

ALKALI-AGGREGATE REACTION AND BASALT AGGREGATES

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ABSTRACT

Basalt is a basic igneous rock, deficient in silica, and as such is not expected to be prone to alkali-aggregate reaction. However, some basalts contain silica-rich phases in the form of alteration products or glassy phases, which could render them susceptible to alkali reactivity. Moreover, basalts contain feldspar minerals which are capable of releasing alkali to the pore solution of concrete, thereby enhancing the reactivity of other relatively aggregates that may be present. This paper provides data on some of the Australian basalts which cover both categories of direct involvement in AAR and contribution to the reactivity of other aggregates in concrete.

Keywords: Basalt aggregate, AAR, Alkali release

1 INTRODUCTION

Alkali-aggregate reaction (AAR) involving siliceous aggregates occurs in concrete containing sufficient amounts of alkali and silica-rich aggregate types in which silica is in an unstable form. Examples of aggregates susceptible to AAR are those of acid volcanic and meta-sedimentary origins (e.g. some rhyolites, dacites, meta-quartzites, phyllite, greywacke). Basalt is a silica-deficient, mafic rock, usually lacking in free silica minerals, which are needed for AAR. However, some young unaltered basalts could contain excess silica or silica-rich glassy phases that could react in high alkali concrete to cause AAR, for instance, basaltic sand from some beaches in Iceland, where the reactive component is believed to be an opaline material (Guðmundsson and Asgeirsson, 1975). In addition to this direct role in AAR, basalts contain a large amount of feldspars which could release alkali into the pore solution of concrete, enhancing its potential for AAR, when reactive aggregates are present. This is particularly the case when fine crushed basalt is used as a concrete sand. Release of alkali from feldspar (Van Aardt and Visser, 1977) and from basalt (Way and Cole, 1982) into saturated calcium hydroxide solution has been well established, and results from partial dissolution of feldspar in the saturated lime solution. The latter authors found that finer basalt particles release much more alkali than coarser particles.

Goguel (1995) also found that basalts release considerable amounts of alkali to the concrete, corresponding to about 1.6% Na₂O equivalent alkali addition to a low alkali cement. The well-crystalline

basalts (dolerite) released less alkali than poorly crystallised (rapidly cooled) basalt. Poulsen et al. (2000) showed that alkali released from feldspar increased the expansion of mortar bars containing reactive chert, as compared to mortar bars containing the same chert and non-reactive quartz sand; both cases using a low alkali cement. Feldspar minerals in a granitic rock also released a considerable amount of alkali when rock powder was digested in saturated Ca (OH)₂ solution (Shayan and Quick 1992), but it was argued that this would exaggerate the release of alkali from coarser aggregate particles in concrete. Berube et al. (2002), using different aggregates in the 1.25 – 5 mm particle size range, and various extracting solutions, found that a 0.7M KOH solution extracted more Na from the aggregates than the saturated lime solution, and that feldspar-bearing rocks released more alkali than other rock types; the range being the equivalent of <0.1 to 3.4 kg/Na₂O equiv/m³ (12.7 kg/m³ for phonolite, a nepheline-bearing rock).

In addition to the alkali released by the partial dissolution processes, basalts may contain exchangeable alkali, particularly those containing secondary clay minerals (Sameshima and Way, 1982; Shayan et al. 1990), that could also be released into concrete. Recently, Constantiner and Diamond (2003) measured the contribution of alkali released from feldspar into the pore solution of mortar by expressing and analysing the pore solution itself. They confirmed that the feldspars released significant amounts of alkali, some of which was consumed by alkali-silica reaction caused by the reactive calcined flint aggregate used. This paper provides data on both aspects of participation of basalt aggregates to

alkali-aggregate reaction, i.e. direct reaction of the basalt aggregate itself, and its contribution to the reactivity of other reactive aggregates by supplying additional alkali to the pore solution of concrete.

2 REACTIVITY OF BASALT AGGREGATES

Basalt-dolerite rock types are very common sources of aggregate in the metropolitan area of Melbourne, Australia, and are widely used in both flexible road pavements and concrete structures. In some basalts, olivine and glassy phases are deuterically altered to smectitic clay minerals which, when present in significant amounts, render the rock dimensionally unstable. Aggregates produced from such sources are susceptible to significant drying shrinkage, and can cause concrete cracking. However, these aggregates are not susceptible to AAR, and perform well in the accelerated mortar bar test, as reference non-reactive aggregates (Aggregates DP and PIO in Figure 5 of Shayan et al. 1988). They also performed well in relatively large cylindrical concrete specimens (250 mm dia. \times 300 mm long) containing about 7.3 kg Na₂O equiv/m³, and subjected to accelerated curing conditions of 50°C under water, whereas very slowly reactive aggregates caused significant expansion and cracking under these conditions (Shayan, 1989). Analyses conducted on the whole basalt and its various phases (Shayan, et al. 1990) showed that the glassy components were rich in Mg and Fe, and had silica contents (~53%) similar to that of the basalt itself (~50%). This type of glassy phase does not appear to be deleterious, with respect to AAR.

However, reactive components are present in some other basalts. As mentioned earlier, some basaltic sands from Ireland are known to be reactive. Shayan and Quick (1988) reported a reactive basalt from Queensland, Australia which could not be detected by petrographic examination as reactive, but which was found to contain about 1.6% opaline silica (91.8% SiO₂ content) as the reactive component on subsequent scanning electron microscope examination. This basalt caused large expansions and cracking in a mortar bar test ASTM C-227 (38°C, 100% RH), in the AMBT (1M NaOH, 80°C), and in a concrete prism test (CPT), similar to ASTM C-1293.

Shrimer (1996) reported a reactive diabase (dolerite) which could not be correctly identified by petrography, but caused large expansions in the Canadian AMBT (CSA A23.2-25A) and in the Canadian Concrete prism (CSA A23.2-14A) tests and was classed as reactive. A very fine-grained form of quartz was identified as the reactive

component, which had a "cloudy appearance" in the thin section.

Another Australian basalt (TS) which behaved similarly to the Queensland basalt was subjected to more detailed investigation. Polished thin sections of the basalt were analysed using an electron probe. It contained a silica-rich glassy phase with a composition, determined by quantitative wavelength-dispersive X-ray spectrometry, to be SiO₂ (87.8%), Al₂O₃ (7.3%), TiO₂ (0.15%), Fe₂O₃ (1.4%), CaO (2.2%), Na₂O (0.20%), K₂O (0.60%). Glass formed a minor phase in the basalt, amounting to <10%.

Figure 1 shows a back-scattered electron image of such a glassy patch in the thin section of the basalt. The bright areas are the inter-grown ilmenite and iron oxide phases and the dark areas the silica-rich glass, surrounded by the lighter grey areas (feldspar). Mortar bars made with this basalt and subjected to the AMBT (1M NaOH, 80°C), produced an expansion of about 0.30% in 21 days, which continued with time and exceeded 0.8% in 42 days. The mortar bars exhibited significant map-cracking at the end of the test (Figure 2). Thin sections made of the cross section of mortar bars showed cracks running through the reacted particles (Figure 3a) and connecting some reacted particles (Figure 3b). Some portions of other cracks in some other locations (which were much wider than those shown here) appeared to be filled with AAR products.

Examination of the fracture surfaces of the broken mortar bar verified the presence of various AAR products as seen in Figures 4 (a, b, c). Figure 4a represents AAR products filling a pore, whereas Figures 4b and 4c show the AAR products on the aggregate particles. The composition of each of the products, represented by the EDX spectra, confirm their alkali-rich nature.

Concrete prisms made with this basalt and containing 7.5 kg Na₂O/m³ showed about 0.03% expansion after 1 year of storage at 40°C, 100% RH. Similar concrete prisms that had first been steam cured at 75°C, and subsequently stored at 50°C, 100% RH expanded significantly, reaching about 0.18% at 1 year. Very little expansion was noted under these curing and storage conditions when the alkali content of the specimens was 5.5 kg Na₂O equiv/m³. The above results indicate that basalt TS could be considered reactive under high alkali contents, particularly in steam-cured concrete.

Reactive basalts such as those mentioned above cause expansion in both the AMBT and the concrete prism tests. However, some basalts have been noted that cause very large mortar bar expansions in the AMBT, but do not cause deleterious expansions in concrete (Ross and Shayan, 1996; Shayan et al. 2003). The Western Australian basalt reported by

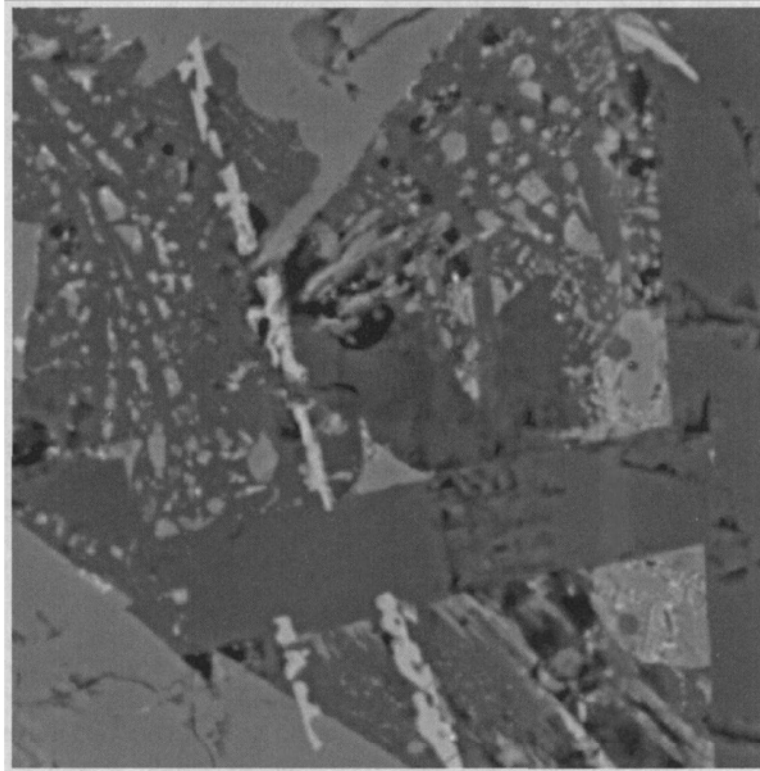


Fig. 1 - Back-scattered electron image of a glassy patch in the polished thin section of basalt (TS). Bright particles are ilmenite and iron oxide particles included in the glass (dark area).

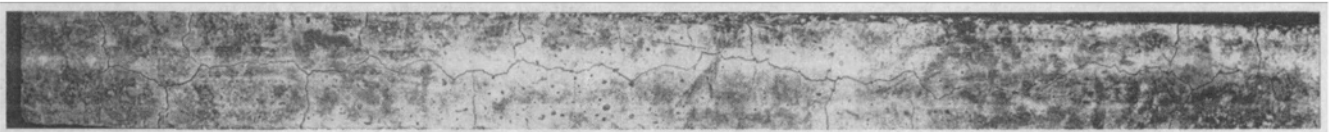


Fig. 2 - View of the mortar bar containing the glassy basalt and subjected to the AMBT conditions of 1M NaOH, 80 C.

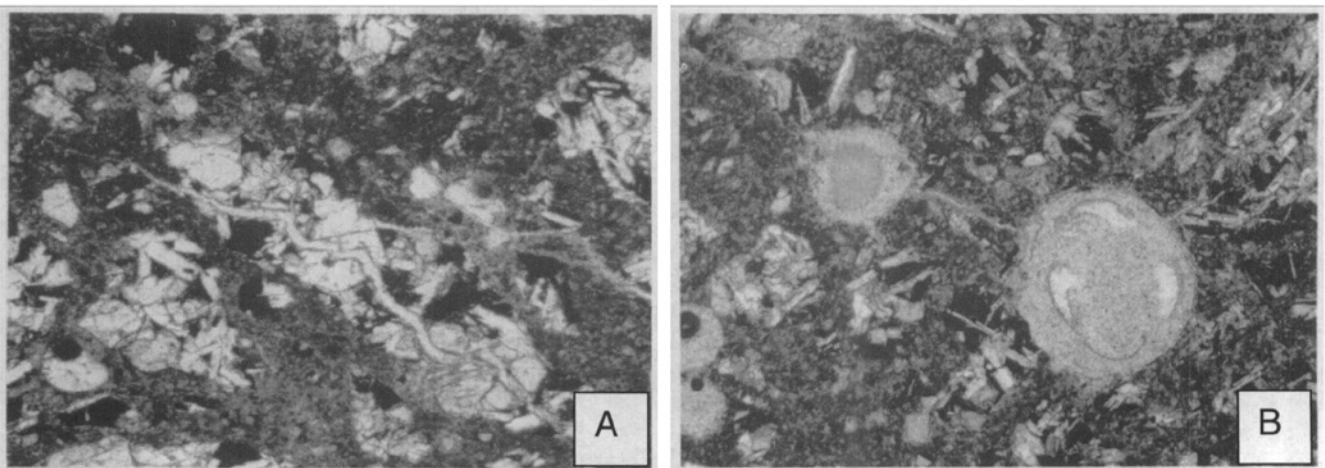


Fig. 3 - Photomicrographs of thin sections of the mortar bars showing (A) AAR-induced cracks running through basalt aggregate particle and extended into the paste, and (B) reacted particles connected by fine micro cracks. Magnification 40X.

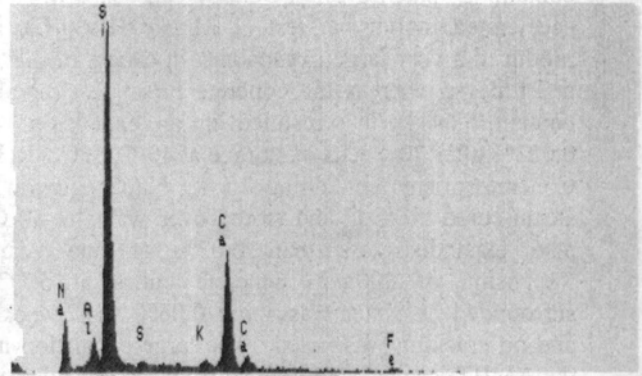


Fig. 4a - AAR product filling a void in the mortar bar subjected to the AMBT

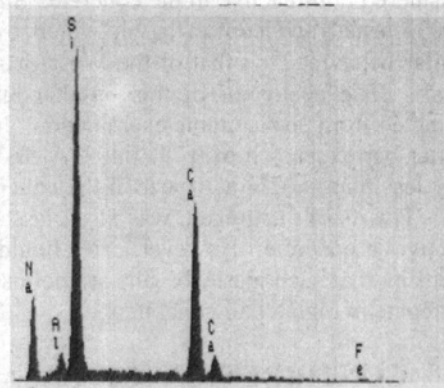
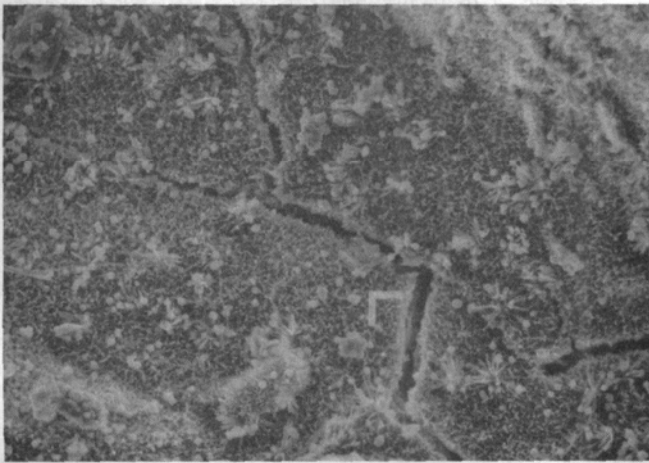


Fig. 4b - A layer of AAR product forming around the reacted basalt particles in the mortar bar

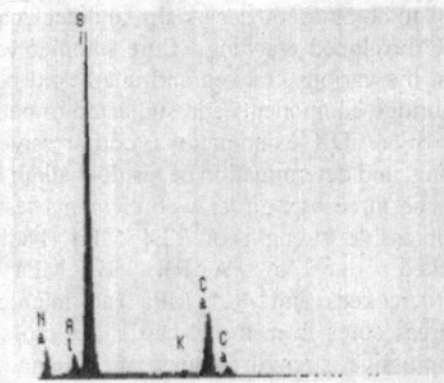


Fig. 4c - AAR rosettes formed on a reacted basalt particle in the mortar bar

Ross and Shayan (1996) was a dense basalt containing patches of a glassy phase. In the accelerated mortar bar test (1 M NaOH, 80°C), it produced a very large expansion, in excess of 0.8% at 21 days, whereas the concrete prism test (alkali content 6.64 kg/m³) resulted in an expansion of 0.023% after 70 weeks of storage at 40°C, 100% RH. Concrete prisms containing 7.5 kg Na₂O equiv/m³, steam-cured at 75°C and stored over water at 50°C also expanded less than 0.02% at one year. Expansion of 300 mm concrete cubes at 50°C, surrounded by water was about 0.06% at 62 weeks and no cracking was noted. The large expansion in the AMBT is suggested to arise from the crushing of the coarse aggregate and exposure of the glassy particles to alkali, and its consequent AAR, whereas in the concrete only a limited amount of the glassy phase was available for reaction with the alkali.

The latter coarse aggregate could, therefore, be considered non-reactive in the concrete. Shayan et al. (2003) tested a Victorian basalt which exhibited a similar behaviour too that of the Western Australian basalt. The behaviour of this basalt could not be predicted from petrographic examination. It caused a mortar bar expansion of 0.7% in the AMBT test and only less than 0.02% at 1 year in the concrete prism test. This basalt aggregate was also classed as non-reactive in concrete. However, care should be taken to ensure that such glassy basalts are not used as fine aggregate in high alkali concrete.

3 CONTRIBUTION OF BASALT TO AAR BY ALKALI RELEASE

In recent years, the author has investigated the cause of cracking of a major bridge structure in New Zealand. One portion of the bridge is free of cracks, whereas in other portions various elements such as webs to box girders, deck slabs, and deck cantilevers, have developed cracking. Core samples were taken from the various cracked and uncracked portions of the bridge components and subjected to petrographic and SEM/EDX examinations, compressive strength testing, and determination of residual alkali content.

The three box girder web elements tested had a compressive strength of 22.4 MPa (badly microcracked due to AAR), 37.7 MPa (mildly microcracked) and 48.1 MPa (no microcracking), whereas cores from a pile cap and a crosshead had compressive strength values of 50 and 54 MPa, respectively, neither showing signs of cracking cores from two columns without microcracking had compressive strengths of 46.5 MPa.

Petrographic examination showed that the box girders and the deck slabs contained a non-reactive basalt as coarse aggregate, whereas the two columns

and one pile tested had rounded river gravel, which was petrographically judged to be reactive. However, the former elements which contained the coarse basalt aggregate had a fine aggregate consisting of reactive chert, tuffaceous and rhyolitic particles, microcrystalline silica, as well as basalt dust. Those that contained the river gravel had a fine aggregate function of the same nature, also judged to be reactive, but no basalt dust. A third group (crosshead and precast I girders and pile cap) contained the coarse basalt aggregate and a non-reactive sand, and did not show cracking.

SEM/EDX examination of concrete samples taken from these elements showed that AAR products were present in those containing the coarse basalt aggregate and basalt dust, due to the reaction of the chert and rhyolitic components of the sand. However, AAR products were absent from the elements that contained the reactive river gravel as coarse and fine aggregate. Hot water extraction and determination of the soluble alkali content of concrete samples taken from the various cores showed that the concrete containing the river gravel and river sand had soluble alkali contents of 2.7 – 3.5 kg Na₂O equiv/m³, whereas those containing coarse basalt and basalt dust, had 6.6 – 9.0 kg Na₂O/m³, largely contributed by the basalt. This alkali was probably derived directly from the basalt aggregate itself (crushed for the extraction purpose), as well as that contributed from the basalt dust to the concrete. SEM and EDX analysis of the pure cement paste regions indicated that a large amount of alkali had been incorporated in it. This was far in excess of the alkali content of the paste in the absence of basalt dust.

It is considered that the enhanced level of alkali, contributed from the basalt, promoted the reactivity of the chert and rhyolitic components of the sand, whereas lack of similar alkali inhibited the reaction in the elements containing the river gravel. It can reasonably be concluded that the basalt dust was indirectly responsible for AAR in the affected elements.

4 CONCLUSIONS

This work has shown that different basalts can behave very differently with respect to alkali reactivity. The following categories are identified.

- Group 1 Basalts that cause insignificant expansion in both the AMBT and the CPT methods. These are considered non-reactive.

- Group 2 Basalts that cause significant deleterious expansion in both the AMBT and CPT. These are considered reactive.
- Group 3 Dense glassy basalts that cause significant AMBT expansion but very little CPT expansion. These are considered non-reactive when used as coarse aggregate, but may cause reaction in sand form.

In addition to the above, basalt dust or fine aggregate may enhance the reactivity of other reactive aggregates by supplying extra alkali to the pore solution of concrete.

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