ALKALI AGGREGATE REACTION IN WESTERN AUSTRALIA: INVESTIGATIONS ON THE CAUSEWAY BRIDGE AND SOME AGGREGATE SOURCES

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ABSTRACT

Alkali-aggregate reaction (AAR) was identified in the Causeway Bridge over 10 years ago, and because of this the Main Roads Western Australia became involved in investigations related to various aspects of AAR, through the following programs in collaboration with CSIRO.

1. The microstructural characterisation of the concrete and the reaction products and the identification of reaction phases.
2. Determination of residual expansion of the affected concrete, with a view to repair the structure at a suitable time.
3. Assessment of various aggregate sources of interest to Main Roads for AAR, development of test methods and criteria for rapid evaluation of their alkali-reactivity and determination of alkali tolerance of the aggregates.
4. Assessment of mineral additives to suppress the AAR expansion of concrete made with the identified reactive aggregates.

The paper provides data relevant to the above aspects and suggests an approach for dealing with future Main Roads projects to ensure durability of their concrete structures.

Keywords: alkali aggregate reaction, ettringite, concrete cracking, expansion, testing, fly ash.

INTRODUCTION

The Causeway Bridge was constructed during 1940-51 using two types of aggregate from the same quarry (granitic and metadolerite) and several types of cement, some imported from overseas. The presence of AAR in the Causeway Bridge, Perth, was suspected after an inspection late in 1982, and confirmed after drilling and examination of cores from various parts of the structure in 1983. The findings were reported elsewhere (Shayan & Lancucki, 1986), and provided some microstructural details on the affected concrete as well as mineralogical and chemical data on the reaction products. The two aggregate types used in the concrete, ie. a metadolerite and a gneissic granite were both found to have reacted in the concrete. Certain parts of the bridge containing the same aggregates but presumably having low alkali cement, did not show any sign of AAR.

These findings prompted the Main Roads to investigate some of its potential aggregate sources, and as a result of this work, done at CSIRO during 1983/84, some reactive aggregates were identified (Shayan, et al., 1986). It was found that the existing Australian Standard test methods for determining the alkali-reactivity potential of aggregates (AS1141 sections 38, 39) were inadequate. Subsequently more rapid test methods and criteria were developed for assessing the slowly reactive Australian aggregates, (Shayan et al., 1988; Shayan, 1989).

This paper provides details of a more recent investigation of the Causeway Bridge, including the measurement of residual expansion of drilled cores. Additional studies of the reactivity of WA aggregates and prevention of their AAR expansion in concrete are discussed.

RECENT INVESTIGATIONS OF THE CAUSEWAY BRIDGE

An inspection of the bridge in 1992, nearly ten years after initial identification of AAR showed that cracking in some zones have worsened and crack width increased considerably. Spalling at joints had occurred in a number of locations. Figure 1 shows some features of the cracking observed in the 1992 inspection. In order to initiate a repair strategy, it was decided to determine the residual expansion potential of the concrete from various parts of the bridge, using drilled cores. Figure 2 shows the condition of the concrete in various zones where cores were drilled.

Fig. 1. **Some features of cracking in various parts of the bridge, observed in 1992. Left and middle pictures show cracking in the top of a pylon, where some parts of the concrete have become separated (arrow). The right picture shows map cracking in the ground section of the pylon with some spalling.**

These cores were about 350mm long and 100mm in diameter and correspond to those locations sampled for the earlier study (Shayan and Lancucki, 1986). The composition of the cores was the same as the earlier cores, confirmed by petrographic examination.

MICROSTRUCTURE OF CORES

Cores 1, 2, 3, 4 and 5 contained reacted and cracked aggregate particles, with Core 2 being the most internally cracked; consistent with the appearance of the concrete in that location. No evidence of AAR was seen in Cores 6 and 7. Details of scanning electron microscope (SEM) examination and a variety of crystalline and gel-like reaction products found on fracture surface of cores from affected zones were reported in the 1986 study. In this work sawn surfaces of 10mm slices cut from the cores were examined. Therefore, crystalline materials normally seen as reaction rims on fracture surfaces of reacted aggregate particles had been removed, and only gel phases could be observed. This was to enhance any veins of reaction products that could be present.

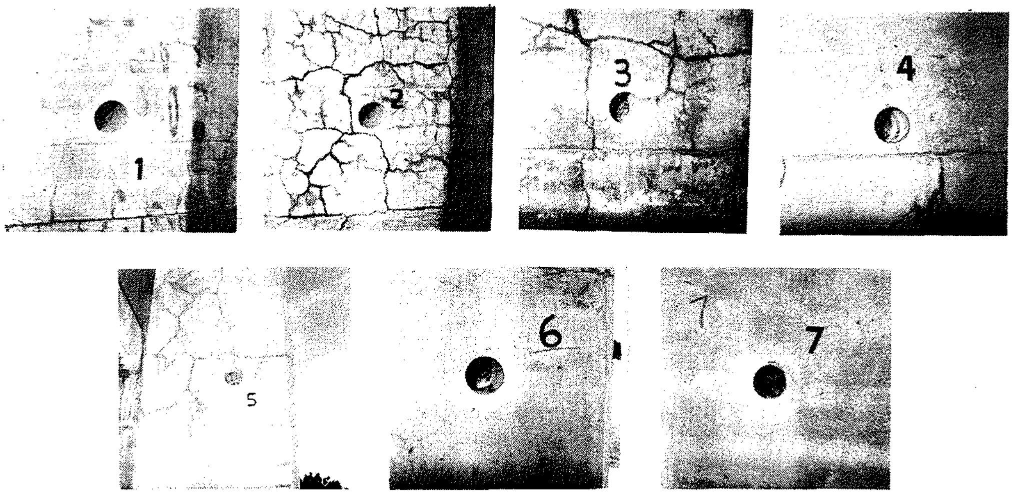


Fig. 2. **Condition of concrete in various zones where cores were taken. Cores 1 - 5 came from the east abutment pier and columns, and cores 6, 7 from the west abutment columns.**

The SEM examination revealed that in the concrete samples from reacted zones the mortar phase was impregnated with AAR gel generated in the reacted particles. This feature was more prevalent in the more extensively affected concretes. Even Cores 1 and 4 from the vicinity of cracked zones contained considerable amounts of gel. Cores 6 and 7 were free of AAR gel. Figure 3 shows examples of the gel in the mortar phase. These gels particularly those that were present in the cracks within reacted aggregate particles (ie. less access to Ca from the cement phase) are highly rich in silica and alkali, largely potassium. Some gels present on the mortar phase had a considerable amount of Ca as a result of contact with this phase.

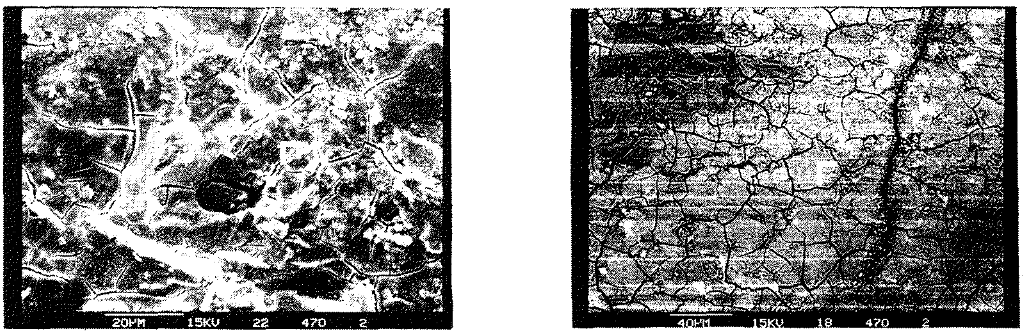
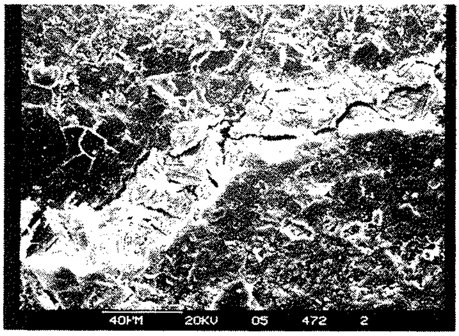
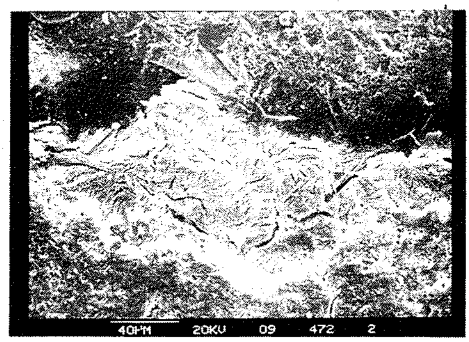


Fig. 3. **Scanning electron micrographs showing AAR gel on sawn surfaces of core slices. (A) secondary electron image, (B) back scattered electron image. For more microstructural features and compositions see Shayan and Lancucki (1986).**

In addition to the AAR products reported by Shayan and Lancucki (1986), this study provides details of the ettringite phase in the AAR affected samples. Cores 1 and 4 contained ettringite needles largely in holes and cracks, but massive ettringite mats in veins were not common, whereas no ettringite mats was noted in Core 3, 6 and 7. In Cores 2 and 5, where large amounts of AAR gel are present, mats and veins of ettringite were common, and were found both at the mortar/aggregate interface and in veins in the mortar phase. Figure 4 shows examples of the ettringite phase in the various cores.

This form of ettringite is a consequence of AAR cracking (Shayan and Quick 1992), and does not cause expansive forces (Scrivener and Taylor 1993) nor deterioration of the concrete.





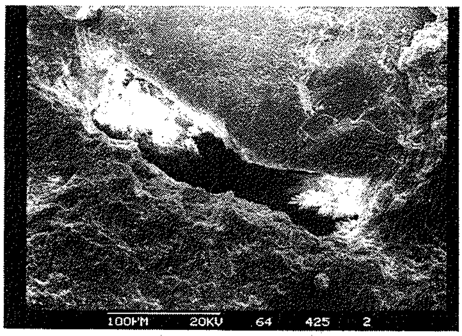


Fig. 4. **Scanning electron micrographs showing various morphological features of ettringite at cement/aggregate interfacial zones. The lower left micrograph shows a gap at the interface partially filled with ettringite.**

RESIDUAL EXPANSION OF CORES

Figure 5 shows representative expansion curves for the cores under the two different storage conditions indicated on the curves. The curves show that the specimens stored in the NaOH solution expanded deleteriously and cracked, or further cracking developed in those taken from the cracked zones (or existing micro cracks widened). Cores from locations 1-5 behaved similarly whereas cores from completely uncracked location 6 and 7 expanded less in the NaOH solution, probably because of either smaller amounts of reactive components or use of low alkali cement, or both, in these parts and/or higher strength of the mature concrete.

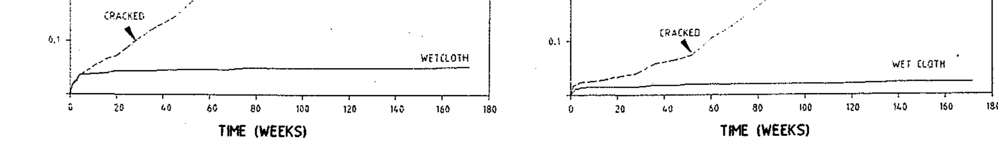


Fig. 5. **Expansion curves for cores under the two different storage conditions. Cores from locations 1, 2, 4 and 5 behaved similarly to those from location 3 (left). Cores from location 7 expanded half those from location 6 (right).**

Expansion in the NaOH solution indicates that reactive components are still present in the concrete, and further expansion may result if alkali penetrates into the concrete.

Lack of expansion under the moist conditions, without excess alkali, may indicate that expansion has ceased in the concrete due to consumption of some of the alkali in the original concrete, although stress relief during the time elapsed between drilling and start of the measurements may have dissipated some of the expansion potential. As indicated earlier possible leaching of alkali during the brief soaking period may also have contributed to the lack of expansion.

ON-SITE MEASUREMENT OF EXPANSION

Demec disks were fitted to the structure at several locations both across cracks and on the adjacent uncracked positions. The strains measured over the past twelve months indicate that a number of the cracks have ceased to move whilst in the case of others the situation has been less clear. Some readings have shown significant variations making judgements on crack stability difficult to assess. To supplement the data from the demec readings a short length of crack was filled with a weak material (poly filler) to determine visually if the cracks were widening. None of the filled cracks has shown any sign of opening after a six month period, although this is too short to make a judgement.

It appears that much of the expansion potential of the AAR affected concrete has been exhausted. The existing conditions of the concrete calls for limited repairs to be undertaken to inject and seal the cracks with suitable materials to prevent secondary deterioration of the concrete materials and the steel reinforcement bars.

ASSESSMENT OF WA AGGREGATE SOURCES

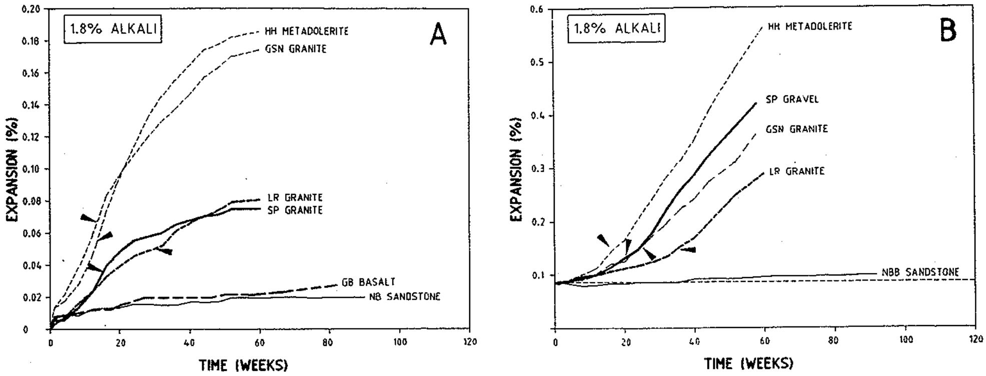
In previous studies using both conventional (Shayan et al., 1986) and accelerated methods (Shayan et al., 1988; Shayan, 1989) three siliceous river gravels (HC, TKA and SPG) two metadolerites (GSN and HHM), a sandstone (NBB) showing the pessimum effect and a granitic rock (GSG) were identified as reactive. However, another granite rock and two metadolerites (TRM and JDM) were classed as non-reactive.

The initial work employed a concrete mix containing 407 kg cement/m^3 and cement alkali levels of 0.84 and 1.38% Na_2O equivalent, yielding concrete alkali contents of 3.4 and 5.6 kg Na_2O/m^3.

To assess the behaviour of the aggregates under much higher alkalinity a new concrete mix containing 580kg cement/m^3, W/C = 0.4, and a cement alkali level of 1.84% Na_2O equivalent was used. This yielded a concrete alkali content of 10.7 kg/m^3. A similar mix containing a low Ca fly ash (25% by mass of cement) was used to evaluate the effectiveness of the fly ash in preventing AAR expansion.

Concrete prisms (75 x 75 x 285mm) and concrete blocks (300 x 300 x 300mm) were made from mixes without and with fly ash. The specimens were demoulded 24 hours after casting, and after one week of curing in a fog room at 23°C (protected from leaching under plastic cover) were placed in containers of water and stored in a room at 50°C. The initial length measurement was made twenty-four hours after conditioning at 50°C, and all the subsequent measurements were also made at this temperature for about two years. A non-reactive basalt aggregate was treated similarly for comparison.

Figure 6 shows expansion curves for the concrete blocks and prisms. Except for the sandstone (NBB) and the non-reactive basalt, all the aggregates caused deleterious expansions, and cracking occurred in concrete blocks at ages varying from 3.5 to 13 months. Similar results were obtained for concrete prisms except that the shapes of the expansion curves were different and cracking ages did not correspond to those of concrete blocks. In addition, one of the metadolerites (TRM) did not cause cracking in concrete prisms. The flyash was effective in reducing AAR expansion (Fig. 6C)



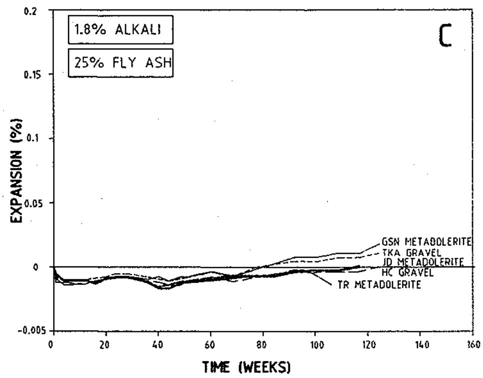


Fig. 6. **Expansion curves for concrete prisms (A) and blocks (B) made at high alkali content (10.7 kg Na_2O/m^3). Storage conditions were in water at 50°C. Arrows indicate when cracking was noted. Flyash in the mix eliminated the AAR expansion (C).**

These results show that the concrete mix containing 580kg cement/m³ was a more severe test than the accelerated test in 1M Na OH, as more aggregates were classed as reactive. The water/cement ratio of 0.4 and cement alkali level of 1.84%, yields a pore solution of about 1.5M Na OH concentration, compared to 1M NaOH in the accelerated test, making the concrete test more severe.

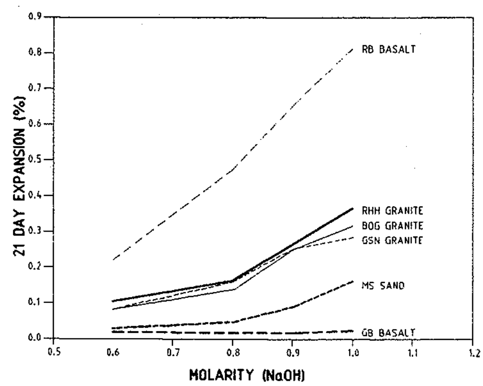


Fig. 7. **Results of accelerated testing of mortar bars made with the various aggregates at different Na OH concentrations (80°C).**

ASSESSMENT OF ALKALI TOLERANCE OF W.A. AGGREGATES

In more recent studies a short-term and a long-term approach have been adopted to determine the alkali tolerance of some WA aggregates with the aim of correlating the two and validating the short-term approach. In the former, the mortar bar accelerated test (Shayan et al. 1988) was applied at NaOH concentrations of 0.6, 0.8, 0.9 and 1.0 M and 21 day expansion values measured. Considering the cement content used and W/C = 0.43, the NaOH concentrations employed correspond to concrete alkali contents of 3.2, 4.4, 5.0 and 5.5 kg Na_2O equivalent / m³. In the long-term tests, a concrete mix (410 kg cement/m³, W/C = 0.43) was used at alkali contents of 2.3, 3.0, 4.0, 5.5 and 6.5 kg Na_2O equivalent/m³ to manufacture concrete prisms (75 x 75 x 285 mm), blocks (300 x 300 x 250 mm) and blocks (300 x 300 x 300 mm) for storage at 40°C, 100% RH; 50°C in water and outdoor exposure, respectively, and to measure their long-term expansion.

Figure 7 presents the results of the accelerated tests and clearly shows the different tolerances of the various aggregates. The failure criteria for NaOH concentrations for lower than 1.0 M would be different from the 0.1% expansion at 21 days because some reactive aggregates would certainly not expand to 0.1% in 21 days in 0.6M NaOH solution. This lower concentration corresponds to a cement alkali level of 0.8% Na_2O equivalent, at which deleterious expansion is to be expected when using these aggregates in the proposed concrete mix.

The program needs to be extended to cover lower NaOH concentrations of 0.5M and 0.4M to correspond to concrete alkali contents of 3.0 and 2.30 kg Na_2O equivalent/m³ in the proposed concrete mix.

Figure 8 shows expansion curves for concrete prisms stored at 40°C, 100% RH. The three granite aggregates behaved similarly at the age of 60 - 70 weeks, concrete prisms that contained the granite aggregates at the two highest alkali levels have expanded deleteriously and cracked as shown by the arrows (Fig. 8A). Surprisingly, the basalt that had shown high sensitivity to alkali in the accelerated test has not caused much expansion in the concrete prisms, even at high alkali levels (Fig. 8B). The reason for this difference may be a particle size effect. Petrographic examination of the basalt has shown that it contains patches of glass which within one coarse aggregate particle are not exposed to alkali. Crushing of these coarse particles produces a finer particle size which exposes the glassy patches, and these are exposed to alkali attack in the accelerated test. This hypothesis needs further investigation.

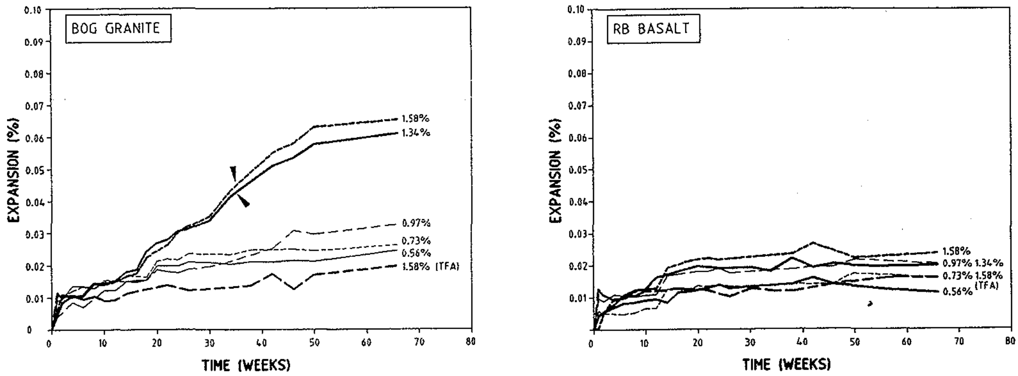


Fig. 8. **Expansion curves for concrete prisms made at different alkali contents and stored at 40°C, 100% RH. Arrows indicate when cracking was noted.**

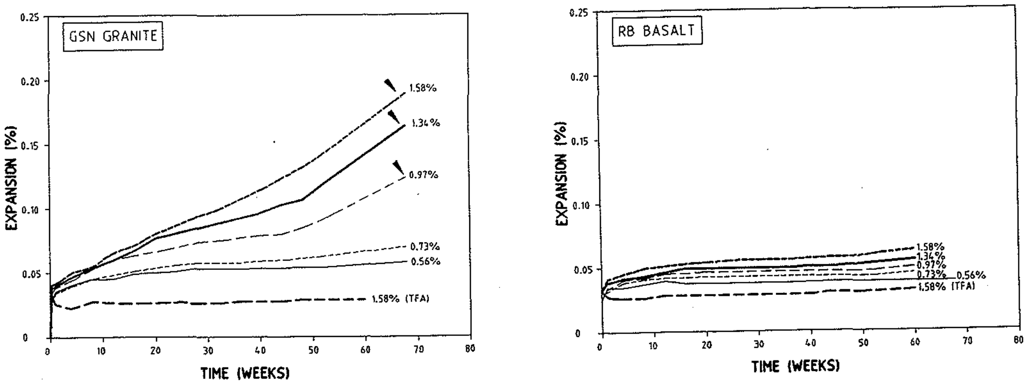


Fig. 9. **Expansion curves for concrete blocks stored in water at 50°C. Numbers on the curves indicate cement alkali level. Cement content of concrete was 410 kg/m³. TFA indicates 25% fly ash replacing cement on mass basis. Arrows indicate when cracking was noted.**

Figure 9 shows expansion curves for the corresponding concrete blocks, stored in water at 50°C. Specimens made with two of the granites (GSN and BOG) which are nearly 79 weeks old have cracked at alkali levels down to 0.97%. Those made with the other granite (PHH) are younger and may crack at a similar age, but those made with the basalt have shown much less expansion, as for the concrete prisms.

Expansion of concrete prisms made at alkali levels below 1.35% and concrete blocks at alkali levels below 0.97% have been slow and longer term expansion data are required for reliable interpretation of the expansive behaviour of concrete mixes at these alkali levels. The correlation with the accelerated test would also need to wait until the concrete data for low alkali level is available.

CONCLUSIONS

Research work carried out on ARR in Western Australia has shown that:

1. The premature deterioration of the Causeway bridge has resulted from AAR, and that both the granitic and metadolerite aggregates used in the concrete are reactive. Other secondary reactions like formation of ettringite in the AAR - induced spaces are taking place although this may not be of much consequence. There are indications that expansion of the AAR - affected concrete has ceased, but this would need confirmation. Appropriate remedial action is recommended.
2. A number of Western Australian aggregates which are of interest to the Main Roads Department have been identified as potentially reactive in concrete of high alkali contents. However, incorporating 25% of a low Ca fly ash, replacing cement on a mass basis, eliminated the AAR expansion. Use of effective mineral admixtures is recommended.
3. Work on determining safe alkali levels for potentially reactive aggregates, using both concrete specimens and the accelerated mort bar test, is in progress and promising results have been obtained. Further longer term data are needed for correlating the results of the accelerated test with those of the concrete tests in order to determine whether the accelerated procedure can be used to estimate safe alkali levels for aggregates in concrete.

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