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on

Alkali-Aggregate Reactivity

ALKALI–AGGREGATE REACTION IN AUSTRALIA

A. Shayan
CSIRO Division of Building, Construction and Engineering
PO Box 56, Highett, Victoria 3190, Australia

W.K. Green and F.G. Collins
Taywood Engineering Limited
15 Ellingworth Parade, Box Hill, Victoria 3128, Australia

ABSTRACT

Australia has a long history (dating back to the early 1940s) of research into alkali– aggregate reaction (AAR). Vivian and coworkers at CSIRO undertook several research programs and produced much needed information on the reaction during the 1940s and 1950s. As a result of research on AAR in the past decade, many cases of AAR in concrete structures have been discovered in Australia, and a considerable number of potentially reactive aggregates identified.

This paper provides a review of past and recent published cases of AAR in Australian structures, a history of AAR research in Australia (including likely future trends), the development of standard and accelerated tests for assessing AAR susceptibility of aggregates, and the past and present procedures for the repair and maintenance of Australian structures affected by AAR.

Keywords

Alkali–aggregate reaction, affected structures, accelerated testing, repair and maintenance.

HISTORY OF AAR-AFFECTED STRUCTURES IN AUSTRALIA

Cases of AAR in Australian structures were reported anecdotally in the late 1970s and published cases have been recorded since the early 1980s. A summary of published cases of AAR in Australian structures is shown in Table 1, although there are other cases not reported in the open literature. The types of affected structures include bridges, marine structures, culverts, parapets, railway sleepers, dams, water-storage tanks, and earth-retaining walls. However, it is highly likely that the problem is more geographically widespread, as evidenced by the distribution of aggregates identified as reactive. Alderman *et al.* (1947) reported a small number of reactive aggregates from Queensland, Tasmania, South Australia, Northern Territory, Western Australia and Victoria. Shayan (1992) reported additional reactive aggregates, and new sources are being identified as more diagnostic work is reported on AAR-affected structures. The list of reactive aggregates identified so far in Australia is given in Table 2.

HISTORY OF AAR RESEARCH IN AUSTRALIA

Past

Australia, through research work at CSIRO, is one of the few pioneering countries that investigated some aspects of AAR after it was first reported in the USA by Stanton (1940).

Table 1. Summary of AAR-affected structures in Australia

Name or type of structure	Location	Source
Upper Yarra Dam	Gippsland, Victoria	Cole *et al.* (1981); Shayan (1988)
Dam	Western Australia	Shayan (1995, unpublished)
Dam	Victoria	Shayan (1988)
Water tank	Northern Victoria	Leaman & Shayan (1996)
Bridges	Victoria	Shayan (1994a)
Bridge at Nerang (1 No.); Toowoomba (1 No.); Warwick (2 No.); Rockhampton/Townsville (74 No.); Cloncurry (9 No.); Cairns (5 No.); Bundaberg (2 No.)	Queensland	Carse (1990)
Tarong Power Station Cooling Tower	Queensland	Carse (1993)
Causeway Bridge	Perth, WA	Shayan & Lancucki (1986)
Load-out jetty	Western Australia	Davies *et al.* (1996)
Gordon River Power Development Intake Tower	Tasmania	Blaikie *et al.* (1996)
Railway sleepers	Undisclosed	Shayan and Quick (1992)

Table 2. Summary of Australian aggregates identified as alkali–aggregate reactive

State	Source
Queensland	Brisbane river sand; quartz-feldspar porphyry from Brisbane; trachyte from Beerburrum; ignimbrites/rhyolites; greywacke; quartzite; river gravels; basalt
Victoria	Opal from Gippsland; scoria from Mount Noorat; several river gravels; dacite; phyllite; hornfels
Tasmania	Derwent River sand; other siliceous coarse and fine aggregates
South Australia	Surface gravel from Oodnadatta; quartzite from Cooper Pedy
Northern Territory	Gravel from Tennant's Creek (sandstone); river gravel from Katherine (quartzite); river gravel from Matarauka (quartzite); rhyolite
Western Australia	Various granitic rocks; metadolerite; gravels from northern areas; quartzitic sandstone
New South Wales	River sand; river gravel; quartzitic rocks; recrystallised granitic rock; metagreywacke

In 1942, an extensive testing program, entitled 'Studies in Cement–Aggregate Reactions', was undertaken by CSIRO, and the first report on testing 67 aggregates in combination with Australian-produced cements (Na_2O equivalent ranging from 0.12 to 1.1%) was published by Alderman *et al.* (1947). A small number of reactive aggregates were identified in various parts of Australia.

In subsequent studies at CSIRO during the 1940s and 1950s, Vivian and coworkers investigated several aspects of AAR (e.g. Vivian 1950) using a highly reactive opal as their model aggregate, and produced over 25 publications in the series 'Studies in Cement–Aggregate Reactions'. Vivian and coworkers produced much needed information on the reaction, including the effects on AAR of alkali content, type of alkali, hydroxyl ion, particle size and proportion of reactive aggregate, storage conditions (RH, temperature), void space, form of silica in aggregate, movement of alkali in hardened mortar, and confining load.

Comparatively very little work was done on AAR in Australia in the 1960s and 1970s. Although Vivian (1983) proposed that the limit of expansion for the mortar bar test should be 0.05% at one year, rather than 0.05% at three months or 0.1% at six months, this did not alter the limits of the standard mortar bar test.

Recent Work

The identification of AAR in a dam in Victoria (Cole *et al.* 1981) and in the Causeway Bridge in Perth, Western Australia, in 1982 (Shayan & Lancucki 1986) resulted in new interest in AAR testing of Australian aggregates. A number of Western Australian aggregates were tested in 1983 (results reported by Shayan *et al.* (1986)) according to the quick chemical test (Australian Standard AS 1141, Section 39) and the standard mortar bar test (AS 1141, Section 38). Similar testing was also started in Queensland on two aggregates (Carse 1984). Both studies showed discrepancies and/or inadequacies in the standard tests in predicting the reactivity of some slowly reactive aggregates.

This experience with standard test procedures was confirmed as more aggregates were subjected to testing, and the need for developing more reliable test procedures and criteria were recognised. Non-standard concrete prism tests were also undertaken in the above work, but for some aggregates they were very slow in producing expansion results. During 1985 and 1986 a number of accelerated techniques were trialed at CSIRO, which included storage of concrete prisms in saturated NaCl solution and in 1M NaOH at 50 and 80°C. The results obtained on concrete prisms were unsatisfactory, but much more consistent results were obtained when mortar bars were used, as also recommended by Oberholster and Davies (1986). The results of the accelerated testing of a number of aggregates in mortar bars and concrete prisms stored in 1M NaOH at 80°C (Shayan *et al.* 1988) showed that the mortar bars produced more reliable results, but concrete prisms behaved erratically. Subsequent unpublished work showed that this behaviour of concrete prisms may arise from the denser nature of the matrix in concrete prisms compared to the mortar bars, and probably from difficulty of penetration of alkali into the concrete. When alkali was incorporated in the concrete prisms, more consistent results were obtained, but the strength of the concrete was reduced considerably.

Aggregate evaluation criteria were established (Shayan *et al.* 1988) based on the field performance of a number of Australian aggregates in concrete structures and the results of accelerated mortar bar tests for those aggregates. As a result, expansion of 0.1% or greater after 10 days of immersion in the NaOH solution (total age of 13 days) identifies reactive aggregates, and the same expansion after 21 days of immersion (total age of 24 days) identifies slowly reactive aggregates.

In the early 1990s it was also shown that the accelerated mortar test could be applied to evaluate the effectiveness of some mineral admixtures in suppressing AAR expansion (Shayan 1990; 1992).

Likely Trends

Acceleration of AAR in rapid test methods has been through increasing both the level of alkali and the temperature in the manufacture and storage of the specimens. Considerable work remains to be done to determine the influences of these parameters on the mechanisms of various reactions taking place in the specimens, and their implications for the evaluation of aggregates.

The lack of published Australian data related to the repair and maintenance of concrete structures (as discussed later) indicates the need to implement long-term investigations to examine:

- the effectiveness of different treatments;
- the longevity of repairs;
- the structural consequences of repairs; and
- the cost-effectiveness of repairs versus replacement

DEVELOPMENT OF STANDARD TEST METHODS FOR AAR

Past

The test method utilised to predict aggregate reactivity, prior to the introduction of AS 1141, Sections 38 and 39, was that developed in 1942 by CSIRO and used in the extensive testing program entitled 'Studies in Cement–Aggregate Reactions' (Alderman *et al.* 1947; Vivian 1950).

The test procedure consisted of combining the appropriately graded fine aggregate with the various cements in mortar bars measuring 25 × 25 × 285 mm. The cement to aggregate ratio was 0.5 and water to cement ratio 0.4–0.5. The specimens were stored in sealed containers (100% RH) at room temperature (annual mean temperature 15°C) and their length change periodically monitored for two years, after which the bars were inspected optically for the presence of reaction sites in order to broadly correlate the measured expansion with the extent of reaction. It should be noted that these conditions were not unduly accelerated.

Current Australian Standards

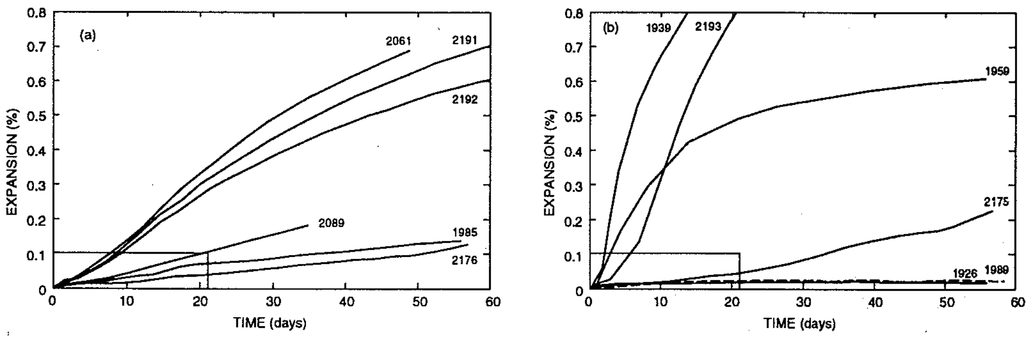
Test methods which were introduced into the Australian Standards were essentially those ASTM standards developed in North America to deal with the AAR problems there. The well-known quick chemical test (ASTM C–289) and the mortar bar test (ASTM C–227) were adopted in Australia under the designations Australian Standard AS 1141, Section 39, and AS 1141, Section 38, respectively.

As previously discussed, the standard test methods are inadequate for assessing the AAR susceptibility of most Australian aggregates. Examination of a number of Queensland aggregates by the accelerated mortar bar test and comparison with the long-term concrete prism test verified its applicability as well as showing the shortcomings of the standard test methods applied to the same aggregates (Shayan 1992). Table 3 compares the results of evaluations of a number of aggregates by various test methods, and clearly shows the inadequacy of the standard test methods. Figure 1 shows that within each aggregate type, the accelerated test can discriminate between non-reactive and potentially reactive ones. This accelerated test was found to be more reliable than an autoclave test used overseas, so far as the slowly reactive Australian aggregates are concerned (Shayan *et al.* 1992). Carse and Dux (1990) suggested steam curing of concrete and subsequent storage at 50°C, 100% RH, but only limited data has been published on this procedure.

Table 3. Classification of aggregates by different test methods (Shayan 1992)

Aggregate	Service record	Test methods			
		Chemical	Standard mortar bar[a]	Concrete prism	Accelerated mortar bar[b]
MG	—	NR	NR	PR[c]	R
ALT	—	NR	NR	NR	NR[d]
NB	—	R	NR	NR	Pessimum
ASP	—	Borderline	NR	R	R
UY	R	R	R[e]	PR[c]	R
GSN	R	NR	NR	R[f]	R
GSG	R	NR	NR	R[f]	R
MDC	R	NR	NR	R	R
VB	—	NR	NR	NR	NR
AA	—	NR	NR	R	R
AB	—	Borderline	NR	R	R
AC	—	Borderline	NR	R	R
AD	—	NR	NR	R	R
AE	—	NR	R	R	R
AF	R	R	R	R	R

[a]Cement alkali = 1.38% Na_2O equivalent; [b]Based on criteria proposed by Shayan *et al.* (1988); [c]Depends on the level of alkali in concrete; [d]Except for one batch; [e]Expansion exceeded 0.1% after one year, but not six months; [f]At high alkali content.
R = reactive; PR = potentially reactive; NR = non-reactive.



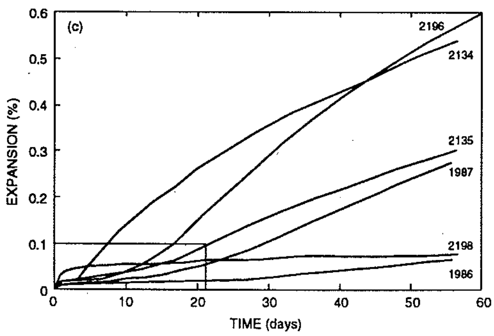


Figure 1. Expansion curves for mortar bars made with various aggregate types and subjected to accelerated testing in 1M NaOH at 80°C. Expansion can vary widely within each aggregate type depending on its mineralogical composition and history: (a) various granites; (b) various basalts; and (c) various sands.

Likely Trends

As a result of the AAR work in the past few years, it is likely that the current test methods for AAR will be extensively altered by the Australian Standards Committee CE/12, and new test methods including the accelerated mortar bar test and the concrete prism test (both normal and steam-cured) introduced. The petrographic analysis ASTM C–295 is likely to remain as a useful tool for the identification of possible reactivity.

REPAIR AND MAINTENANCE

History of Methods

Repair and maintenance of AAR-affected structures has not received much attention in Australia and, therefore, there is little published local data on the subject. As discussed earlier in this paper, Australian work has concentrated on diagnostic and preventative strategies; i.e. the identification of the mechanisms of AAR, methods of identifying AAR risk of aggregates in concrete, and the formulation of concrete mixes containing certain mineral additives that would prevent AAR expansion and damage. It is likely the repairs and maintenance to AAR-affected structures have been performed for secondary problems (e.g. reinforcement corrosion initiated from chlorides transported through cracks caused by AAR).

Current Procedures

Published Australian works on structures affected by AAR focus on the identification of AAR in the structure, however strategies for repair and maintenance of the structures concerned are seldom discussed. Most authors conclude that there is a need to address repair techniques for structures displaying AAR distress (e.g. Carse 1990).

Shayan (1994b) asserts that once AAR expansion causes cracking, deleterious agents such as chlorides can be transported into the concrete, thus causing reinforcement corrosion. If the repair locks up sufficient moisture in the concrete there is the potential for continued alkali–aggregate reaction, thus causing further distress to the repaired concrete member. Ideally, the repair should be done at a time when the rate of expansion has levelled off and the potential for further expansion has considerably diminished. The ideal repair should prevent moisture ingress while allowing the concrete to dry out at the same time, if this is possible. Shayan (1994a) has outlined important points to be considered in the repair and maintenance of AAR-affected structures. Shayan (1995) reported results of a field survey, by CTI Consultants, on AAR-affected concrete railway sleepers with and without a silane coating. This work showed that silane treatment is most effective when applied before the initiation of visible cracking. Otherwise its effects are only moderate on slowing down AAR expansion.

Davies *et al.* (1996) report the results of two years of monitoring repairs to an AAR-affected marine structure in Western Australia. The structure is approximately 40 years old and the structural capacity of beams within the structure may be reduced as a result of AAR. The paper discusses the laboratory monitoring of cores procured from the structure and also in-situ monitoring of two beams, treated with and without a silane coating. The observed difference in expansion between beams (65–180 microstrain for the treated and 100–340 microstrain for the untreated beams) indicate the silane coating significantly reduces AAR expansion. The effectiveness of the coating is expected to increase as the beams dry out further (provided the silane coating is maintained). Nevertheless, the study found that the internal AAR stresses were high, and, despite silane coating treatment, critical structural members may need to be replaced for structural reasons.

Protective coatings for the reduction of AAR expansion need to have sufficient compatibility to concrete; i.e. adequate adhesion or penetration (in the case of silanes) to an irregular surface profile and moist alkaline substrate, and the ability to accommodate the expected ongoing AAR expansion Although certain epoxy coating formulations have sufficient adhesive strength to withstand the build up of water vapour pressures, they do not permit the outward movement of water vapour and hence the concrete remains sufficiently moist for AAR to continue. The selected protection needs to be sufficiently robust to withstand the rigours of normal service life, under which the coating needs to remain functional despite the effects of ultraviolet light, wave splash and abrasion (in the case of marine structures), wetting and drying, heating and cooling, etc.

CONCLUSIONS

As a result of research on AAR in the past decade, many cases of AAR-affected concrete structures have been discovered in Australia, and a considerable number of potentially reactive aggregates identified. Because of a poor correlation with service performance of aggregates, it has been found that the current standard test methods for assessing AAR susceptibility of aggregates are inadequate and require revision. Newly developed accelerated mortar bar and concrete prism tests are considered more reliable and should replace the existing test methods.

Further research is needed to determine the influences of various parameters (e.g. temperature, alkali content, mineral additives) on the mechanisms of reaction in the concrete, and their implication for the evaluation of aggregates.

The lack of published Australian data related to repair and maintenance of AAR-affected concrete structures indicates the need to implement long-term investigations to examine such issues as the effectiveness of different treatments, longevity of repairs, the structural consequences of repairs, and the cost-effectiveness of repairs versus replacement.

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