Aggregate Reactivity

REACTIVE QUARTZ GRAVEL FROM EASTERN VICTORIA

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ABSTRACT

Several cases of damage (cracking) due to alkali–aggregate reaction (AAR) in bridges have been identified in eastern Victoria in the past few years. They are distributed in south-east and north-east Victoria, and the aggregate that caused the damage in both regions was predominantly quartz gravel. Examination of the affected concretes has shown the susceptible aggregate to be composed largely of strained quartz.

Laboratory testing of aggregate samples from nine localities, including the one that supplied aggregate to the damaged structures in the southern region, and large pieces of reef quartz from the northern region confirm their strained nature and associated alkali reactivity.

A geological interpretation of the sources of the gravels suggests that they originate from veins in highly sheared metamorphic early Palaeozoic rocks in the highlands of eastern Victoria, and have been shed into the north- and south-flowing rivers both in modern times and earlier in the Tertiary period.

The identification of AAR in the widely separated northern and southern regions suggests that reactive quartz gravel may be more widespread in eastern Victoria than the presently diagnosed cases of AAR would indicate, and it is expected that other cases of AAR will be found in the future. This work has also shown that the traditional viewpoint that considers coarse quartz gravel as non-reactive is misleading.
Keywords: Strained quartz, microcrystalline quartz, gravel, alkali reactivity, Victoria.

INTRODUCTION

Previous unpublished work carried out on bridges in north-east and south-east Victoria indicated that coarse quartz gravel was the chief reactive aggregate component in structures damaged by alkali–aggregate reaction (AAR). In most cases the quartz involved exhibited lattice strain in the form of undulatory extinction Although strained quartz has been associated with several reported cases of AAR, it has often been in the form of fine quartz grains in complex rock types, e.g granite and quartzite (Mullick *et al.* 1986), metadolerite and granite (Shayan & Lancucki 1986; Shayan 1993), phyllite, quartzite and granite gneiss (Buck 1986), and granite (Grattan-Bellew 1986). Cases of reactivity of coarse quartz gravel are not common, although Buck (1986) refers to some cases in the USA. Based on the results of a concrete prism test, Grattan-Bellew (1986) concluded that strained quartz was not necessarily associated with AAR. However, the concrete test method he used at the time appears to have been inadequate as it has recently been updated and the cement content in the concrete increased from 310 to 420 kg/m^3 and the alkali content of cement from 1.08 to 1.25%. All his rock types may cause deleterious expansions under the new test conditions. Nevertheless, Grattan-Bellew (1990; 1992) considered that it is the amount of microcrystalline quartz associated with strained quartz that determines the reactivity and not the size of the undulatory extinction angle. However, using the quick chemical test (ASTM C-289) as an indicator, Barisone and Restivo (1992) concluded that both the undulatory extinction angle and particle size were important factors, with the latter probably having more weight. Mullick *et al.* (1992) recommended testing mortar bars, made at 1% cement alkali level, at 60°C, 100% RH in order to detect the reactivity of quartzites containing strained quartz. Smith *et al.* (1992) suggested that not only undulatory extinction angle and grain size, but the texture of quartz is also important in determining its reactivity.

Examination of the geology of the provenance of the Victorian gravels indicated sources in the eastern highlands where Cambrian, Ordovician, Silurian and Devonian rocks had been folded, faulted, widely invaded by quartz veins, and in some major belts metamorphosed to greenschist and biotite-silimanite grade. If this material was eroded and spread in the region through the river systems, then the cases of AAR observed in the northern and southern parts of east Victoria could be explained to originate from the same parent materials. This would also indicate that more cases of concrete structures damaged by AAR would be expected in the region.

In order to assess the AAR potential of gravel sources in the region, some of the gravel deposits in the lower valley courses of major streams draining both northwards and southwards from the highland area were sampled and evaluated for alkali–aggregate reactivity.

PREVIOUSLY IDENTIFIED CASES OF AAR IN VICTORIA

Concrete cracking in highway bridges and other structures, that had become manifest after several years of service life, was recently investigated at a number of sites in Victoria (*Fig. 1*) and attributed to AAR (confidential reports). In *Fig. 1*, sites 1, 2 and 3 refer to highway bridges, built around 1958 in the southern region, in which cracking has occurred in pile caps, columns, crossbeams and abutment walls, as shown in *Fig. 2*. Quartz gravel is the major reactive component of the concretes in all the cases. Precast beams, containing other aggregate types and probably imported from elsewhere, did not show any cracking.

Sites 4, 6 and 8 refer to non-highway structures, with extensive cracking. They are similar in appearance, and examination of concrete cores from site 6 verified AAR in the concrete to be a consequence of using reactive quartz gravel. *Figure 3* shows examples of cracking in these structures.

Site 5 refers to two dams (outside the map area), where the reactive aggregates responsible for AAR damage are of acid igneous and sedimentary origins, rather than quartz gravel. Cases of AAR with hornfels aggregate are also present in the north-west and west of Victoria. These are mentioned to avoid giving the impression that AAR cases in Victoria are all related to quartz gravel.

Site 7 refers to a highway bridge built in 1958 in the northern region, using quartz gravel, which shows similar signs of reactivity to those in sites 1, 2 and 3.

Site 9 refers to another highway bridge built in 1930, using quartz gravel, and showing severe AAR cracking. The reaction has caused a few generations of cracking, developed after each one had been treated with epoxy resin. *Figure 4* shows some microstructural features of AAR in bridges at sites 1, 2 and 3, which are also present in this bridge and all the other cases mentioned above.

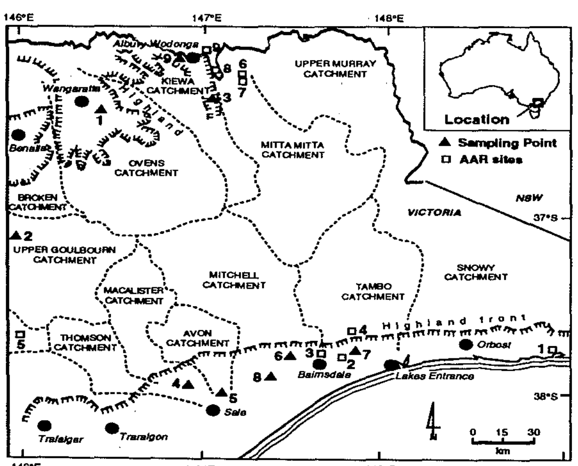


Figure 1. Simplified map of eastern Victoria showing locations of AAR sites and sampling positions of the gravel sources. Streams flow north and south from the central highlands of east Victoria, within the delineated catchments.

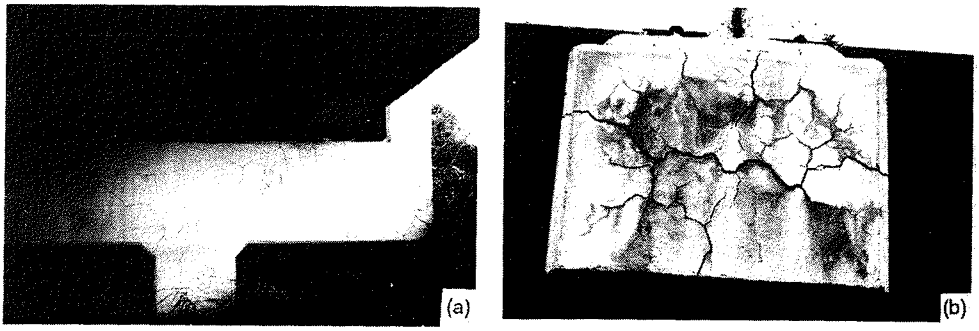


Figure 2. Cracking features of some damaged structures in the south-eastern regions of Victoria corresponding to sites 1, 2 and 3: (a) crossbeam of top of a column; (b) end of crossbeam; and (c) pile cap. Columns with single or pattern cracks were also present.

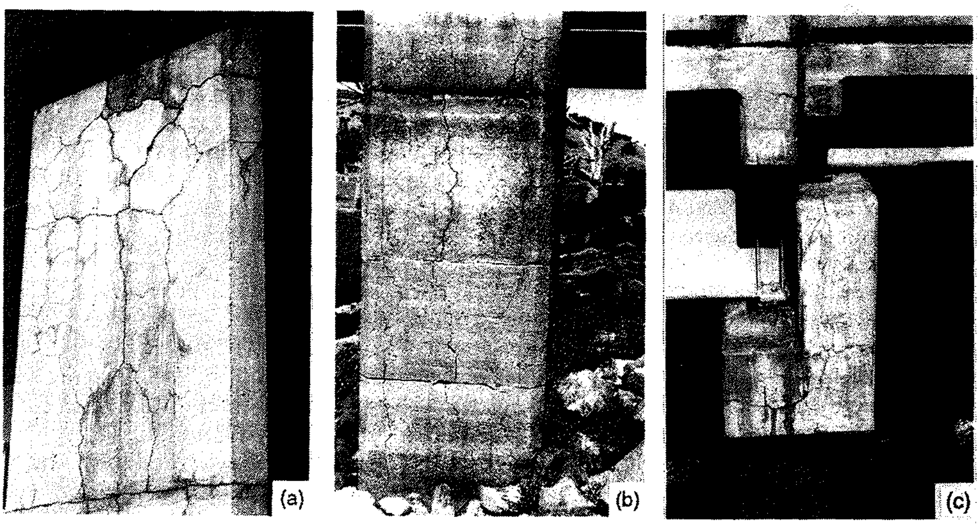


Figure 3. Cracking features of some damaged structures in the north-eastern regions of Victoria corresponding to sites, 6, 7 and 9: (a) and (b) are columns; and (c) is the end of a crossbeam. Slender columns with single vertical cracks were also observed.

GRAVEL SAMPLING LOCATIONS

Sampling locations were chosen to tap representative gravels brought down the major north- and south-flowing streams from the highland belt of eastern Victoria, using operating gravel extraction sites wherever possible. The sample localities were as follows (see *Fig. 1*).

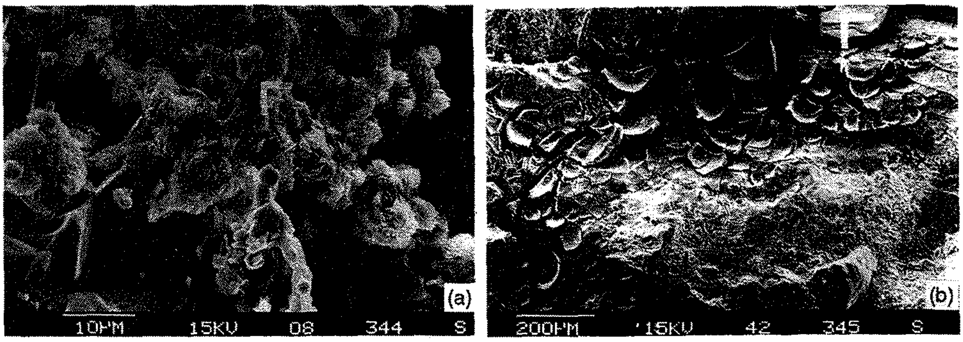


Figure 4. Two examples of microstructural features of AAR in concretes from the damaged bridges, showing: (a) crystalline AAR product on quartz aggregate; and (b) AAR gels at aggregate boundary.

1. A northern tributary of the Ovens River near Milawa 18 km south-east of Wangaratta. The sample came from a quarry that washes, crushes and screens aggregate for premixed concrete. This aggregate was predominantly iron-oxide-impregnated sandstone, with lesser amounts of quartz. Sandstone with small quartz veins and fine-grained cherty rocks were minor components.
2. Seymour gravel extracted from an older buried channel of the Goulbourn River. This gravel is predominantly vein quartz, but has considerable quantities of friable grey-green sandstone. It is used locally in premixed concrete.
3. Kiewa River at Kergunyah. This sample was taken from an eastern distributary channel, and consists of large milky quartz pebbles and boulders. Upstream from here is the highly fractured metamorphic area described by Beavis (1961), which it was thought would yield strained quartz.
4. Tertiary gravel deposits east of Maffra. This is a hilltop bedded gravel deposit from the gravel fan system which borders the highland front of much of east Gippsland. It is almost certainly deposited from earlier streams flowing from the present Macalister Catchment area.
5. Gravel from the Avon River at Stratford. This is a very mixed gravel with large fractions of Devonian-Carboniferous sandstones and porphyritic volcanics from the Avon Catchment.
6. Gravel from the Mitchell River at Wuk Wuk near Lindenow, again with sandstone pebbles outnumbering quartz.
7. Tertiary gravel from hilltop road cuts 3 km south of Bruthen. This is a typical quartz gravel like others from east Gippsland (e.g. 4 above), but is from an embayment in the highland front and can only have been derived from the Tambo Catchment, and would have had a contribution from the southern end of the metamorphic belt.
8. Toms Creek, between Bairnsdale and Sale. This Tertiary gravel was used in structures in sites 1, 2, 3 and probably 4, and caused considerable AAR and cracking of concrete. Gravel samples from this source have been shown to exhibit alkali reactivity in the laboratory both by the accelerated mortar bar procedure (Shayan *et al.* 1988) and by the Chinese microbar method (Tang *et al.* 1983). The latter was carried out at the Nanjing Institute of Chemical Technology.
9. A quarry at Wodonga extracting gravel from the floodplain of the Murray River, which is widely used for concrete in the Albury–Wodonga area, and consists largely of quartz and sandstone.

A number of large pieces (150–200 mm) of white reef quartz, previously collected from AAR site 8, were also included in the study.

EXPERIMENTAL WORK

From each of the gravel samples collected from the above localities, eight subsamples of 250 pebbles were randomly withdrawn and combined to make a sample of 2000 pebbles. The percentage of individual rock types were then determined in each sample, as detailed in *Table 1*. Representative pebbles from the various rock types were selected for preparation of petrographic thin sections, and the remainder of the segregated single rock types for each locality were crushed to meet the grading requirements for mortar bars (Aust. Standard AS 1141–38), and then used in the accelerated mortar bar procedure described earlier (Shayan *et al.* 1988). For the reef quartz, in addition to the above work, concrete prisms were made with the crushed quartz using a concrete mix containing 500 kg cement/m^3, water/cement ratio of 0.4 and cement alkali levels of 1.38 and 1.8%, achieved by adding appropriate amounts of NaOH to the mixing water. A non-reactive basalt containing the same sand as that used in combination with the reef quartz was used for comparison at the 1.8% alkali level.

Table 1. Rock types — per cent at localities sampled

Rock type	*Locality*								
	1	*2*	*3**	*4**	*5*	*6*	*7**	*8**	*9*
Quartz, mostly milky	23	68	100	100	17	14	100	100	67
Quartz, blue grey	1								7
Sandstone	65	27			54	54			13
Sandstone with small quartz veins	9	3			10	21			5
Cherty fine grained rocks	1	2			3				2
Volcanic rocks (mostly chyolite porphyry)					16	12			5
Miscellaneous	1								1

* *Only quartz pebbles sampled.*

RESULTS AND DISCUSSION

Accelerated mortar bar procedure (1 M NaOH, 80°C)

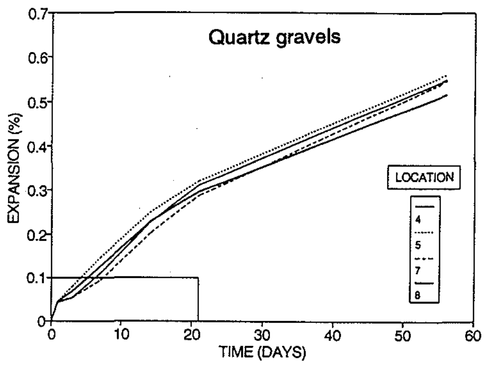
Expansion results to 56 days in the accelerated test and the reactivity criteria (Shayan *et al.* 1988) are given in *Fig. 5*. These results show that mortar bars made with quartz aggregates (pebbles) from each locality expanded significantly (0.27–0.37%) in 21 days. Among sandstones, those from sites 5 and 6 caused the highest expansions (0.24–0.26%), and those from sites 1 and 9 gave smaller expansions (0.12–0.15%). All these aggregates are classed as potentially reactive. Sandstone from site 2, which was friable and somewhat permeable, did not exceed the 21-day limit, and neither did the porphyry aggregate from site 5, and are considered non-reactive.

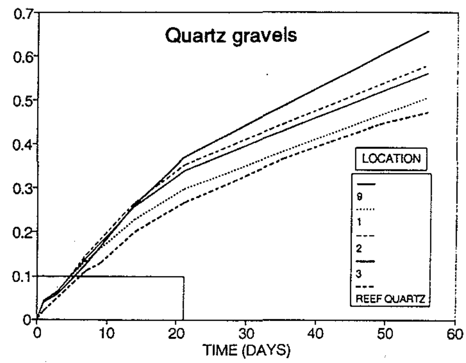
Figure 6 shows expansion curves for concrete prisms made with the reef quartz and the non-reactive basalt. Those made with the reef quartz have expanded deleteriously at both alkali contents, and cracked at 34 weeks of age as shown by arrows, indicating their alkali reactivity.

These results show a broad correlation between the laboratory assessment of the quartz gravel sources (i.e. reactive) and the damage to concrete structures in the northern and southern parts of east Victoria.

Petrographic examination of quartz pebbles

All the quartz specimens were vein quartz which showed flow banding, occasional comb structure, multiple fillings of veins and some fine cross-cutting veins. The hand specimens ranged from 10 to 150 mm in size, and only pieces larger than 30 mm were used for





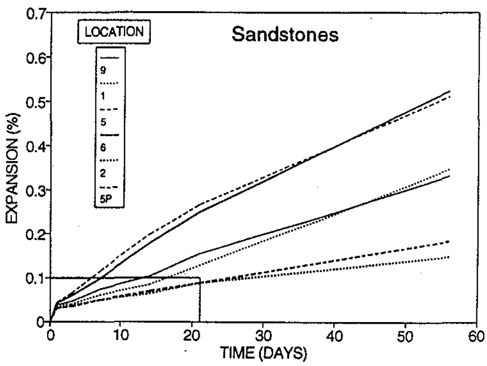


Figure 5. Expansion curves for mortar bars made with the various components of the gravels and subjected to the accelerated test in 1 M NaOH solution at 80°C. Expansions greater than 0.1% at 10 days indicate reactive aggregate, and greater than 0.1% at 21 days slowly reactive aggregate. 5P refers to porphyry aggregate from location 5.

making thin sections. The colour of pebbles ranged from milky white to milky/translucent, blue-grey, slightly stained (reddish), somewhat milky and multicolour.

Very different textural details were seen among different varieties of quartz pebbles and even within some single pebbles. Some milky quartz showed only slight undulatory extinction with largely regular grain boundaries. Occasionally, some overgrowth of secondary silica was observed at some grain boundaries.

Some other milky quartz (e.g. the white reef quartz) showed severe distortion in the quartz lattice, producing a mottled blotchy look and complex extinction. Fracture and microcrystalline growth was evident in some parts of such pebbles. Some of the milky quartz pebbles exhibited extensive microcrystallisation of the strained quartz. The blue quartz pebbles were the most severely strained among the pebbles, including blotchy mottle extinction, crystal assemblages of various fine sizes and mosaics of smaller crystals forming at grain boundaries of other larger crystals, which also had sutured boundaries.

Microcrystalline quartz grains were found on some of the crystal boundaries and in thin linear cross-cutting veins representing the last phase of crystallisation. Many specimens showed the signs of pervasive cracking after this last vein formation. Even in hand specimens, fracture or shear lines were discernible. The stained-milky and clear/milky quartz pebbles showed intermediate features. *Figure 7* shows some of the features of the strained quartz and *Fig. 8* some grain boundaries. Examination of reacted quartz gravel pieces in concrete cores from AAR-affected structures also showed the same features. In addition, some dark cherty particles and some sandstone pieces also showed severe attack by alkali.

The observed features of the quartz pebbles mentioned above appear to make them susceptible to alkali attack in concrete, and this is corroborated by the results of the accelerated mortar bar test and behaviour of such coarse quartz gravels in field concretes.

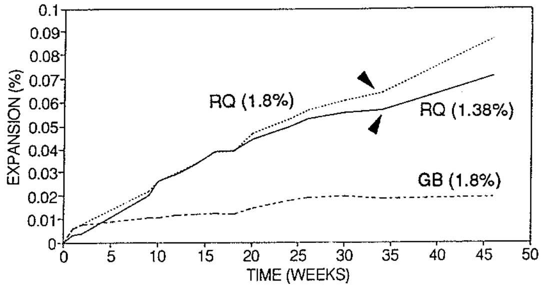


Figure 6. Expansion curves for concrete prisms made with the reef quartz (RQ) at 1.38 and 1.8% cement alkali levels, and with the non-reactive basalt (GB) at 1.8% alkali level. Storage conditions were 40°C, 100% RH. Arrows indicate when cracking was noted.

CONCLUSIONS

Quartz gravels from major streams flowing south and north from the highlands of eastern Victoria contain a variety of quartz pebbles which have been shown petrographically to be mildly to severely strained, and prone to alkali attack in the accelerated mortar bar test (1 M NaOH, 80C). Quartz pebbles caused the highest expansions, and early Palaeozoic sandstone pebbles also caused deleterious expansions. These results correlate well with the observed field behaviour of the quartz gravels in concrete structures in eastern Victoria, where a number of structures have been damaged by AAR. For the reef quartz, both the accelerated mortar bar test and concrete prism test indicated considerable alkali reactivity.

From the distribution pattern of these gravels in eastern Victoria, it is expected that more cases of AAR-damaged structures will be found in the region. However, a larger number of gravel sources needs to be investigated to get a better understanding of the distribution of reactive gravels.

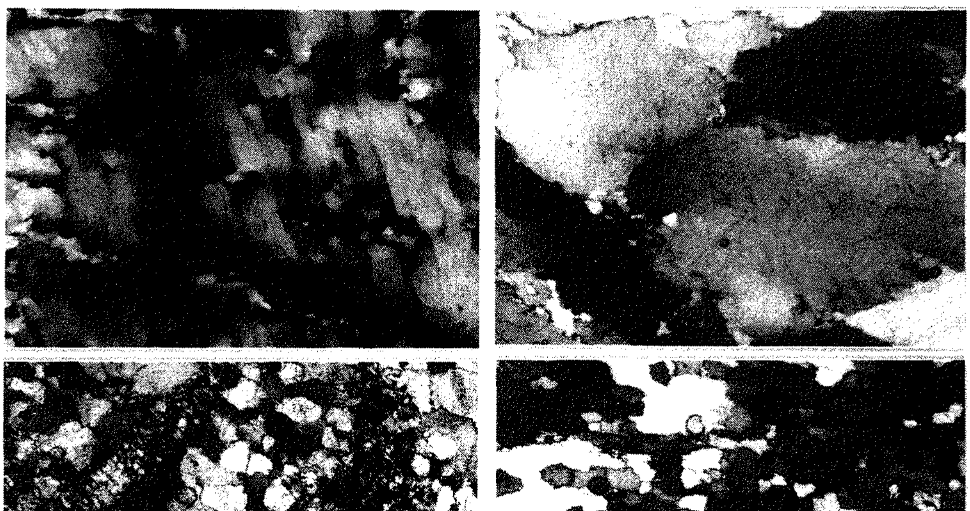


Figure 7. Micrographs showing the various features of strained quartz in thin sections made from the various varieties of quartz pebbles. These features are indicative of alkali reactivity.

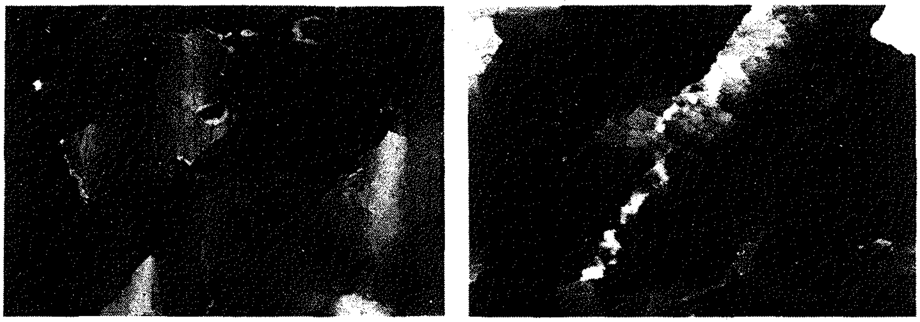


Figure 8. Two examples of grain boundaries in strained quartz pebbles. These irregular boundaries indicate strain and overgrowth of secondary silica.

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