

SUSCEPTIBILITY OF VARIOUS UK AGGREGATES TO ALKALI-AGGREGATE REACTION.

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A group of lithologically varied UK aggregates have been incorporated into concrete prisms of variable alkali content to ascertain the alkali levels at which significant AAR first occurs. Petrographical analysis has been carried out on these prisms to identify the cause of the expansion and microcracking observed.

INTRODUCTION

The earliest identified cases of AAR affecting UK structures were confined to ones involving sea-dredged flint-bearing sands in S.W England (Fookes et al (1)) and chert-rich gravels from the Trent Valley (Nixon and Gillson (2)). Research with the Thames Valley flint river gravel has indicated this also to be a potentially reactive aggregate in some mixes (Nixon and Bollinghaus (3)). There have been a number of more recent examples in which lithologically varied aggregates from other regions have been implicated. These have included siltstones (West and Sibbick (4)), silicified limestones (Pettifer (5)) and greywackes (Zhang et al (6)). This work reports the results of expansion tests and petrography carried out on concrete prisms containing these lithologically varied aggregates, and compares their performance with those of similar mixes made using aggregates already well established as being susceptible to AAR. A strained granite was also included in the study to answer the unresolved question of whether strained quartz in a UK aggregate represents a potentially reactive constituent (Smith (7)).

Mix design

The concretes investigated were all of constant mix proportions, with water / cement ratio of 0.5, aggregate / cement ratio of 4.6 and cement content of 400 kg/m³. The aggregate consisted of a mixture of 2 parts coarse aggregate (20-5mm) to 1 part fine aggregate, the nature of the coarse aggregate being varied (as indicated in Table 1) and the fine aggregate being composed of an unreactive limestone. The Portland cement was of composition shown in Table 2, with a low alkali content (0.324% Na₂O equivalent). Appropriate additions of NaOH were made to the mix water to produce concretes with various required alkali contents, in the range 3.0 -7.0 kg/m³ Na₂O equivalent.

TABLE 1 - Petrographical Descriptions of the Coarse Aggregates used in Prism Mixes.

1.SILTSTONE, Dark grey chloritic siltstone containing quartz, chlorite, pyrite, muscovite, calcite and clay minerals all cemented together by fine silica. This rock shows a well developed cleavage.

AGE: Silurian.

LOCATION: North Yorkshire.

2.SILICIFIED LIMESTONE, Light grey highly silicified limestone. The majority of the quartz is found as discrete cryptocrystalline masses within the matrix. This chert material makes up 25% of the total rock.

AGE: Lower Carboniferous. LOCATION: Lancashire.

3.GREYWACKE, Light grey-green quartzo-feldspathic greywacke composed of rounded quartz, feldspars, clasts of volcanic rocks and quartzites. These particles are supported in a phyllosilicate matrix.

AGE: Lower Cambrian.

LOCATION: Gwynedd

4.STRAINED GRANITE, Igneous granitic rock now heavily altered by high grade metamorphism to schist. The rock is composed mainly of crystalline quartz, plagioclase, orthoclase, muscovite, and opaque minerals. The quartz is heavily strained exhibiting strong undulatory extinction.

AGE: Pre Cambrian.

LOCATION: Anglesey, North Wales.

5.TRENT VALLEY GRAVEL, Polymictic well rounded river gravel composed mainly of chert, quartzites, and vein quartz, but also containing other rock types.

AGE: Quaternary.

LOCATION: Derbyshire.

6.THAMES VALLEY GRAVEL, A well rounded river gravel made up almost entirely of Cretaceous flints / chert, but also containing smaller amounts of vein quartz and quartzites.

AGE: Quaternary.

LOCATION: Berkshire.

7.INERT LIMESTONE, An almost pure calcium carbonate fossiliferous limestone. The silica content amounts to less than 0.1% of the rock.

AGE: Lower Carboniferous. LOCATION: Somerset.

With the Thames Valley flint gravel mix only 50% of the coarse aggregate was Thames Valley gravel the rest being inert limestone. This resulted in a mix of near-pessimum proportion.

TABLE 2 - Chemical Analysis of Portland Cement.

CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	SO ₃	MgO	Na ₂ O	K ₂ O	Ignition Loss
66.0	22.6	4.87	0.31	3.16	0.27	0.14	0.2	1.55

Experimental method

The prisms, which were of dimensions 75x75x250 mm, were made in accordance with the relevant specification, (British Standards Institution (8)) and cured in moist air for 7 days. Gauge markers were affixed to the prisms and they were wrapped in absorbent towelling

soaked with 200 ml of distilled water. They were then sealed within three polyethylene bags to prevent moisture loss and stored at $38 \pm 2^\circ\text{C}$ in a thermostatically controlled room. At monthly intervals, they were removed from this environment and allowed to cool to normal laboratory temperature ($20 \pm 3^\circ\text{C}$) for 24 hours before being measured. The strains recorded over a period of up to 12 months are shown in Figures 1-5.

RESULTS

In Figure 1 the behaviour of the various aggregates in mixes of constant high alkali level (7 kg/m^3 Na_2O equivalent) are compared. It is apparent that the Thames and Trent Valley gravels, which have often been considered amongst the more reactive land-based UK aggregates, (French (9)) suffer relatively modest expansions in comparison with those recorded for other less well-documented aggregates studied here. These lithologically varied aggregates are therefore apparently more susceptible to AAR than the chert-rich gravels.

It is apparent from the Figures shown that all of the coarse aggregates studied with the exception of the control material, inert limestone, gave rise to expansion of the concrete prisms to an extent which depended on the alkali contents of the mixes. The most interesting results are those for the strained granite (Figure 5). This rock has never previously been examined for its AAR potential. Clearly it is affected quite severely by an expansive reaction the cause of which is discussed later in the petrographical analysis. The lowest alkali levels (expressed in terms of Na_2O equivalent) at which appreciable expansion and visible surface micro-cracking were detected were as follows, with the corresponding minimum alkali levels required to produce expansions in excess of 0.05% within six months shown in brackets :

Siltstone	- 3.5 kg/m^3	(4.5 kg/m^3)
Silicified Limestone	- 3.5 kg/m^3	(4.0 kg/m^3)
Greywacke	- 4.5 kg/m^3	(6.0 kg/m^3)
Strained Granite	- 4.5 kg/m^3	(6.0 kg/m^3)
Thames Valley Gravel	- 6.0 kg/m^3	(Not detected)
Trent Valley Gravel	- 7.0 kg/m^3	(Not detected)

Note: An expansion greater than 0.05% within six months storage at 38°C has previously been proposed as a criterion signifying AAR in concrete prisms (Concrete Society (10)).

The main conclusion of these various tests is that AAR may be induced in concretes made from certain British aggregates at alkali contents as low as 3.5 - 4.0 kg/m^3 , expressed in terms of Na_2O equivalent. In view of this, the present recommendations for minimising the risk of AAR in the UK (Concrete Society (10)), which call for a limit of 3.0 kg/m^3 Na_2O equivalent on alkali derived from concrete mix materials, do not seem unduly conservative.

PETROGRAPHICAL ANALYSIS

Mixes containing four of the aggregate types shown above have been examined petrographically to ascertain the source and cause of the AAR identified from the expansion test data.

Siltstone

Petrographical analysis of specimens containing siltstone coarse aggregate, which had suffered expansion, exhibited microcracking to an extent that increased with the increasing

alkali content of the concrete. The microcrack networks were expansive in form, but also showed a preference to follow the inherent cleavage of the rock in a stepped form and to run along the long axis of the aggregate particles, a feature common amongst many reactive greywackes. By tracing the networks back to their origin, the centres of expansion were located within the siltstone. Alkali-silica gel was found extensively throughout the concrete, as plug like deposits at the aggregate/cement paste interface, within voids, and as side deposits on many of the microcracks in the cement paste. Alkali-silica gel was also found within the siltstone aggregate but was quite rare in this location. The source of reactivity appeared to be microcrystalline quartz spread throughout the rock matrix and as bands running sub-parallel to the rock's inherent cleavage. The concrete satisfies all the petrographical criteria to confirm that the major cause of expansion was ASR. No ettringite was detected in any of the sections examined.

Silicified Limestone

Specimens containing silicified limestone aggregate tended to contain more large microcracks (>100 microns wide) than the siltstone concrete and a lot more of the overall microcrack network involved peripheral cracks running on the edges of the coarse limestone particles. The microcracking network, though unusual, was still of an expansive form and tended to run along the long axis of the aggregate particles. The centres of this expansion were traced back to the coarse silicified limestone aggregate. Where areas of the limestone were richer in chert, the microcracking appeared more severe. The darker bituminous-rich particles were seen to be more heavily cracked and to be associated with greater amounts of alkali-silica gel than lighter material. The gel was either light brown to orange in colour or colourless and contained clearly visible banding. Voids and microcracks in the cement matrix were localities where deposits of alkali-silica gel tended to accumulate, but gel was also found in large amounts in specific coarse aggregate particles. The most likely source of the ASR in this concrete would be the chert found widely throughout the rock as infills and inclusions. This chert was often so finely disseminated in the matrix calcite that observation microscopically was very difficult. No ettringite was identified in these concretes.

Greywacke

The greywacke aggregate concretes expanded less severely than those already discussed (Figure 4) and petrographical analysis confirmed that the amount of visible microcracking was noticeably reduced. Tracing the microcracks back to their source revealed the overall network to be expansive in nature with the centres of expansion within the coarse greywacke aggregate. Close examination showed that the microcracks progressively reduced in size and split up as they entered the greywacke particles. The microcracks eventually became indistinct from the linear features of the matrix minerals. These microcracks did not generally split the clastic materials in the greywacke but passed around them. Though ASR gel was observed, it was relatively rare in comparison to that seen in the previous concretes examined. The most common location for the gel was in voids. Here it took a number of unusual layered and spherical forms. It was also found as plug-like deposits at the aggregate/cement paste interface. These petrographical observations are consistent with the view that ASR contributes to the expansion caused by greywacke aggregates, but further work is needed to assess the possible role of an alkali-silicate reaction mechanism (Gillot et al. (11)) for the particular aggregate studied in the present work. Recent studies conducted elsewhere (Blackwell (12)) have suggested that ASR, rather than alkali-silicate reaction, is likely to be the predominant cause of expansion.

Strained Granite

The strained granite (Figure 5) showed a form of microcracking similar to that seen in the greywacke mixes. The rock has been so heavily metamorphosed that it should really be classified as a schist. The concrete contained networks of expansive microcracks centred on the strained granite coarse aggregate particles and originating from microcrystalline areas of quartz in the rock matrix. This material is all that now remains of heavily shattered larger quartz

crystals that had undergone extreme strain and therefore contained a high density of dislocations. The microcracking was also frequently seen associated with secondary recrystallised quartz in some fractures in the rock. Cracks did not usually run through the larger quartz crystals even when they were clearly very heavily strained. It was also apparent that the microcracks had a preference to run along bands of chlorite and muscovite found in veins or fractures in the rock, parallel to these minerals' cleavage direction. Alkali silica gel was clearly identified in all the samples examined. Gel was most commonly found in voids in the cement paste, but was also seen in microcracks in both aggregate and cement paste. The gel was colourless or brown and on occasions, appeared to have occurred in two separate pulse 'generations'. Clearly all petrographical criteria have been met to indicate that the strained granite had undergone a form of AAR and the most likely source for this reaction was the microcrystalline quartz found throughout the rock. No evidence was found of the larger strained quartz crystals being reactive.

CONCLUSIONS

From this work it can be concluded that all the aggregates petrographically analysed have been primarily affected to varying degrees by AAR. The source constituents of the AAR in these different aggregate types were: microcrystalline quartz in the siltstone matrix, chert inclusions in the silicified limestone, and microcrystalline quartz areas in the strained granite. The most likely source of reaction in the greywacke was also considered to be the micro to cryptocrystalline quartz found in its matrix. This would imply that all these varied aggregates have been primarily affected by alkali silica reaction derived from similar reactive constituents.

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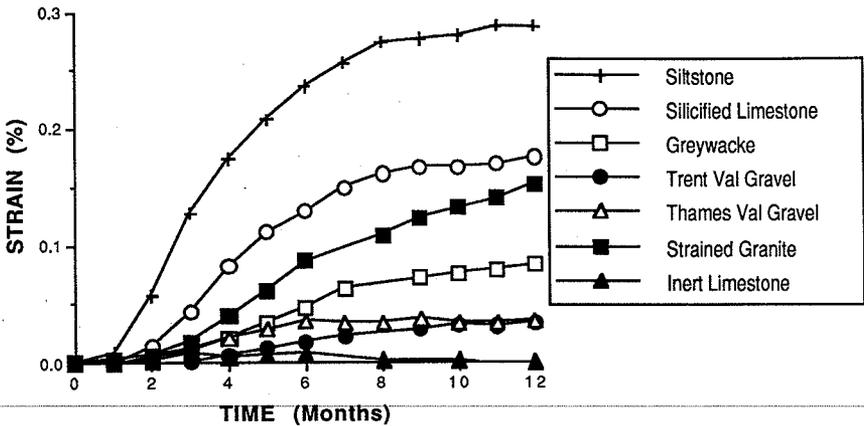


Figure 1 Expansion of concrete with various aggregates at alkali content of $7 \text{ kg/m}^3 \text{ Na}_2\text{O}$

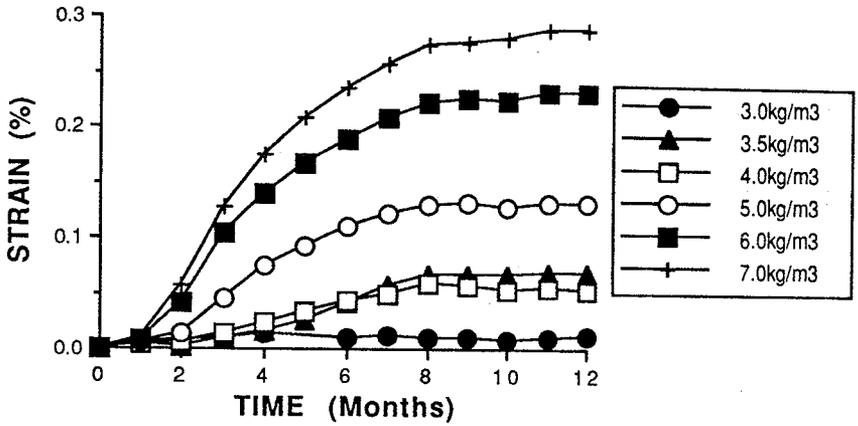


Figure 2 Expansion of siltstone aggregate concretes.

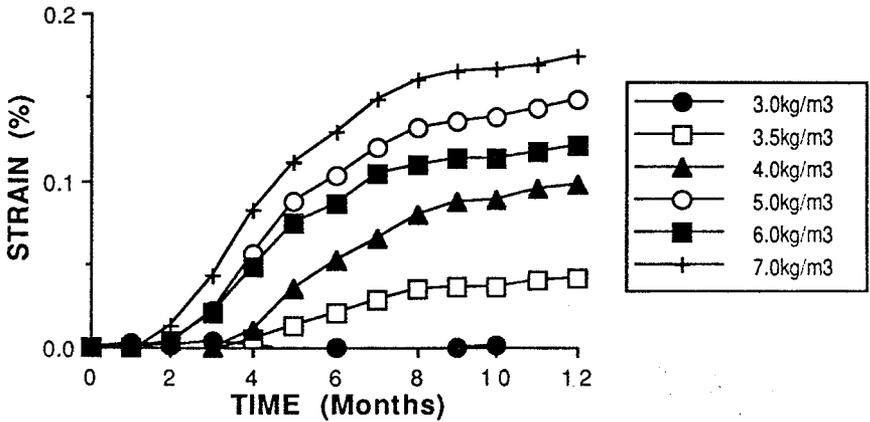


Figure 3 Expansion of silicified limestone aggregate concretes.

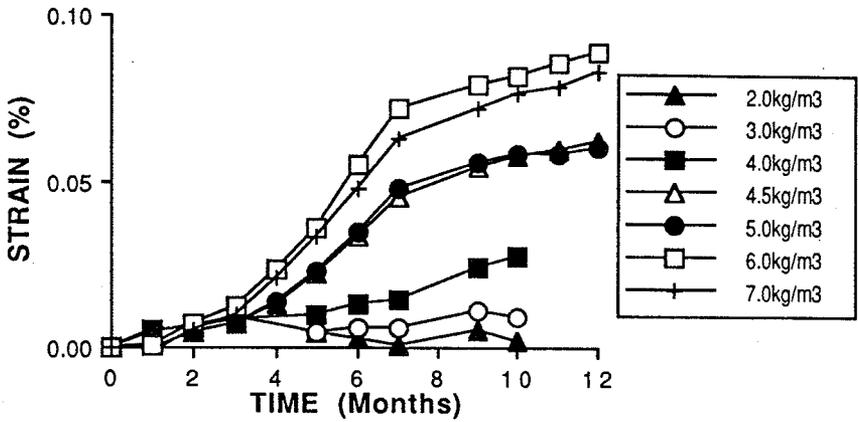


Figure 4 Expansion of greywacke aggregate concretes.

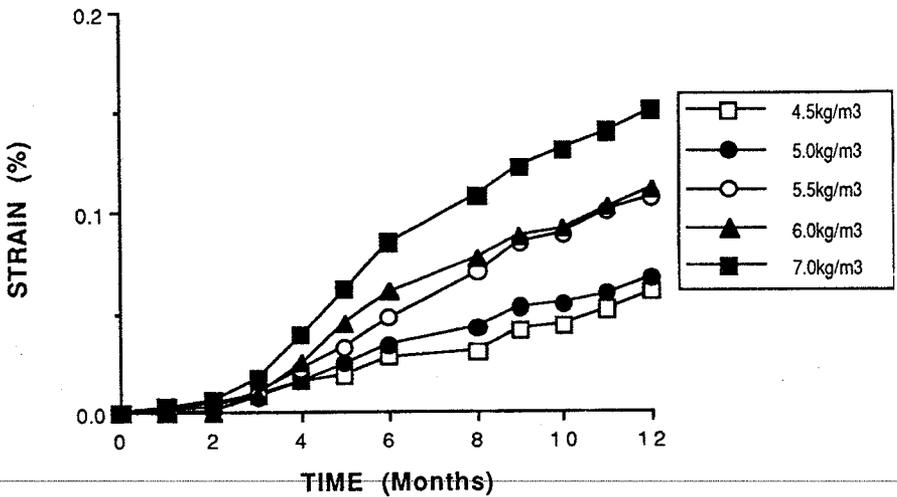


Figure 5 Expansion of strained granite aggregate concretes.