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THE IDENTIFICATION OF ALKALI-AGGREGATE REACTION AT THE GARDINER DAM, OUTLOOK SASKATCHEWAN

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ABSTRACT

This paper documents the identification of alkali-aggregate reaction in some portions of the concrete structures associated with the Gardiner Dam on the South Saskatchewan River. The AAR-related portions of an intensive, long term, concrete materials investigation that was undertaken are also summarized. This information, supplemented by more recent tests on the aggregate materials shows that pattern cracking evident on some of the works is related to AAR, and highlights the effectiveness to date of the preventative measures taken during construction.

The Gardiner Dam was constructed, between 1958 and 1968. The concrete works include a spillway, five tunnels with vertical control shafts, surface drainage works and a relief well drainage conduit. In total, about 500,000 cubic metres of reinforced and mass concrete were placed. Prior to construction, the potential for alkali aggregate reaction was identified. The reactive rock types in the granular aggregate source were lightweight, opaline, siliceous shalestones and some chert particles, comprising one to two percent by mass of the total aggregate. Measures to prevent AAR were incorporated into the concrete production program including the use of low-alkali cement and heavy-media flotation of the coarse aggregate size fractions. However, these measures were not applied consistently to all of the concrete on all of the structures. In the late 1980's, concrete condition surveys were conducted on all of the exposed and accessible portions of the aforementioned structures. Significant pattern cracking was identified on the pier pedestals of the spillway and on two minor surface-drainage structures. Sources of external alkalies were identified for these areas.

Keywords: Alkali-aggregate reaction, concrete, diagnosis, Gardiner Dam, laboratory testing, pattern cracking, Saskatchewan.

INTRODUCTION

The Gardiner Dam was constructed on the South Saskatchewan River (South Saskatchewan River Project - SSRP), approximately 25 kilometres southeast of the town of Outlook, Saskatchewan, Canada. Construction took place over an 11 year period between 1958 and 1968. The dam consists of a zoned, compacted-earth embankment with appurtenant concrete structures. These include: a chute spillway 1170 metres long and varying in width between 107 and 160 metres; five 6-metre (inside) diameter tunnels having a total combined length of 6270 metres, each with a vertical control shaft, intake and outlet structures; surface drainage works comprised of seven concrete flumes with inlet, outlet and bridge crossing structures; and a relief well drainage conduit. In total, about 500,000 cubic metres of reinforced and mass concrete were placed. An extensive concrete materials investigation was undertaken prior to and during construction to evaluate, among other durability properties, the potential for alkali-aggregate reaction (AAR), and to determine what mitigative measures, if any, would be required. Since that time, concrete condition surveys and additional laboratory investigations have been conducted to investigate further the presence of AAR.

GARDINER DAM CONCRETE MATERIALS INVESTIGATION

An extensive materials investigation was undertaken starting in the 1950's and spanned almost three decades. This testing program initiated in-depth studies of concrete materials and mixtures from the standpoint of compressive strength development, sulphate resistance, alkali-aggregate reaction and resistance to weathering (freeze-thaw). Investigations on the alkali-aggregate reactivity of the various constituent materials included petrographic examination, mortar bar tests, quick chemical tests, and concrete prism tests.

Reconnaissance Investigation

In 1960, a field reconnaissance survey was conducted to investigate evidence of AAR in the region. Approximately 44 structures in southern Saskatchewan were inspected, varying in age between 3 and 56 years. Several of the structures showed deterioration with many of the classic signs of AAR including pattern cracking, reaction rims or cracks in the reactive particles and the presence of alkali-silica gel. However, as many of the structures were constructed using lean mixes of non-air-entrained concrete, the predominant signs of distress were attributed to freeze-thaw deterioration and sulphate attack. It was therefore difficult to gauge the contribution of AAR to the overall degree of deterioration observed.

Characterization of Aggregate Materials

The aggregate source was the "Plateau Deposit", immediately adjacent to the proposed dam site on the left abutment. The sand and gravel source was deposited as a glacial outwash plain approximately 60 metres above the valley bottom. A variety of rock types were present in the deposit (Table 1), all of which have been subjected to rigorous water transportation. Lightweight, porous, highly absorptive, opaline siliceous shale particles (herein after referred to as shalestones) were present in the deposit and are commonly found in aggregate sources throughout central and southern Saskatchewan (Price 1958, 1961, Mollard et al. 1967, Roy 1993). These materials originated from shale outcroppings of the Manitoba Escarpment along the western Manitoba border, in the Odanah Member of the Riding Mountain Formation, and have been mixed into natural gravels by glacial and glacio-fluvial processes. This material is generally present in proportions less than 2 or 3% by mass and is commonly associated with concrete surface popouts.

TABLE 1: Processed Plateau Deposit Aggregate - Major Rock and Mineral Types

Rock Type	Coarse (%)	Fine (%)	Rock Type (cont'd)	Coarse (%)	Fine (%)
granite	38.2	6.2	chert, cherty limestone & claystone	2.7	2.4
limestone, dolomite	26.8	13.2	ironstone	1.3	0.8
quartz, quartzite	9.9	64.8	rhyolite	1.1	0.4
metamorphics	9.3	2.0	siliceous shale(stone)	0.2	1.4
andesite, basalts	3.7	1.0	feldspar	0.4	5.7
diorite, gabbro	3.6	0.4	other trace materials	--	0.8
sandstone, siltstone	2.8	0.9			

Petrographic Examination

In 1960, a detailed petrographic examination of the processed Plateau Deposit concrete aggregates was conducted to appraise the material's overall suitability for use in concrete and to determine the cause of expansion observed in early mortar bar testing. Reacted particles in mortar bars were predominated by the shalestones but also included chert, cherty limestone and cherty claystone, all reacted to a lesser degree. Despite inherent difficulties involved in determining the precise opal content in the shalestone, it was estimated that the shalestone contained approximately 50% opal, 30% clay minerals and 20% quartz.

It is important to note that the petrographer speculated that low-alkali cements might not completely mitigate the potential for AAR where the soil, water or aggregate contained water soluble salts of sodium or potassium. The Bearpaw (marine) shale, present at many structure locations, and the associated ground water were known to contain high percentages of sodium salts, and were considered to be possible sources of external alkalies.

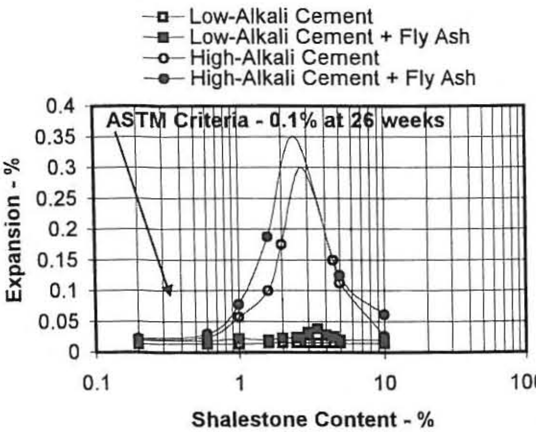

Fig. 1. Pessimum effect of Gardiner Dam fine aggregate with varying percentage of shalestone materials using the Mortar Bar Test (ASTM C-227).

Laboratory Testing

With the exception of one fine aggregate sample, all Quick

Chemical Tests (ASTM 1957(T)) indicated that the composite coarse and fine aggregate materials were inert. When the shalestone particles were removed (by heavy media flotation) from the 2.38 to 4.75 mm size fraction of the one fine aggregate sample that had failed the test previously, the processed fine aggregate tested inert. When the individual rock and mineral types were tested separately, the opaline siliceous shalestone, quartz and quartzite, and lightweight chert and flinty chert were all shown to be deleterious. Granite materials were classified as borderline deleterious.

Samples of fine aggregate obtained from processed aggregate stockpiles were tested using the Mortar Bar Test (ASTM 1958(T)). All of the tests met the six-month criteria and only two bars cracked prior to completion. The reasons cited (Lenz 1992) for the improved performance included: 1) an overall reduction in the shalestone contents of the processed fine aggregate material due to the mechanical effects of log-washing, 2) a change in the overall gradation of the fine aggregate caused by field processing resulting in a reduction in the largest sand size, where the shalestone particles were concentrated, and 3) a change in laboratory storage containers and environment. This latter change may have reduced the expansion by leaching of alkalies from the mortar bars (Rogers and Hooton 1989, 1991).

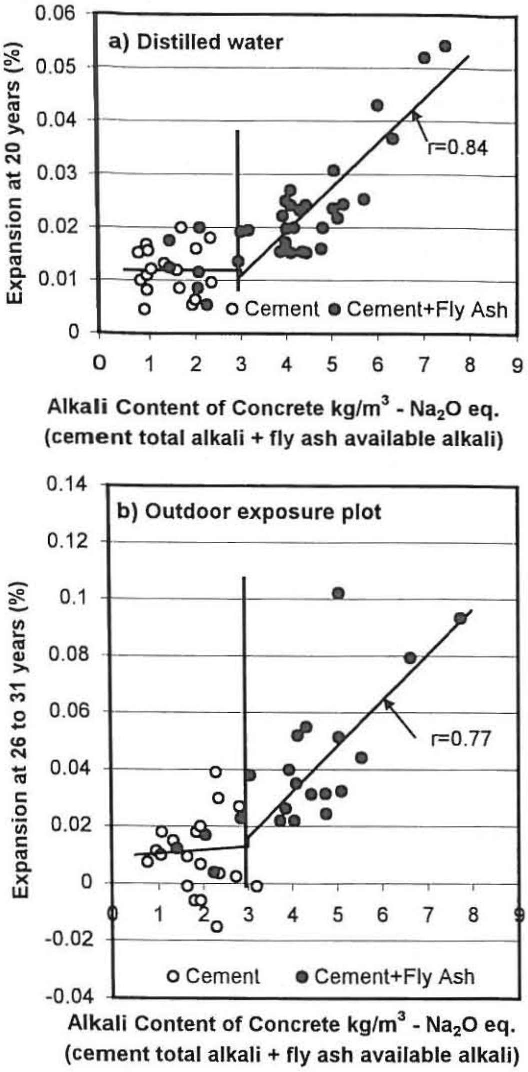

Fig. 2. Concrete prism expansion vs concrete alkali content (kg/m^3 as Na_2O eq.), stored: a) in distilled water for 20 years and b) at outdoor exposure plot for 26 to 31 years.

Mortar Bar tests were also used to determine if there was a pessimum shalestone content at which maximum expansion would occur. Fig. 1 shows that excessive expansion did not occur using the low-alkali cement, both alone and in combination with the high-alkali fly ash. In the high alkali-cement mixes, excessive expansion was noted in both the straight-cement and fly ash mixes.

Concrete prisms were manufactured using a variety of cement and cement-fly ash combinations, and stored: over water in sealed containers, in a 38° C environment; in distilled water at room temperature; and in a field exposure plot containing high sulphate soils. Fly-ash levels ranged from 0 to 28 % as a percentage of total cementing materials. Specimens stored over water for periods up to 3 years did not show excessive expansion. Again, it is unknown if the testing conditions leached alkalies from the test specimens. Prisms stored in distilled water and in the field exposure conditions for 20 to 31 years showed a linear relationship for increased expansion when the concrete alkali content exceeded 3 kg/m^3 (Fig. 2).

CONSTRUCTION MATERIALS

Due to the potential for AAR identified during the concrete materials investigation, preventative measures were taken to control the potential expansion. These included aggregate benefication and the specification and use of low-alkali cement.

Processing for the majority of the aggregate produced included crushing, primary washing, logwashing, primary screening, heavy media separation (coarse aggregate only), final screening, classification and dewatering. Pre- and post-processing shalestone contents by mass were 1.0% and 0.2% respectively, for the coarse aggregate, and 1.4 and 0.85% for the fine aggregate. As construction of the project neared completion, additional production and processing of one coarse aggregate size fraction was required. Heavy media flotation was not performed and the average shalestone content of the processed 4.75 to 9.5 mm coarse aggregate size fraction was 0.60%. As will be discussed later, this material was used in those portions of the spillway and surface drainage works that showed signs of AAR.

Low-alkali cement was specified for the construction of all of the major concrete structures appurtenant to the Gardiner Dam. In general, all of the cement supplied during construction met the specifications, the average alkali-content of the cements supplied being 0.45 % Na_2O eq. Low-alkali cement was not used on the surface drainage works concrete structures. The total alkali content of this cement was 0.82 % Na_2O eq.

Saskatchewan fly ash was specified for use on various concrete components of the spillway. Type CI (CSA 1998b), lignite fly ash, from the Boundary Dam Generating Station near Estevan, contained total alkali contents of 7 to 8 % Na_2O eq., and available alkali contents ranged from 2 to 4.5 % and averaged 3.2 %. The calcium-oxide content of the fly ash used during construction was approximately 13 %. The components constructed using fly ash included the crest section weir, abutment and buttress walls, wing walls, piers, chute wall footings, first lift of high chute walls and bridge pedestals. Generally the proportion of fly ash to total cementing material used in the mixes ranged from 24 to 30 % by mass.

As will be discussed in the following section, AAR was identified in structures related to two components of the Gardiner Dam concrete works; the spillway pier pedestals and (two) small surface drainage structures. The concrete used to construct the spillway pier pedestals contained 25 % Saskatchewan fly ash by mass of total cementing materials. The alkali content of the mix, based on a cement content of 246 kg/m^3 (0.45 % Na_2O eq. total alkali) and on a fly ash content of 78 kg/m^3 (3.2 % Na_2O eq. available alkali) equalled 3.6 kg/m^3. The alkali content of the concrete mixture would be much higher if the total alkali content of the fly ash were considered (i.e. 6.6 kg/m^3). The cement content of concrete used in the construction of the surface drainage works was 326 kg/m^3. At a cement total-alkali content of 0.82 % Na_2O eq., this resulted in a total alkali content of 3.0 kg/m^3 in the concrete mixture.

CONDITION SURVEYS AND ASSESSMENTS

Identification of AAR

Concrete condition surveys were conducted on the exposed and accessible portions of appurtenant works of the Gardiner Dam in 1987 and 1989. The upper portions of the pier pedestals (16 upstream and 16 downstream) showed pattern cracking to varying degrees. Some portions were hollow sounding and the top surfaces had varying numbers of shalestone popouts present (Fig. 3). Cores retrieved from the pier pedestals showed pattern cracking throughout their length and when crack faces were exposed, numerous reacted shalestone particles in the 4.75 to 9.5 mm size fraction were observed. These were soft, dark and severely reacted as evidenced by profuse amounts of gel over the entire crack surface.

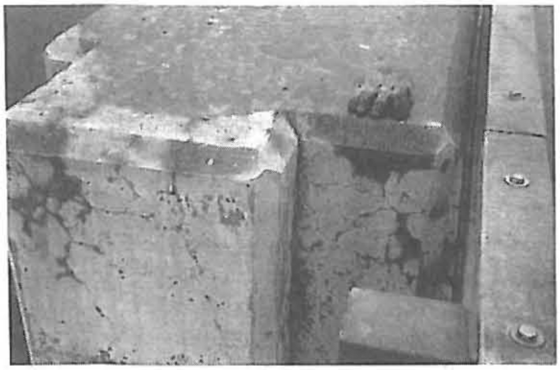

Fig. 3. Pattern cracking and surface popouts on upstream spillway pier pedestal # 8.

The possible influence of other destructive mechanisms on the deterioration noted in the pier pedestals was investigated. On the basis of mix parameters, freeze-thaw testing and air-void analyses on hardened concrete, the concrete in the pier pedestals was judged to be sufficiently durable to resist deterioration from freeze-thaw cycles. Deicing salts (NaCl) have been routinely applied directly to the highway adjacent to the structure. Powder samples from a drill hole on a pier pedestal indicated that concrete contained chloride levels ranging from 730 μg/g to 3900 μg/g. Although the pattern of cracking observed was not directly attributed to corrosion of the reinforcing steel, the chloride levels observed were sufficient to de-passivate the reinforcing steel, and corrosion may be contributing to the degree of deterioration noted. There is also a strong possibility that the deicing salts have influenced the rate of the reaction caused by AAR and have been a source of external alkalies.

The inlet structure on Flume E and the basin structure on Flume B of the surface drainage works both showed extensive pattern cracking. The majority of the pattern-cracked concrete was confined to areas exposed to direct sunlight. Shaded areas immediately adjacent to these contained minimal cracking. Visual and microscopic examination of cores revealed: several reacted shalestone particles in both the coarse (4.75 to 9.5 mm) and fine aggregate size fractions and large quantities of alkali-silica gel. An air-void analysis conducted on the core recovered from Flume E inlet revealed an air-void system adequate to protect the concrete from freeze-thaw damage in a severe environment.

The inlet structure to Flume E has frequently been exposed to groundwater that has seeped from the abutment. Chemical analysis of this water showed 92 mg/L of Sodium ions and 9 mg/L of Potassium. As well, Flume B has been used intermittently to transport water that is pumped from a foundation relief well. This water contained 1035 mg/L of Sodium and 5 mg/L of Potassium. Both water samples contained corresponding concentrations of Sulphate ions. The presence of these salts is considered a source of external alkalies. This was confirmed through chemical analyses conducted on pulverized concrete core samples. Water- and acid-soluble alkali contents in the concrete exceeded (computed) levels from the time of construction, corrected for base levels of alkali in the aggregate.

RECENT LABORATORY TESTING

Additional laboratory testing of the Gardiner Dam aggregate materials has been undertaken since the positive identification of AAR on some of the structures. These have included Mortar Bar, Accelerated Mortar Bar and Concrete Prism tests.

Mortar Bar Tests (ASTM 1987) were conducted using the Gardiner Dam fine aggregate. Although one sample failed the 0.05 % maximum criteria for 3 months, the material met the 0.10 % criteria for six months. This may be indicative of the variable nature of the shalestone content in the fine aggregate or of the possibility of alkali leaching that has been documented by others (Rogers and Hooton 1989, 1991).

Fig. 4 shows the expansion at completion of Accelerated Mortar Bar Tests (CSA 1994c) between three Gardiner Dam aggregate size fractions, along with the corresponding shalestone contents, indicating a direct relationship. Accelerated

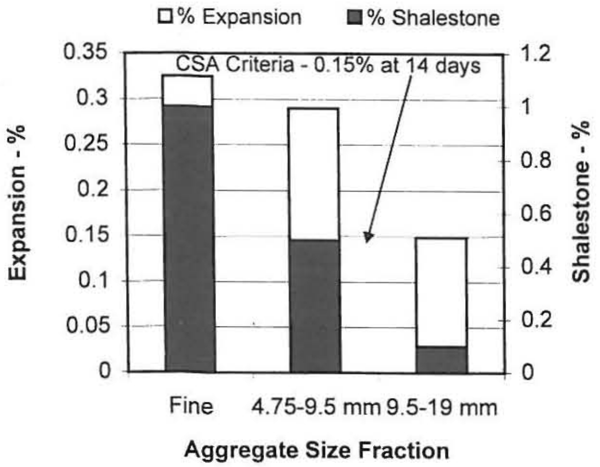

Fig. 4. Accelerated Mortar Bar Test (CSA A23.2-25A) results on various size fractions of Gardiner Dam aggregate.

Mortar Bar tests also indicated a pessimum shalestone proportion of about 10 % (Fig. 5). As this proportion is significantly different from the results obtained using the Mortar Bar test (ASTM 1958(T)) conducted prior to and during construction (Fig.1), it is felt that the pessimum proportion may be more representative of the test's more severe exposure conditions.

Fig. 6 shows the relative expansions for the control mix, 30 % Saskatchewan fly ash and a low-alkali Alberta fly ash (30%). Both fly ashes significantly reduced expansion. When the length of the test was extended beyond the 14 day standard test period, expansion continued at an increased rate.

Fig. 7 shows three Concrete Prism Test (CSA 1994b) results using a variety of aggregate combinations. In all cases, the coarse aggregate used was the Gardiner Dam material that had been processed by heavy media flotation. Both the 1977 (CSA 1977) and 1994 (CSA 1994b) versions of the Concrete Prism test showed minimal expansion ranging from 0.008 to 0.023% at two years.

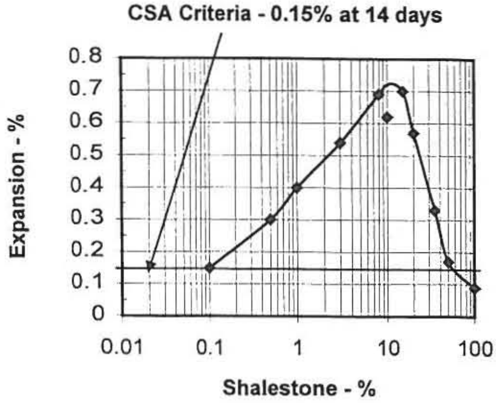

Fig. 5. Pessimum effect of shalestone materials using the Accelerated Mortar Bar Test (CSA A23.2-25A).

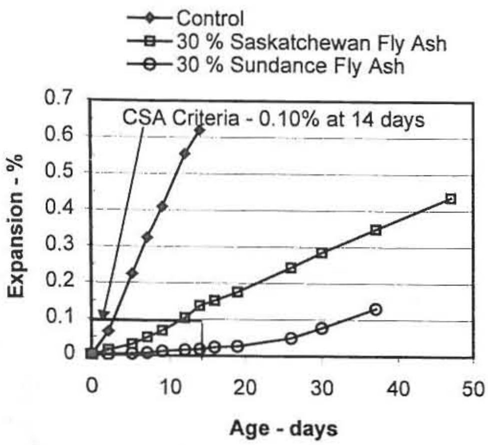

Fig. 6. Effect of cement replacement with 30 % Saskatchewan and Alberta fly ashes using the Accelerated Mortar Bar Test (CSA A23.2-25A).

In 1988, the Gardiner Dam fine aggregate was used as a control fine aggregate in a concrete prism inter-laboratory study on Alkali-Carbonate Reactivity (Rogers 1990). The expansion of the specimens containing the Gardiner fine aggregate was generally much greater than the average of all remaining labs (excluding outliers). The expansion was especially greater in the 5 % NaCl, room temperature condition. Upon visual and microscopic observation by the study coordinator of one specimen that had been submerged in 5 % NaCl, he remarked that the prism was covered in alkali-silica gel. This confirms that the Gardiner Dam fine aggregate is alkali-silica reactive. Furthermore, it indicates that there is a tendency for increased reactivity when exposed to NaCl.

PROGNOSIS FOR FURTHER DETERIORATION

Thus far, deleterious expansion has been limited to concrete: in areas where deicing salts and groundwater have been present, with direct exposure to sunlight (heat), containing the 9.5 to 4.75 mm coarse aggregate size fraction with the higher shalestone contents, and containing either a high-alkali cement or a low-alkali cement used in combination with a high-alkali fly ash. However, the need for mitigation and repair of the affected structures, at the time of the investigations, was deemed unnecessary. In areas where the prognosis for continued deterioration is likely or where significant potential expansion is identified, alternative mitigative measures could be researched in the field on minimally deteriorated areas. Examples include the use of surface sealers to reduce the access of external alkalies and moisture, or lithium salts to slow or stop the reaction.

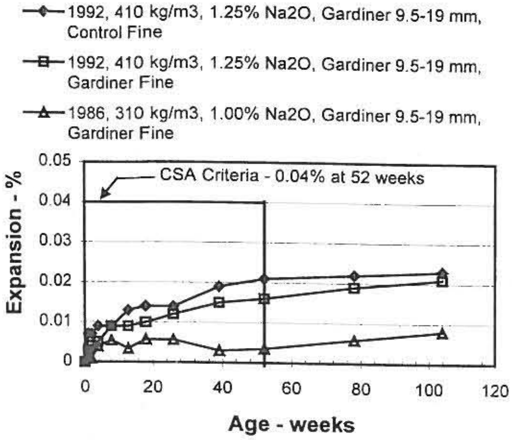

Fig. 7. Concrete prism (CSA A23.2-14A) expansion data using processed Gardiner Dam aggregate.

CONCLUSIONS

1. The 1960 reconnaissance investigation did not identify evidence of concrete deterioration primarily attributable to AAR, in the region.
2. In early and more recent testing, quick chemical and mortar bar tests confirmed that opaline siliceous shalestones, even present in small percentages in granular material sources throughout the region, are highly alkali-silica reactive. Concrete prism tests performed to date on this material have been inconclusive; however, some concrete prism data suggest that the fine aggregate which contains 1 to 2 % opaline shalestones may be particularly susceptible to expansion in the presence of NaCl.
3. Mortar bar test data suggested the limited effectiveness of the local high-alkali fly ash in controlling expansion of specimens incorporating reactive opaline shalestone particles.
4. Timely condition surveys of the Gardiner Dam concrete have shown that (1), extensive pattern cracking related to AAR has occurred in isolated areas where external alkalies have been available, and (2), specified preventive measures (low-alkali cement, fly ash and heavy media flotation of coarse aggregate) have been effective to date in controlling the reaction in areas where access to external alkalies is limited or non-existent.

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