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What happened? Where are we? What now?

Alkali-Silica Reaction — 40 Years Later

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The highlights of experience and discovery since identification some 40 years ago of the alkali-silica reaction (ASR) are noted and described. Happenings in special cases and with unusual materials are mentioned. Termination of significant ASR without diminishing the serviceability of interior concrete in three arch dams in the southwest is reported. Means of avoiding the problem despite use of an otherwise acceptable as well as economic aggregate is discussed.

Keywords: alkali-aggregate reactions; alkalies; cement-aggregate reactions; chemical attack; cracking (fracturing); failure; high-alkali cements; opal; quartz; silica gel; **siliceous aggregates;** weathering.

Introduction

The Alkali-Silica Reaction (ASR) is a chemical reaction between alkalies in the cement and certain responsive, siliceous minerals and rock types in the aggregate portion of a given concrete.[1] The resultant sodium silicate gel will imbibe moisture, if available, causing the gel to swell from osmosis and develop pressure. Such pressures are the cause of the expansion of interior concrete. In relation to comparatively dry surface concrete, subject to drying shrinkage also, this internal expansion causes conspicuous map cracking in surface areas, and primarily longitudinal cracks on the faces of beams and columns, and the tops of walls. In the early years, beads of this gel emerged along such a longitudinal crack in the top of the Parker Dam parapet and from a crack in the floor along the river wall of the pump room in the powerhouse.

The first recognized cases of ASR

In the late 30s abnormal cracking of concrete structures in Southern California was drawing the attention of materials engineers and consultants. A seawall in Ventura County was grotesquely opened with longitudinal cracks. Lower portions of schools in Santa Barbara were extremely cracked. The Sixth Street bridge in Los Angeles had a gross pattern of cracks in the portal blocks and disturbing vertical cracks in its piers. Such cracking in certain highway structures had aroused the concern of the concrete section of the materials laboratory of the then California Division of Highways, directed by Thomas E. Stanton. Research was conducted. Stanton and his staff in Sacramento were the first to recognize that the troublesome cracking beyond drying shrinkage was due to the internal expansion as above described, from the alkali-silica reaction. Stanton's article in the *Engineering News-Record* February 1, 1940,[2,3,4] was the first publication to correctly describe the ASR and some of the aggregate minerals which fostered it. The sodium and potassium oxides in cement and opaline, noncrystalline siliceous elements of the aggregates were clearly responsible.

This stimulated wider concern and in particular the U.S. Bureau of Reclamation noted the evidence of ASR at Parker Dam on the Colorado River[5] and at Stewart Mountain Dam on the Salt River in Arizona. The builder of Parker Dam used the same cement and aggregates to build Gene Wash and Copper Basin arch dams nearby for the Metropolitan Water District of Southern California as part of the Colorado River Aqueduct system. Sure enough, the same evidence of ASR was evident on these dams also.

Further study and research, observation and experience

Probably nothing during the 40s received more attention in the capable USBR laboratories in Denver than aspects of the ASR. The clue from Sacramento needed amplification. How much and what kind of alkalies could be detrimental in cement? What rock types other than opaline were susceptible to the ASR? What methods of test were reliable to measure and judge the ASR potential of a given cement-aggregate combination? What were safe critical limits to be placed on the results of these tests? Under what conditions would the ASR occur and under what not? Continuing into the 50s these inquiries included possible means of eliminating opaline (Dana — opal, G=1.9-2.3) lightweight reactive pieces in aggregates and the capability of mineral admixtures to minimize or neutralize effects of the ASR. Also there was continuing observation of the effects of the resultant expansion and surface cracking on field structures and on their serviceability.

The alkali content of cement

Soon a consensus in the concrete industry was widely believed that if alkalies in cement as Na_2O (that is $Na_2O + 0.658K_2O$) did not exceed 0.60 percent, concrete would be essentially safe from ASR. There were, however, some exceptions to this assurance that were by no means marginal in later performance, as predicted by mortar-bar tests. Professor Charles F. Scholer, Sr. did not feel safe from results of the Kansas-Nebraska cement-aggregate reaction unless the alkalies were well below 0.6 percent. The most glaring example in California was the highway bridges at Bishop which left no doubt that ASR had been present despite use of so-called "low" alkali cement. There are doubtless other cases elsewhere.[6]

"Low" alkali cement was specified for Matilija Dam[*] near Ventura, California, but there is no reason to believe it was furnished. At Friant Dam near Fresno, California, low-alkali cement was specified and used in the mass concrete[†] but it was not regularly available in war time for the appurtenant works and parapets which have exhibited ASR.

Where cement used is naturally produced with 0.40 percent alkalies or less we are unaware of evident ASR, even in the Snake River Valley where most aggregates contain reactive siliceous volcanic elements. Interstate highway structures (at least in the vicinity of American Falls, Idaho), presumably made with such cement and aggregate, are in excellent condition. In the vicinity of Parker Dam and built with petrographically similar Colorado River terrace gravels, but fortuitously with cement having naturally an equivalent alkali content of about 0.38 percent, the Intake and Gene Pumping Plants of the Colorado River Aqueduct have no sign whatever of ASR.[5]

The range of reactive aggregate

Experience and research have lengthened the list of potentially reactive aggregate materials. It was soon learned that they went considerably further than the opaline silicas to include glassy to cryptocrystalline rhyolitic, dacitic, and andesitic volcanic rocks and their tuffs, and others. At the Buck Hydroelectric Plant in Virginia, built in 1912, increasing difficulty was encountered in keeping shafts in alignment.[7] By 1929 it was evident that expanding concrete was distorting the positions of bearings in the power and generating equipment. Petrographic study of the concrete later showed that the phyllite aggregate was developing sufficient ASR expansion to cause the distortion. At the Drum Afterbay Dam near Colfax, California, built in 1924, the slate coarse aggregate was found in 1965 to have been subject to ASR. In this case, however, although the ASR had not damaged the concrete above water level, sulfates were also developed below reservoir level, sufficient to deteriorate the concrete to a degree requiring replacement of the dam.[8]

Unlike in the concretes containing the opaline and volcanic rock aggregate, which in a very few years exhibited expansion and gross surface cracking, the phyllite and slate aggregate ASR tendencies were much slower to become evident. In recent years "strained" quartz has shown that it, too, has an ASR potential that may not appear for 10 years. Aggregates for the concrete features of Tarbella Dam in Pakistan were considered to have no reactive elements when the work was started some 10 years ago. Now strained quartz is found to be responsible for some ASR. Strained quartz has been reworked under such high heat and pressure that it is sufficiently finely divided to provide very high surface area for chemical attack. Then there is the unique "cement-aggregate reaction" in the Kansas, Nebraska, Wyoming area. Aggregates from this area, in ways different from ASR, have caused alkalies to concentrate near pavement surfaces; resultant surface cracking has contributed to deterioration.[1] Another form is the "expansive alkali-carbonate reactivity" with certain limestone, usually dolomitic, aggregates. Although similar to ASR in expansion and surface cracking where there is moisture, there is a general absence of gel exudations.[1]

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[*] Completed in 1948, with cement specified to be "low-alkali," Matilija Dam has exhibited ASR expansion and cracking in upper portions. Upstream movement of the arch commenced in 1963 and has not yet discontinued (1981). In 1965, 180 ft (54.9 m) of the crest was lowered 40 ft (12.2 m) to allay fears for the dam's safety. Reactive elements of the aggregate include opal. No records were kept of the alkali-content of the cement, but it evidently was variable and often excessive.

[†] A local pumicite pozzolan was used in the mass concrete at Friant dam. There was some autogenous shrinkage, no expansion.

Tests developed to determine ASR potential

The ASTM C 227 mortar-bar test method was developed to determine the "Potential Alkali Reactivity of Cement-Alkali Combinations."[9] It is a good test provided it is performed with the correct equipment and facilities by careful and experienced operators. Otherwise this test can be grossly misleading, often making things appear better than they are. The limits for concern in Section 11.2, of 0.05 percent expansion in 3 months and 0.10 percent in 6 months, were moved forward from 6 months and 1 year for dubious reasons palliative to producers. A return to the original criteria should be seriously considered because the safety at stake is not subject to such fine distinctions. Test results well beyond a year would provide valuable information and should be included when feasible.

Another use of the above mortar-bar test is ASTM C 441 for evaluation of the "Effectiveness of Mineral Admixtures in Preventing Excessive Expansion Due to the Alkali-Aggregate Reaction."[9] Similarly, the same considerable care in performing the test is required to assure reliable results. Section 11.3 suggests that for significant "prevention" the bars should not expand more than 0.02 percent in 14 days of the prescribed storage.

ASTM C 289 is a chemical "Test for Potential Reactivity of Aggregates."[9] Reduction in alkalinity by the test method is plotted against the quantity of dissolved silica on Fig. 2 of C289. Dividing lines on this chart presume to designate areas denoting that the aggregate tested is "Considered Innocuous," "Potentially Deleterious," or "Considered Deleterious," if the test result value falls within them. Again marginal innocuous results are too often taken seriously and results become misleading. They have also been seriously in error when the caution in Section 17.2 is either overlooked or ignored, that results may not be correct for aggregates containing many of the carbonate and other rocks.

Preferable to either the "mortar-bar" or "chemical" test, particularly the latter, is the ASTM C 295 "Petrographic Examination of Aggregate for Concrete."[9,12] The siliceous rock minerals which have reacted deleteriously with cement alkalies in concrete are now well known and recognizable to experienced petrographers. If they are there they can be seen and results are not dependent on laboratory facilities, methods, or personnel.

As margins and limiting amounts are approached in any of these tests and examinations, the question of what will be safe and serviceable arises. The combinations and possibilities are infinite. As noted elsewhere,[10] it is not likely to be possible to determine exactly what may be required to assure serviceability, but usually the extra cost of making sure is small insurance to avoid maintenance and too-early replacement costs. However, service records can provide the best means of judging safe action when unfavorable test results are relatively minor, provided it is certain that such records include the essential items: What was the alkali content of the cement? What amount of cement? Were there any mineral admixtures used? If so, what and how much? Without such information, it is only known, presumably, that the aggregate was similar to that under consideration. Results could be disappointingly different if the other ingredients were to be different in the contemplated concrete.

Mineral admixtures

Pozzolans as an ingredient of concrete were under study in progressive laboratories even in the decade before ASR was identified. Soon its ability to control the ASR became well known through its performance in such tests as the C 441 mortar-bar test. The well-known reaction between the noncrystalline silica in a pozzolan and the calcium hydroxide (lime) from the hydrated cement, consumes the alkalies present, creating innocuous calcium alkali silicates. Some early work by the USBR is summarized in Fig. 3 of Reference 11 showing both F and N-type pozzolans capable of controlling the expansion due to a high-alkali cement when correct amounts are used. In Fig. 16 of Reference 13, Brink and Halstead showed sometime before 1956 that with 2 percent opal in Ottawa sand and a cement having 0.90 percent Na_2O equivalent alkalies, bars with the three "least effective" fly ashes expanded little more in 1 year than the three "most effective" fly ashes, when 35 percent of the cement was replaced. Relative to expansion of the mortar without fly ash, these expansions were re-

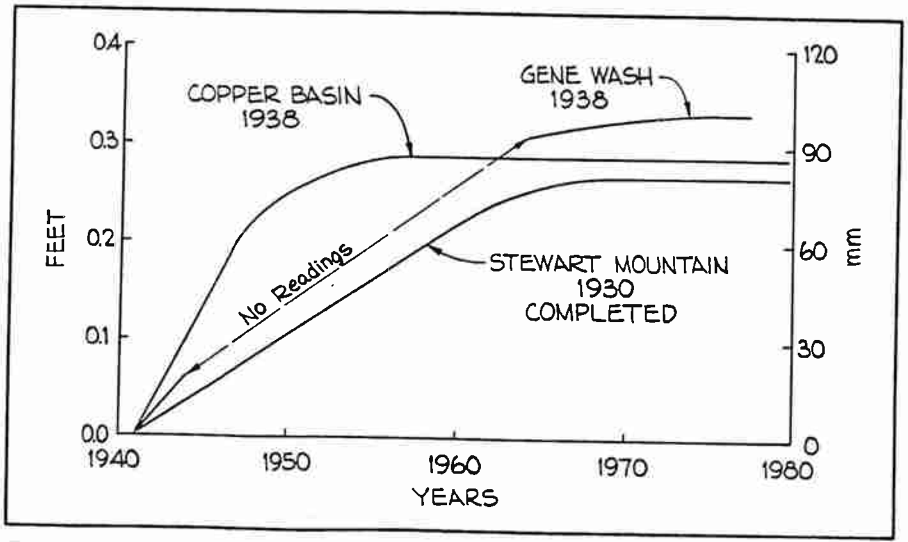

Fig. 1 — Increase in elevation of midcrest of three arch dams as a result of concrete expansion due to ASR.

duced from 100 to 8 and 2, respectively. The USBR data in Fig. 3 of Reference 11 show that much less replacement from 10 percent (opal) to 18 percent (calcined shales), will reduce expansion in 15 months to less than 0.05 percent, — no more than with the nonreactive quartz control aggregate.

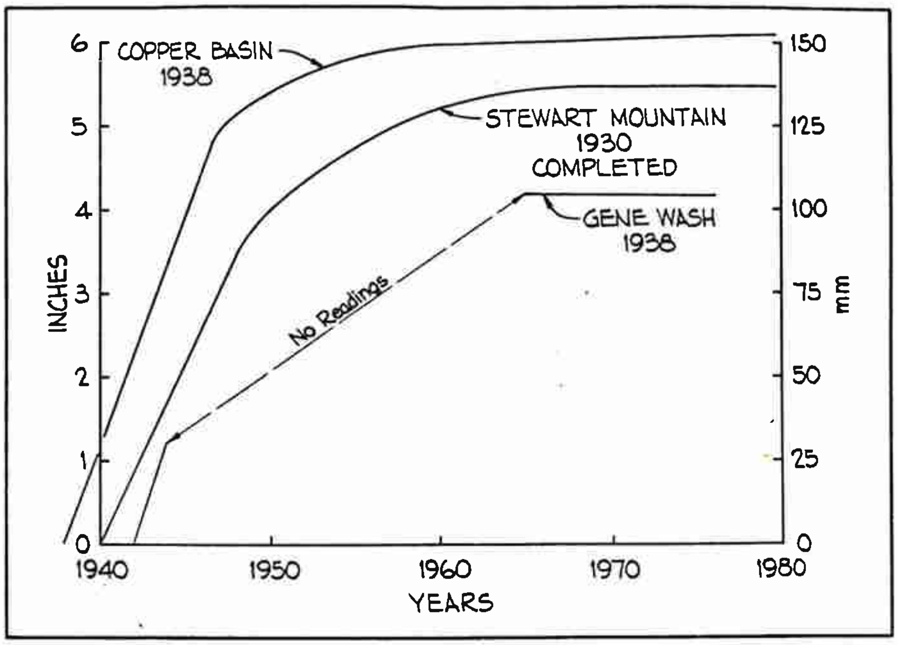

Fig. 2 — Upstream movement of crests of three arch dams as a result of concrete expansion due to ASR.

Nevertheless, until recent years little use was made of pozzolans for this purpose. The so-called low-alkali cement (0.60 percent limit)[6] was available for little or often no premium. Although pozzolans were usually cheaper to buy than cement, it was another material, and all costs to use it might approach that of cement. The combinations usually had a lower early-strength. Sometimes a nonreactive aggregate was overall less expensive or borderline materials would be used. Sometimes it worked. Sometimes it didn't. But with present-day energy and environmental restrictions on production of low-alkali cement, and the pressures to utilize the by-product fly ash (pozzolan), there is motivation now to use the well-demonstrated pozzolan alternate to control and eliminate ASR. Moreover, when pozzolan replaces some of the cement, the amount of alkalies in the concrete is reduced. Such control is an automatic fallout of the now wide use of pozzolan in mass concrete for temperature control and other values. *The practical effect of ASR on concrete performance* was, through its heavy map cracking of flatwork and surfaces of structures subject to moisture, to expose such concrete more deeply than usual to deterioration from freezing and thawing and from chemical corrosion, where such potential existed. Great damage was done to architectural concrete such as the massive decorative eagles on the crest of Coolidge Dam in Arizona. Much of the affected concrete, although unsightly, was sufficiently serviceable. Some required replacement. Some could be repaired.

A larger problem was posed by the three massive dams afflicted by the internal expansion and surface cracking caused by ASR. In the early years, of course, it was unknown how far this would go in affecting their performance and safety. As indicated in Fig. 1 and 2, it was soon noted that the expansion was causing an increase in elevation of midcrest points on the dams and movement of the crest centers upstream as the arches lengthened between the relatively unyielding abutments. The amount of rise and movement of the crests is a function of the size of dam and the particular combination of reactive aggregate and alkalies in each concrete. It is only the general and consistent shape of the curves that is important. From time to time cores were taken to monitor any effect on the strength and elasticity of the concrete. Essentially, these continued to be acceptable, leaving ample margins of safety, even when stress was computed against the narrower remaining interior section, after discounting the cracked exterior surface layer.*

Evidence of termination of ASR

From the expansion data summarized in Fig. 1 and 2, it is clear that the ASR has come to a conclusion in these dams.† There were encouraging signs of this by 1960 after some 20 years and it was positive by 1970, after 30 years. This has been confirmed by petrographic examination of cores in later years. They now show that reaction products have solidly filled the micro-fractures caused by the earlier expansive forces. Apparently the reactive elements have now been consumed. Fortunately, creep characteristics of the concrete permitted it to yield and adjust through the active years of the ASR expansion, so that destructive stresses were never developed.

Conclusion

It is gratifying to know that this disturbing experience with concrete work need never happen again. The pumping plants of the

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*At Parker Dam[5] only the growing width of the characteristic ASR surface cracks was measured for a number of years. Presumably the data on expansion obtained by the USBR at Stewart Mountain Dam and by the MWD of SC at Gene Wash and Copper Basin Dams was considered sufficiently representative. Parker Dam was unique in that its foundation was 235 ft (72 m) below river bed, while only 85 ft (26 m) extended above.

†The thus-far continuing expansion of the concrete in Matilija Dam is considered to be the result not only of the ASR primarily based on the opaline elements of the aggregate, but also on the ASR based on attack on the less susceptible rock types, in part utilizing alkalies drawn from the calcium-alkali-silica gels produced by the ASR involving opal.