

# Diagnosis and Control of Alkali-Aggregate Reactions in Concrete

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## Introduction

Aggregates containing certain constituents can react with alkali hydroxides in concrete. The reactivity is potentially harmful only when it produces significant expansion (Mather 1975). This alkali-aggregate reactivity (AAR) has two forms—alkali-silica reaction (ASR) and alkali-carbonate reaction (ACR, sometimes called alkali-carbonate rock reaction, or ACRR). ASR is more often a concern than ACR because the occurrence of aggregates containing reactive silica minerals is more common. Alkali-reactive carbonate aggregates have a specific composition that is not very common.

Alkali-silica reactivity has been recognized as a potential source of distress in concrete since the late 1930s (Stanton 1940 and PCA 1940). Even though potentially reactive aggregates exist throughout North America, ASR distress in structural concrete is not common. There are a number of reasons for this:

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

To reduce ASR potential requires understanding the ASR mechanism; properly using tests to identify potentially reactive aggregates; and, if needed, taking steps to minimize the potential for expansion and related cracking.

Alkali-carbonate reaction in concrete was not documented until 1957. Although ACR is much less common, this report also briefly reviews the mechanism, visual distress symptoms, identification tests, and control measures.

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## Alkali-Silica Reaction

### MECHANISM OF ASR

Concrete consists of aggregates—stone or gravel and sand, in a matrix of cement paste. The cement paste contains interconnected microscopic pores through which water or ions in solution can migrate. The pore water in concrete is an alkaline solution; the measure of alkalinity is pH.<sup>†</sup>

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. The reaction can be visualized as a two-step process:<sup>††</sup>

1. Alkali + reactive silica → alkali-silica gel
2. Alkali-silica gel + moisture → expansion

The presence of gel does not necessarily indicate destructive ASR. Some gels expand very little or not at all. If a gel is low swelling, it will not create problems. High-swelling gel may cause pressures exceeding the tensile strength of concrete, which results in cracking of the concrete. Rate of migration of pore fluids to the reaction site and temperature also influence swelling pressures (Diamond, Barneyback, and Struble 1981). Consequently, the presence of gel must be linked to destructive cracking for a positive identification of harmfully expansive ASR.

<sup>†</sup> pH is approximately calculated from the concentration of hydroxide ions (OH<sup>-</sup>) in the solution. The pH of concrete pore solution is at least 12.5, at which point the solution is in equilibrium with calcium hydroxide (Ca(OH)<sub>2</sub>), an abundant hydration product present in concrete. The pH of the concrete pore solution increases as the alkali content of the cement increases. Alkalies, sodium (Na) and potassium (K), in concrete are primarily derived from cementitious materials. The alkali salts dissolve in the pore solution and increase its alkalinity.

<sup>††</sup> Hydroxide, alkali, and calcium ions react with silica in the aggregate particle to form a gel. Reactive silica dissolves in the high-pH solution. The dissolved silica reacts with alkalies and calcium to form a calcium-alkali-silicate-hydrate gel. The gel has a tendency to swell by absorbing water from the surrounding paste. The swelling gel forms the initial cracks in the aggregate and cement paste. Microcracks form near the reaction sites, which propagate and join to form large cracks and an overall expansion of the concrete. ASR gels of certain characteristic composition and viscosity have swelling properties. The characteristic composition has not been accurately established. Initially, gel containing less calcium, however, will swell to a greater extent. As the gel moves through concrete, it picks up more calcium, which reduces its swelling potential.



## Factors Affecting ASR

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

- reactive forms of silica in the aggregate
- high-alkali (pH) pore solution
- sufficient moisture

The amount of gel formed in the concrete depends on the amount and type of reactive silica, and the alkali hydroxide concentration in the concrete pore solution. Natural aggregates contain various forms of silica minerals, which have varying reactivities—measures of the readiness of the silica to react with alkali. Internal sources of alkali (sodium and potassium) can come from the cement, pozzolans, aggregates, admixtures, and mix water. When the alkali and silica react, they form the gel reaction product. External alkalies can come from a number of sources, but the predominant source is anti-icing or deicing chemicals. Exact composition will vary, but the gel always contains alkali, calcium, silica, and water (Xu 1987).

**Reactive silica in the aggregate.** Reactivity is a function of the type and form of constituents composing the aggregate. \*\* Silica minerals in aggregates are generally stable if crystalline and reactive if amorphous, but there are exceptions. For instance, there are a few common crystalline forms of silicon dioxide: quartz, tridymite, and cristobalite. Quartz, unless it is microcrystalline or highly strained, is stable. Tridymite and cristobalite are crystalline also, but are low density, porous materials, and are susceptible to attack from alkali hydroxides. An aggregate that presents a large surface area for reaction—poorly crystalline, many lattice defects, amorphous, glassy, micro-porous—is susceptible to reaction (Poole 1992).

The constituent minerals of an aggregate are obtained from a petrographic analysis. The following rock types contain critical amounts of potentially reactive forms of silica: chert and flint containing chalcedony; acidic and intermediate volcanic rocks, such as rhyolite, dacite, latite, and andesite, and the associated porphyries and tuffs; shale and slate; sandstone, siltstone, and quartzite; siliceous carbonate rocks; graywackes; argillites; phyllites; granites and grano-diorites; granite and grano-diorite gneisses. The list is not all inclusive, and many aggregates listed will perform adequately in concrete that contains more than enough alkali to promote ASR. Fine and coarse aggregate containing more than the following quantities of constituents are considered potentially reactive (adapted from NRMCA 1993):

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

See also ASTM C 33 (AASHTO M 6/M 80), C 294, C 295, and Table 1 of this document.

**High-alkali-content pore solution.** Alkali hydroxides in solution will react readily with reactive forms of silica in aggregate. As the aggregate

reactivity increases, gel reaction products can be formed with lesser concentrations of alkali. That is why use of low-alkali cements alone may not be sufficient to control ASR with highly reactive aggregates.

As the pH, or alkalinity, of the pore solution increases, potential for the alkali-silica reaction increases. At higher concentrations of alkali hydroxides, even the more stable forms of silica are susceptible to attack (Xu 1987). If the alkali concentration is great enough, the alkali hydroxides break stronger silicon bonds found in less reactive aggregates to form the gel reaction product. This explains why aggregates thought to be nonreactive sometimes exhibit ASR.

Repeated cycles of wetting and drying can create high localized concentrations of alkalies. As moisture travels through concrete, dissolved alkalies move in solution, remaining when the moisture evaporates from the concrete surface. This process, known as alkali migration, can cause high alkali concentrations at an evaporative surface even when the overall concrete alkali content is low.

**Sufficient moisture.** Moisture allows migration of alkali ions to reaction sites, and the resulting gel absorbs moisture, leading to expansion. For this reason, deleterious ASR does not occur in concretes that are dry in service. Research has shown that expansive ASR can occur in concrete having a relative humidity above 80% (Stark 1991). However, it is possible for well cured concrete in arid regions to have a relative humidity constantly at or above 80% just beneath its surface, even after several decades (see Fig. 1).

Any reduction in permeability, by using a low water-cement ratio, supplementary cementitious materials (SCMs), or other means, reduces movement of moisture and alkalies into and within the concrete. Stark found that sealed lower water-cement ratio (0.35) concretes expanded less than higher water-cement ratio concretes at ages up to 19 months (Stark 1995a).

**Concrete alkali content.** The potential for ASR increases as the alkali content of concrete increases. For example, a concept used in Canada addresses the total alkali “loading” in concrete. Using field performance as a guide, alkali limits are established in concrete to control ASR. The approach is most applicable with concretes using portland cement as the sole cementitious material. However, it can also be applicable, with refinement, to concrete containing supplementary cementitious materials.

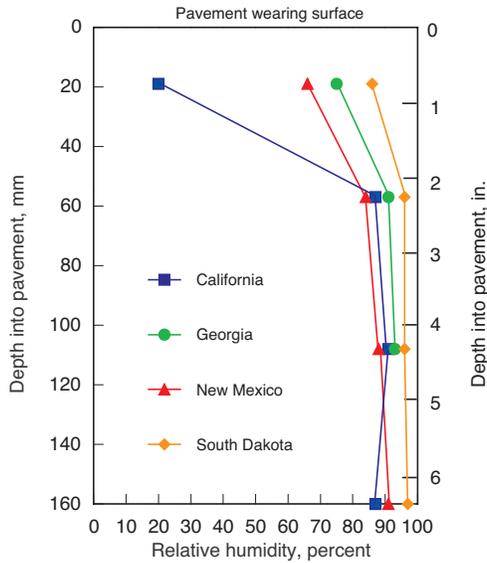
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\*\* Reactive minerals: Silica, SiO<sub>2</sub>, can exist in a variety of textures and crystalline structures. Forms of silica are generally related to the rate at which volcanic magma cooled during formation of the rock. Forms of siliceous minerals in aggregates range from amorphous or glassy (non-crystalline) to cryptocrystalline, microcrystalline, and crystalline, listed in order of decreasing cooling rate. During the formation of quartz crystals, some strain may be introduced. This strain can be seen under a microscope under polarized light. Aggregate containing strained quartz tends to be reactive. Cristobalite and tridymite are crystal forms of silica that exist at higher temperatures and are “frozen” as such due to rapid cooling. These crystal forms are unstable (metastable) at normal temperatures, and rocks containing them are reactive. Opal is an amorphous form of silica with a variable amount of water in its structure. It is a very reactive form of silica. ASTM C 294 contains a description of silica minerals.

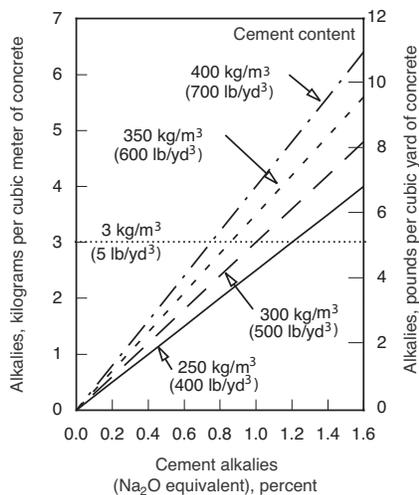
The reactivity of silica is related to the degree of order in the crystal structure. The forms vary from very reactive silica glass or opal to nonreactive unstrained quartz. One of the convenient ways of classifying silica minerals is as follows:

- metastable group: opal, tridymite, cristobalite, intermediate glass (52%-66% SiO<sub>2</sub>), acid glass (more than 66% SiO<sub>2</sub>)
- quartz: cryptocrystalline quartz; microcrystalline quartz; chalcedony group, which includes chalcedony, agate, chert, flint, and jasper; and optically strained or fractured quartz.

Aggregates containing silica minerals in the metastable group typically react more rapidly than those in the quartz group.



**Figure 1. Relative humidity versus depth of concrete for pavement in various climates. (Stark 1993).**



**Figure 2. Alkalies (as Na<sub>2</sub>O equivalent) per cubic meter (cubic yard) of concrete as a function of cement alkali and cement content.**



**Figure 3. This parapet wall has been severely affected by ASR. Notice the cracking, joint closing, spalling of concrete surfaces, and lateral offset that have developed. (IMG12295)**

Ideally, the concept of total alkali loading should include the alkalis from all of the concrete ingredients. However, it is common to include only the alkalis from the cement, and sometimes other cementitious materials, in the determination because alkali contribution from other ingredients is usually small. Therefore, total alkali content of concrete is calculated as follows:

$$(\text{kg cement/m}^3) \times (\% \text{ Na}_2\text{O equivalent}^{++} \text{ in cement})/100 = \text{kg alkali/m}^3$$

$$(\text{lb cement per yd}^3) \times (\% \text{ Na}_2\text{O equivalent in cement})/100 = \text{lb alkali/yd}^3$$

*Note: If supplementary cementitious materials are present, a portion of their alkalis may be added to this equation. In certain European countries, such as the United Kingdom, the effective alkali content is the summation of the total sodium oxide equivalent for portland cement, natural pozzolan, and silica fume, and a percentage of the total sodium oxide equivalent for fly ash and slag (17% for fly ash and 50% for slag). Other countries, such as Canada, do not include the alkalis in supplementary cementitious materials in the calculation. See also the section on limiting concrete alkalis.*

When potential for ASR exists, the accepted allowable limits for alkali content of concrete used in Canada range between 1.8 kg/m<sup>3</sup> and 3.0 kg/m<sup>3</sup> (3.0 lb/yd<sup>3</sup> and 5.0 lb/yd<sup>3</sup>), based on aggregate reactivity, size of concrete element, and environment (CSA-A23.1 2004). Fig. 2 shows the total alkali content of concrete for various cement alkali levels and cement contents, along with a 3.0 kg/m<sup>3</sup> (5.0 lb/yd<sup>3</sup>) limit.

In the United States, the method often used to control the concrete alkali content is to specify a low-alkali cement (defined in ASTM C 150 [AASHTO M 85] as having an equivalent sodium oxide content of no more than 0.60%). However, concrete made with low-alkali cement can still exhibit expansive ASR if moisture movement concentrates the alkalis in one location (Perenchio, Kaufman, and Krause 1991); if the aggregate is extremely reactive; if alkalis are provided by certain supplementary cementitious materials and chemical admixtures, as well as from the aggregates and mixing water; or if total alkali content of concrete is high due to a high cement content. Alkalies from external sources (discussed below) can also contribute significantly to the concrete alkali content.

**External alkalis.** External alkalis may increase expansion due to ASR, especially when concrete is cracked or is highly permeable (Grattan-Bellew 1992). Common sources of external alkalis are deicing salts, seawater, groundwater, and water from industrial processes. In particular, use of pavement deicers can contribute significantly to alkalis. Sodium chloride deicing salt solutions and seawater can provide virtually unlimited amounts of alkali (Helmuth 1993). Immersing concrete prisms containing reactive aggregates in a sodium chloride solution has demonstrated increases in expansion and deterioration of the concrete, especially at elevated temperatures (Swamy and Al-Asali 1987, and Stark 1995). Certain nonchloride anti-icers and deicers, such as potassium acetate or sodium formate, are currently being investigated regarding their effect on ASR.

There are ways to reduce the ingress of external alkalis. In addition to proper handling, placing, and curing of concrete, the use of supplementary cementitious materials and a low water-cementitious materials ratio will reduce concrete permeability, slow the entrance of external alkalis, and reduce potential ASR expansion. Protective coatings and sealers provide a barrier to seawater, deicing salts, and other alkali sources. In some cases, regular cleaning of the structure might be worthwhile so that unwanted

<sup>††</sup> The total (acid soluble) alkali content of portland cement includes both sodium oxide (Na<sub>2</sub>O) and potassium oxide (K<sub>2</sub>O), but is conventionally expressed as equivalent sodium oxide as follows: Na<sub>2</sub>O equivalent = Na<sub>2</sub>O + 0.658(K<sub>2</sub>O). Sodium and potassium oxides may be determined as part of chemical tests by methods in ASTM C 114. The Na<sub>2</sub>O equivalent is typically reported on a mill test report.

salts are carried away before they have a chance to enter the concrete and contribute to reaction. Unfortunately, some of these may not be practical solutions for structures such as pavements.

**Wetting and drying.** Dry exposures reduce potential for expansive cracking due to alkali-silica reactivity. Indoor concrete is usually drier than exterior concrete. Concrete that has high initial water content, however, may maintain a high internal relative humidity if not permitted to dry. High humidities can sustain the ASR reaction. It's unknown whether continuous saturation or cycles of wetting and drying cause more damage (Palmer 1992). It is known, however, that alkali migration can occur with alternate wetting and drying, concentrating alkalis near the drying zone and inducing reaction there (Perenchio, Kaufman, and Krause 1991). It is desirable to minimize both available moisture and wet-dry cycles by providing good drainage.

**Temperature.** Structures in warmer exposures are more susceptible to ASR than those in colder exposures because the ASR rate usually increases with increasing temperature (Perenchio, Kaufman, and Krause 1991). For the majority of aggregates, higher temperatures also mean larger ultimate expansions. However, there are studies showing that lower temperatures, 13°C and 20°C (55°F and 68°F) compared to 38°C (100°F), resulted in significantly larger ultimate expansions with certain aggregates (Wood, Young, and Ward 1987, and Jones and Poole 1987). The effect of high or low temperatures on ultimate expansion is aggregate dependent, with most aggregates reacting more at higher temperatures.

## Visual Symptoms of Expansive ASR

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

The British Cement Association outlines a procedure for diagnosing ASR and assessing its impact on a structure. The procedure includes the following steps: (1) site inspection and testing, (2) sampling, (3) laboratory investigation, (4) evaluation, and (5) risk assessment of future reaction (Palmer 1992). Visual observation of the structure is a major component of this program.

### Expansion

Typical indicators of ASR presence are longitudinal cracks, map (random pattern) cracking, and in advanced cases, closed joints, spalled concrete surfaces, or relative displacements of different portions of a structure (see Fig. 3). Because ASR deterioration is slow, the risk of catastrophic failure is low. ASR can cause serviceability problems and can exacerbate other deterioration mechanisms such as those that occur in freeze-thaw, deicer, or sulfate exposures. For instance, a concrete pavement might experience map cracking, and with subsequent freeze-thaw damage, begin to break apart. Likewise, cracking from other mechanisms can allow an ingress of alkalis and/or moisture,



**Figure 4. Longitudinal cracks induced by ASR in a concrete pavement. (IMG21371)**

which then exacerbates ASR. Some of the more serious concerns regarding in-service concrete expansion relate to hydro-electric dams. High-speed rotating equipment requires that strict tolerances be maintained between the machinery and the concrete to which it is anchored (Danay 1994 and U.S. Committee on Large Dams 1995).

### Cracking

Concrete deleteriously affected by expansive ASR is characterized by a network of cracks (see Figs. 4 and 5). A visual inspection should note the location, length, width, apparent depth, and continuity of cracks, and whether the cracks go through or around the aggregate. Any other associations with stress directions, reinforcement, restraint conditions, or discolorations should also be made in order to accurately describe the cracking. Stark (1991a) has numerous illustrations of ASR in highway structures.



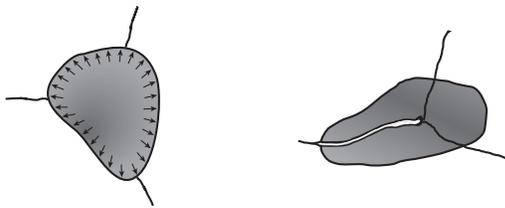
**Figure 5. Close-up view of well developed cracking in a pavement, a typical pattern associated with ASR. The prominent cracks are in a longitudinal direction as there is less restraint to lateral expansion. (IMG13049)**

Wide cracks are easy to see. Fine cracks aren't always visible, but they may be easier to see on a wet concrete surface that is beginning to dry. Drying occurs unevenly and provides a contrast that makes fine cracks more prominent (see Fig. 6). For this reason, some inspectors prefer to examine a concrete structure as it is drying, such as after a rainfall.

Expansive ASR begins with the formation of gel either in or on a reactive aggregate particle within the concrete. As the gel absorbs water, it can exert a fairly uniform pressure up to 10 MPa (1450 psi) or more in all directions (Figg 1987). This pressure exceeds the tensile strength of conventional concretes, which is generally about 10% of compressive strength. The concrete cracks in a 3- or 4-pronged star pattern. This cracking is usually enough to relieve the pressure and accommodate the resulting volume increase (see Fig. 7) (Figg 1987). As more particles react, cracks radiating from these "stars" join with others to form a pattern resembling a map (see Fig. 8) (Poole 1992). ASR is not the only mechanism to cause map cracking; cycles of freeze-thaw or other mechanisms causing shrinking or swelling of the concrete mass can cause similar patterns.



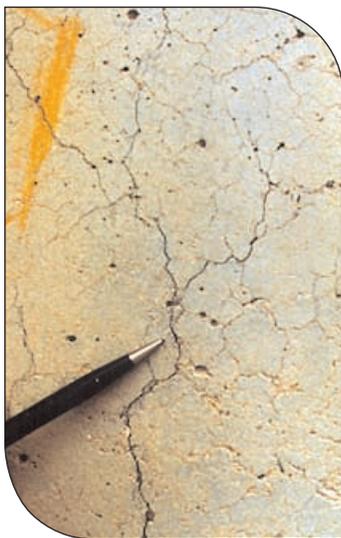
**Figure 6. Cracks can be more easily seen when the concrete has been wetted and is starting to dry. (Stark 1991a). (IMG12986)**



**Figure 7 . ASR often induces three or more cracks at each reacted aggregate particle location to relieve pressure caused by expansive forces (Figg 1987).**

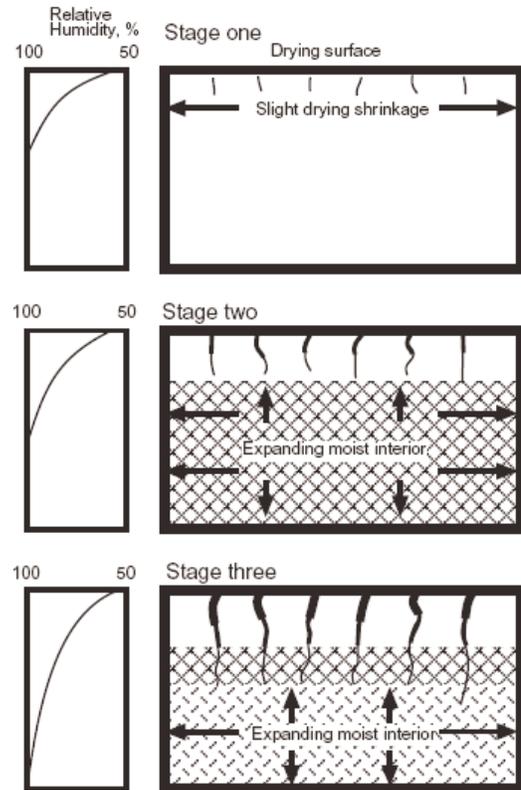
**Pavement and slabs on grade.**

In pavements and slabs on grade, cracking from expansive ASR often begins near free edges and joints where moisture is abundant (Figg 1987). The ASR cracks are usually perpendicular to transverse joints, and parallel to free edges along the roadside, and against asphalt pavement, where there is less



**Figure 8. Cracks caused by a reacted particle will often join other cracks of nearby reacted particles. This leads eventually to a pattern of cracks resembling lines on a map (Stark 1991a). (IMG13068)**

restraint. These cracks often progress to a map pattern. Continuously reinforced pavements will typically have ASR cracks parallel to the reinforcement. Traffic loads aggravate crack formation. Fig. 9 illustrates the progression of ASR cracking in concrete pavements (Helmuth 1993). Though this model is developed specifically for pavements, the sequence of events is similar in other structures. These cracks should be differentiated from D-cracks (typically associated with freeze-thaw distress). Freeze-thaw damage usually results in cracks parallel to transverse joints and free edges.



**Figure 9. Model for ASR cracking in unrestrained slabs on ground. Drying shrinkage occurs in Stage One, reaction and expansion of the interior concrete in Stage Two, and continued drying at the surface accompanied by continued reaction in the interior during Stage Three. Relative humidity vs. depth is shown on the left (Helmuth 1993).**

Stark (1991a) illustrates the difference between cracking caused by ASR versus freeze-thaw damage in pavements. In the first stage, moisture is lost at the top surface of the slab. This results in a slight drying shrinkage and some very fine cracking at the concrete surface. At this point, there is no appreciable alkali-silica reaction or expansion. Concrete can remain in this stage indefinitely.

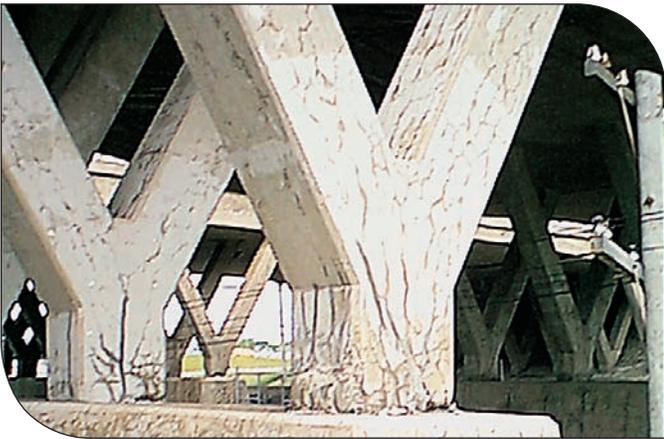
Stage two might begin only months after concrete placement or many years later. Reactive aggregates and high-pH pore solutions speed progress to stage two, the onset of which is marked by gel formation and subsequent swelling. Usually, gel forms in cracks inside the aggregate particle, but sometimes it forms on the rim of the particle. Formation of the gel may represent an initial reduction in volume, but as the gel absorbs moisture, it swells and exerts a force on

the surrounding concrete. The unrestrained concrete surface has no way of resisting the swelling, so the surface cracks begin separating. Widening cracks are an indication that ASR is occurring. The widened cracks then allow easier moisture access to the concrete interior, sustaining additional gel formation and swelling. During this phase, gel may exude from the widening cracks.

In stage three, continued drying slows reaction in the zone near the surface. But reaction continues in the moist interior concrete, contributing to formation and expansion of gel, exerting pressure on the surface, and widening the surface cracks.

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

**Other structures.** Observed cracking is usually most strongly developed in areas of structures where the concrete has a constantly renewable supply of moisture, such as close to the waterline in piers, from the ground behind retaining walls, beneath pavement slabs, or by wick action in piers or columns (Liu 1981).



**Figure 10. Cracking associated with stress directions. Predominant cracks are oriented longitudinally in this column. (IMG12421)**

In the absence of directional restraint, concrete cracks in a random pattern when ASR damage occurs. If the concrete is restrained, as most concrete structures are, cracks will be oriented along the stress direction (Poole 1992): for example, vertical cracks form in piers (Fig. 10). Since reinforcement parallels the major stress direction, linear ASR cracks occur roughly parallel to the steel bars. Unlike steel corrosion cracks that appear directly over the bars, linear ASR cracks commonly appear between the bars. A roughly rectangular cracking pattern results when the reinforcement is configured fairly evenly in two directions (Figg 1987).

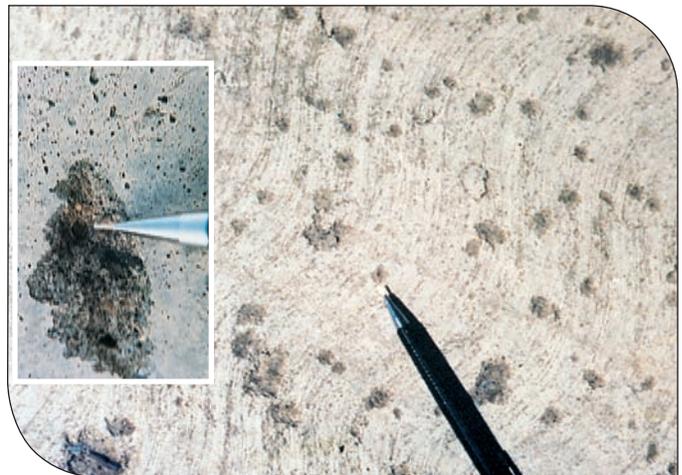
In unreinforced concrete, external restraint influences the orientation of major cracks. In gravity dams, expansion is less restrained in an upward direction and cracking is thus predominantly horizontal.

### Surface Deposits (Efflorescence)

Deposits of ASR gel or calcium carbonate (from carbonated pore solution) can be found along cracks in concrete, leaving a deposit on the surface ranging in color from white to dark gray. These deposits are sometimes called efflorescence or exudations. The material exuding from the cracks can be white, yellowish, or colorless, and viscous, fluid, waxy, rubbery, or hard. Surface deposits may or may not accompany expansive ASR. However, their presence is not indicative of ASR, as other mechanisms (such as frost action) or the transmission of water through concrete can also cause efflorescence (without the presence of ASR gel). It is good investigative practice during a site survey, however, to record the extent and location of surface deposits along with their color, texture, dampness, and hardness. A chemical analysis is also helpful to determine if ASR gel is present in the deposit.

### Popouts

A popout is caused by a fragment breaking out of the surface of the concrete, leaving a hole that may vary in size, but is usually 25 mm to 50 mm (1 in. to 2 in.) wide. Popouts caused by sand-sized particles can be much smaller (see Fig. 11). A fractured aggregate particle can be found at the bottom of the hole.



**Figure 11. Popouts caused by sand-sized particles. Inset shows close-up of such a popout. (IMG12318, IMG12983)**

The number, size, and location of popouts provide valuable information about the quality of aggregates in a concrete. Most commonly a popout is caused by the expansion and contraction of porous aggregate during freezing and thawing cycles. Another cause of popouts is expansive ASR: popouts occur to relieve pressure created by gel formed just beneath the concrete surface. Locating gel at the site of a popout is a strong indication of ASR.

Floor coverings may play a role in development of ASR popouts at later ages. Especially on slabs placed over wet cohesive soils, condensation can occur under the covering to develop popouts. Examination of the aggregate at the bottom of the resulting pit can usually explain the cause of the popout.

Popouts are a cosmetic nuisance and usually do not affect the serviceability or durability of the concrete. Still, there are ways to minimize their occurrence from ASR (Landgren and Hadley 2002):

- Do not use hard steel troweled surfaces where not needed, such as on most exterior slabs.
- Choose wet curing methods, such as continuous sprinkling with water, fogging, or covering with wet burlap instead of poly films, curing papers, or curing compounds. Flush the surface with water before final drying.
- Use blended cement or a supplementary cementitious material such as fly ash that has been demonstrated to control ASR.

The presence of ASR-induced popouts is not necessarily an indication that the concrete structure will expand and have map cracking or other signs of ASR distress.

Popouts can also be caused without ASR by freezing and thawing of low-density porous aggregate at or near the concrete surface. For example, porous chert can absorb water and upon freezing, expand and form a popout.

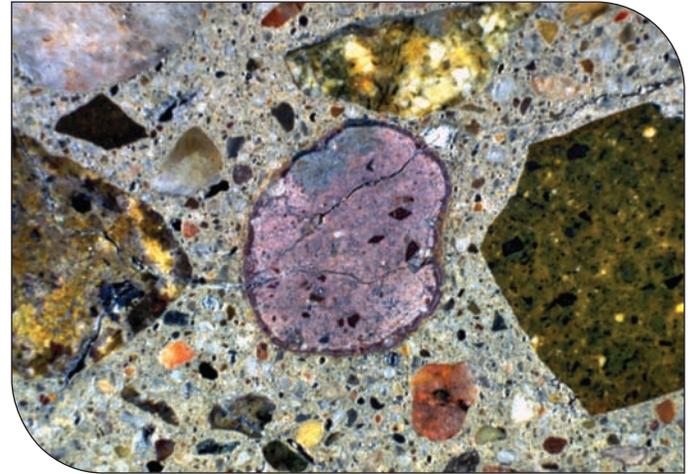
### Color Change

Surface discoloration is common in conjunction with cracking (Poole 1992). Darkened or blotchy areas are often associated with ASR. Areas along cracks may be bleached, pinkish, or brownish in color, extending several millimeters (tenths of an inch) from the crack.

## Methods For Identifying ASR Distress

It is important to distinguish between the ASR reaction and damage resulting from the reaction. In the diagnosis of concrete deterioration, it is most likely that a gel product will be identified. In some cases, significant amounts of gel are formed without causing damage to concrete. It is therefore important that in analysis of deteriorated concrete, signs of distress, such as microcracks and separation of aggregate from the paste, be accurately attributed to ASR gel formation if the damage is to be associated with ASR. Other causes of distress should not be precluded.

To pinpoint ASR as the cause of damage, the presence of ASR gel must be verified. However, other characteristics of the concrete should be studied, as ASR may only be a result of other concrete distress. A site of expansive reaction can be defined as an aggregate particle that is recognizably reactive or potentially reactive and is at least partially replaced by gel (see Fig. 12). ASR-affected coarse aggregates usually exhibit internal fracturing, with cracks extending into the surrounding concrete matrix. If only fine aggregate is reacting, cracks can form in the matrix without affecting coarse aggregate particles. Gel can be present in cracks and voids and may also be present in the area around aggregate particle edges. A network of internal cracks connecting reacted aggregate particles is a strong indication that ASR is responsible for cracking.



**Figure 12. Reacted particles are identified by dark areas that indicate ASR gel (either inside the particle, or along edges of particles), cracks extending from aggregate particles into the surrounding paste, and ASR gel reaction products. (IMG13650)**

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

A second method for detecting alkali-silica gel in concrete is the uranyl-acetate treatment procedure, discussed in the Annex to ASTM C 856 (AASHTO T 299). A freshly exposed concrete surface is sprayed with a solution of uranyl acetate, rinsed with water, and then viewed under ultraviolet light (Stark 1991a and Natesaiyer and Hover 1992). Reacted particles and gel appear as bright yellow or green areas.

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 that which is detrimental. Not all fluorescence is an indication of ASR gel. For instance, some aggregates fluoresce naturally. Also, 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. The uranyl-acetate solution is slightly radioactive. While the level of radioactivity presents minimal risk, its use is regulated and care must be taken in removing all materials that have been in contact with the uranium.

The third and newest procedure for detecting gel in concrete is the Los Alamos staining method, which is used in the field as well as the laboratory. It is a modified staining procedure traditionally used to identify potassium feldspar in rocks using a solution of sodium cobaltinitrite. In this method, the reagent is applied to a fresh concrete surface and viewed for yellow staining, which indicates gel containing potassium. A second reagent, rhodamine B, provides contrast for the yellow stain. The

rhodamine B solution is applied to the rinsed surface and allowed to react. The surface is again rinsed with water. The rhodamine B stain produces a pink background with darker pink stain in the vicinity of the yellow stain. The darker pink stain corresponds to calcium-rich ASR gel. According to test developers, the dark pink stain indicates an advanced or advancing state of degradation (Powers 1999).

A positive identification of gel by both the uranyl-acetate treatment and the Los Alamos staining procedure does not necessarily mean that destructive ASR has occurred. Both tests are ancillary to more definitive petrographic examinations and physical tests for determining concrete expansion. The uranyl-acetate treatment procedure and the Los Alamos staining method must not be used alone to diagnose ASR (Powers 1999).

## Control of ASR in New Concrete

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

Because different geographic regions have different needs and materials available, PCA developed a guide specification for concrete subject to alkali-silica reactions (PCA 2007). It is based on a document (NRMCA 1993) written for a region on the East Coast of the United States. Fig. 13 illustrates a guide specification process in determining if potential reactivity exists and in selecting materials to control ASR.

**AASHTO Guide Specification.** The American Association of State Highway and Transportation Officials (AASHTO) has also developed guidelines and technologies for treating and preventing ASR. Available is a Transition Plan (<http://leadstates.transportation.org/asr/transition/>), which includes: (1) A survey of State Highway Agencies to assess the extent of ASR; (2) an updated *Handbook for the Identification of ASR in Highway Structures*, SHRP-C-315 (<http://leadstates.transportation.org/asr/library/C315/>); and (3) an *AASHTO Guide Specification on ASR-Resistant Concrete* (<http://leadstates.transportation.org/asr/library/gspec.stm>).

The *Guide Specification on ASR-Resistant Concrete* proposes the following tests for aggregates: AASHTO T 303 [ASTM C 1260] (expansion limit of 0.08% at 14 days for metamorphic aggregates and 0.1% for all others), and ASTM C 1293 (expansion limit of 0.04% at 1 year) and ASTM C 295, petrographic examination. Suggested materials to prevent ASR in new concrete include: (1) low alkali and/or blended cements; (2) minimum 15% Class F fly ash, 30% Class C ash, 25% slag, or 5% silica fume cement replacement; and (3) lithium admixtures.

Methods to demonstrate prevention of deleterious ASR using project materials include: (1) ASTM C 441 (expansion limit of 0.10% at 56 days or 0.15% at 56 days, when AASHTO T 303 aggregate test result was less

than 0.50%; or, when SCMs are used, expansion is less than that of a control with low-alkali cement [between 0.40% and 0.60%]; or, when low-alkali cements are used, expansion at 14 days is at least 55% lower than a control mixture with high-alkali cement [ $1.00\% \pm 0.05\%$ ]); (2) AASHTO T 303 [ASTM C 1260] (expansion limit of 0.08% at 14 days for metamorphic aggregates and 0.10% for all others); or (3) ASTM C 1293 (expansion limit of 0.04% at 2 years).

## Identification of Potentially Reactive Aggregate

Field performance history is the best method of evaluating the susceptibility of an aggregate to ASR. When evaluating past field performance, the following should be determined: (1) are the cement content of the concrete, the alkali content of the cement, and the water-cement ratio of the concrete similar to that proposed for future use, (2) is the field concrete at least 15 years old, (3) are the exposure conditions for the field concrete at least as severe as anticipated for new construction, and (4) are pozzolans or slags used in the field concrete and are content and properties similar to those proposed for future use? In addition, the current aggregate supply should be examined petrographically to be sure that it is representative of that used in the field concrete. When field history is not available, laboratory tests can be used to evaluate the potential reactivity of aggregate. Fig. 13 illustrates the process of evaluating an aggregate.

Several tests to identify potentially reactive cement-aggregate combinations were developed in the 1940s and 1950s, while newer tests were developed in the 1990s. Each test has advantages and disadvantages, as well as limitations, that are outlined below. A description of each test follows. See Table 1 at the end of this document for details of test conditions, required samples, and measurement criteria.

### Mortar-Bar Method (ASTM C 227)

The *Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method)*, ASTM C 227, measures the expansion of mortars made with the test aggregate. The aggregate should conform to a standard grading, and may require crushing to meet the grading. Either a job cement or reference cement may be used. Alkali content of the reference cement should be at least 0.6%  $\text{Na}_2\text{O}_{\text{eq}}$ , and, preferably, have the highest alkali content representative of the cement use intended. At least four mortar bars, two from each of two batches using this aggregate and cement are prepared to standard dimensions: 25x25x285 mm (1x1x11<sup>1</sup>/<sub>4</sub> in.).

The bars are stored over water at 100% RH at 37.8°C (100°F). Length measurements are taken periodically beginning at 14 days and extending to 12 months or longer. According to ASTM C 33 (AASHTO M 6 / M 80), the maximum allowable expansion for an aggregate to be considered potentially nonreactive is 0.10% at six months, or 0.05% at three months if longer testing periods aren't feasible. Longer test periods are preferred for differentiating the reactivity of an aggregate. The method is usually not applicable for testing carbonate aggregates.

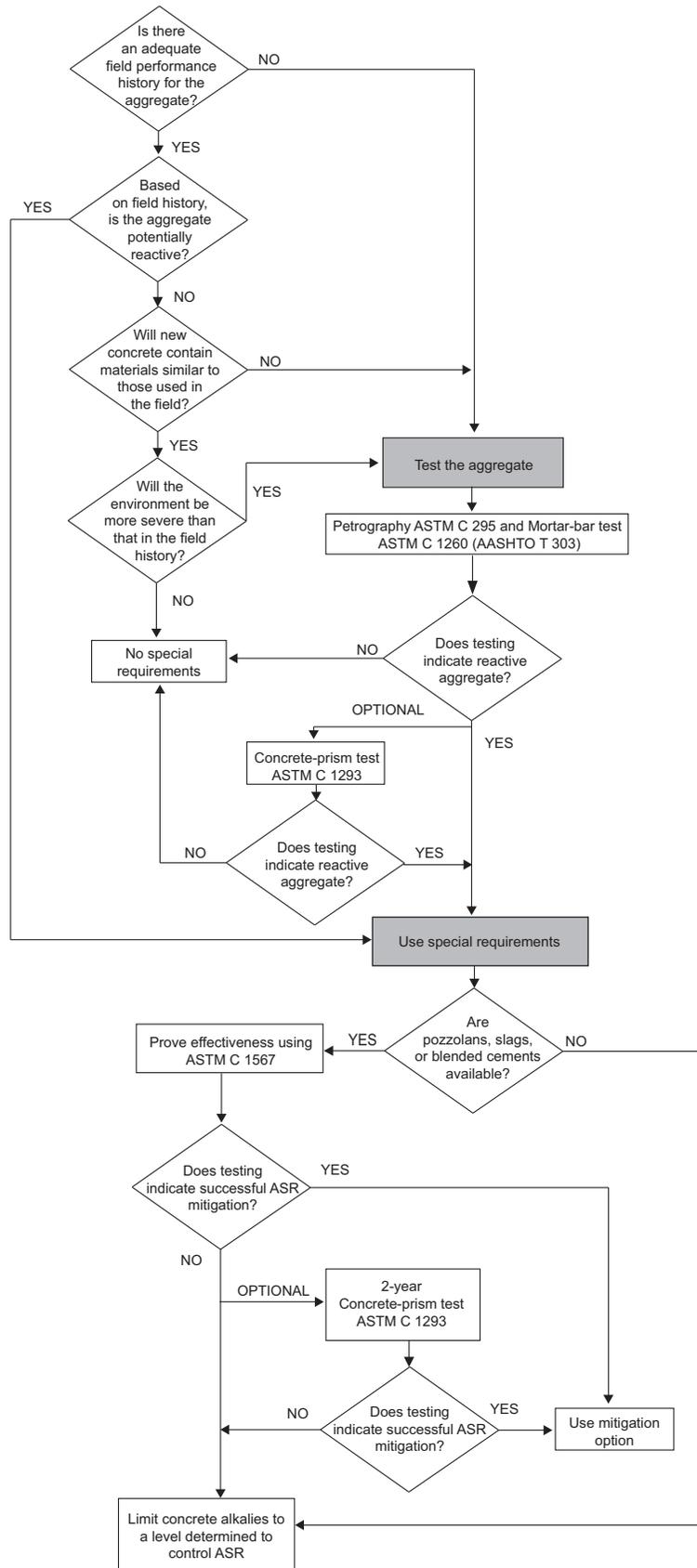


Figure 13. Flow chart listing steps to be taken to control ASR.

One positive aspect of this test is that it measures the ASR susceptibility of cement-aggregate combinations. Unless very reactive materials are being tested, though, obtaining meaningful results may require a year or more (Stark 2006). It is frequently impractical to wait a year for test results. Lack of time to run an adequate test is one of the major drawbacks associated with C 227. Even after long test periods, not all deleterious aggregates will exhibit expansive behavior. Sometimes, the C 227 test fails to distinguish between slowly reacting aggregates and innocuous ones because the test conditions aren't severe enough or the test would have to be run for several years (Stark 1993). A petrographic analysis of the aggregate is helpful in determining if this test is suitable for testing particularly slowly reactive aggregates. Problems with the test setup have also been identified. The test method requires the inside of the container to be lined with wicks to maintain a high relative humidity. The wicks cause water to condense on the bars thus leaching alkalis from the mortar. Reduced expansions have been observed in some containers using wicks. Although not a perfect test, it is a useful method for studying the ASR susceptibility of cement-aggregate combinations.

#### **Chemical Method (ASTM C 289)**

The *Test Method for Potential Reactivity of Aggregates (Chemical Method)*, ASTM C 289, commonly called the quick chemical test, estimates the potential reactivity of siliceous aggregate. An aggregate is crushed and sieved to yield three samples of 25 grams each. This material is then reacted with an alkaline solution (1 N sodium hydroxide) at 80°C (176°F). At 24 hours, the amount of dissolved silica from the aggregate and the reduction in alkalinity of the solution are measured. By plotting these data against a provided curve, it's possible to estimate reaction potential. The aggregate falls into one of three ranges: innocuous, deleterious, or potentially deleterious.

ASTM C 289 identifies highly reactive aggregates fairly reliably; however, it fails to identify slowly reactive aggregates. Also, certain aggregates have high amounts of soluble silica present, but produce only small expansions in service. Thus, the test does not always give reliable results (Stark 1993 and 1994). The method also is usually not applicable for testing carbonate aggregates. This test is a helpful research tool and may be useful for initial screening of aggregate; however, other tests should be relied upon to better define which aggregates are potentially reactive.

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

Mineral composition is a good indicator of potential aggregate reactivity. The *Guide for Petrographic Examination of Aggregates for Concrete*, ASTM C 295, is used to determine mineral composition and form (page 2 of this document discusses aggregate sources and mineral compositions that are prone to ASR). Petrographic examination should be used as a screening method for aggregates. It gives quick results to help predict possible aggregate reactivity but can't give quantitative information about the aggregate's actual behavior in concrete.

A petrographic evaluation of an aggregate sample, by an experienced petrographer, will identify potentially reactive minerals in an aggregate

sample. The ASTM practice provides guidance on megascopic and microscopic methods of analyzing an aggregate sample. Descriptive nomenclature for minerals is found in ASTM C 294.

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

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

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

#### **Rapid Mortar-Bar Test (ASTM C 1260 or AASHTO T 303)**

Assessing aggregate reactivity by accelerated methods is increasingly common. The shortcomings of ASTM C 227 and C 289 prompted development of a rapid test method for assessing potential reactivity of aggregate. ASTM C 1260 (AASHTO T 303), *Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)*, offers a relatively rapid test to supplement lengthier test methods. It involves measuring the length change of mortar bars made with the sample aggregate stored in a strongly alkaline solution at an elevated temperature.

This test measures potential aggregate reactivity, not reactivity of specific cement-aggregate combinations. A nonmandatory appendix to C 1260 (AASHTO T 303) classifies an expansion of 0.10% or less at 14 days as innocuous behavior. Expansions of more than 0.20% are indicative of potentially deleterious expansion. Between 0.10% and 0.20%, aggregates may exhibit either innocuous or deleterious behavior in field performance. Various organizations use different criteria depending on local experience; however, unless testing and field experience demonstrate that modifications to the procedure are justified for local materials, the standard test conditions and criteria should be used to provide the most meaningful results (Thomas et al. 2005). The expansion level of the aggregate may determine what materials are used in concrete.

ASTM C 1260 (AASHTO T 303) should be used as a screening test in conjunction with other tests to determine the potential reactivity of an aggregate. Due to the severe test conditions, aggregates with

good field performance and no history of ASR can sometimes test to be reactive. This is because aggregates in field concrete are rarely exposed to the severe alkali and temperature conditions of the test method. Thus, aggregates identified as potentially reactive by ASTM C 1260 (AASHTO T 303) may perform well in practice when exposed to more reasonable alkali levels and temperature conditions. ASTM C 1260's (AASHTO T 303's) severity makes it useful for identifying slowly reacting aggregates, which may not be identified by ASTM C 227.

A variation of ASTM C 1260 (AASHTO T 303) evaluates the effectiveness of supplementary cementitious materials. This procedure has been standardized as ASTM C 1567 (see below). Thomas et al. (2005) show a good relationship between rapid mortar-bar testing at 14 days and expansion of outdoor specimens. They note a marked increase in false positives and false negatives (compared to concrete testing) with a 28-day version of the test (42%), compared to the standard 14-day test (23%).

### Concrete Prism Test (ASTM C 1293)

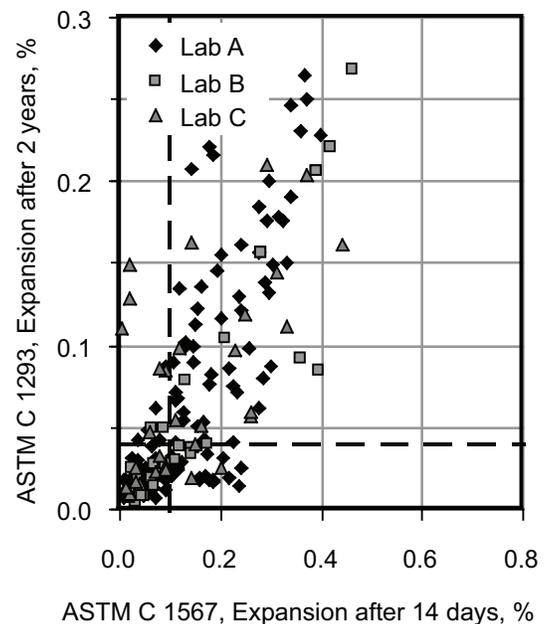
The *Standard Test Method for Concrete Aggregates by Determination of Length Change of Concrete Due to Alkali-Silica Reaction*, ASTM C 1293, measures the expansion of concrete prisms made with the fine or coarse aggregate in question and a Type I high-alkali ( $0.90\% \pm 0.10\%$   $\text{Na}_2\text{O}$ -equivalent) cement plus added NaOH to simulate a 1.25%  $\text{Na}_2\text{O}$  equivalent cement. Concrete proportions are strictly defined, including a water-cement ratio of 0.42 to 0.45. At these proportions, concrete has an alkali content of  $5.25 \text{ kg/m}^3$  ( $8.85 \text{ lb/yd}^3$ ). At least three concrete prisms are prepared to standard dimensions:  $75 \times 75 \times 285 \text{ mm}$  ( $3 \times 3 \times 11\frac{1}{4} \text{ in.}$ ). An additional prism can be made for petrographic examination. All prisms are stored in a sealed container over water at 100% RH at  $38^\circ\text{C}$  ( $100^\circ\text{F}$ ). Length change measurements are compared to the reading taken at one day and are calculated to the nearest 0.001%. Measurements are taken at 7, 28, and 56 days, and 3, 6, 9, and 12 months. Additional readings, if required, are at 6-month intervals. Appendix X1 of the standard offers the following interpretation of results: potentially deleterious behavior is indicated if the one-year expansion is greater than or equal to 0.04%.

ASTM C 1293 is similar to C 227 in that both involve cement-aggregate combinations, and both can require a year or more to obtain meaningful results. C 1293 is currently considered the most representative test method when compared to structures in the field. C 1293 should be used to supplement results obtained from C 227, C 295, C 289, C 1260 (AASHTO T 303), or C 1567 and has the potential to resolve uncertainties about results obtained with C 227, C 1260 (AASHTO T 303), and C 1567, when no additional alkalis are expected to become available to the system. In Canada, the equivalent to ASTM C 1293 is CSA A23.2-14A, *Potential Expansivity of Aggregates (Procedure for Length Change Due to Alkali-Aggregate Reaction in Concrete Prisms)*. In a variation to C 1293, Touma, Fowler, and Carrasquillo (2001) suggest that the duration of the test be shortened from 12 months to 3 months (91 days) by increasing the storage temperature of the concrete prisms from  $38^\circ\text{C}$  ( $100^\circ\text{F}$ ) to

$60^\circ\text{C}$  ( $140^\circ\text{F}$ ). Research on this modified procedure is still in progress. Exact test criteria have not been established.

### Accelerated Mortar-Bar Test (ASTM C 1567)

ASTM C 1567, *Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method)*, assesses expansion of specimens made with the aggregate in question and blended cement or cement plus pozzolan or slag under the same accelerated test conditions as ASTM C 1260 (AASHTO T 303). It tests the effectiveness of cement-pozzolan-aggregate combinations. It may be required to test different levels of pozzolan and ground granulated blast-furnace slag to determine the amount required to reduce expansion to an acceptable level. Pozzolans and ground granulated blast-furnace slag may be tested separately or in combination. It is recommended to test the same aggregate and hydraulic cement (without pozzolans and slag) using Test Method C 1260 (AASHTO T 303) for a comparative control. Results obtained using this test method may overestimate the reactivity of some types of aggregates if used in service with the same pozzolans or slag and low-alkali cement. In addition,



**Figure 14. Comparison of 2-year expansion of the concrete prism test (ASTM C 1293) with expansion of the same SCM-aggregate combinations in the accelerated mortar-bar test (ASTM C 1567) at 14 days (Thomas et al. 2005).**

this test method may underestimate the expansion of cementitious systems containing pozzolans with an alkali content  $> 4.0\%$   $\text{Na}_2\text{O}_{\text{eq}}$ . Such materials should be tested using Test Method C 1293. Similar to ASTM C 1260 (AASHTO T 303), a nonmandatory appendix to C 1567 classifies an expansion of 0.10% or less at 14 days (16 days after casting) as innocuous behavior. Thomas et al. (2005) show a good relationship between rapid mortar-bar testing at 14 days and expansion of outdoor specimens. They note a marked increase in false positives and false negatives (compared to concrete testing) with a 28-day version of test (42%), compared to the standard 14-day test (23%).

### Comparison between Accelerated Mortar-Bar Test (ASTM C 1567) and Concrete Prism Test (ASTM C 1293)

Thomas et al. (2005) show comparisons of the two methods for various aggregate types. Fig. 14 shows that using the 14-day expansion limit of 0.10% in the ASTM C 1567 test to assess combinations of reactive aggregate and supplementary cementitious materials provides a reasonable prediction of the same aggregate-SCM combinations when tested in accordance with the 2-year ASTM C 1293 test using a 0.04% expansion limit. The researchers found only a small risk associated with using the 14-day limit of 0.10% in ASTM C 1567 tests to accept SCM-aggregate combinations for use in construction. Thirteen of the 182 combinations tested expanded by more than 0.040% when tested in concrete, but passed the 0.10% criterion when tested in mortar. The (relatively low) risk of expansion associated with relying on the outcome of this test has to be balanced against the quicker time frame for obtaining results.

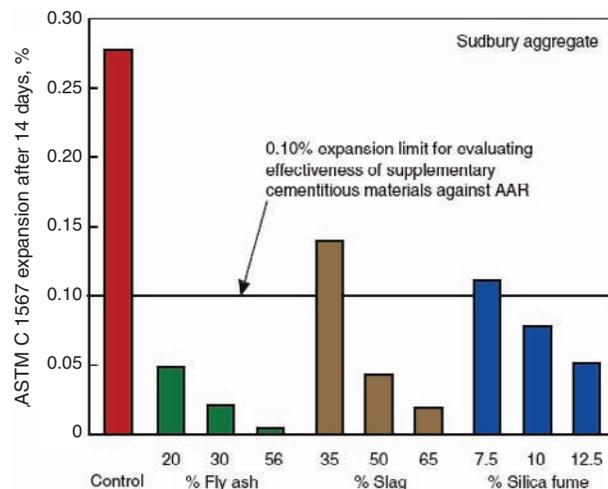
### Designing Mixtures to Control ASR

Most concrete is not affected by ASR and special requirements are not needed. However, if historical experience or the tests discussed above demonstrate that ASR is a potential concern, then concrete mixtures must be specifically designed to control ASR. The concrete mixture should be designed with a safe and economic combination of locally available materials. Historical guidance or tests must be used to establish the ASR resistance of selected material combinations. Fig. 13 illustrates what steps should be taken to assist in the mixture design.

When pozzolans, slags, or blended cements are used to control ASR expansion, their effectiveness must be determined. The limits on expansion referenced in ASTM C 595 (AASHTO M 240), ASTM C 989 (AASHTO M 302), and ASTM C 1157 may not be applicable. The tests do not use job aggregate, and the limits may be more restrictive than is necessary or achievable. An alternative comparative procedure is described in ASTM C 311, where—using the ASTM C 441 test procedure—expansions of fly ash and natural pozzolan are compared to a control mixture with low-alkali portland cement.

Where possible, different amounts of pozzolan or slag should be tested to determine the optimum dosage. Some materials exhibit a “pessimum” effect: dosages that are too low may actually result in higher ASR-related expansions than if no pozzolan or slag were used (Chen et al. 1993 and Carrasquillo and Farbiarz 1989). Fig. 15 illustrates the need for optimization of dosage of pozzolan or slag to control ASR. ASTM C 1567 results at 14 days are considered to be conservative when compared to ASTM C 1293 results at 2 years. Therefore, lower replacements may have been recommended, if the 2-year ASTM C 1293 test had been used.

ASTM C 1293 and CSA A 23.2-28A recommend a 2-year test period for the concrete prism test to evaluate supplementary cementitious materials. Petrographic examination of the test specimens is also helpful. Although a limit of 0.04% is used by ASTM and CSA to establish effectiveness, some researchers suggest a comparison against a low-alkali control (Bérubé



**Figure 15. Influence of different amounts of fly ash, slag, and silica fume by mass of cementitious material on mortar-bar expansion (ASTM C 1567) after 14 days when using reactive aggregate (Fournier 1997).**

and Duchesne 1992). This may also apply to ASTM C 227. Bérubé and Duchesne (1992) provide comparison between test methods.

### Materials and Methods to Inhibit ASR

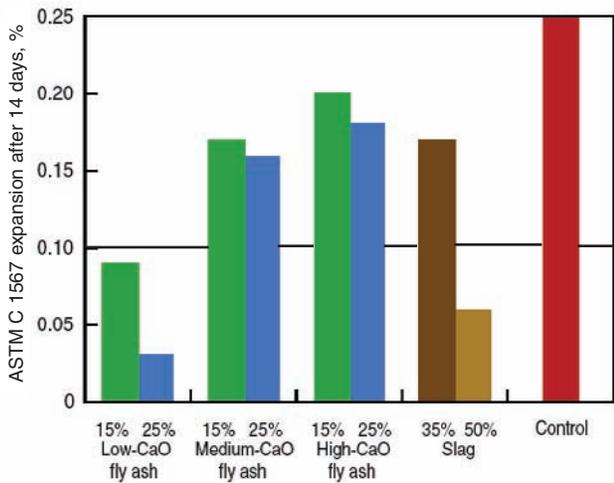
A variety of locally available materials can be used to control ASR. Using the above tests where applicable to demonstrate effectiveness in controlling ASR, the supplementary cementitious materials listed below can be included either as a concrete ingredient added at batching or as a component of a blended hydraulic cement, or both. Blended hydraulic cements should conform to ASTM C 595 (AASHTO M 240) or ASTM C 1157.

SCMs added directly to concrete are governed by ASTM C 618 or AASHTO M 295 (fly ash and natural pozzolans), ASTM C 989 or AASHTO M 302 (slag), or ASTM C 1240 or AASHTO M 307 (silica fume). Specifiers should invoke the optional physical and chemical ASR requirements in these standards. The following options are not listed in priority and can be used in combination with one another.

**Fly ash.** Decades of laboratory and field research demonstrate that certain fly ashes can control ASR. Generally, this works through one (or more) of the following three mechanisms (Detwiler 2002):

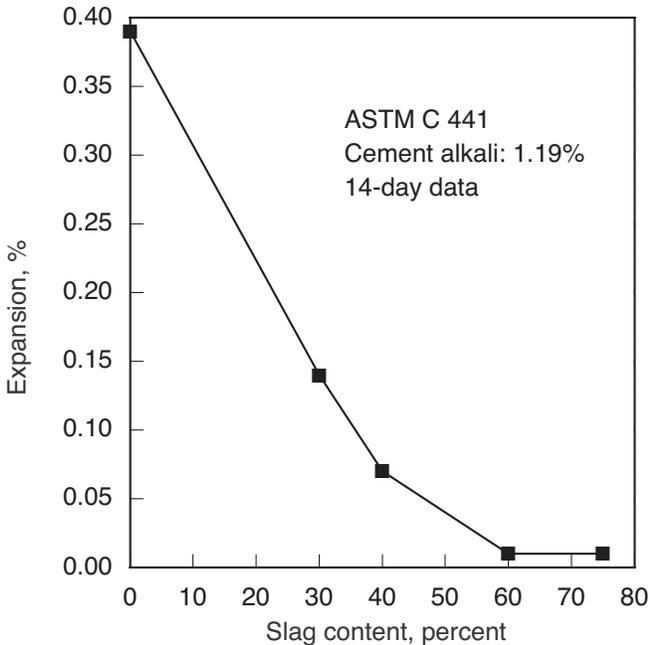
1. Reduction of concrete permeability and diffusivity due to the pozzolanic reaction of the fly ash with the calcium hydroxide produced by the hydration of the cement
2. Removal of some of the alkalis from the pore solution by binding them into the low CaO/SiO<sub>2</sub> ratio hydration products
3. Dilution of the cement alkalis by a fly ash with a lower alkali content, or at least a lower available alkali content

The type of ash, its alkali content, chemical composition, and dosage all affect how effectively it will control expansion. In general, Class F fly ashes work better than Class C ashes. Class F ashes have higher silicon dioxide contents and lower lime contents, properties that increase the ability to control expansive reactivity. In general, ASR expansion decreases as the ash content increases (see Fig. 15). Ashes require different dosages

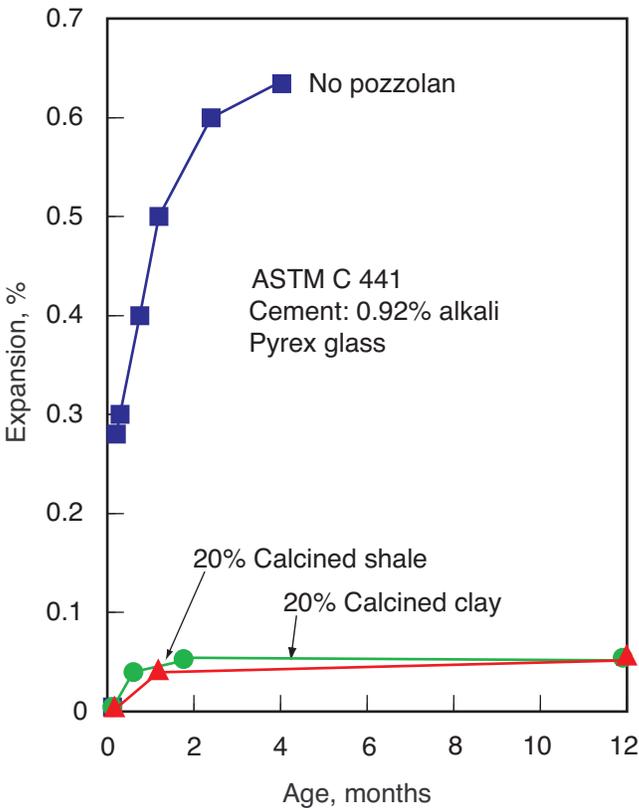


**Figure 16. Effect of different fly ashes and slag on alkali-silica reactivity. Note that some ashes are more effective than others in controlling the reaction and that dosage of the ash or slag is critical. A highly reactive natural aggregate was used in this test. A less reactive aggregate would require less ash or slag to control the reaction. A common limit for evaluating the effectiveness of pozzolans or slags is 0.10% expansion using this rapid mortar-bar test (Detwiler 2002).**

depending on their chemical composition, the alkali content of the concrete, and the reactivity of the aggregate. Laboratory results show that certain high-alkali/high-calcium fly ashes are not effective at normal dosages to control ASR (see Fig. 16). Some of these materials may even exacerbate ASR expansion when used at lower amounts (pessimum effect) (Chen et al. 1993 and Carrasquillo and Farbiarz 1989). Generally, the amount of fly ash required to control ASR will increase as any of the following parameters increase: (1) lime or alkali content of the fly ash,



**Figure 17. ASR mortar bar expansion versus slag content (Buck 1987).**



**Figure 18. ASR mortar bar expansion versus calcined natural pozzolan additions used with Pyrex glass aggregate (Lerch 1950).**

(2) reactivity of the aggregate, or (3) amount of alkali available in the concrete for reaction (Shehata and Thomas 2000).

**Slag.** In some parts of the country it is common to control ASR by using slag cement (ground granulated blast-furnace slag). Slag is usually used at higher dosages (25% to 50%) than fly ash to be effective (see Figs. 15 and 17) (Buck 1987). In one concrete mixture, for example, about 50% slag might be needed to control expansion in concrete with highly reactive aggregate, while only 25% to 35% slag may be required to control expansion in concrete with moderately reactive aggregate. Generally, the amount of slag required to control expansion increases as either the reactivity of the aggregate or the amount of alkali in the mixture increases (Thomas and Innis 1998).

**Silica fume.** Silica fume is also an effective supplementary cementitious material for controlling ASR. Compared to fly ash and slag, only small dosages of silica fume are needed (Fig. 15) (Buck 1987). However, the amount of silica fume required to control expansion with a highly reactive aggregate is around 10% or more. This amount of silica fume is higher than that typically used in concrete and can lead to problems with placing and finishing. The use of silica fume is perhaps most beneficial and practical when used as part of a ternary system (see page 14).

**Natural Pozzolans.** Raw or calcined natural pozzolans are sometimes used to control ASR (see Fig. 18) (Lerch 1950). Metakaolin, a

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

**Ternary systems.** Laboratory data (Fournier et al. 2004) show the beneficial effect of silica fume in combination with fly ash or slag to control ASR. Also, combining two or more supplementary cementitious materials may reduce the quantities needed to control ASR compared to using the materials individually. For example, 4% to 6% silica fume combined with moderate levels of slag (20% to 35%) or fly ash (Class F or Class C), were found to be very effective in controlling the expansion of highly reactive aggregates (Folliard et al. 2006).

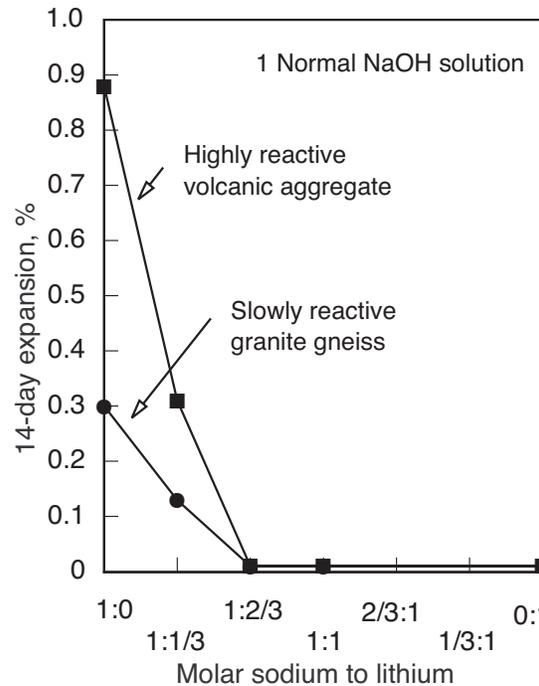
**Low-alkali portland cement.** Low-alkali portland cement (ASTM C 150 or AASHTO M 85), with an alkali content not exceeding 0.60%  $\text{Na}_2\text{O}_{\text{eq}}$ , can be used to reduce ASR. Its use has been successful with slightly reactive to moderately reactive aggregates. Higher alkali levels (between 0.65% and 0.80%) also have been safely used with certain moderately reactive aggregates. However, low-alkali cements are not available in all areas. Also, deleterious reactivity has been observed with certain highly reactive glassy volcanic aggregates, especially andesite and rhyolite rocks, even when low-alkali cements (alkali contents of 0.35% to 0.60%) were used (Stark 1981 and Kosmatka and Fiorato 1991). Thus, the use of locally available cements in combination with pozzolans, slags, or blended cements is preferable for controlling ASR.

**Limiting concrete alkalis.** Canadian experience indicates that deleterious expansion usually does not take place when reactive aggregates are used in concrete containing less than 3 kg of alkali/ $\text{m}^3$  (5 lb/ $\text{yd}^3$ ) in mixtures containing 100% portland cement as the cementitious material.

In Canada, CSA Standard A23.2-27A, *Alkali-Aggregate Reaction*, dictates the requirements for supplementary cementitious materials used to control ASR. A supplementary cementitious material may be used to control ASR provided it meets two criteria: (1) it must conform to certain chemical requirements and (2) it must be used at or above the minimum dosage specified. If less than the required minimum amounts are to be used, the concrete prism expansion test (CSA Test Method A23.2-14A) or the mortar-bar accelerated expansion test (CSA Test Method A23.2-25A) is conducted to verify the material's effectiveness in controlling expansion. Per the chemical requirements, blast-furnace slag can have a maximum 1.0% total alkali content (as  $\text{Na}_2\text{O}$  equivalent). Fly ash can have a maximum total alkali content of between 3.0% and 4.5%, and silica fume can have a maximum total alkali content of 1.0%. A minimum SCM dosage is required depending on the reactivity of the aggregate, the service life and size of the structural element, the exposure environment, and the composition of the fly ash or slag. The minimum silica fume dosage is calculated based on total alkali content of the concrete.

Appendix B of CSA A23.1 (2004) cautions that restricting concrete alkali content to 3 kg/ $\text{m}^3$  (5 lb/ $\text{yd}^3$ ) may not be an effective strategy, however, when:

- the concrete will be used in mass concrete structures that cannot tolerate even slight expansions



**Figure 19. Fourteen-day expansion of mortar bars versus sodium-to-lithium ratio. The effective molar ratio was about 1 to 2/3 for these two reactive aggregates (Stark 1993).**

- the concrete will be exposed to external alkali sources
- highly reactive aggregates are used

As an alternative to the 3-kg limit, specifiers can determine the effective alkali burden from tests on properly performing field structures in a locality. Then they can specify the historically established limit for new structures built with similar materials in a similar environment.

**ASR-inhibiting compounds.** Certain chemical admixtures or cement additives can control ASR (Stark 1992 and 1993, Gajda 1996 and Lane 2002). For example, lithium compounds can effectively reduce ASR expansion in concrete. When lithium hydroxide or lithium nitrate is added to concrete, a lithium-bearing ASR gel is formed. Lithium-bearing gels have a greatly reduced potential for expansion; some are even non-expansive. Also, less gel is formed in the presence of lithium.

The degree to which lithium compounds suppress expansive ASR depends on two factors: aggregate reactivity and concrete alkali content. Fig. 19 shows the reduction in expansion with two highly reactive aggregates and varying proportions of sodium to lithium (Stark 1993). The optimum level of lithium hydroxide monohydrate to control expansive ASR appears to be equal to that of the equivalent alkali content of the cement (Gajda 1996). It has been shown that insufficient quantities of certain lithium compounds may actually increase expansion. This is related to the increased hydroxyl ion concentration in the pore solution, as many lithium compounds combine with calcium hydroxide, producing insoluble calcium salt and lithium hydroxide. Lithium nitrate does not behave in this manner due to the high solubility of calcium nitrate (Stokes et al. 1997). The efficient molar ratio  $[\text{Li}]/[\text{Na}+\text{K}]$  to sup-

press expansion may vary from as low as 0.56 to over 1.11 depending on the aggregate source. The Federal Highway Administration (FHWA) has published *Interim Recommendations for the Use of Lithium to Mitigate or Prevent Alkali-Silica Reaction (ASR)* (Folliard et al. 2006), which provides information and guidance to test, specify, and use lithium compounds in new concrete construction.

Neither ASTM C 1260 (AASHTO T 303) nor ASTM C 1567 should be used to test the effectiveness of lithium compounds. ASTM C 1293, with a test duration of two years, should be used to assess lithium compounds (Folliard et al. 2006).

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

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

It may be possible to blend reactive aggregate with nonreactive aggregate to mitigate the effects of ASR. This blending sometimes occurs as part of the quarrying process, when only small amounts of reactive aggregate are present. Nonreactive aggregates can be purposefully blended with known reactive aggregates. In some cases, this means of diluting aggregates can adequately control expansive ASR. An example of this method is limestone sweetening.

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

### Controlling Existing ASR

Lithium salts have also been applied topically to treat ASR in existing concrete. Laboratory studies show that treating small samples with lithium can reduce expansion (Stokes et al. 2000). In the field however, lithium may not penetrate sufficiently into the structure to mitigate the reaction below the surface, allowing continuous deterioration (Folliard et al. 2006). Tuan (2005) found that insufficient amounts of lithium penetration into hardened concrete may even enhance ASR expansion. Methods of driving lithium ions into the concrete using electrical fields or vacuum impregnation are being studied to improve penetration. FHWA (2006a and 2006b) has published guidance for selecting ASR-affected structures for lithium treatment. They identify ideal structures for lithium treatment as those for which, (1) ASR has been confirmed as the principal cause for deterioration; (2) the deterioration has reached a certain severity, and (3) laboratory testing or in-situ monitoring indicates a potential for significant further expansion if the structure is left untreated.

## Recycled Concrete as Aggregate

When recycled concrete is used as coarse aggregate in new concrete, it should be evaluated in the same manner as virgin aggregate (see Fig. 13).

Recycling concrete for use as coarse aggregate in new construction can be economical, saving disposal costs of old concrete and reducing the need for virgin aggregate. Increased environmental concerns and diminishing quarry resources may make recycling even more popular in the future (ACPA 1993 and ECCO 1999).

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

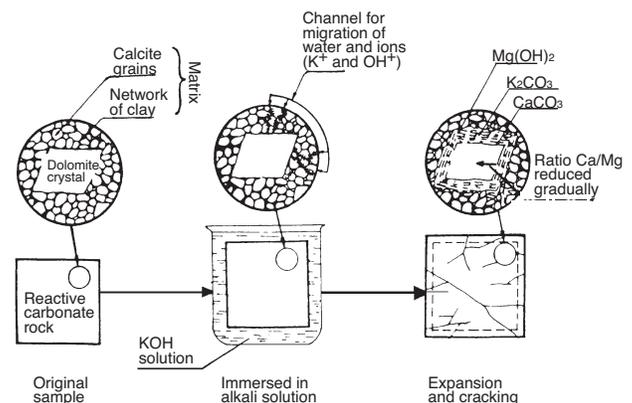
Research was undertaken to study expansion of new concrete made with recycled ASR-affected concrete as aggregate (Stark 1996). It was determined that potential for ASR in the new concrete is affected by the old concrete's original alkali level, extent of expansion, and the remaining potential reactivity of the aggregate. Also, the alkali content of new concrete had a significant effect on subsequent expansions due to ASR. The use of a low-lime Class F fly ash greatly reduced expansions due to ASR in new concrete.

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

## Alkali-Carbonate Reaction

### MECHANISM OF ACR

Reactions observed with certain dolomitic rocks are associated with alkali-carbonate reaction (ACR). Reactive rocks usually contain larger



**Figure 20. Schematic diagram of the mechanism of alkali-carbonate reaction. A dolomite crystal combines with alkalis in solution to form brucite, and potassium and calcium carbonates (Tang, Liu, and Han 1987).**

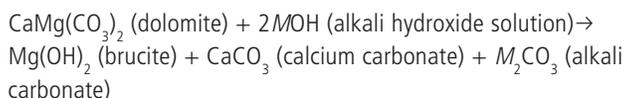
crystals of dolomite scattered in and surrounded by a fine-grained matrix of calcite and clay. Calcite is one of the mineral forms of calcium carbonate; dolomite is the common name for calcium-magnesium carbonate. ACR is relatively rare because aggregates susceptible to this reaction are usually unsuitable for use in concrete for other reasons—strength potential, etc.

Argillaceous dolomitic limestone contains calcite and dolomite with appreciable amounts of clay and can contain small amounts of reactive silica. Alkali reactivity of carbonate rocks is not usually dependent on clay mineral composition (Hadley 1961). Aggregates have potential for expansive ACR if the following lithological characteristics exist (Ozol 2006 and Swenson and Gillott 1967):

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

### Dedolomitization

Dedolomitization, or the breaking down of dolomite, is normally associated with expansive ACR (Hadley 1961). Concrete that contains dolomite and has expanded also contains brucite (magnesium hydroxide,  $\text{Mg}(\text{OH})_2$ ), which is formed by dedolomitization. Dedolomitization proceeds according to the following equation (Hadley 1961):



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

Fig. 20 illustrates this process. Expansion may be due to a combination of migration of alkali ions and water molecules into the restricted space of the fine-grained matrix surrounding the dolomite rhomb, migration of these materials into the rhomb, and the growth and rearrangement of the dedolomitization products, especially brucite, which exerts pressures as it crystallizes (Tang, Liu, and Han 1987).

The dedolomitization reaction and subsequent crystallization of brucite may cause considerable expansion. Whether dedolomitization causes expansion directly or indirectly, it's usually a prerequisite to other expansive processes (Tang, Deng, and Lon 1994). In one investigation of pavement deterioration, dolomite did not appear to be altered, as no brucite was found. Cracking was due to expansive forces arising from a chemical reaction and expansion of the clay minerals in the aggregate matrix (Wong 1996).

### Other Factors

The nominal maximum size of the reactive aggregate influences the amount and extent of reaction. Testing done with a particular ACR rock and high-alkali cement showed that both the rate and degree of expansion decreased with a decrease in nominal maximum aggregate size (Swenson



**Figure 21. Map cracking pattern caused by ACR (IMG12982).**

and Gillot 1960). Concrete can contain a certain percentage of carbonate reactive aggregates without experiencing detrimental expansion.

Alkali-carbonate reaction is also affected by pore solution alkalinity. ACR can occur in a solution with a relatively low pH. As the pH of the pore solution increases, potential for the alkali-carbonate reaction increases. During ACR, calcium hydroxide produced by portland cement hydration can combine with the alkali carbonate produced in the initial reaction (see equation above) to regenerate alkali hydroxide and calcium carbonate. This reaction not only regenerates alkali, but also reduces the concentration of carbonate ions and aggravates the dedolomitization reaction. Low-alkali cements and supplementary cementitious materials—even at high levels—are thus ineffective at reducing ACR to acceptable limits (Tang, Deng, and Lon 1994).

## Visual Symptoms of Expansive ACR

ACR, like ASR, is a chemical process that can induce physical damage—expansion and cracking of concrete (Fig. 21). Information obtained from a site inspection should be evaluated along with testing to determine the destructive mechanism.

ACR-affected concrete does not exhibit telltale features to distinctly identify alkali-carbonate reaction as the cause of cracking. The crack pattern will be influenced by restraint conditions and moisture availability. In slabs, decks, and footings, when a top-to-bottom or side-to-side moisture gradient exists, map cracking is likely to occur. This growth can cause closed joints, misalignment of adjoining members, crushed concrete, and pavement blowups (Ozol 2006). Because low levels of alkali can initiate ACR and higher levels can exacerbate it, the use of deicer salts that contain alkalies can increase damage.

## Test Methods for Identifying ACR Distress

Brucite is usually formed during destructive ACR and is evident in expanded concrete. Its presence must be determined through petro-

graphic or other analysis. The concrete and carbonate rocks must be examined petrographically in accordance with ASTM C 856 and C 295 respectively. Physical expansion tests, such as ASTM C 586, performed in a laboratory are also helpful to verify the presence of ACR.

## Test Methods for Identifying Potentially Reactive Aggregate

ACR is rather uncommon because the carbonate rocks containing proportions of dolomite, calcite, and insoluble material that will lead to dedolomitization do not often compose a major portion of the aggregate supply (Mather 1975). The three tests commonly used to identify potentially alkali-carbonate reactive aggregate are described below and in Table 2 at the end of this document.

### Petrographic Examination (ASTM C 295)

Petrographic examination, ASTM C 295, can be used to establish the character of rock. Potentially alkali-carbonate reactive aggregates have a characteristic lithology that makes them easy to identify. The rock is considered to be reactive if the physical make-up is a fine-grained matrix of calcite and clay surrounding rhombic crystals of dolomite. With no known exceptions, all rocks with the characteristic lithology have expanded in an alkaline environment, and all rocks in concrete that have expanded due to ACR exhibit the characteristic lithology (Ozol 2006). Petrographic testing identifies ACR-susceptible rocks.

### Rock Cylinder Method (ASTM C 586)

ASTM C 586, *Test Method for Potential Alkali Reactivity of Carbonate Rocks for Concrete Aggregates (Rock Cylinder Method)*, can determine the expansive characteristics of carbonate rocks. A small rock cylinder 35 mm long by 9 mm dia. (1.38 in. x 0.35 in.) is immersed in an alkaline (1 N NaOH) solution at room temperature. Length change of the specimen may be monitored for up to or over a year, but expansive tendencies are usually evident after about 1 month. A 28-day expansion of 0.10% or more indicates potential for deleterious expansion in a service environment.

This test procedure has a few disadvantages. Obtaining a representative sample may be difficult and test duration may be long. Furthermore, this test is intended only as a supplement to other test procedures. Expansive behavior of aggregate can be predicted by the rock cylinder method. But since expansion of concrete depends on other variables that include water-cement ratio, water-soluble alkalis, and the paste-to-aggregate ratio, ASTM C 586 alone should not be used as an acceptance test for aggregate (Ozol 2006).

### Concrete Prism Tests (ASTM C 1105 and CSA A23.2-14A)

ASTM C 1105, *Test Method for Length Change of Concrete Due to Alkali-Carbonate Rock Reaction*, is best used to verify potential reactivity of an aggregate that is known to contain ACR-susceptible rock. Six concrete prism specimens are fabricated with the aggregate in question and the job cement. If the job cement is not known, a Type I or Type II cement conforming to ASTM C 150 (AASHTO M 85) should be used. The test should preferably run for one year, but 3 or 6 months can be used if longer test times are not feasible. An expansion equal to

or more than 0.03% at one year, 0.025% at 6 months, or 0.015% at 3 months indicates potentially deleterious aggregate (ASTM C 1105, Appendix).

This test makes it possible to measure expansive tendencies of cement-aggregate combinations rather than expansive characteristics of the rock alone, but the year-long test duration is a drawback. If this test has been performed on a cement-aggregate combination involving an aggregate that has not been examined petrographically using C 295, or has not been measured by the rock prism expansion test (C 586), one or both of those tests should also be performed.

The Canadian Standards Association CSA A23.2-14A, *Potential Expansivity of Aggregates (Procedure for Length Change Due to Alkali-Aggregate Reaction in Concrete Prisms)*, is similar to C 1105, as both tests require similar specimens and storage conditions. Cement alkali levels, aggregate gradation, and limits that indicate expansive behavior differ slightly for the two methods. The Canadian version of the test stipulates the cement alkali level to be used, making the test more standardized and allowing comparison among test results. The higher cement alkali content in A23.2-14A makes it a more aggressive test than C 1105, so it should identify potentially reactive rocks that might pass C 1105.

## Control of Alkali-Carbonate Reaction

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

### Selective Quarrying

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

### Blended Aggregate

Another option is blending reactive aggregate with aggregate proven by testing—and service record, if possible—to be nonreactive. This can mitigate the reactive aggregate's detrimental effects on concrete. Accordingly, the Appendix in ASTM C 1105 limits the safe proportion of reactive aggregate to 20% for either the coarse or fine sizes when used alone, or a limit of 15% total when used in combination. Test the resulting diluted or blended aggregate using ASTM C 1105 to be certain it is acceptable for use in portland cement concrete.

### Aggregate Size

Limiting the nominal maximum size of aggregate is another way to minimize expansion due to ACR. Use the smallest practical nominal maximum size of aggregate to minimize detrimental expansion (Swenson and Gillott 1967).

## Low-Alkali Cement

Low-alkali cement is not generally effective in controlling expansive ACR. Even cements with alkali levels as low as 0.40% can produce pore solutions with sufficient alkalinity to initiate reaction. Due to the chemistry of the alkali-carbonate reactions, alkalies are regenerated rather than consumed. They undergo a series of reactions with aggregates and are then available to react again with more aggregate (Hadley 1961). The cement alkali level is of less concern than the alkali content of concrete, which should be kept as low as possible when using alkali-carbonate reactive aggregate.

## Pozzolans

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

## ACR-Inhibiting Compounds

While some researchers have found that lithium compounds appear to control ACR (Gajda 1996), others found that lithium hydroxide and lithium carbonate increase expansion of alkali-carbonate reactive rock (Wang, Tysl, and Gillott 1994).

## Common Questions about AAR

*Q:* If an aggregate has good field performance, why test the aggregate for deleterious behavior?

*A:* This requires a two-part answer. Field history is a valuable source of information that indicates an aggregate's behavior in service. If conditions of service and the ingredients, including total alkali content of the concrete, are the same in the existing and proposed concrete structures, there is no need to test an aggregate that has a good record of service. If, however, the aggregate varies significantly within the quarry, or if exposure conditions of the proposed structure will be more severe than in structures exhibiting good performance, or if the concrete ingredients are significantly different, the aggregate should be tested.

*Q:* If an aggregate passes ASTM C 1260 (AASHTO T 303) and other ASR requirements, should there be restrictions on cementitious materials, such as limits on cement alkalies?

*A:* No. Nonreactive aggregate can be used without undue restrictions on cementitious materials.

*Q:* Should an aggregate be eliminated from use if it fails ASTM C 1260 (AASHTO T 303) or other ASR tests?

*A:* No. First, deleterious behavior must be confirmed by field history or ASTM C 1293 before an aggregate is classified as potentially reactive. Even then, aggregates that are classified as potentially reactive can be safely used with pozzolans, slags, or ASR-inhibiting compounds, blended cements, or by limiting the total alkali content of the concrete. Another option would be to blend the aggregate with a nonreactive aggregate to a level that is not harmfully reactive.

*Q:* Is it possible for ASTM C 1260 (AASHTO T 303) to give a false negative? A false positive?

*A:* Yes to each. False negatives, where a reactive aggregate is identified as nonreactive, are not common with ASTM C 1260 (AASHTO T 303). Most reactive aggregates will be identified by this test because it is so severe. False positives, where a nonreactive aggregate is identified as being reactive, are more common, again because the test method is so severe. The alkali hydroxide concentration of most field concretes is much lower than that of the test method and is at a level that does not induce harmful reactivity for many aggregates that fail C 1260 (AASHTO T 303). It cannot be stressed enough that supplemental information should be developed to evaluate an aggregate.

*Q:* If a pozzolan is required in a given concrete mixture, should the aggregate be tested alone to determine its potential for ASR? Should all of ASTM tests C 227, C 289, C 295, C 1260 (AASHTO T 303), C 1293, and C 1567 be performed?

*A:* If the concrete is required to contain a pozzolan anyway, consider using ASTM C 1567 to investigate expansive tendencies of the combination of aggregates and cementitious materials. Note that some pozzolans at some dosages can increase ASR potential, so the mixture design should be strictly defined and adhered to in order for the combination of materials to work effectively. It is not necessary to require every test to prove effectiveness and it's not very efficient. Choose one test, such as C 1567, that uses the proposed cementitious materials to evaluate their effectiveness at controlling expansion. If one or two years are available, C 227 or C 1293 can be performed using the pozzolan.

*Q:* Isn't the easiest way to control ASR to avoid using potentially reactive aggregate and require use of a low-alkali cement?

*A:* Though this can effectively control ASR, it would not be efficient. Not all geographical areas have nonreactive aggregates or low-alkali cements. Requiring these materials would probably result in extra costs and lost time. Concrete mixtures should be designed to be economical in addition to being safe from ASR potential. Local materials usually provide the greatest availability and best economy.

*Q:* Are all fly ashes and slags equal at controlling expansion from ASR, and is there one single dosage that will always be effective?

*A:* All fly ashes and slags are not equal at controlling expansion due to ASR. Class F ashes (typically low CaO) as a group are usually more effective than Class C ashes. And within a group, one ash can be more effective than another. Slags are generally less variable in composition than fly ashes due to their origin. Also, aggregates of different degrees of

reactivity and different cement alkali levels require different dosages of fly ash or slag. Since no one dosage is effective with all fly ashes or slags, it is necessary to investigate any fly ash's or slag's ability to control ASR by testing. Concurrent testing of various dosages helps determine the appropriate fly ash dosage. Use ASTM C 1293 or ASTM C 1567.

Q: Can I use ASTM C 1260 (AASHTO T 303) or ASTM C 1567 to test the effectiveness of a portland cement to control ASR?

A: No. The standard tests as written are not designed to test the effect of different portland cements on ASR. The test specimen alkali content rises to approach that of the solution in which it is submerged, regardless of the original alkali content of the cement.

Q: A pavement engineer wants to replace some of the cement in a standard mixture with fly ash to control ASR but is concerned about poor strength gain in cold weather. Any solutions?

A: Yes. Use the fly ash as an addition or partial replacement to the standard mixture instead of replacing the cement. The fly ash will still control ASR, and the mix will gain strength in cold weather similar to that of the cement-only mixture. Chemical admixtures or Type III cement can also be used to accelerate strength gain.

- *Development of a Cement to Inhibit Alkali-Silica Reactivity* (RD115)
- "Developments in Alkali-Silica Gel Detection," *Concrete Technology Today* (PL991) ([http://www.cement.org/pdf\\_files/pl991.pdf](http://www.cement.org/pdf_files/pl991.pdf))
- *Substitution of Fly Ash for Cement or Aggregate in Concrete: Strength Development and Suppression of ASR* (RD127)
- *Surface Popouts Caused by Alkali-Aggregate Reaction* (RD121)

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Web site: [www.cement.org/bookstore](http://www.cement.org/bookstore)

## Related Publications

The publications cited in this text, as well as other related publications, are available from Portland Cement Association.

The following are particularly useful:

- *Guide Specification for Concrete Subject to Alkali-Silica Reactions* (IS415)
- *Alkali-Silica Reactivity: An Overview of Research* (LT177)
- *Handbook for the Identification of Alkali-Silica Reactivity* (LT165)
- "Detecting and Avoiding Alkali-Aggregate Reactivity," *Concrete Technology Today* (PL913) ([http://www.cement.org/pdf\\_files/pl913.pdf](http://www.cement.org/pdf_files/pl913.pdf))
- "Cornell's Gel Fluorescence Test Identifies ASR Products in Concrete," *Concrete Technology Today* (PL922) ([http://www.cement.org/pdf\\_files/pl922.pdf](http://www.cement.org/pdf_files/pl922.pdf))
- "Lithium-Based Admixtures—An Alternative for Preventing Expansive Alkali-Silica Reaction," *Concrete Technology Today* (PL931) ([http://www.cement.org/pdf\\_files/pl931.pdf](http://www.cement.org/pdf_files/pl931.pdf))
- *Design and Control of Concrete Mixtures* (EB001)
- *Alkali-Silica Reactivity: Some Reconsiderations* (RD076)
- *Lithium Salt Admixture—An Alternative Method to Prevent Expansive Alkali-Silica Reactivity* (RP307)
- *Field and Laboratory Studies on the Reactivity of Sand-Gravel Aggregates* (RX221)
- *The Use of Recycled-Concrete Aggregate from Concrete Exhibiting Alkali-Silica Reactivity* (RD114)

**Table 1. Test Methods for Alkali-Silica Reactivity**

Test name	Purpose	Type of test	Type of sample	Duration of test	Measurement	Criteria	Comments
Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method) (ASTM C 227)	To test the susceptibility of cement-aggregate combinations to expansive reactions involving alkalies	Mortar bars stored over water at 37.8°C (100°F) and high relative humidity	At least 4 mortar bars; standard dimensions: 25x25x285 mm (1x1x11.1 in.)	Varies: first measurement at 14 days then 1, 2, 3, 4, 5, 6, 9, and 12 months and every 6 months after that as necessary	Length change	Per ASTM C 33, maximum 0.10% expansion at 6 months, or if not available for a 6-month period maximum of 0.05% at 3 months	Test may not produce significant expansion, especially for carbonate aggregate Long test duration Expansions may not be from AAR
Potential Alkali Reactivity of Aggregates (Mortar-Bar Method) (ASTM C 1260/ AASHTO T 303)	To test the potential for deleterious alkali-silica reaction of aggregate in mortar bars	Immersion of mortar bars in alkaline solution at 80°C (176°F)	At least 3 mortar bars	16 days	Length change	If greater than 0.10%, go to supplementary test procedures; if greater than 0.20%, indicative of potentially deleterious expansion	Very fast alternative to C 227 Useful for slowly reacting aggregates or ones that produce expansion late in the reaction
Potential Alkali-Silica Reactivity of Aggregates (Chemical Method) (ASTM C 289)	To determine potential reactivity of siliceous aggregates	Sample reacted with alkaline solution at 80°C (176°F)	3-25 gram samples of crushed and sieved aggregate	24 hours	Drop in alkalinity and amount of silica solubilized	Point plotted on graph falls in deleterious or potentially deleterious area	Quick results Some aggregates give low expansions even though they have high silica content—Not reliable
Determination of Length Change of Concrete Due to Alkali-Silica Reaction (Concrete Prism Test) (ASTM C 1293)	To determine the potential ASR expansion of cement-aggregate combinations	Concrete prisms stored over water at 38°C (100.4°F)	3 prisms per cement-aggregate combination, standard dimensions: 75x75x285mm (3x3x11.1 in.)	Varies: first measurement at 7 days, then 28 and 56 days, then 3, 6, 9, and 12 months and every 6 months after that as necessary	Length change	Per Appendix XI, potentially deleteriously reactive if expansion equals or exceeds 0.04% at 1 year (or 0.04% at 2 years if SCMs are to be evaluated)	Preferred method of assessment Best represents the field Long test duration for meaningful results Use as a supplement to C 227, C 295, C 289, C 1260, and C 1567 Similar to CSA A23.2-14A
Potential Volume Change of Cement-Aggregate Combinations (ASTM C 342)	To determine the potential ASR expansion of cement-aggregate combinations	Mortar bars stored in water at 23°C (73.4°F)	3 mortar bars per cement-aggregate combination, standard dimensions 25x25x285mm (1x1x11.1 in.)	52 weeks	Length change	Per ASTM C 33, unsatisfactory aggregate if expansion equals or exceeds 0.200% at 1 year	Primarily used for aggregates from Oklahoma, Kansas, Nebraska, and Iowa
Effectiveness of Pozzolans or GBFS in Preventing Excessive Expansion of Concrete Due to the Alkali-Silica Reaction (ASTM C 441)	To determine effectiveness of pozzolans or GBFS in preventing excessive expansion from ASR	Mortar bars—using Pyrex glass as aggregate—stored over water at 37.8°C (100°F) and high relative humidity	At least 3 mortar bars and also 3 mortar bars of control mixture	Varies: first measurement at 14 days, then 1, 2, 3, 4, 6, 9, and 12 months and every 6 months after that as necessary	Length change	Per ASTM C 989, minimum 75% reduction in expansion or 0.020% maximum expansion or per C 618, comparison against low-alkali control	Highly reactive artificial aggregate may not represent real aggregate conditions Pyrex contains alkalies
Constituents of Natural Mineral Aggregates (ASTM C 294)	To give descriptive nomenclature for the more common or important natural minerals—a good starting point to predict behavior	Visual Identification	Varies, but should be representative of entire source	Short duration—as long as it takes to visually examine the sample	Description of type and proportion of minerals in aggregate	Not applicable	These descriptions are used to characterize naturally-occurring minerals that make up common aggregate sources
Petrographic Examination of Aggregates for Concrete (ASTM C 295)	To evaluate possible aggregate reactivity through petrographic examination	Visual and microscopic examination of prepared samples—sieve analysis microscopy, scratch or acid tests	Varies with knowledge of quarry: cores 53 to 100mm in diameter (2 1/4 to 4 in.), involve 45 kg (100 lb) or 300 pieces, or 2 kg (4 lb)	Short duration—visual examination does not involve long test periods	Particle characteristics, like shape, size, texture, color, mineral composition, physical condition	Not applicable	Usually includes optical microscopy, may include XRD analysis, differential thermal analysis, or infrared spectroscopy—see C 294 for descriptive nomenclature
Petrographic Examination of Hardened Concrete (ASTM C 856/ AASHTO T 299)	To outline petrographic examination procedures of hardened concrete—useful in determining condition or performance	Visual (unmagnified) and microscopic examination of prepared samples	At least one core 150 mm diameter by 300 mm long (6 in. diameter by 12 in. long)	Short duration—includes preparation of samples and visual and microscopic examination	Is the aggregate known to be reactive? Orientation and geometry of cracks Is there any gel present?	See measurement—this examination determines if ASR reactions have taken place and their effects upon the concrete Used in conjunction with other tests	Specimens can be examined with stereomicroscopes, polarizing microscopes, metallographic microscopes, and SEM
Uranyl-Acetate Treatment Procedure (ASTM C 856 Annex)	To identify products of ASR in hardened concrete	Staining of a freshly exposed concrete surface and viewing under UV light	Varies: core, lapped surface, broken surface	Immediate results	Intensity of fluorescence	Lack of fluorescence	Identifies small amounts of ASR gel whether they cause expansion or not Opal, a natural aggregate, and carbonated paste can glow—interpret results accordingly Text must be supplemented by petrographic examination and physical tests for determining concrete expansion
Potential Alkali-Silica Reactivity of Cementitious Materials and Aggregate Combinations (Accelerated Mortar-Bar Method) (ASTM C 1567)	To test the potential for deleterious alkali-silica reaction of cementitious materials and aggregate combinations in mortar bars	Immersion of mortar bars in alkaline solution at 80°C (176°F)	At least 3 mortar bars for each cementitious materials and aggregate combination	16 days	Length change	If greater than 0.10%, indicative of potential deleterious expansion; use C 1293 (2-year test) to confirm	Very fast alternative to C 1293 Allows for evaluation of supplementary cementing materials and determination of optimum dosage

**Table 2. Test Methods for Alkali-Carbonate Reactivity**

Test name	Purpose	Type of test	Type of sample	Duration of test	Measurement	Criteria	Comments
Potential Alkali Reactivity of Carbonate Rocks for Concrete (Rock Cylinder Method) (ASTM C 586)	To determine the expansive characteristics of carbonate rocks	Immersion of rock cylinders in alkaline solution at 23°C (73.4°F)	One rock cylinder, 35 mm long and 9 mm in diameter (1.38 in. long and 0.35 in. diameter)	Up to or over 1 year, but expansive tendencies are usually evident after 28 days	Length change	Not applicable	Securing representative sample may be difficult Can be a long test period Intended as supplement to other test procedures
Length Change of Concrete Due to Alkali-Carbonate Rock Reaction (ASTM C 1105)	To determine susceptibility of cement-aggregate combinations to expansive ACR	Concrete prisms stored at 23°C (73.4°F) and high relative humidity	6 concrete prisms 75x75x285mm (3X3X11.1in.) —or 100 mm (4 in.) square for 50 mm (2 in.) maximum size aggregate	1 year	Length change	Aggregate is most likely reactive if length change at 1 year (preferred measurement) is greater than or equal to 0.030% (0.025% at 6 months or 0.015% at 3 months)	Long test period Best used as a verifier of potential reactivity for a rock known to contain a potentially deleterious alkali-carbonate rock—see Appendix
Potential Expansivity of Aggregates (Procedure for Length Change Due to Alkali Aggregate Reaction in Concrete Prisms) (CSA A23.2-14A)	To evaluate the potential expansivity of both coarse and fine aggregates	Concrete prisms stored over water at 38°C (100.4°F)	3 prisms 75x75x285mm (3X3X11.1in.) and an additional (fourth) prism may be cast for petrographic examination	1 year	Length change	Aggregate is most likely reactive if length change is greater than 0.04% at 1 year	Long test period Use in conjunction with other information such as petrographic examination Similar to ASTM C 1293
Constituents of Natural Mineral Aggregates (ASTM C 294)	To give descriptive nomenclature for the more common or important natural minerals—a good starting point to predict behavior	Visual identification	Varies, but should be representative of entire source	Short duration—as long as it takes to visually examine the sample	Description of type and proportion of minerals in aggregate	Not applicable	These descriptions are used to characterize naturally occurring minerals that make up common aggregate sources
Petrographic Examination of Aggregates for Concrete (ASTM C 295)	To evaluate possible aggregate reactivity through petrographic examination	Visual and microscopic examination of prepared samples—sieve analysis, microscopy, scratch or acid tests	Varies with knowledge of quarry; cores 53 to 100 mm in diameter (2 1/8 to 4 in.), 45 kg (100 lb) or 300 pieces, or 2 kg (4 lb)	Short duration—visual examination does not involve long test periods	Particle characteristics, like shape, size, texture, color, mineral composition, physical condition	Not applicable	Usually includes optical microscopy; may include XRD analysis, differential thermal analysis, or infrared spectroscopy—see C 294 for descriptive nomenclature
Petrographic Examination of Hardened Concrete (ASTM C 856)	To outline petrographic examination procedures of hardened concrete—useful in determining condition or performance	Visual (unmagnified) and microscopic examination of prepared samples, acid etching	At least one core 150 mm diameter by 300 mm long (6 in. diameter by 12 in. long)	Short duration—includes preparation of samples and visual and microscopic examination	CaOH crystals are smaller than in undamaged concrete Are rims or partial rims depleted in CaOH? Pale color of rims may indicate gel	See measurement—this examination determines if ACR reactions have taken place and their effects upon the concrete Used in conjunction with other tests	Specimens can be examined with stereomicroscopes, polarizing microscopes, metallographic microscopes, and SEM

## ASTM and AASHTO Standards

ASTM International and equivalent AASHTO documents related to alkali-aggregate reactivity that are relevant to or referred to in the text are listed as follows. The latest edition of these documents can be obtained at [www.astm.org](http://www.astm.org) and [www.aashto.org](http://www.aashto.org) respectively. Note that AASHTO standards may not exactly replicate ASTM standards.

ASTM C 33 (AASHTO M 6 / M 80)	Standard Specification for Concrete Aggregates
ASTM C 114	Standard Test Methods for Chemical Analysis of Hydraulic Cement
ASTM C 150 (AASHTO M 85 )	Standard Specification for Portland Cement
ASTM C 227	Standard Test Method for Potential Alkali Reactivity of Cement-Aggregates Combinations (Mortar-Bar Method)
ASTM C 289	Standard Test Method for Potential Alkali-Silica Reactivity of Aggregates (Chemical Method)
ASTM C 294	Standard Descriptive Nomenclature for Constituents of Concrete Aggregates
ASTM C 295	Standard Guide for Petrographic Examination of Aggregates for Concrete
ASTM C 311	Standard Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use in Portland-Cement Concrete
ASTM C 441	Standard Test Method for Effectiveness of Pozzolans or Ground Blast Furnace Slag in Preventing Excessive Expansion of Concrete Due to the Alkali-Silica Reaction
ASTM C 586	Standard Test Method for Potential Alkali Reactivity of Carbonate Rocks as Concrete Aggregates (Rock Cylinder Method)
ASTM C 595 (AASHTO M 240)	Standard Specification for Blended Hydraulic Cements
ASTM C 618 (AASHTO M 295)	Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete
ASTM C 856 (AASHTO T 299)	Standard Practice for Petrographic Examination of Hardened Concrete
ASTM C 989 (AASHTO M 302)	Ground Granulated Blast Furnace Slag for Use in Concrete and Mortar
ASTM C 1105	Standard Test Method for Length Change of Concrete Due to Alkali-Carbonate Rock Reaction
ASTM C 1157	Standard Performance Specification for Hydraulic Cement
ASTM C 1240 (AASHTO M 307)	Standard Specification for Silica Fume Used in Cementitious Mixtures
ASTM C 1260 (AASHTO T 303)	Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)
ASTM C 1293	Standard Test Method for Concrete Aggregates by Determination of Length Change of Concrete Due to Alkali-Silica Reaction
ASTM C 1567	Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method)

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**WARNING:** Contact with wet (unhardened) concrete, mortar, cement, or cement mixtures can cause SKIN IRRITATION, SEVERE CHEMICAL BURNS (THIRD DEGREE), OR SERIOUS EYE DAMAGE. Frequent exposure may be associated with irritant and/or allergic contact dermatitis. Wear waterproof gloves, a long-sleeved shirt, full-length trousers and proper eye protection when working with these materials. If you have to stand in wet concrete, use waterproof boots that are high enough to keep concrete from flowing into them. Wash wet concrete mortar, cement, or cement mixtures from your skin immediately after contact. Indirect contact through clothing can be as serious as direct contact, so promptly rinse out wet concrete, mortar, cement, or cement mixtures from clothing. Seek immediate medical attention if you have persistent or severe discomfort.

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