the structural parameters of the aggregates such as permeability; porosity and specific surface.

Composition factors involve determination of the minerals present in the rock and their relative concentration. With sedimentary rocks, consideration of these properties means concerning oneself with the type and contents of the cementitious binding materials within the rock matrix, as well. Acidic magmatic rocks that have undergone tectonic stresses and severe alteration are more vulnerable than basic rocks to alkalis.

A crystalline or lithographic limestone, which is usually inert, can become reactive if it contains a siliceous or clay fraction disseminated within the mass. If the siliceous fraction consists of micro quartz, reactivity will be slight. But with amorphous silica, reactivity will be high.

### 4.1.2 Cements

Very high alkali content in the pore water phase is usually due to presence of the alkalis in the cement and other cementitious materials. Alkalis can also come from certain aggregates (feldspars) or admixtures. However, the presence of free Ca (OH)$_2$ is prerequisite for expansion to occur. Limiting permissible alkali content in portland cement is considered a sufficient control measure. However, today there is beginning to emerge general agreement that the swelling risk with reactive aggregates is proportional to the total alkali content of the concrete. Control measures should recognize this fact as in British practice. With reactive aggregates, the use of alkali-rich Portland cements can cause problems after only a few years.

### 4.1.3 Mixing Water and Admixtures

Alkalies can also come into concrete from mixing water and chemical admixtures in concrete. In many of the projects, ground water or boring water and runoff river water is used in concrete. The ground water may contain dissolve alkalies from the surrounding soil/rocks and river water may also contain industrial and agricultural effluent which may be the source of alkalies.

### 4.2 External Influences

#### 4.2.1 Environmental Humidity

The alkali-aggregate reaction is greatly promoted by a relative humidity of 80% or more.
4.2.2 Temperature

Like all chemical reactions, AAR is affected by temperature. In general the rate of reaction and formation of gel will increase as the temperature rises. At the same time, gel at high temperatures will be less viscous and more able to escape into cracks and voids within the concrete. Temperature of concrete is governed by ambient conditions once the heat of hydration has subsided.

4.2.3 Compressive Stresses

The expansion and damage due to AAR are greatly influenced by the presence of restraints and stresses applied to the concrete. In fact well distributed compressive stresses can reduce the concrete expansion in the direction of compression and prevent cracks to open, limiting in this way the water circulation.

From this point of view there is a difference between primary cracking directly due to irregular local concrete expansion (typical map cracking pattern) and secondary, or structural, cracking which is produced by any structural restraint opposing the expansion.

From some observations it appears that the expansion at the bottom section of dams, where stresses are high, is likely to be less important than at higher elevations. As such stresses, also called backpressures, are produced by the expansion itself, they may likely be one of the causes which in some cases slow down the expansion and eventually stop it.

4.3 Time

Cracks appear after variable lengths of time. Concrete swelling may be gradual or may occur suddenly at a later time. Swelling may eventually stop when all the reactive fractions of polyphase aggregate have been exhausted. The structures where this was studied were never in any danger of immediate failure.

5.0 PREVENTION OF AAR

5.1 Environment

Prevention of AAR depends upon many considerations, all of which must be made before the concrete is placed. The first consideration is the environment in which the concrete structure will function, i.e. the effects of the environment on the completed structure.

5.1.1 Moisture

A supply of moisture is required for alkali-silica reaction to occur, which in turn causes gel to form with attendant damage due to its swelling. It is considered that damage will not happen, or
its progress will cease, at a relative humidity less than about 80 % providing the air is the only source of moisture. Ambient moisture level need not be continuous; the reaction will proceed every time the humidity rises above the 80 percent level. Some authorities believe that cycles of wetting and drying can cause a higher rate of damage than continuous exposure to saturated or near saturated conditions and there is some evidence to support this.

All exposed concrete, even mixtures containing only small amounts of deleterious materials, should be considered susceptible to AAR. Concrete may only be considered non-susceptible if it can dry so the internal humidity drops below 80 percent, and thereafter is permanently protected from the weather and other sources of moisture, including heavy condensation, capillary moisture, and seepage water.

5.1.2. External Sources of Alkalis

There are a number of sources of alkalis which might potentially raise the alkalinity of the pore solution within the concrete matrix. They attack the external faces of the concrete and reinforcement which is particularly vulnerable to these contaminants.

It is doubtful that alkalis are absorbed from external sources and cause damage from AAR. However, it is important to recognize the effect of the contaminants so as not to confuse them with AAR.

a) Sea water which contains mainly sodium salts but also very small amounts of potassium salts.

b) De-icing salt (sodium chloride), used on roads, footpaths, and other surfaces during freezing conditions. The main problem created by de-icing salts is the corrosion of reinforcement and other embedded metal caused by the chloride ion content, but the sodium salt in solution can be absorbed by the concrete with detrimental effects.

It is not only the surfaces directly treated with de-icing salts which are at risk. Salt laden water can be sprayed onto other surfaces by passing traffic or can drip into concrete through joints and drainage holes.

c) Sodium and potassium compounds from industrial and agricultural effluent of run-off go into rivers and reservoirs and come into contact with concrete.

5.1.3. Precautions against Environmental Effects

It is highly unlikely that damage due to AAR would occur if external sources of water could be prevented from coming into contact with the concrete. However, it is difficult, and in most cases impracticable to prevent this. Even where waterproof membranes or coatings are a practical consideration; it is doubtful whether they could be relied upon to give complete and permanent protection over the life of the structure. Waterproofing should not be used as a substitute for good concrete materials and mixtures and construction practices which, in themselves, minimize the risk of damage due to AAR.
It has been observed that damage due to AAR is often greatest where structures are wet, such as at leaking joints; therefore, care in detailing of the structure can help to reduce deterioration.

If reactive or potentially reactive aggregates have to be used in areas with high ambient temperatures, it would be wise to reduce the alkali levels in cement and concrete below those necessary in more temperate climates. There is however, insufficient information available to quantify such reductions.

5.2. Aggregates

A major consideration for avoiding AAR is in the selection of aggregates.

5.2.1. Reactive Constituents

A number of forms of silica have been implicated in cases of AAR throughout the world. Notably these are microcrystalline and crypto crystalline silica, often found in flint and chert. Strained quartz found in some quartzites has also been implicated. Opaline silica is perhaps the most reactive form. Reactive forms of silica are also found in more complex rock forms such as siliceous limestones, granites, etc. Table 1 presents a list of reactive constituents of aggregates to be avoided.

In addition to the dangers of aggregates containing reactive silica, there have been cases of aggregates containing alkalis which can leach into the pore water and increase its alkalinity to a level where damage can be caused. Such cases have been reported in France and elsewhere. Leaching tests have been performed in the United States. There are thus very few parts of the world where the possibility of AAR can be completely discounted.

5.2.2. Effect of Aggregate Size

Damage has been reported due to reaction occurring in both coarse and fine aggregates, but in many cases, particularly with opaline sands, damage has been the result of reaction in the coarser particles of fine aggregate, i.e. particles in the 2 to 5 mm size range. The effect of the aggregate size has been reported by a number of researchers.

5.2.3. The Pessimum Effect

The maximum expansion seems to depend on a certain proportion of the reactive material, such as silica in the aggregate to the total. This is known as the "pessimum" (as opposed to optimum) content, and can vary from about 3.5 % for a highly reactive aggregate, like opal, up to 10 or 20 % for less reactive materials, over a broad range influenced by the alkali content of the cement in the mixture. It should be noted that not all types of aggregate show a pessimum effect.
When the proportion of reactive silica in the total amount of aggregate is small, the reactive silica, if accessible, will be used up very quickly by the reaction without forming sufficient gel to cause subsequent damage. On the other hand, when the proportion of reactive silica is large, the alkali ion concentration in the pore water is reduced to below a threshold level during setting and hardening of the concrete and subsequently the volume of gel formed does not produce a damaging amount of expansion. Between these extremes there can be a critical or "pessimum" proportion of reactive silica at which maximum expansion of the concrete occurs and is called" the pessimum effect ".

The pessimum proportion of reactive aggregate and expansion it causes varies with the type of reactive silica and with concrete mixture design factors such as the water content and alkali content.

Because highly reactive minerals, such as opal, can show very sharp pessimum curves, while other less reactive minerals produce much flatter curves, or sometimes no apparent pessimum effect at all, and because it is also difficult to determine how much reactive silica is present when it is contained as inclusions in a complex rock matrix, it is impractical to use the pessimum as a means for reducing the possible damage from AAR, although its effects have been observed in practice. For example, there have been cases where a reactive form of flint or chert did not cause damage when used for the whole of the aggregate, but when used in conjunction with a relatively inert limestone or granite coarse aggregate in a similar concrete there was expansion. This probably was due to the pessimum value of reactive chert being more closely approached when used with an inert coarse aggregate, thus lowering the total reactive content.

### 5.2.4. Tests for Reactive Aggregates

With regard to alkali-silica reaction (ASR), several tests are used throughout the world to assess the alkali reactivity of aggregates. These are:

- **ASTM C 289**: “ Standard Test Method for Potential Alkali-Silica Reactivity of Aggregates (Chemical Method)"
- The **ASTM C 295**: “Standard Test Method for Petrographic Examination of Aggregate”
- **ASTM C 586**: “Standard Test Method for Potential Alkali Reactivity of Carbonate Rocks for Concrete Aggregates (Rock Cylinder Method)"
- **ASTM C 441-05**: “Standard Test Method for Effectiveness of Pozzolans or Ground
### Monograph on Alkali Aggregate Reaction

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<th>Test</th>
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<td>Blast-Furnace Slag in Preventing Excessive Expansion of Concrete Due to the Alkali-Silica Reaction”</td>
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<td>• ASTM C 856: “Standard Practice for Petrographic Examination of Hardened Concrete”</td>
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<td>• ASTM C 1105: “Standard Test Method for Length Change of Concrete Due to Alkali-Carbonate Rock Reaction”</td>
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<td>• ASTM C 1293: “Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction”</td>
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<td>• ASTM C 1567: “Standard Test Method for Determining the Potential alkali-silica reactivity of combinations of cementitious materials and aggregate (accelerated mortar-bar method)”</td>
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<td>• AASHTO T 303: “Accelerated Potential Alkali Reactivity of Aggregates (Mortar Bar Method)”</td>
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<td>• AASHTO T 299: “Rapid Identification of Alkali-Silica Reaction Products in Concrete (Also appended to ASTM C 856)”</td>
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<td>• BS 812-123: “Testing Aggregates- Method for Determination of Alkali-silica Reactivity (Concrete Prism Method)”</td>
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<td>• BIS 2386 Part-VII: “Methods of Test for Aggregates for Concrete : Alkali Aggregate Reactivity a) Determination of Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar Bar Method); b) Determination of Potential Reactivity of Aggregates (Chemical Method)”</td>
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<td>• BIS 2386 Part-VIII: “Methods of Test for Aggregates for Concrete : Petrographic analysis”</td>
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<tr>
<td>• Korean Standards, NE Concrete Prism Test</td>
<td></td>
</tr>
</tbody>
</table>

Specific tests may be performed on specific aggregates. Neither of these tests can be relied upon to give reliable results for any aggregates but those for which they were designed.
An examination of past records on the use of the aggregate can give useful information. However, data collected will only be of value if it relates to the use of the aggregate when combined with cement of similar alkali content and used in concrete with mixture proportions similar to those proposed for the new work. It must also be remembered that the characteristics of the aggregate might vary as the quarry or pit is worked out. Problems can be caused by small intrusions or lenses of reactive materials within a quarry of otherwise unreactive material.

While carrying out the examination of an aggregate it must be remembered that no tests, either singly or in combination, will give a definitive indication of what the aggregate's performance will be in actual practice. Tests and other assessments can only provide the evidence to make an engineering judgment on whether to use the aggregate or not, or whether other precautions need to be taken if the aggregate is used.
## Table 1: Minerals, rocks and other substances which are potentially deleteriously reactive with alkalis in cement.

<table>
<thead>
<tr>
<th>MINERALS</th>
<th>ROCKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opal.</td>
<td>Rocks</td>
</tr>
<tr>
<td>Chalcedony.</td>
<td>Reactive component</td>
</tr>
<tr>
<td>Tridymite.</td>
<td>Igneous rocks</td>
</tr>
<tr>
<td>Cristobalite.</td>
<td>Granites, Granodiorites, Charnockites</td>
</tr>
<tr>
<td>Cryptocrystalline, microcrystalline or glassy quartz.</td>
<td>Pumice, Rhyolites, Andesites, Dacites, Latites, Perlites, Obsidians, Volcanic tuffs</td>
</tr>
<tr>
<td>Coarse-grained quartz which is intensely fractured, granulated and strained internally or filled with submicroscopic inclusions of which illite is one of the most common. Silicic, intermediate and basic volcanic glasses.</td>
<td>Basalts</td>
</tr>
<tr>
<td>Vein quartz.</td>
<td>Metamorphic rocks</td>
</tr>
<tr>
<td></td>
<td>Gneisses, Schists</td>
</tr>
<tr>
<td></td>
<td>Quartzites</td>
</tr>
<tr>
<td></td>
<td>Hornfelses, Phillites, Argillites</td>
</tr>
<tr>
<td>Sedimentary rocks</td>
<td></td>
</tr>
<tr>
<td>Sandstones</td>
<td>Strained quartz as above; 5 percent or more chert; opal.</td>
</tr>
<tr>
<td>Greywackes</td>
<td>Strained quartz as above; microcrystalline to cryptocrystalline quartz.</td>
</tr>
<tr>
<td>Siltstones</td>
<td>Strained quartz as above; microcrystalline to cryptocrystalline quartz; opal.</td>
</tr>
<tr>
<td>Shales</td>
<td>Tillite</td>
</tr>
<tr>
<td></td>
<td>Chert</td>
</tr>
<tr>
<td></td>
<td>Flint</td>
</tr>
<tr>
<td></td>
<td>Diatomite</td>
</tr>
</tbody>
</table>
# Monograph on Alkali Aggregate Reaction

<table>
<thead>
<tr>
<th>Argillaceous dolomitic limestones</th>
<th>Dolomite; phyllosilicates exposed by dedolomitisation.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argillaceous calcitic dolostones</td>
<td></td>
</tr>
<tr>
<td>Quartz-bearing argillaceous calcitic dolostones</td>
<td></td>
</tr>
</tbody>
</table>

**OTHER SUBSTANCES**

- Synthetic glass; silica gel
5.3. Cements and Pozzolanic Materials

A means for preventing or minimizing the risk of alkali-aggregate reaction can be found in the most appropriate of the following options where it is not possible to avoid the use of an aggregate containing reactive constituents:

- use low-alkali portland cement so total quantity of alkalis in the concrete mixture lies below a specified limit
- use blended cements
- replace part of the portland cement with finely ground granulated blast furnace slag or pozzolanic materials.

5.3.1. Hydraulic Cements

5.3.1.1. Portland Cements

All commercial Portland cements contain alkalis derived primarily from the raw materials used in the manufacturing process. In recent years the proportion of alkalis has increased with the use of more efficient fume recycling plants, required for conservation and fuel-saving, a practice which is expected to continue.

The alkali content of Portland cement is normally measured as sodium and potassium oxides ($\text{Na}_2\text{O}$ and $\text{K}_2\text{O}$) and is expressed as the "equivalent sodium oxide" content:

$$\text{% equiv. Na}_2\text{O} = \text{% Na}_2\text{O} + 0.658 \times (\text{% K}_2\text{O}).$$

Depending on the type of cement analysis, equivalent sodium oxide can be expressed as acid-soluble or water-soluble % equivalent Na$_2$O.

Portland cements containing less than 0.60 % equivalent sodium oxide are considered to be low-alkali cements. North American experience has indicated that deleterious expansion from alkali-aggregate reaction is not likely to occur as long as the alkali content of portland cement does not exceed the equivalent of 0.60 % Na$_2$O. This was based upon experience with ASR, since caused by amorphous silica and ACR. ASR, since caused by silicates was overlooked until recently.

Expansion potential is a function of the reactivity of the aggregate and of the total quantity of reactive alkalis available per cubic metre of concrete. The safe level for the content of reactive alkalis available in the concrete must be determined experimentally for each combination of aggregate and cementitious materials. It is obvious that the alkalinity of the pore fluid in the concrete is controlled both by the alkali level of the cement and by the amount of cement in the concrete. When alkali sources other than cement are absent, the reactive alkalis available in a portland cement concrete are normally calculated by:
\[ A = \frac{C \times a}{100} \]

Where:
- \( A \) = alkali content of concrete (kg/m\(^3\))
- \( C \) = portland cement content of concrete (kg/m\(^3\))
- \( a \) = acid-soluble alkali content of portland cement expressed as a percentage by weight of Na\(_2\)O equiv.

In fact, any calculation relating to the reactive alkali content of the concrete should consider the variation of both the cement content in concrete and the alkali content in cement. Therefore, the British Guidance Notes published by the British Concrete Society on minimizing the risk of damage to concrete by alkali-silica reaction recommend "\( C \)" as the target mean portland cement content of concrete and that "\( a \)" be the certified average alkali content of portland cement.

According to the Guidance Notes, "\( a \)" can be expressed in the following different ways:

- Acid-soluble alkali content (the average of the last 25 determinations carried out on daily samples prepared in accordance with the British Standards).
- Acid-soluble alkali content which shall not be exceeded (the value of acid-soluble alkali which the cement manufacturers declare will not be exceeded without prior notice).
- Certified maximum acid-soluble alkali content (the value of acid-soluble alkali content which shall not be exceeded for any cement delivery).

Proper allowance also has to be made for alkalis introduced into the concrete by sources other than cement. Alkalis may come from the aggregate, from admixtures, and from brackish water if used as mixing water. The aggregates can be responsible either because of alkali salt contamination or through soluble alkalis release, but the latter event is considered infrequent.

Some safe levels of alkali content of concrete in places are summarized below:

<table>
<thead>
<tr>
<th>Countries</th>
<th>Type of mineral</th>
<th>alkali content</th>
</tr>
</thead>
<tbody>
<tr>
<td>United Kingdom</td>
<td>Reactive aggregates</td>
<td>less than 4 kg/m(^3)</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>aggregates containing opaline silica</td>
<td>safe level of 3 kg/m(^3)</td>
</tr>
<tr>
<td>New Zealand</td>
<td>reactive aggregates</td>
<td>3.5 kg/m(^3)</td>
</tr>
<tr>
<td>USSR, Japanese Industrial Standard, Iranian Standard</td>
<td>reactive aggregates</td>
<td>3 kg/m(^3).</td>
</tr>
</tbody>
</table>

---
Monograph on Alkali Aggregate Reaction

In the case of concretes made with different Malmesbury aggregates (south-western Cape in South Africa), where the active alkali content is taken as the available alkali content of a cement determined according to ASTM C 311-88 but without the addition of calcium hydroxide:

* Above an active alkali content of 3.8 kg Na₂O equiv. per m³, deleterious expansion will occur.
* Below 1.8 kg Na₂O equiv. per m³, the expansion damage is avoided.
* Between 3.8 and 1.8 kg Na₂O equiv. per m³, the degree of expansion depends on the reactivity of the aggregate and the active alkali content of the concrete. Fig. 9, Shows the relation between the active alkali content of cement/ the cement content of concrete and the resultant damage potential of the concrete.

With the orthoquartzites of the Table Mountain Group, the lower and upper limits are 2.5 and 4.5 kg active Na₂O equiv. per m³ of concrete, respectively.

The quantities given for the Malmesbury aggregates and for the orthoquartzites are referred to concrete containing 350 kg/m³ of cement and stored under ASTM C 227 conditions. The aggregate is considered deleteriously expansive if the concrete expands more than 0.05 % at one year of ageing.

It is difficult to show equivalence in the American and British practice as described individually above because these standards have empirical bases. However, in the case where alkali sources other than cement are absent, the British practice is less restrictive than the American.

5.3.1.2. Blended Cements

The alkali content of portland cements is a reliable guide to their potential reactivity in the presence of reactive aggregates, because normally nearly all the alkalis are released during the hydration of the cement. In the case of non-portland cements or blended cements, the total alkali content is no longer a satisfactory guide, because some of the alkali in these materials may be combined in mineral forms incapable of releasing alkali ions into the concrete pore fluid.

The alkali content of these cements, if measured by the normal methods, will include both the alkali in the portland cement and that of blast furnace slag or pozzolanic materials which, with few exceptions, are comparable to or greater than those of portland cement. However it is assumed that the alkalis of these mineral admixtures, being "entrapped" in the hydrated silicates during the hydration process, are not promptly available to promote the alkali-aggregate reaction in the same manner as the alkalis derived from portland cement. Only the small proportion of their alkalis that are water soluble seems to contribute to the alkalinity of the pore solution to the early stages. The value of 0.6 % as equivalent Na₂O usually accepted as the alkali limit for a low-alkali portland cement is therefore not applicable to the blended cement, blast furnace or pozzolanic cement.
In the case of portland blast-furnace slag cements, a distinction is needed between those with a medium slag content more than 50 % and those with a high slag content more than 65 %. To be considered "low alkali" they must meet the following requirements:

- More than 50 % slag, Less than 0.9 % Na₂O equiv.
- More than 65 % slag, Less than 2.0 % Na₂O equiv.

Through a series of expansion tests, an empirical formula was derived for computing an "Effective Alkali" for blast-furnace slag cement, which could be directly compared to the 0.60 % Na₂O equivalent limit for portland cement.

The proposed formula is:

\[
Aff = A[1 - \left( \frac{H}{Ho} \right)^2]
\]

Where:
- A = alkali content of portland blast-furnace slag cement.
- H = slag component in % by weight.
- Ho = an experimental constant representing the slag content, in % by weight, which will not produce any expansion (72 % was found from experimental data to satisfy this condition).

**Fig. 10** shows the relationship of slag content with 0.60 % effective alkali content. All cements that fall below the curved line would behave like portland cements with alkali contents between 0 and 0.60 % Na₂O equivalent.

There is now considerable experience of the use of portland blast-furnace slag cements with some types of reactive aggregates, and although the current recommendations probably are on the cautious side, there are no known instances of deleterious alkali reactions when the above stated limits have been observed.

In the case of portland pozzolanic cements the cement manufacturer should be able to match the characteristics of the particular cement and pozzolan to ensure adequate compensatory action under the conditions of intended use, but, despite accumulated experience with portland pozzolanic cements, the variability in their properties does not yet permit recommendation for their use in minimizing the risk of alkali-aggregate reaction.

Natural pozzolans with optimum properties are not available in all countries, and the importing of material is not always feasible. The use of artificial pozzolans such as suitable fly ash or silica fume is a practical solution. Pozzolanic materials can be added to the concrete on site but,
because proper mixing of such very fine powders is difficult with conventional concrete mixing plant, it should be better undertaken by powder blending techniques.

Proposed blended cements should always be tested before use, by the ASTM C 441-81 testing method and safe alkali limit should regard the alkali content of concrete mixtures.

In order to calculate the total alkali in blended cements it is necessary to know, according to the British Guidance Notes, the acid soluble alkali content of the portland-cement component, the proportions of the blend and the alkali in mineral admixtures. These should be supplied by the cement manufacturer. The real alkali contribution of the mineral admixtures is still a subject of research. Reference could be made to the water-soluble alkali levels, but the reactive content could be significantly higher. The British Cement Makers' Federation recommends that 1/6 of the alkali content of fly ash and 1/2 of the alkali content of blast-furnace slag be considered as reactive alkali.

The amount of reactive alkali derived from blast-furnace slag or pozzolanic material should be included in the total amount of alkali in the concrete by the formula:

\[
A = [C \times \frac{a}{100}] + D
\]

\[
D = E \times \frac{d}{100}
\]

Where,

- \( D \) = equivalent alkali content contributed by blast-furnace slag or pozzolanic material (kg/m\(^3\)).
- \( E \) = target mean blast-furnace slag or pozzolanic material content of the concrete (kg/m\(^3\)).
- \( d \) = average reactive alkali content (%) of blast-furnace slag or pozzolanic material.

5.3.1.3. Ground Granulated Blast-Furnace Slag

Blast-furnace slag is a nonmetallic product, consisting essentially of silicates and aluminosilicates of calcium and other bases that is developed in a molten condition simultaneously with iron in a blast furnace. When a blast furnace is rapidly cooled by immersion in water, a glassy, granular material is formed called granulated blast-furnace slag. This material is then grounded to a fine powder.

In the 1950s the first experimental results demonstrated the effectiveness of blast-furnace slag in reducing the expansion action in high-alkali portland cement, identifying the ideal slag percentage at about 50-60 % by weight of cement. This was later confirmed by other results that
showed the improved behaviour of the cement with blast-furnace slag over normal portland cement, even with the total alkali content being greater in the cement with blast-furnace slag (the total alkali content in blast furnace slag generally varies from 0.2 to 0.3 % as Na$_2$O and from 0.2 to 1.5 % as K$_2$O).

Through the study of numerous cement blends containing from 23 to 65 % slag and embracing a broad range of alkali content, it was shown that the alkalis in slag do not contribute significantly to expansion from alkali-aggregate reaction (Fig. 11). In fact, expansion diminishes rapidly as the blast-furnace slag content rises (Fig. 12). It also has been shown that the expansion diminishes as the slag become finer.

### 5.3.2. Pozzolanic Materials

When the use of potentially reactive aggregate cannot be avoided and a low-alkali portland cement or suitable blended cement is not available, the replacement of part of the Portland cement with finely ground pozzolanic materials can constitute a valid defence against alkali-aggregate reaction.

Natural and artificial pozzolans (fly ash and silica fume) were found to be effective in reducing expansion to an acceptable level due to alkali-aggregate reaction. However investigations have to be made to ascertain the effectiveness of each pozzolanic material and to determine its optimum minimum addition to reactive aggregate. In general this depends on the reactivity of the aggregate and on the quality and composition of the pozzolanic material itself.

#### 5.3.2.1. Natural Pozzolans

Natural pozzolans include certain" incoherent" and "compact" deposits of volcanic origin, highly siliceous rocks which are probably the residues of minerals having undergone considerable chemical change, and siliceous materials composed of the skeletons of living organisms. The best known are the Italian pozzolans, Santorin earth (Greece), the German trasses and the American pozzolans. These deposits are often quite different both mineralogically and chemically. Their primary constituent is silica, but the quantity may vary significantly. The alumina content maybe as high as 20 %, while the calcium content is usually lower. Pozzolans have a least one thing in common: their ability to fix lime which is referred to as “pozzolanic activity”.

"The quantity of alkalis is usually high but, since confirmation on their behavior in relation to the alkali-aggregate reaction is lacking, no limitations on their alkali content is normally indicated, although ASTM C 618-89 prescribe an available alkali content of 1.5 % as Na$_2$O equiv., for the raw or calcined natural pozzolan. Available alkalis refer to the amount of alkalis that are released after curing with calcium hydroxide for 28 days according to ASTM & BIS procedures.

Recent studies have shown that many natural pozzolans are effective in reducing expansion due to alkali-aggregate reaction.
Monograph on Alkali Aggregate Reaction

There seems to be more or less equivalence for all the natural pozzolans, with an optimal pozzolan content of around 30 % by weight of cement. More extensive researches on both mortar and concrete made with natural pozzolana and reactive aggregates should however be carried out to confirm the validity of these results.

5.3.2.2. Fly Ash

Fly ash is a by-product of the combustion of pulverized coal in thermal power plants. It is removed by a dust collection system as a fine particulate residue from the combustion gases before they are discharged into the atmosphere. Fly ash particles are typically spherical, the majority of diameters being less than 45 microns. The chemical composition of fly ash is determined by the types and amounts of mineral matter in the coal. More than 85 % of most fly ashes are composed of chemical compounds and glasses formed of silicon, aluminium, iron, calcium, magnesium and alkali.

Two general classes of fly ash are recognized: high-calcium and low-calcium. High-calcium fly ash is normally produced from lignite or sub-bituminous coals, while low-calcium fly ash is normally produced from bituminous coals. The high-calcium fly ash differs from low-calcium fly ash principally in that it tends, of itself, to be a cementitious material, not requiring the free lime of an already hydrated portland cement to be present.

The effectiveness of fly ash in controlling alkali-aggregate reactivity has been widely reported. Beltane opal, or chert as reactive aggregate in combination with high-alkali portland cement have demonstrated that the expansions are significantly reduced if a sufficient quantity of fly ash (about 30 %) is used. At the same time, test results the alkali content of fly ash must also be taken into account.

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 (Fig. 13). 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 (Fig. 14).

Accordingly, when using fly ash to prevent unacceptable damage in concrete due to alkali-aggregate reaction, it is necessary to look at both the alkali content of the cement and the available alkali content of the fly ash. Although many test results give evidence that supports the thesis that fly ash exercises a specific action against alkali-aggregate reaction.
5.3.2.3. Silica Fume

Silica fume, also known as microsilica, is a byproduct of the reduction of high-purity quartz with coal in electric furnaces in the production of silicon and ferrosilicon alloys. Silica Fume is also collected as a byproduct in the production of other silicon alloys such as ferrochromium, ferromanganese, ferromagnesium, and calcium silicon. Before the mid-1970s, nearly all Silica Fume was discharged into the atmosphere. After environmental concerns necessitated the collection and landfilling of Silica Fume, it became economically justified to use Silica Fume in various applications.

Silica Fume consists of very fine vitreous particles with a surface area on the order of 215-280 ft$^2$/lb (20,000 m$^2$/kg) when measured by nitrogen absorption techniques, with particles approximately 100 times smaller than the average cement particle. Because of its extreme fineness and high silica content, Silica Fume is a highly effective pozzolanic material. Silica Fume is used in concrete to improve its properties. It has been found that Silica Fume improves compressive strength, bond strength, and abrasion resistance; reduces permeability; and therefore helps in reduction in ASR and prevent deleterious expansion due to ASR. Most of the results to date, both in laboratory and in field, indicate that the material is effective even with smaller quantities added than the other pozzolanic materials.

In Iceland, where the alkali-aggregate reaction has been a serious problem, silica fume was used for almost 20 years with excellent results. Fig. 15 (According to the Icelandic practice) gives the expansion curves for mortars containing a reactive aggregate and various amounts of silica fume.

In Iceland 5 to 7.5% silica fume is inter ground with the cement clinkers at the cement plants. In other countries, however, the range of portland cement alkali levels can vary considerably and a more flexible approach is required so silica fume is most often mixed with the other constituents in the concrete mixer.
Figure-9: Relation between the active alkali content of cement/the cement content of concrete and the resultant damage potential of the concrete.

(A) Cement content of Concrete (kg/m³)
(B) Active alkalis in cement (% Na₂O eq.)

1. Innocuous, less than 1.8 kg alkali/m³
2. Potentially deleterious
3. Deleterious, more than 3.8 kg alkali/m³
Figure-10: Influence of blast furnace slag on the alkali limits of cements with low effective alkali content

(A) Na$_2$O equivalent of the cement in weight (%)  
(B) Slag content of the cement in weight (%)  

(1) Field of cements with low effective alkali.
Figure-11: Relations between expansion of mortar prisms and the total alkalies as Na$_2$O content

(A) Expansion of mortar prisms at 3 years (%)
(B) Total alkalies as Na$_2$O contributed by the portland cement component of the blend

(1) Total alkalies as Na$_2$O in the blends range from 0.46 to 1.19 %. (Pyrex glass aggregate)
(2) Total alkalies as Na$_2$O in the blends range from 0.46 to 1.27 %. (Saticoy sand aggregate)
Figure-12: Influence of the clinker/slag ratio on the alkali-reaction

Clinker/total alkali = 1.26
Slag/total alkali= 1.30

(A) Expansion (%)
(B) Slag content (%)
(C) Clinker content (%)

(1) 12 months
(2) 1 month
(3) 14 days
(4) 9 days
Figure-13: Mortar bar expansion test results for mixes made using flyashes having an available alkali content of less than 1.5% (controlled aggregate)

(A) Expansion at 6 month (%)
(B) Cement replaced, % by weight

(1) Flyash available alkalies
(2) Cement total alkalies
Figure-14: Mortar bar expansion test results for mixes made using flyashes having an available alkali content of more than 1.5% (controlled aggregate)

(A) Expansion at 6 month (%)
(B) Cement replaced, % by weight

(1) Flyash available alkalies
(2) Cement total alkalies
Figure-15: Rhyolite (R) and silica fume (SF) versus mortar bar expansion

(A) Expansion (%)
(B) Age (years)

(1) OPC
(2) OPC + 10% R
(3) OPC + 5% SF
(4) OPC + 15% R
(5) OPC + 7.5% SF
(6) OPC + 10% SF
(7) OPC + 25% R
(8) Requirement as per Iceland code


5.4 Controlling Alkali-Carbonate Reaction using Pozzolanic Materials

The use of ground blast-furnace slags and pozzolanic materials as admixtures for portland cements or in blended cements have been widely proved to be effective in controlling alkali-aggregate reaction involving siliceous aggregates. However, on the contrary, few experimental results are available for ACR. A case in which the addition of 30 % oil-shale ash to cement showed a reduction of expansion due to alkali-carbonate reaction has been reported, but experimental studies have found pozzolans were not effective for controlling ACR; it may be due to the quality of the pozzolans tested were not suited for that purpose and the pozzolanic reaction was found too slow to prevent dedolomitization.

A general guide for cements in preventing the alkali-carbonate reaction could be the use of low-alkali cements (probably 0.40 % of Na₂O equiv. or lower), as recommended by ACI.

5.5 Lithium Compounds to Control ASR in New and Existing Concrete Structures

The use of lithium compounds has been known to be effective in controlling ASR induced expansion for about 50 years. There have been only limited field applications. In the past 10 years, however, there has been renewed interest in using lithium as either an admixture in new concrete or as a treatment for existing structures. Lithium compounds have proven to be effective in both new and post treating hardened concrete that has already expanded from ASR, thereby reducing or eliminating future expansion.

What is Lithium

Lithium is an alkali metal found in Group IA of the periodic table and has an atomic number of 3. Lithium is a soft, silver-white metal and is the lightest dense metal, with a density about half that of water (0.53 g/cm³). Lithium is a very reactive metal because of its tendency to expel its outer electron (it has a valence of +1). It does not occur freely in nature, but rather it is bound in stable salts or minerals.

Commonly produced lithium compounds include Lithium carbonate (Li₂CO₃), lithium hydroxide (LiOH), lithium hydroxide monohydrate (LiOH•H₂O), lithium chloride (LiCl), lithium fluoride (LiF), Lithium Nitrate (LiNO₃) and Lithium Sulphate (Li₂SO₄).

The studies have been carried out by using all above Li based salts. An important trend in recent years has been the emergence of LiNO₃ as the preferred lithium compound in controlling ASR. Stokes et al. (1997) reported that a major advantage of LiNO₃ over other lithium compounds is that LiNO₃ does not increase the pH of the pore solution, thereby eliminating the risk of the pessimum effect as described earlier. Using LiNO₃ avoids this effect because its addition to cement paste results in an increase in the lithium and nitrate ion concentrations of the pore solution with no significant increase in the OH⁻concentration (Stokes et al., 1997). Another
important advantage of using LiNO\textsubscript{3} as an admixture is that it is closer to a neutral pH than other lithium compounds, making it safer to handle.

5.5.1 Use of Lithium Compounds in New Concrete

Lithium based compounds can be used in new concrete as admixture for preventing ASR Performance-based guidelines are presented in this section.

5.5.1.1 Performance-based Guidelines for using Lithium Compounds in New Concrete

Laboratory performance tests emphasizes determining the appropriate dosage of lithium to use in combination with a given reactive aggregate, either with or without the combined use of SCMs, especially fly ash and slag. The performance testing described in the ASTM C 1293 (Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction), provides practitioners with the necessary tools to determine lithium dosages required to suppress expansion and represents an alternative to prescriptive recipes.

Clearly, there is not a trend between aggregate reactivity, as it is typically defined, and the response of an aggregate to lithium treatment, making it difficult to integrate aggregate reactivity into prescriptive guidelines. Based on a review of literature, a molar ratio Li:(Na + K) of 0.74 has been found to suppress expansion for the majority of aggregates, and a wider range of molar ratios, from 0.60 to 0.90, essentially brackets the range of lithium dosages needed to control expansion for the aggregate-lithium combinations reported in literature. For a given aggregate, a lower dosage of LiNO\textsubscript{3} is needed to control expansion, compared to other forms of lithium. a minimum LiNO\textsubscript{3} dosage of 0.74 will be recommended for all aggregates. Dosages higher or lower than this value may be used provided that previous testing was performed using ASTM C 1293. The efficacy of lithium in reducing expansion is a strong function of aggregate reactivity (i.e., more reactive aggregates require more lithium), and that using fly ash in conjunction with lithium yielded synergistic reductions in expansion.

Prescriptive Guidelines for using Lithium Compounds in Concrete

- These guidelines are valid only for concrete mixtures with a total alkali content less than 5 kg/m\textsuperscript{3}.
- When using concrete without supplementary cementitious materials (SCMs), a molar ratio Li:(Na + K) of 0.74 should be used, unless previous testing has demonstrated that lower dosages are effective or higher dosages are necessary. A molar ratio of 0.74 equates to 4.6 L of 30 percent LiNO\textsubscript{3} solution per kg of Na\textsubscript{2}O.
- When using concrete with high-calcium fly ash (CaO > 15 percent) or slag, a molar ratio of 0.74 is recommended, based only on the alkalies in the portland cement. Thus, the total lithium dosage in the concrete will be reduced in proportion to the level of replacement of Portland cement.
- When using concrete with low-calcium fly ash and where the level of replacement of the fly ash is equal to or greater than 15 percent (by mass of total cementing materials), a molar ratio of 0.56 (75 percent of the typical 0.74 molar ratio) is recommended, based only on the
alkalies in the portland cement. Thus, the amount of lithium required is reduced not only by the dilution effect (replacing cement with fly ash), but also by the synergistic effect of combining low-lime ash with lithium. If the level of fly ash replacement is less than 15 percent, a molar ratio of 0.74 is recommended, based on the alkalies in the portland cement.

5.5.2 Use of Lithium Compounds in Existing Concrete

Although the parameters that affect the efficiency of lithium-based compounds as chemical admixtures for controlling expansion due to ASR in new concrete have been established by laboratory studies and confirmed by field evaluations, the efficacy of these products in terms of treating existing ASR-affected concrete have not been established so far. However, it is clear from laboratory studies that treating small samples with lithium can reduce expansion (e.g. Stokes et al., 2000), but data are lacking from field cases. Although a number of structures have been treated in the field (especially topical applications of lithium to pavements and bridge decks) there is no unequivocal evidence to demonstrate that these treatments have been successful, or indeed, that the treatment has had any beneficial impact. In most cases, this is due to the failure to implement appropriate monitoring programs to evaluate the effect of the treatment.

Lithium treatment will only address the problems related to future ASR deterioration. Clearly, it will not reinstate the concrete to its original condition, and if the deterioration present is likely to contribute to other deterioration processes, such as freeze-thaw or corrosion (by allowing access to chloride ions), then these problems have to be addressed separately. This may be achieved by sealing the cracks or applying an overlay.

5.5.3 Methods

There are three types of methods of application of Li based compounds viz. electrochemical extraction, vacuum impregnation, and topical treatment. Selection of these methods is depends on types of concrete structures/elements affected by ASR in different environments.

The success of topical treatments with lithium compounds is likely to be influenced by a number of parameters, including:

- The lithium compound being used.
- The rate of application and the number of treatments.
- The temperature and moisture content of the concrete at the time of treatment.
- The quality of the concrete (e.g. permeability).
- The thickness of the element being treated.
- The extent of deterioration at the time of treatment. The presence of other deterioration process (e.g. freeze-thaw).

Many of these factors will, of course, affect the amount of lithium that infiltrates the concrete and the lithium's effective penetration depth.
There are two things to consider about the application rate: (1) if the application rate is too high, the solution may run off the surface to be treated, resulting in waste (and possibly increasing environmental concerns), and (2) under certain conditions, solution ponded on the surface may evaporate, precipitating LiNO$_3$ salt on the treated surface, which may lead to reduced surface friction of trafficked surfaces. Experience has indicated that the optimum application rate for most cases is in the range of 0.16 to 0.40 liters of 30 percent LiNO$_3$ solution per square meter of concrete surface. A number of other controls may be necessary, and the following points are reproduced from a recent specification to serve as an application:

- Clean the surface before the treatment (e.g., by using a road sweeper).
- Ensure that the surface is free of loose sand, debris, and similar materials, but it need not be dry.
- Do not apply the treatment during periods of rain, or if rain is expected within 6 hours.
- A final coverage rate of the treatment shall not exceed 0.37 l/m$^2$.
- Apply the treatment at least twice.
- Each application shall not exceed 0.20 l/m$^2$ with each application.
- Individual applications shall be applied at least 30 minutes apart.
- The application rate shall be adjusted to provide uniform surface coverage, such that the material does not run off the surface.
- If a white residue covers more than 5 percent of the applied surface area due to evaporation, water shall be applied to the surface.

It is expected that concrete with a high permeability that has been subjected to prolonged periods of drying before treatment will more readily absorb the solution applied to the surface. Also, a thin section with a high surface area to volume ratio will permit a greater volume of the concrete to be infiltrated. However, these conditions clearly cannot be controlled.

6.0 DIAGNOSIS AND ASSESSMENT OF DAMAGE

6.1. General Criteria

AAR generally manifests itself as cracking on the surface of the concrete or as expansion of the mass of concrete. There are many causes of concrete cracking and expansion and both cracking and evidence of expansion can take a number of forms, none of which is distinctively indicative of AAR. AAR cannot be positively identified by visual inspection alone.

A reliable diagnosis can only be made after a detailed examination of the site, the records of materials and methods used in the construction and the subsequent history of the concrete, and examination of samples taken from the concrete in the laboratory.

Alkali reactivity is often not an isolated phenomenon. Alkali-silica gel can be observed in sound concrete, so that the presence of alkali-silica gel in the concrete cannot be taken as conclusive evidence that AAR is the cause of any cracking which has taken place. The investigation of cracked, or otherwise deteriorated concrete, should begin with the assumption that the deterioration might be due to any of the many possible causes. The deterioration should not be
attributed to anyone cause until every other cause has been eliminated.

Only a general description of the diagnosis and assessment of damaged structures has been attempted here.

6.2. Site Inspection

Site inspection should include an examination of the construction records, and any other information on the history of the structure and the environment since construction. Such records often indicate whether AAR or some other phenomenon may possibly have occurred. Other older concrete structures in the local geographic region should also be examined and their material sources ascertained to the extent possible so that comparisons can be drawn.

Cracking is the most common sign of AAR. In large, lightly stressed masses of unreinforced concrete, the cracks are most likely to appear in a semi-random, 3-armed star pattern joining up to form a hexagonal grid of cracks.

The cracks can be very wide on the surface but often do not penetrate far into the concrete. The concrete surface adjacent to cracks sometimes has a different colour from the main body of the concrete. Reinforcement may change the pattern, with the cracks often reflecting the line of the reinforcing bars below the surface.

High stresses in the concrete, such as in heavily loaded columns can also create different crack patterns with cracks forming at right angles to the stress, i.e. along the length of the member. This also happens in prestressed concrete members where longitudinal cracks following the direction of the tendons are often seen.

General expansion of the concrete may also be apparent. This will show itself by the closure of expansion joints, with the extrusion of jointing and sealing materials and sometimes spalling of the concrete near the joints. Relative displacement of adjacent concrete blocks and the sticking or jamming of moving parts attached to the concrete, such as gates and other machinery also may be seen.

Many authorities quote the exudation of gel from cracks in the concrete as a sign of AAR. The absence of gel on the surface should not, however, be taken as evidence to discount the presence of AAR. In the UK, for example, it is very rare for gel to be found exuding from the surface of concrete cracked due to AAR. However, the presence of copious exudations of calcium carbonate formed from calcium hydroxide leaching from the hydrated cement paste is common on water retaining structures subject to seepage. Alkali-silica gel also carbonates on exposure to air and becomes almost indistinguishable from the normal calcium carbonate deposits. Pop outs also are often reported as a sign of AAR but, often, they may be entirely absent. Where pop-outs occur in the UK they are likely to have been caused by frost action.

The deterioration of the concrete and the structure should be carefully assessed in relation to various phenomena capable of causing such defects. This, together with the observations from
site records, will indicate whether AAR might be among the phenomena to be investigated by laboratory testing which should be the next stage in the diagnosis.

6.3. Sampling

6.3.1. Sampling scheme

The precise plan for sampling will depend on the details of the structure, its degree of deterioration, variability of the construction materials, access and many other factors, but, in general, ASTM C-823 should be followed.

The concrete in many structures or their elements will not be uniform, but contain areas of varying quality of concrete so sufficient samples should be taken to produce representative results for analysis.

6.3.2. Types of Samples

Samples should, whenever possible, be taken by coring with the size of the core determined by the maximum size of aggregate.

Where the diameter of the core has to be limited, a greater number of cores should be drilled so as to build up a more accurate picture of the internal condition of the concrete. Some cores should be drilled through cracks to determine their depth of penetration. Samples should not be taken by knocking off lumps of concrete. This may cause internal fracturing and other damage which will bias the results of subsequent investigations. Immediately after cores have been extracted they should be wrapped in layers of thin plastic sheet and sealed inside a plastic bag so that they can be brought in the laboratory with the same moisture content as when drilled.

6.4. Laboratory Examination and Tests

6.4.1. General Approach

Concrete samples can be examined and a number of tests performed to determine whether AAR has been the cause of deterioration or expansion. Tests of component materials prior to design of the concrete mixture are generally applicable to assessing problems, as well. In general, the provisions of ASTM C-823 should be followed as a starting point.

6.4.2. Preliminary Examination

When received in the laboratory, cores should be unwrapped and observed as they dry out. If they have already dried they can be wetted under running tap water. If gel is present, it often will show as damp patches on the surface of the concrete as the sample dries. The pieces of broken core should be re-assembled and photographed.
6.4.3. Examination of Sawed Surfaces and Thin Sections

Petrographic thin sections should be made and examined by a skilled petrographer, experienced in the examination of concrete. In North American practice this is done in accordance with ASTM C-856.

Considerable information may be obtained from the examinations of particles of cement clinker, calcium hydroxide crystals, carbonation, voids, aggregate mineralogy, cracking and gel. These observations will provide an understanding of the materials, mixtures and quality of the concrete. Thin sections will also permit direct examination of the alkali-aggregate reaction products, if any, and their form, distribution and frequency.

Considerable information can be obtained from the examination of sawed and polished surfaces of the concrete samples. This includes descriptions of aggregates, detection of cracks, and evaluation of mixture proportions. If the concrete is impregnated with fluorescent dye before sawing and polishing, microcracks will show up when examined under ultra-violet light. The observation of extensive microcracking will indicate that expansion of the concrete has taken place (but not necessarily that the expansion was caused by AAR).

6.4.4. Alkali Content of Hardened Concrete

Measuring the alkali content of the concrete is useful but can also lead to mis-interpretation if the alkali has leached out. However, if it can be said with confidence that the original alkali content of the concrete was low and that little or no alkali was extracted from the aggregates then the concrete probably has not suffered from AAR.

6.4.5. Expansion Testing

Cores can be kept at a relative humidity of 100 % and at appropriate temperature, say 38°C, and their expansion measured periodically. The results can provide useful information on whether any reaction is exhausted or whether there is a possibility of further expansion. The reaction may have ceased due to the depletion of the alcalis. Any remaining reactive silica, however, may be detected by storing the specimens in a sodium hydroxide solution and measuring the expansion.
7.0 MITIGATING ASR IN EXISTING CONCRETE

When ASR-induced expansion and damage already has manifested itself in a field structure, there are some available techniques that can help extend the service life of the structure, as described in detail in CSA A684-00, Guide to the Evaluation and Management of Concrete Structures Affected by Alkali-Aggregate Reaction. To minimize future damage to such structures:

- Provide adequate or improved drainage (to minimize availability of moisture).
- Apply claddings or coatings to further limit moisture ingress. Application of flexible epoxy coatings, elastomeric acrylic or cementitious coatings and or geo-membranes can be used for this purpose.
- Treat existing cracks to minimize future expansion (and direct moisture ingress, deicing salts, etc.). The cracks can be treated by injecting flexible epoxy or chemical grouts.
- Avoid future use of deicing salts that will increase alkali content within the structure.
- Restrain or confine expansion of structural element.
- Chemically suppress ASR using lithium compounds.
- Remove seriously affected portion of concrete if required and repair with fresh one.

8.0 LABORATORY TESTING

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:

i) Petrographic Examination
ii) Rapid Chemical Test
iii) Mortar Bar Test
iv) Concrete Prism Test
v) 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:

vi) Accelerated Tests
vii) Scanning Electron Microscopy (SEM), and Infra Red Spectroscopy (IR).
All the above tests are briefly described below.

### 8.1 Petrography

A petrographic examination of the aggregate can yield useful information and should always be made when attempting to assess an aggregate source. ASTM C 295-85 covers "standard Practice for Petrographic Examination of Aggregates". An experienced petrographer may be able to supply sufficient information about potential reactivity of aggregates. In the conventional case, the identification of the reactive minerals present in the rock is done but in the case of strained quartz in quartz bearing aggregates, the undulatory extinction angle and the percentage of quartz grains strained are measured by the optical microscope.

Alan D. Buck, based on his research work, established that aggregates containing more than 20% strained quartz with undulatory extinction angle greater than 15° are reactive.

### 8.2 Rapid Chemical Test

ASTM C 289 and IS:2386 (Part VII)-1963 prescribes a quick chemical method for determination of potential reactivity of an aggregate with alkalies in Portland cement concrete as indicated by the amount of reaction during 24 hours at 80°C between 1N sodium hydroxide solution and aggregate that has been crushed and sieved to pass 300 micron IS sieve and retained on 150 micron IS sieve. The amounts of silica dissolved (Sc) and reduction in alkalinity (Rc) determined. The values of Sc and Rc are plotted on a graph and compared with data given in the standard 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.16 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 drawback 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.

### 8.3 Mortar Bar Test

The ASTM C 227 and IS:2386 (Part VII)-1963 "Mortar-bar" test is perhaps the most useful single test for determination of potential alkali reactivity of aggregates, but it may take many months before any significant results are obtained. In this test a sample of the aggregate is crushed and mixed with high alkali cement and water to produce a standard mortar which is cast into bars 25 x 25 x 285 mm. These are kept in saturated air at 37.8° C (100° F) and their lengths measured periodically.
No expansion criteria have been prescribed in the relevant Indian Standard for declaring an aggregate as deleterious. However, ASTM C 227-81 prescribes that expansion is generally considered to be excessive if it exceeds 0.05% at 3 months or 0.10% at 6 months. Expansions greater than 0.05% at 3 months should not be considered excessive where the 6-month expansion remains below 0.10%. Data for the 3 month tests should be considered only when 6-month results are not available. This method is suitable only when the aggregates are containing conventional deleterious minerals which can cause expansion in concrete and is not adequate to judge the deleterious expansion potential due to the presence of strained quartz in the aggregate.

8.4 Concrete Prism Test

The concrete prism test (CSA A23.2-14A) was developed in Canada and can be used with a high degree of confidence to identify potential alkali-carbonate reactive aggregates and to evaluate the effectiveness of using low alkali cement and other potential corrective measures. The test has also been used successfully for late-expansive siliceous aggregates & lime-stones containing reactive silica. The concrete prism test specimens of 3 x 4 x 16 in. (76.2 x 101.6 x 406.4 mm) size, which are stored at 23°C ± 1.7°C in a moist room with free water on the entire surface area at all times, are monitored for length change after 7, 14, 28, 56, 84, 112 & 128 days moist storage and at 6 month interval thereafter.

Linear expansions of about 0.03% or more indicate potentially deleterious reactivity. For concrete that will be subjected to moist environment for most of its service life and where expansion will cause distress in adjacent concrete i.e., a bridge deck, expansion should be considered excessive if it exceeds 0.02 percent at 3 months. For concrete in a relatively dry environment for most of its service life, expansion should be considered excessive if it exceeds 0.04 percent at 3 months.

Some rock types continue to expand well beyond 3 months period and, where possible, expansion measurements should be continued beyond 3 months until expansion has virtually ceased.

8.5 Rock Cylinder Test

This method as per ASTM C 586-81 covers determination of the expansive characteristics of carbonate rocks while immersed in a solution of sodium hydroxide (NaOH) at room temperature. This method is used for carbonate rocks but has been used for siliceous aggregates also. This method is essentially used for preliminary screening of aggregate sources to indicate the presence of material with a potential for deleterious expansion when used in concrete.

Test specimens used are in the form of right circular cylinders with conical ends, with overall length of 35±5 mm and a diameter of 9±1 mm, but square prismatic specimens can also be used. The length of the specimens is measured after 7, 14, 21 & 28 days of immersion in 1N NaOH solution and at 4-week intervals thereafter. If the test continues beyond 1 year, the measurements are taken at 12-week intervals. As per ASTM C586, expansions in excess of 0.10 percent are taken as indicative of chemical reaction warranting further testing in concrete; however, the minimum period of immersion for this criterion is not specified. It should be noted that ASTM has a more recent standard C 1105 for the study of the Alkali-Carbonates Reaction directly on Concrete Samples.
8.6 Accelerated Tests

For rocks containing strained quartz, the aggregates must be tested in the accelerated test condition. These tests are briefly described below. This method has been accepted by the Canadian Standard Organization, and on a trial basis by the ASTM.

8.6.1 Testing at 60°C & 90% Relative Humidity

Alan D. Buck has proposed that the mortar bar test should be made using sand containing quartz or quartzite pebbles from gravel per bar with storage temperature of 60°C and relative humidity 90%. Length change criteria to declare aggregate containing strained quartz as potentially reactive are a minimum of 0.025% and 0.040% at 6 & 12 months respectively.

8.6.2 Testing at 80°C in 1N NaOH Solution for 22 Days

Oberholster et al. have proposed an accelerated method for testing aggregates containing strained quartz. In this method, the mortar prisms are prepared in accordance with ASTM C 227-87. The prisms are demoulded after 24 hours, then immersed in water in a closed container which is placed in an oven & kept at a constant temperature of 80°C. After 24 hours in the oven, the prisms are removed to a room with a temperature of 23°C, and before significant cooling takes place, their lengths are measured using a vertical comparator accurate to 2 micron. This reading is used as the zero reading. After the initial reading, the prisms are totally immersed in a 1N NaOH solution kept at 80°C. This solution is stored in a tightly covered plastic container, not corroded by caustic solution. The prisms are then measured each working day over 14 days at a room temperature of 23°C and their linear expansion calculated. The average expansion of the triplicate prisms for each day is then calculated; if none of the values differs from the mean by more than 15%, the repeatability is considered satisfactory. The average expansion after 12 days is taken as the reference value for assessing potential alkali reactivity. The lower limit of expansion for deleterious aggregates is taken as 0.11% at 12 days.

Shayan et al. have indicated that the accelerated method proposed by Oberholster et al. needs modification. They have found that this accelerated method is able to identify reactive aggregates in 10 to 22 days. They have stipulated that a lower limit of 0.1% expansion at 22 days would identify aggregates with a longer induction phase, whereas 0.1% expansion at 10 days is adequate for identification of aggregates with a short induction phase.

8.7 Scanning Electron Microscopy (SEM) and Infra Red Spectroscopy (IR)

Some institutions investigated the applicability of the above techniques to the aggregates containing strained quartz. The aggregate specimens after prolonged exposures to NaOH and KOH solutions at elevated temperature are examined under SEM and IR.

The image is formed in an SEM by scanning an electron beam across a sample and collecting some signal from the beam-sample interaction, which is used to control the intensity of the spot
8.8 ASR Kit

It is a simple colored dye field test to detect Alkali Silica reaction (ASR)

**Method:** Simply apply each of the two reagents (yellow reagent and pink reagent) to the broken surface of a concrete core drilled in a suspect structure and rinse off the excess. On ASR contaminated concrete, the resultant stains reveal the presence of ASR. The stain’s distribution shows the extent of ASR in the concrete, and their proximity to different components of the aggregate gives clues to the source of trouble. The two gels that are identified—one staining yellow, the other pink—indicate the stage of ASR’s progression. Yellow signals that degradation has begun. Pink warns that degradation is advancing. Typically, ASR occurs in cracks and these cracks often cut through the aggregate and usually do not follow the aggregate-paste boundaries. ASR tends to fill air voids.

**Advantages:** In contrast to the two established methods of ASR detection petrographic analysis and uranyl acetate analysis, ASR Detect has numerous benefits. Because the reagent stains are clearly visible even before the treated sample dries, a complete diagnosis is possible in less than 5 minutes. ASR Detect systems are relatively inexpensive. Petrographic analysis requires shipment to a laboratory, adding time and raising the costs per sample, also the uranyl acetate reagent is almost prohibitively expensive. ASR Detect is simple enough to use in the field. Its reagent stains are visible to the naked eye and are distinctive enough to be recognized and interpreted by anyone with minimal training.

**Applications:** ASR Detect is both a practical and a scientific tool. It’s principal application is analyzing existing concrete structures. By identifying ASR deterioration in its earliest stages, ASR Detect facilitates the problem being identified when remediation techniques can be applied; for example, treating the concrete with a lithium-bearing solution to inhibit further deterioration. Where deterioration is advanced, ASR Detect provides a clear picture of the extent and depth of the damage. As a scientific tool, ASR Detect can be applied to improving the understanding of where, how and why ASR occurs. That understanding is basic to developing ASR preventatives that allow high-alkali cements or poor-quality aggregates to be used in concrete mixes without risking the development of ASR.

**Technical:** ASR Detect was developed by Los Alamos National Laboratory as part of its ongoing effort to characterize concrete degradation mechanisms and to improve concrete durability. ASR Detect exploits the cation-exchange and compositional properties of ASR gels to pinpoint ASR degradation in a chemically specific way. Most gels contain cations (positively charged atoms or molecules) that readily exchange with other cations in solution. ASR Detect’s two reagents react with cations found in the two gels associated with ASR. The first reagent exchanges sodium with the potassium found in some ASR gels and then reacts to form a bright yellow precipitate. The second reagent reacts with calcium-rich ASR gel to form a bright pink stain. In concrete containing ASR, the result is a brightly colored surface showing the presence of the targeted gels; concrete with no ASR is unaffected.
8.9 Uranyl-acetate Treatment

The uranyl-acetate treatment is a method that helps to detect alkali-silica gel on polished and broken surfaces of concrete specimens; it also has been used to detect ASR gel in field structures. By applying a uranyl-acetate solution to a surface containing the gel, the uranyl ion substitutes for alkali in the gel, thereby imparting a characteristic yellowish-green glow when viewed in the dark using short wavelength ultraviolet light. ASR gel fluoresces much brighter than cement paste due to the greater concentration of alkali and, subsequently, uranyl ion in the gel.

The uranyl-acetate treatment procedure requires experienced technicians for correct interpretation. The test does not differentiate between a harmless presence of gel or reactivity and one that is detrimental. Not all florescence indicates ASR gel. For example, some aggregates fluoresce naturally. In addition, uranyl ions can be absorbed on cement hydration products and appear as broad, faint areas of fluorescence. Neither of these conditions is an indication of ASR gel. Furthermore, positively identifying gel by this technique does not necessarily mean that destructive ASR has occurred. The test is ancillary to more definitive petrographic examinations and physical tests to determine concrete expansion. The uranyl-acetate treatment procedure must not be used alone to diagnose ASR. Because of the potentially hazardous nature of the product, preparing, using, and handling the uranyl-acetate solution should be done cautiously, following appropriate health and safety procedures.

8.10 Other Tests

Other tests may also be used, such as the gel-pat, or alkali-immersion test which can be very helpful in indicating the presence of reactive aggregate particles.

In the gel-pat test a sample of the aggregate is cast into a concrete sample which is then diamond-sawn and the surface lapped flat to give a smooth test surface. The sample is then immersed in a strong sodium and potassium hydroxide solution saturated with lime. Reactive aggregate particles may be expected to show themselves by the formation of gel on their surfaces. This will normally occur in less than 28 days.

The short summary of some of the tests are given in Table-2.
Figure-16: Illustration of Division Between Innocuous and Deleterious Aggregates on Bases of Reduction in Alkalinity Test

- Aggregates causing mortar expansion more than 0.1 percent in a year when used with a cement containing 1.38 percent alkali.
- 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.
Table-2: The brief details of some of the tests are given below:

<table>
<thead>
<tr>
<th>Test Name</th>
<th>Purpose</th>
<th>Type of Test</th>
<th>Duration of Test</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM C 227, Potential alkali-reactivity of cement-aggregate combinations (mortar-bar method)</td>
<td>To test the susceptibility of cement-aggregate combinations to expansive reactions involving alkalis</td>
<td>Mortar bars stored over water at 37.8°C (100°F) and high relative humidity</td>
<td>Varies: first measurement at 14 days, then 1, 2, 3, 4, 6, 9, and 12 months; every 6 months after that as necessary</td>
<td>Test may not produce significant expansion, especially for carbonate aggregate. Long test duration. Expansions may not be from AAR.</td>
</tr>
<tr>
<td>ASTM C 289, Potential alkali-silica reactivity of aggregates</td>
<td>To determine potential reactivity of siliceous aggregates</td>
<td>Sample reacted with alkaline solution at 80°C (176°F).</td>
<td>24 hours</td>
<td>Quick results. Some aggregates give low expansions even though they have high silica content. Not reliable.</td>
</tr>
<tr>
<td>ASTM C 294, Constituents of natural mineral aggregates</td>
<td>To give descriptive nomenclature for the more common or important natural minerals—an aid in determining their performance</td>
<td>Visual identification</td>
<td>Short duration—as long as it takes to visually examine the sample</td>
<td>These descriptions are used to characterize naturally-occurring minerals that makeup common aggregate sources.</td>
</tr>
<tr>
<td>ASTM C 295, Petrographic examination of aggregates for concrete</td>
<td>To outline petrographic examination procedures for aggregates—an aid in determining their performance</td>
<td>Visual and microscopic examination of prepared samples—sieve analysis, microscopy, scratch or acid tests</td>
<td>Short duration—visual examination does not involve long test periods</td>
<td>Usually includes optical microscopy. Also may include XRD analysis, differential thermal analysis, or infrared spectroscopy.</td>
</tr>
<tr>
<td>ASTM C 342, Potential volume change of cement-aggregate combinations</td>
<td>To determine the potential ASR expansion of cement-aggregate combinations</td>
<td>Mortar bars stored in water at 23°C (73.4°F)</td>
<td>52 weeks</td>
<td>Primarily used for aggregates.</td>
</tr>
<tr>
<td>ASTM C 441, Effectiveness of mineral admixtures or GBFS in preventing excessive expansion of</td>
<td>To determine effectiveness of supplementary cementing materials in controlling expansion from ASR</td>
<td>Mortar bars—using Pyrex glass as aggregate—stored over water at 37.8°C (100°F) and high relative humidity</td>
<td>Varies: first measurement at 14 days, then 1, 2, 3, 4, 5, 9, and 12 months; every 6 months after that as</td>
<td>Highly reactive artificial aggregate may not represent real aggregate conditions. Pyrex contains alkalis.</td>
</tr>
<tr>
<td>Table Title: Monograph on Alkali Aggregate Reaction</td>
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<tr>
<td></td>
<td>concrete due to alkali-silica reaction</td>
<td>humidity</td>
<td>necessary</td>
<td>Specimens can be examined with stereomicroscopes, polarizing microscopes, metallographic microscopes, and scanning electron microscope.</td>
</tr>
<tr>
<td>ASTM C 856, Petrographic examination of hardened concrete</td>
<td>To outline petrographic examination procedures for hardened concrete—useful in determining condition or performance</td>
<td>Visual (unmagnified) and microscopic examination of prepared samples</td>
<td>Short duration — includes preparation of samples and visual and microscope examination</td>
<td></td>
</tr>
<tr>
<td>ASTM C 856 (AASHTO T 299), Annex uranyl-acetate treatment procedure</td>
<td>To identify products of ASR in hardened concrete</td>
<td>Staining of a freshly-exposed concrete surface and viewing under UV light</td>
<td>Immediate results</td>
<td></td>
</tr>
<tr>
<td>Los Alamos staining method (ASR Kit)</td>
<td>To identify products of ASR in hardened concrete.</td>
<td>Staining of a freshly-exposed concrete surface with two different reagents.</td>
<td>Immediate results</td>
<td></td>
</tr>
<tr>
<td>ASTM C 1260 (AASHTOT303), Potential alkali reactivity of aggregates (mortar-bar method)</td>
<td>To test the potential for deleterious alkali-silica reaction of aggregate in mortar bars</td>
<td>Immersion of mortar bars in alkaline solution at 80°C (176°F)</td>
<td>16 days</td>
<td></td>
</tr>
<tr>
<td>ASTM C 1293, Determination of length change of concrete due to alkali-silica reaction (concrete prism test)</td>
<td>To determine the potential ASR expansion of cement-aggregate combinations.</td>
<td>Concrete prisms stored over water at 38°C (100.4°F)</td>
<td>Varies: first measurement at 7 days, then 28 and 56 days, then 3, 6, 9, and 12 months; every 6 months as after that as necessary</td>
<td></td>
</tr>
<tr>
<td>Accelerated concrete prism test (modified ASTM C 1293)</td>
<td>To determine the potential ASR expansion of cement-aggregate combinations.</td>
<td>Concrete prisms stored over water at 60°C (140°F)</td>
<td>3 month (91 days)</td>
<td></td>
</tr>
<tr>
<td>ASTM C 1567, Potential alkali-</td>
<td>To test the potential for</td>
<td>Immersion of mortar bars in</td>
<td>16 days</td>
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</tbody>
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### 9.0 INTERPRETATION OF LABORATORY TESTS

Aggregates and other concrete constituents shall be tested in accordance with the above specified methods before a concrete construction is taken up. Out of the above tests, any or some of the methods can be performed as per the site conditions or requirements.

Also, in existing concrete, causes of distress and extent of damage can be accessed by above methods in a concrete structure so that appropriate remedial measures can be taken up.

The presence of cracks will be indicative of the occurrence of AAR, but there may be the other causes of distress as mentioned earlier. However, the exact cause of cracks or distress can be assessed on the basis of above test methods.

### 10.0 RECOMMENDATIONS

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.

Many concrete surfaces in large dams and their appurtenant works will inevitably be in direct contact with water. Considering that concrete has a 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.
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.

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

a) Is the aggregate potentially deleterious?

b) How much alkali will be brought into the system by each of the materials to be used?

### 11.0 CASE STUDIES

### 11.1 Projects from India

**Hirakud Dam**

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Country</strong></td>
<td>India</td>
</tr>
<tr>
<td><strong>Location and Type</strong></td>
<td>Composite structure of earth, concrete and masonry across river Mahanadi upstream of Sambalpur (Orissa)</td>
</tr>
<tr>
<td><strong>Size of Main Dam</strong></td>
<td>4800 m long (1148.5m of concrete and masonry and rest 3651.5m earth)</td>
</tr>
<tr>
<td><strong>Dykes</strong></td>
<td>21 km on both left and right sides</td>
</tr>
<tr>
<td><strong>Spillway</strong></td>
<td>600m on left and 750m on right side.</td>
</tr>
<tr>
<td><strong>Power dam</strong></td>
<td>282.8m on the right flank.</td>
</tr>
<tr>
<td><strong>Sluices</strong></td>
<td>64 Nos. under sluices and 34 Nos. crest bays</td>
</tr>
<tr>
<td><strong>Year of Built/ Completion and first filling</strong></td>
<td>1956</td>
</tr>
<tr>
<td><strong>Type of Structure</strong></td>
<td>Gravity Dam</td>
</tr>
<tr>
<td><strong>Height of Structure</strong></td>
<td>40 m</td>
</tr>
</tbody>
</table>
Monograph on Alkali Aggregate Reaction

<table>
<thead>
<tr>
<th>Type of Coarse/fine Aggregate</th>
<th>diorite, granite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement and Additives</td>
<td>normal</td>
</tr>
<tr>
<td>Equivalent Alkali in Cement</td>
<td>&gt;0.6</td>
</tr>
<tr>
<td>Type of Reaction</td>
<td>ASR</td>
</tr>
<tr>
<td>Type of Damage to the Structure</td>
<td>spalling, spillway gate jammed, cracking</td>
</tr>
<tr>
<td>Time to Initial Deterioration</td>
<td>30 years</td>
</tr>
<tr>
<td>Repair or Replacement</td>
<td>chemical grout of cracks and inst. of anchors</td>
</tr>
</tbody>
</table>

Materials used for construction

**Cement:** OPC obtained from two different sources. The major supply from the source, Orissa Cements Ltd., Rajgangpur. (data on alkali content not available)

**Fine aggregate:** Sand collected from river Mahanadi with F.M. varying from 2.2 to 2.6

**Coarse aggregate:** Crushed rock obtained from Laxmi Dungri and Chiplima Quarries as well as river shingles from right wing of Mahanadi River.

**Distress Noticed:**

The following manifestations of distress were observed and experienced since 1974 nearly 18 years after completion of the dam:

- Horizontal cracks in the operation gallery, gates haft, sluice barrel and to a small extent in the foundation gallery in all right spillway block. Width of cracks varying from hair cracks to a max. of 6 to 9 mm at the surface. Some of the cracks were found to extent to a maximum depth of about 2 meter. Extensive horizontal cracking on the U/S face of the dam with width of cracks up to 12mm.
- Deflection in the Adit gallery in block No. 47.
- Buckling of embedded frame of manhole opening on the roadway slab over pier in block No. 35.
- Shearing and Snapping of bolts fixing the guide rails of sluice gates.
- Buckling of steel frame fixed above collapsible gate in entrance of operation gallery.
- Horizontal cracks at various levels on the D/S face of right spillway and vertical cracks in two blocks viz. No. 37 & 38 and the width of cracks increasing slowly.
- Binding of radial crest gates.

**Studies carried out on Concrete:**

A petrographic examination and Scanning Electron Microscope study carried out on concrete obtained from the locations where alkali silica reaction was noticed reveals that; River shingles/ quartzite pebbles used in concrete shows occurrence of cryptocrystalline silica
like chert and chalcedony as well as diorite and granite. Presence of grano-diorite in crushed rock aggregate was identified as reactive. These owed their reactivity mainly to strained quartz having undulatory extinction.

Also, an examination on hardened concrete reveals that the concrete has adequate cement content and not attacked by sulphate, acid waters etc. Concrete core samples from the right spillway were found to have undergone alkali silica reaction. The presence of such deleterious reaction being manifest by the occurrence of white, translucent to opaque reaction products on the surface of the aggregate, in the cracks and voids in the concrete, dark reaction rims and alteration of the borders of aggregate.

**Rihand Dam**

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Country</td>
<td>India</td>
</tr>
<tr>
<td><strong>Project Location and Type</strong></td>
<td>Concrete gravity Dam, located on river Rihand (UP)</td>
</tr>
<tr>
<td><strong>Size</strong></td>
<td>934.5m long and 91.46m high</td>
</tr>
<tr>
<td><strong>Year of Built/Construction period</strong></td>
<td>1954-1962</td>
</tr>
<tr>
<td><strong>AAR Noted in Year</strong></td>
<td>1972</td>
</tr>
<tr>
<td><strong>Type of Structure</strong></td>
<td>Gravity Dam</td>
</tr>
<tr>
<td><strong>Height of Structure</strong></td>
<td>93 m</td>
</tr>
<tr>
<td><strong>Type of Coarse Aggregate</strong></td>
<td>granite, gneiss, (muscovite, biotite reach)</td>
</tr>
<tr>
<td><strong>Cement and Additives</strong></td>
<td>15% fly ash</td>
</tr>
<tr>
<td><strong>Equivalent Alkali in Cement</strong></td>
<td>0.6 - 1.8</td>
</tr>
<tr>
<td><strong>Signs of AAR</strong></td>
<td>gel, rims</td>
</tr>
<tr>
<td><strong>Type of Reaction</strong></td>
<td>ASR</td>
</tr>
<tr>
<td><strong>Type of Damage to the Structure</strong></td>
<td>cracking</td>
</tr>
<tr>
<td><strong>Time to Initial Deterioration</strong></td>
<td>10 years</td>
</tr>
<tr>
<td><strong>Repair or Replacement</strong></td>
<td>epoxy grouting; spillway gates, cranes, stoplog gates repaired</td>
</tr>
</tbody>
</table>

**Materials used for Construction**
Cement: OPC obtained from Churk Cement Works, UP. (Record of Alkali content, Na$_2$O equivalent, as high as 1.8%)

Sand: Blend of crushed sand mixed with river sand having F.M. of 2.3 to 2.9

Coarse aggregate: Obtained from Makra quarry which consisted mostly of granite and granite gneiss rock.

Pozzolana: Bokaro flyash to replace 15% by weight of cement.

Admixtures: Indigenous AEA, developed at Rihand Laboratory. P.H. commissioned in 1962.

Distress Noticed:

The following manifestations of distress were observed and experienced since 1972 nearly 10 years after completion of the dam:

- Longitudinal cracks on U/S face (RL- 830ft). Mostly along the lift joints and minor cracks between lift joints. Width of cracks varied from 1mm to 25mm and approximate depth of cracks at various locations were found to vary from 7cm to 45cm by ultrasonic pulse velocity test. Horizontal cracks have also been observed in the walls of the foundation gallery, the sluice operating gallery and the hoist operating gallery.

- Horizontal and vertical cracks observed in scroll casing wall of all the six generating units.

- Cracks in all the 24 columns of penstock gallery. In one column in 1984, nine out of ten 45mm dia. Bars snapped.

- Map cracking in the spillway piers and radial gate pedestals.

- Horizontal and vertical swaying of the gantry crane rails of the power house thereby rendering the crane out of use.

- Vertical cracks at abutments adjacent to spillway crest.

- Cracks in passenger and freight elevator shafts.

- Cracks at tainted gate pedestals.

- Tilting and deformation of draft tube structure and cracking of generator supports.

Operational Problems:

- Going out of alignment of rails of gantry crane of draft tube deck slab.

- Fouling of spillway gates with their wall guides creating difficulty in operation of spillway gates.

- Fouling of the cage of the passenger and freight lift with walls of the elevator shaft.

- Difficulty in operation of draft tube gates due to shifting of guide rails.

- Improper sealing of gates of intake structure.

- Ripping of the generating units due to reduction in vertical labyrinth clearance.

Studies carried out:

Aggregates obtained from the body of the dam and also from the quarry contained strained quartz and alkali feldspar. Investigations carried out on concrete cores by electron microscopy.
reveal the presence of alkali aggregate reaction. Concrete core samples in both the main dam as well as power house structure were found to have undergone alkali silica reaction. The presence of such deleterious reaction being manifest by the occurrence of gel type products inside the concrete. Dark and white reaction rims and alteration of borders of aggregates and presence of micro cracks in the mortar phase as examined visually, petrographically and in the scanning electron microscope. Long term observations up to 200 days in moist alkaline environment indicated further expansion of concrete core samples of the order of 0.1%.

11.2 Projects from Other Countries

Kouga Dam, South Africa

Kouga Dam (formerly Paul Sauer Dam), is a 78m (256 ft) high, 317 m (1040 ft) long, double curvature arch dam completed in 1969. In 1981, an evaluation of the monitoring program revealed that the dam crest was rising slowly with the center of the crest also moving slowly upstream (Elges et al. 1995). The movements, which amounted to 8 mm vertical movement at the time, were suspected to be the results of AAR. A further investigation, which included laboratory testing of concrete cores, concluded the expansion measured in the dam is caused by the alkali-aggregate reaction. The cement used for the construction of the dam is regarded as high-alkali cement. The geodetic measurements taken twice a year from 1972 to date, indicate a continuous expansion trend since 1976. The expansion now amounts to a total upward displacement of 22 mm. A crack on the upstream side indicates that the spillway has suffered more severe AAR, and that the bulging of the spillway sill has raised its level between 25 to 45 mm. Since 1984 expansion appears to be decreasing, but it is not clear whether AAR is decreasing or the successive and prolonged periods of low water levels are responsible for the reduction.

Santa Luzia, Portugal

This thin cylindrical arch dam with a maximum height of 76 m (250 ft) and a crest length of 115 m (377 ft) was completed in 1943. The expansion due to AAR was detected from the continuous upstream and upward movements of the crest (Ramos et al., 1995). Since the first filling of the reservoir, geodetic and alignment measurements have been used to monitor such movements. The maximum upward displacement of the crest accumulated over a period of 40 years is reported to be about 50 mm. During the same period the maximum upstream movement has reached 30 mm. The mineralogical and Petrographic analyses conducted on the dam concrete samples showed that AAR has occurred from the reaction between the reactive silica provided by cataclastic quartz, and the alkalis supplied by feldspars aggregates ("auto-reaction"). Apart from providing the necessary alkaline environment, the low-alkali-content cement has little value to the reaction. Ongoing deformation monitoring, periodic ultrasound pulse velocity tests, and structural analysis are being considered for better characterization of AAR and its effects on the long-term performance of the dam.

Alto-Ceira Dam, Portugal
Monograph on Alkali Aggregate Reaction

Completed in 1949, Alto-Ceira is a thin arch dam with a maximum height of 37 m (121- ft) and a crest length of 120 m (394-ft). Shortly after the first filling of the reservoir, the dam began experiencing increasing movements in the upstream and upward directions, accompanied with extensive cracking both in the upstream and downstream faces of the dam (Ramos et al., 1995). Numerous studies including visual inspections, mapping of cracks, core testing, and petrographic analysis of concrete samples were conducted to identify the source and effects of such expansion on the operation and safety of the dam. The studies concluded that alkali-silica reactions are responsible for the expansion. It was determined that the reactions occur among quartz and metapelite aggregates containing reactive silica, feldspar aggregates as a supplementary source of alkalis, with the cement providing the alkaline environment necessary for the reaction. In such cases, the presence of alkalis in feldspar aggregates creates "auto-reaction" conditions (Ramos et al. 1995), in which the expansion may continue indefinitely. The measured deformations and 3D finite-element analysis of the dam indicate that expansion has now advanced to the entire dam. Recent ultrasound pulse velocity tests showed significant deterioration of the concrete; and a survey of cracks indicated that major cracks have reached a depth of about 60 cm (2-ft). Ongoing expansion continues at approximately constant rate, which if not reduced, inevitably might adversely affect the operation and possibly the safety of the dam.

Horse Mesa, Arizona

The 93 m (305 ft) high Horse Mesa Dam with a crest length, including the abutment spillways, of 201 m (660 ft), is a thin arch dam completed in 1927. Located about 65 miles northeast of Phoenix, the dam impounds Apache Lake on the Salt River in central Arizona. After the discovery in 1946 of AAR problems at Stewart Mountain Dam, cores were taken from the Horse Mesa Dam. Tests showed AAR has occurred, but to an insignificant degree. Additional cores taken in 1968 indicated no deterioration of the concrete and produced satisfactory compressive strength. The reaction has caused typical surface cracking and minor expansions in the dam concrete with permanent deformations of the arch without affecting the integrity of the dam. Also, there appears to be disbanded lift joints as evident by seepage passing along the downstream face of the dam. At the present time, the dam crest is deforming approximately 0.25 mm/year (0.01 inch/year) upward, and between 0.25 and 0.75 mm/year (0.01 and 0.03 inch/year) upstream (Veesaert and LaBoon 1995).

Owyhee, Oregon

Constructed between 1928 and 1932, Owyhee Dam is a concrete thick-arch structure with a maximum height of 127 m (417 ft) and a crest length of 183 m (600 ft). Deterioration and cracking of concrete, which first appeared in 1948, is continuing and is thought to be caused by AAR (Veesaert and LaBoon 1995). An investigation conducted in 1988 concluded that AAR is occurring at varying degrees in the dam. It is strong in the upper and outer portions of the dam, and only mild to non-existent in the lower and deep interior portions. According to Veesaert and LaBoon (1995), a monitoring program began in 1985 shows an upstream movement at an average rate of 9 mm/year (0.37 inch/year) near the center of the dam, with much slower upward movements averaging less than 2 mm/year. Ongoing visual and instrumentation monitoring
Monograph on Alkali Aggregate Reaction

indicate dramatic increase in seepage when the reservoir water level is near or above elevation 2650 ft (crest El. 2675 ft), probably because of significant cracking in the upper 50 to 75 ft of the dam which has occurred as a result of AAR. Although AAR cracks and seepage through the concrete reduce sliding resistance, the computed large factors of safety indicate that the relatively thick gravity-type sections of Owyhee Dam tend to preclude this type of failure.

Fontana Dam, United States

The Dam is a gravity-type concrete structure, 480 ft (146.3 m) high, located in North Carolina, USA. This dam, constructed in the early 1940s, began cracking distress in about 1972. At that time a 4-year program of investigation, analysis, and repair was undertaken. Results revealed that the cracking resulted from stresses caused by both thermal and AAR expansions in the concrete. The primary reactive rock type is a metagraywacke to quartzite aggregate. In the laboratory, concrete samples were subjected to a variety of temperature and moisture conditions to determine the rate and magnitude of growth from AAR. Definite proof of growth was established, but neither the potential magnitude of growth nor the point where the specimen was on the growth spectrum could be detected on a given sample. Cracked blocks in the dam were strengthened by post tensioning and grouting. However, the principal method for relieving the high stresses was the cutting of a 100-ft (30.5-m) deep slot at the contraction joint between the last straight block of the main body of the dam and the first curved block. The slot was constructed by drilling a series of overlapping 5-in. (127 mm) holes. Monitoring since this work was completed confirms the effectiveness of the slot to prevent further cracking during warm seasons.

Matilija Dam, United States

This dam located near the central California coast, USA, is a 190-ft (58-m) high, thin arch dam constructed in 1947. The dam has experienced some foundation problems, having been located on highly sheared and fractured sandstones and shales. In spite of these serious foundation problems, it was the alkali-aggregate reaction of the local aggregates in the dam concrete that was responsible for the ultimate demise of the structure. When the dam was scarcely 20 years old, the State of California ordered that the central portion of the dam be cut away so that the remaining storage would amount to only a few hundred acre feet. Petrographic analyses identified the reactive components of the aggregate to be shales present in the coarse fraction of the fine aggregate. The remaining concrete has now started expanding.

Stewart Mountain Dam, United States

It is a 207-ft (63.1-m) high, thin arch concrete dam flanked by concrete thrust blocks, was constructed during 1928-1930 near Phoenix, Arizona, USA. Field reports as early as 1937 reported excessive movements and cracking on the downstream face, on thrust blocks, and elsewhere. Deflections were sufficient to require severing reinforcing between the dam and powerhouse located at the downstream toe. Laboratory tests conducted in 1943 on cores extracted from the dam confirmed that the concrete was experiencing a phenomenon described
as alkali-aggregate reaction. The reactive aggregate particles in the concrete were glassy to
cryptocrystalline volcanic materials of andesitic to rhyolitic composition. Crest deflections were
monitored almost continuously from the time of construction until recently when reconstruction
was begun. Data show that expansion from AAR continued rapidly and almost linearly from
1930 until about 1950. After the mid-1950's, the rate of expansion was very modest with little or
no expansion occurring in the last few years. Expansion of the concrete over the years due to
AAR forced the crest of the dam, at midpoint of the arch, upstream about 10 in. (254 mm).
During the same time period, the dam crest elevation rose about 5 in. (127 mm). The dam is
currently undergoing a major rehabilitation. Among other work, post tensioning cables installed
in the arch, generally vertically with the lower anchorage in sound bedrock, to restore the
structural integrity of the dam.

**Beauharnois Project, Quebec Province, Canada**

The project was completed at different stages from 1932 through 1960. It has a 2720-ft (829-m)
long powerhouse with a concrete gravity wing dam located at each end. Movements and
cracking have been experienced in all of the project structures for years. The cause of these
deformations has been attributed to alkali-silica reaction. Concrete expansion has caused
cracking of concrete at the base of certain piers of the powerhouse intakes and within the
powerhouse administration building. Misalignment of some of the generating units has also
occurred. Remedial measures have included installation of stressed cables in the right wing dam
(1970-1971), opening of a slot by line drilling (1972-1973), and other means of structural
separation.

**Mactaquac Generating Station, New Brunswick, Canada**

Alkali-aggregate reaction also occurred in the concrete of Generating Station. This 600-MW
power project includes a rockfill dam and a concrete powerhouse. The concrete structures were
built during 1964-1968. The graywacke aggregate and the alkalies in the cement (0.7 percent
Na₂O equivalent) have reacted causing destructive expansions and attendant high stresses. The
aggregate was thoroughly analyzed during preconstruction and met all ASTM criteria at that
time. Openings in some of the horizontal and vertical construction joints caused by the AAR
expansion were first discovered in the mid-1970s. In 1982 fractures were noted in the east pier of
the spillway. Operation of the spillway gate was impeded. High stress and strain rates were
measured. In 1988, a ½ inch (13-mm) wide saw cut was made through the intake to relieve
stresses in the east end pier.

**11.3 Project Where Remedial Measures Taken at Preconstruction Stage**

**TALLOWA DAM – SHOALHAVEN SCHEME, AUSTRALIA**

**Introduction**
Prior to the construction of the Tallowa Dam, an investigation of the properties of the aggregate proposed for use was undertaken by the Snowy Mountains Engineering Authority (SMEC), starting in 1969. Because the aggregate was found to have the potential for alkali aggregate reaction (AAR), it was decided to use fly ash in the concrete in conjunction with Type C (low heat) cement. The cement had an alkali content of less than 0.6% \( \text{Na}_2\text{O} \) equivalent. At that time it was considered that the Type C cement was adequate to resist the alkali aggregate reaction potential. The fly ash was included as an additional safeguard. Concrete was to have a design compressive strength of 2000lb/in\(^2\) (14 MPa) at one year. The objective of this case study is to review some of the test data generated, particularly in regard to AAR and to revisit the dam after a quarter of a century.

**Alkali Aggregate Reaction**

Tests were carried out in accordance with ASTM C441, Standard Method of test for effectiveness of mineral admixtures in preventing excessive expansion of concrete due to the alkali-aggregate reaction. Five samples of fly ash were evaluated with three samples of high alkali control cement. Experience with the ASTM C441 test has shown that it is unusual to get such significant reductions in expansion as were obtained in this series. It is not surprising that the decision was made to use fly ash in the project.

**Follow-up Testing**

During 1995 cores were drilled from the dam crest and from the floor of the lower gallery by Sydney Water Corporation after 20 years of service. Tests conducted on these cores were reported by Shayan, Diggins & Ivanusec as Case Study of Fly Ash Concrete in Tallowa Dam Containing Alkali-reactive Aggregate. By visual inspection, the cores were found to be sound. No evidence of reaction between aggregate and cement could be seen. Microscopic examination of thin sections revealed potentially reactive strained quartz in both greywacke and quartzite, in addition to the reactive chert detected before construction. Accelerated tests were conducted on mortar bars made from samples of the aggregate reclaimed from the cores, which confirmed the potentially reactive nature of the rocks when results were compared with criteria developed by Shayan. Prisms sawn from the cores were soaked in caustic soda solution at 40 deg C. After 14 weeks they showed expansion ranging from 0.005 to 0.015%, compared to about 0.2% for the mortar bars. It was demonstrated with the present day test that the Type C cement alone would not have been sufficient to overcome the alkali aggregate reaction potential. The authors concluded that the use of a suitable fly ash is very beneficial to the long-term performance of field concrete structures. The fly ash concrete in Tallowa Dam has performed well in the past 20 years and is expected to continue this performance in the future. In the Tallowa Dam Project, the incorporation of fly ash provided inexpensive insurance against the disruptive expansion of AAR. In many areas, this insurance can be achieved at no additional cost at all therefore it is a powerful incentive to specify the use of fly ash concrete.
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BIS 2386 Part-VII: “Methods of Test for Aggregates for Concrete : Alkali Aggregate Reactivity a) Determination of Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar Bar Method); b) Determination of Potential Reactivity of Aggregates (Chemical Method)”