PETROGRAPHIC ASPECTS OF ALKALI-SILICA REACTION IN EASTERN AUSTRALIAN CONCRETES

A.S. Joyce
Geochempet Services, 198 Chapel Hill Road, Brisbane

ABSTRACT

Within eastern Australia the forms of potentially reactive silica most likely to threaten a deleterious degree of reaction in concrete aggregates are finely microcrystalline quartz and strained quartz. The former is involved in deleterious reaction in various concrete structures in Queensland in which the aggregate includes devitrified acid tuff or volcaniclastic arenite and siltstone or chert and jasper. The latter is involved less commonly in deleterious reaction in concrete at locations spread from Victoria to Cairns: the strained quartz is present in coarse aggregate which is variously quartzite or foliated meta-greywacke. Chert, jasper and quartzite or other forms of strained quartz are common in many eastern Australian concrete sands, and they have reacted in some places.

Other forms of potentially more reactive silica of possible significance comprise opal, chalcedony and glass, but they seem not to have given rise to problems yet in eastern Australia.

Source rocks from eastern Australian known or suspected to be potentially alkali reactive in concrete are acid and quartzose intermediate tuffs, volcanic rocks and derived volcaniclastic sedimentary rocks containing finely microcrystalline quartz, strained quartzose metamorphic rocks, strained quartzose intrusive intermediate and acid igneous rocks, strained vein quartz, finely siliceous chert and jasper, opaline to chalcedonic silcrete and sufficiently siliceous glassy volcanic and tuffaceous rocks (mainly confined to some old intermediate to acid rocks in the Hunter Valley/Port Stephens area of NSW and to some more widespread, young basalts carrying fractionated, late, siliceous glass in addition to earlier innocuous basaltic glass).

Keywords: AAR, aggregate, alkali-silica, Australia, reactive

INTRODUCTION

Alkali-silica reaction in relation to concrete involves a chemical reaction between alkalis (contributed mainly but not exclusively from the cement) and reactive forms of silica (within the coarse and/or fine aggregate and in some cases deliberately added as a pozzolan). The result of the alkali-silica reaction is an alkali silicate gel.

It should be understood that alkali-silica reaction in concrete is common: it can be unnoticed because it is trivial and/or benign, it can be deliberately induced and beneficial (as in the addition of certain types of pozzolans) or it can be *deleterious*.

The deleterious style of alkali-silica reaction results in the production of a gel rich in sodium and/or potassium and not excessively rich in silica: such gels can take up substantial amounts of water, thereby expanding and consequently cracking the concrete in which they form. Silicate gels formed from mainly calcium, or sodium/potassium silicate gels containing large amounts of silica are considered to be less expansive - thus they may not result in deleterious effects on the concrete.

The key ingredients for deleterious alkali-silica reaction in concrete are *elevated sodium and/or potassium* (mainly from the cement, but supplemented especially from saline external waters in some environments), *enough* but not too much *reactive silica* (Vivian, 1951) and *moisture.* Some other factors contribute to the rate of reaction.

Steps can be taken in the design of concrete mixes and in the design of concrete structures to control and possibly eliminate a deleterious degree of reaction. This paper is more concerned with recognition of aggregates which have reacted or which have potential for deleterious alkali-silica reactivity.

REACTIVE FORMS OF SILICA

It is possible that some silicate minerals may take part in reactions with alkali in concrete (Gillot, 1975), but it seems that significant reactions largely or wholly involve *free silica.*

Free silica refers to silicon dioxide in a disordered state (such as glass) or within various crystalline minerals (of which quartz is only one example). It is different to *combined silica* which refers to silicon dioxide which is chemically combined with other elements or oxides to create chemically more complex silicate minerals (of which feldspar will serve as a common example). The total silica content of an aggregate or sand which can be determined by bulk chemical analysis is not an effective guide to its potential for deleterious alkali-silica reactivity: it reports the total of combined silica and free silica. Determination of the abundance and form of the free silica is best achieved petrographic examination, based mainly on microscopic examination, but supplemented where necessary by X-ray diffraction or electron probe methods.

The most reactive forms of silica are richly siliceous *opal* and *glass*. Both substances are essentially disordered, non-crystalline to cryptocrystalline (individual crystals not resolvable by optical microscopy) and unstable.

Opal is relatively pure silica (SiO_2) mixed with variable, minor amounts of water (commonly 6 to 10%). Some opal is an essentially amorphous colloid and some is partly cryptocrystalline cristobalite (an open structured metastable silica mineral). Quantities of opal as low as about 2% (Payne, 1976) are thought to be quite deleterious within aggregates and sands.

Natural rock glass carries variable amounts of other oxides in addition to silica. Rock glass is generally produced by quenching of volcanic igneous or tuffaceous rocks. Depending on whether the parent rock magma (molten rock) was ultrabasic, basic, intermediate or acid, the resultant glass can be very low in silica (less than 45%), low in silica (about 45-56%), carry moderate amounts of silica (around 52-56%) or be rich in silica (more than about 66%). Although all types of rock glass carry silica in an uncombined or "free" condition, it seems that only those compositions which would have been capable of crystallizing free silica minerals (if not quenched) give rise to deleterious amounts of reaction with alkalis in concrete. Thus, glass of acid and intermediate igneous compositions are usually deleterious, but only some of the most fractionated and therefore most siliceous basic igneous glasses are reactive; the most common types of basic (commonly basaltic) glasses seem innocuous. As in the case of opal, amounts of richly siliceous glass as low as several percent can be quite deleterious within aggregate or sand.

It should be appreciated that construction aggregates and sands won from river sources can carry very siliceous synthetic glass as a contaminant. In most situations it is unlikely to be sufficiently abundant to cause a problem. However, care should be exercised when contemplating the use of other unusual forms of aggregate (e.g. fired pelletised garbage, clinker or smelter or foundry wastes) because they may carry substantial amounts of glass.

Chalcedony represents a form of silica transitional between amorphous, hydrous opal and crystalline, anhydrous silica. It is a quite reactive, microporous substance which can involve cryptocrystalline cristobalite or quartz.

Crystalline free silica is most commonly encountered as *quartz*, a mineral which is generally regarded as innocuous in relation to alkali reactivity unless it is *finely microcrystalline* (less than about 10μm) or *substantially strained.* The fine grainsize apparently enhances the reactivity by offering greater access of alkaline solutions along the many crystal grain boundaries. In the case of strained quartz there may be similarly enhanced access of alkalis because the strain involves a multitude of induced crystallographic discontinuities which probably act as pathways in a similar way to crystal grain boundaries.

There seems to be a continuous spectrum of reactivity from very reactive to innocuous in passing from finest "cherty" quartz (around 5 μm or less) to simple microcrystalline and coarser quartz (coarser than about 10 μm); similarly quartz changes from innocuous to moderately reactive in passing from unstrained to substantially strained (Dolar-Mantuani, 1982).

Some doubt about the completely innocuous nature of "ordinary" quartz is posed by the description published by Cole *et al.* (1981) of alkali-aggregate reaction noticed around sandstone and siltstone fragments in a 30 year old dam: they were able to find little evidence that amorphous silica or strained quartz was involved.

Apart from common quartz (also known as low temperature quartz or α-quartz), crystalline silica can also occur as high temperature quartz (or *β-quartz*), *tridymite, cristobalite, coesite* and *stishovite.* β-quartz inverts promptly to low temperature quartz when cooled below about 573 °C: its bipyramidal (or diamond-shaped) form is commonly recognisable in acid volcanic and tuffaceous rocks, but the cooled mineral is now invariably re-ordered to alpha quartz. Tridymite and cristobalite are both rather open structured crystalline forms of silica stable only at high temperatures, but capable of forming as metastable phases at lower temperatures: the open crystal structures and the metastability at low temperatures both contribute to quite an alkali reactive character. Both tridymite and cristobalite can be difficult to recognise within acid volcanic rocks and tuffs without supplementary X-ray diffraction analysis. They are more likely to be encountered in acid or intermediate lavas and tuffs of Tertiary or younger age (e.g. within PNG, Fiji, New Zealand and Japan) than within the older lavas and tuffs typical of Australia. Coesite and stishovite are rare high pressure forms of silica of no obvious significance in relation to construction aggregates.

OBSERVED REACTIVE COARSE AGGREGATE

Coarse aggregates which have been observed by the author to be alkali reactive in concrete structures in eastern Australia are listed below. Confidentiality requirements preclude naming particular concrete structures and aggregate sources: some details of some relevant examples have been listed by Carse and Dux (1988).

- *Acid tuff:* aggregate derived from sources described variously as acid tuff, rhyolitic tuff, rhyodacitic tuff and ignimbrite have given rise to obvious reaction rims, alkali silicate gel veins and bubble fillings and deleterious expansion and cracking in many concrete structures in north Queensland. The most obvious reaction has taken place in bridges, marine facilities and retaining walls; less obvious damage has taken place in buildings. The free silica involved in observed cases of reaction is considered to be finely microcrystalline quartz formed by devitrification of formerly abundant glass shards and pumice. Not all devitrified tuffs have potential for a deleterious degree of reaction: the potential for reaction is dependent on the degree of recrystallization after devitrification. It is noteworthy that some old tuffaceous rocks in the Port Stephens region of NSW retain actual glass: it is presumed that they have substantial potential for deleterious reaction, but no examples are known at this stage.
- *Volcaniclastic arenite and siltstone:* several examples have been encountered from the central coastal region of Queensland in which concrete generated using arenites and siltstones composed of intermediate and acid volcanic and tuffaceous detritus show mildly deleterious reaction which can be attributed to the presence of finely microcrystalline quartz of mainly devitrification origin. Sedimentary recycling of alkali reactive rock does not have an inherent capacity to reduce the amount of alkali reactive silica -unless there is substantial subsequent diagenesis or incipient metamorphic modification. It should be noted that rocks described as greywacke in northeastern NSW are typically volcaniclastic arenite containing varying proportions of intermediate and acid volcanic/tuffaceous detritus: some may prove to be reactive.
- *Meta-greywacke*: aggregate derived from rock describable as meta-greywacke (or quartzose schist) in north Queensland has yielded some examples of deleterious reaction in marine concrete structures. The reaction seems attributable to the presence of moderately strained quartz. No problems have yet been recognised in concrete produced using less metamorphosed, more feldspathic meta-greywacke in southern Queensland and northern NSW, but there is perceived to be a risk of deleterious reaction under some combinations of conditions which especially favour reaction.
- *Quartzite*: fine quartzite (probably metamorphosed chert), dominated by finely crystalline, mainly only mildly strained quartz is known to have reacted within concrete in a bridge and within an unrelated power station cooling pond, both in southern Queensland. The reaction is a little unexpected because the quartz is not

very finely crystalline and nor is it substantially strained: presumably the combination of high silica content, relatively fine grainsize and at least a mild degree of strain has resulted in significant reaction only under conditions which particularly favour reaction (e.g. the cooling pond).

- *Siliceous river gravel:* within tidal environments in southern Queensland several bridge structures containing coarse aggregate generated from siliceous river gravels show deleterious alkali-silica reactivity which can be seen to originate within pebbles of quartzite (rich in at least moderately strained quartz) and within pebbles of chert and related jasper (both rich in finely microcrystalline quartz). Reaction related to quartzite pebbles has been seen also within a Victorian bridge, although its effects did not seem to be as deleterious as those developed in Queensland.

OTHER POTENTIALLY REACTIVE COARSE AGGREGATE

The following list describes other source rocks which have been used as coarse aggregate in eastern Australia and which are perceived to have potential for deleterious alkali-silica reactivity, but which have not yet been observed to give any problem.

- *Acid volcanic and subvolcanic rocks:* reported under varietal names such as rhyolite, rhyodacite, dacite and porphyry. Some varieties are innocuous, having initially crystallized, or in some cases recrystallized, their free silica as quartz with a sufficiently coarse grainsize and sufficiently low strain to be essentially unreactive. Others are perceived to range between quite reactive and mildly reactive, depending on whether they carry glass (or less commonly cristobalite or tridymite) or finely microcrystalline quartz. In addition to their primary silica components, the rocks can carry opal, chalcedony and microcrystalline quartz as vesicle linings and fillings and as veins and hydrothermal replacements.
- *Silica oversaturated intermediate volcanic and subvolcanic rocks:* reported as trachyte, latite or andesite, and in some cases prefixed with the word quartz. If the contained minor free silica (trace to 10%) exists only as simple quartz coarser than about 10 µm, then the rock may be innocuous, but if it carries glass, opal, chalcedony, tridymite, cristobalite or finely microcrystalline quartz then it is potentially alkali reactive. Silica can be present also within vesicles, veins and hydrothermal replacements.
- *Some basic volcanic and subvolcanic rocks:* reported mainly as basalt. Most basalts, including quite glassy varieties, are innocuous in relation to alkali reactivity, but a few potentially alkali reactive exceptions exist. Olivine basalt can carry blebs or vesicle linings of late, fractionated, silica-enriched, green or yellowish glass (different from and commonly developed in conjunction with more typical and innocuous, brown basaltic glass). Such fractionated glass has been observed in many examples of basaltic aggregate used in Melbourne, but it seems to have reacted only trivially and without generating detectable gel products. Similar glass within some Queensland basaltic aggregates may be more significant because of higher prevailing temperatures and humidity. Other

potentially reactive basic volcanics include calc-alkali or tholeiitic basalts carrying opal, chalcedony, late fractionated glass or microcrystalline quartz, most commonly in or around vesicles.

- *Argillite, slate and phyllite:* argillite is indurated mudstone, originally composed of silt and clay-sized detritus, but now rendered harder and stronger by very fine recrystallization. Quartz in a very fine, and consequently alkali reactive condition, can be present and its abundance can be difficult to assess microscopically. Slate and phyllite are similar in composition, but slightly recrystallized by low grade metamorphism: quartz may be slightly coarsened, but it may also be strained.
- *Limestones dolomites and marbles:* most limestones, dolomites and marbles are innocuous: indeed, many are virtually free of silica. However, appropriate caution is warranted because the carbonate rocks can carry some quite reactive silica. In young or least modified rocks this silica can be in the form of opaline silica of chemical or biochemical origin. In more matured rocks the silica may exist as chalcedony or "cherty" microcrystalline quartz, in some cases as flint nodules, concretions or cavity fillings, but in other cases as inconspicuous disseminations or patchy replacements.
- *Schists and gneisses:* many schists and gneisses are medium to high grade regional metamorphic derivatives of mudstones, sandstones or other quartz-bearing precursor rocks (including tuffs and volcanic rocks). Depending on the interplay between shearing and thermal recrystallization, such rocks can carry slightly, moderately or heavily strained quartz, and, depending on the composition of their precursor rocks that quartz may range from minor to abundant. Thus, schists and gneisses can show potential for AAR ranging from innocuous to moderate.
- *Foliated granites and related intrusive igneous rocks:* granites, aplites, adamellites, granodiorites, tonalites, quartz syenites, quartz monzonites and quartz diorites all carry free silica (abundances in the range from about 40 to 5%). Most such rocks are innocuous in relation to alkali-aggregate reaction because their free silica is in the form of essentially unstrained and relatively coarsely crystalline quartz. However, in some cases the igneous rock was intruded into highly stressed rocks and a foliation (or gneissic character) was generated: quartz is consequently strained. In other cases a later regional metamorphic event has been superimposed on previously unstrained quartzose igneous rock. Thus, such foliated or gneissic, quartzose igneous rocks have potential for alkali-aggregate reaction which depends on the degree of strain shown by their quartz and on the amount of such quartz.
- *Silcrete:* a highly siliceous duricrust material generated by intense weathering and exploited as aggregate in some inland parts of Australia. Silcrete is commonly developed from quartzose sand or sandstone and now consists of remnant, broken sand and silt grains of quartz dispersed through, and cemented by opal, chalcedony and/or microcrystalline quartz. Not only does silcrete contain highly reactive forms of silica, but they are typically abundant. In many cases silcrete has been used in concrete without recognized deleterious effects: there are several

mitigating factors which may explain this. Firstly, the silcrete aggregate has been used in arid, inland locations where moisture levels are persistently low (thereby slowing any reaction which may be proceeding in service) and secondly, some silcrete sources carry so much readily reactive silica that perhaps it has protected the concrete by consuming excess alkali during mixing and initial setting. It is also pertinent that high silica-low alkali gel is less expansive than the more common type of alkali silicate gel (Payne, 1976). All silcrete should be regarded as potentially alkali reactive and appropriate care should be exercised. It is to be expected that all silcrete will react, but not necessarily in a deleterious fashion.

- *Vein quartz:* small quarries can be developed on unusually thick veins of quartz, or on heavily quartz-veined rock; vein quartz can also be substantial component of gravel or sand. Simple, coarse, essentially unstrained quartz may be regarded as innocuous, but many examples of vein quartz involve varying degrees of strain: thus, vein quartz has the potential to range between innocuous and moderately reactive depending on its degree of strain.

POTENTIALLY ALKALI REACTIVE SANDS

There is a tendency to look towards the coarse aggregate in relation to AAR. However, the processes involved in weathering, aqueous transport and reworking do not decrease the potential inherent in source materials for deleterious alkali-silica reactivity in concrete. Indeed, it could be argued that weathering, erosion and transportation tend to enrich natural sands in all siliceous components (including most of the alkali reactive forms) because such components are generally harder and more resistant to weathering than the other mineral and rock fragments.

In Australia the most commonly observed alkali reactive components in sands are strained quartz (as free grains or as quartzite or as strained vein fragments), chert, jasper, chalcedony, silcrete and acid volcanic and tuffaceous rock fragments.

CONCLUSIONS AND COMMENTS

From personal observations it is concluded that deleterious coarse aggregate reaction attributable to silica within acid tuff, volcaniclastic arenite and siltstone, foliated meta-greywacke, fine quartzite and gravels containing strained quartzite and chert/jasper can be found in concrete structures in eastern Australia. It is clear that chert, jasper and quartzite fragments in some concrete sands have also reacted.

The forms of free silica observed to have reacted in coarse aggregate and concrete sands in eastern Australia comprise finely microcrystalline quartz, at least moderately strained quartz and quartz which is both moderately fine and mildly strained.

Recognised or reported occurrences of deleterious AAR are quite sparse in Victoria and NSW, but many affected structures are known to exist between Brisbane and Cairns. Climate may be a significant factor because there are examples of aggregates exploited without apparent reaction in Victoria and NSW which are apparently similar to aggregates which have reacted deleteriously in Queensland.

It seems that the intensity of reaction is greatest in concrete structures placed within marine or tidal environments: an external source of alkali (salt water) may be enhancing the reaction.

REFERENCES

Carse, A. & Dux, P.F. 1988, 'Alkali-Silica Reaction in Concrete Structures', *Univ. of Qld Civil Eng. Research Report Series. No. CE88,* 24p.

Cole, W.F., Lancucki, C.J. & Sandy, M.J. 1981, 'Products formed in an aged concrete', *Cement and Concrete Research,* 11, 443-454.

Dolar-Mantuani, L. 1982, 'Paper 36 Undulatory extinction in quartz used for identifying potential alkali-reactive rocks' *summarized in* Grattan-Bellew, P.E. 'Highlights of the Fifth International Conference on alkali-aggregate reaction'. *World Cement April 1982*, 121-127.

Gillot, J.E. 1975, 'Alkali-aggregate reaction in concrete', *Eng. Geol. 9,* 303-326.

Payne, G.H. 1976, 'Properties of Western Australian concrete aggregates with particular reference to their potential alkali reactivity', *W.A. Govt. Chem. Labs Rept. of Investigations 13.*

Vivian, H.E. 1951, 'Studies in cement-aggregate reactions', Part XIX. *Aust. J. Appl. Sci. 2*, 488-494.