

THE EVALUATION OF GREYWACKE, HORNFELS
AND GRANITE AGGREGATES FOR POTENTIAL ALKALI REACTIVITY

BY

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ABSTRACT.

Widespread deterioration of concrete structures occurs in the Cape Peninsula area of South Africa. This is attributed to an expansive cement-aggregate reaction similar to that encountered in Nova Scotia, Canada.

The difficulties encountered in evaluating the available aggregates such as greywacke, hornfels and granite, in accordance with ASTM Standards and other criteria, are briefly mentioned.

Concrete prisms stored at 38 °C and 100 per cent relative humidity showed that the Malmesbury aggregate, consisting mainly of greywacke and hornfels, is potentially alkali reactive. Mortar prisms, although giving lower expansion values for the Malmesbury aggregate than the minimum limits suggested in ASTM C 227, gave values very close to those of the concrete prisms.

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Introduction

The occurrence of cement-aggregate reaction in South Africa was first mentioned in 1974 (1). At the 1976 Symposium on alkali reactions in concrete held in London, the report on the reactive concrete aggregate from South Africa described the appearance of several concrete structures that showed deterioration due to expansive reactions (2). The appearance of specimens of the concrete, when examined visually and microscopically, was similar to that of concrete from other parts of the world where alkali-aggregate reaction was given as the cause of the deterioration of the affected concrete structures. Subsequent reports (3, 4, 5) on the problem of the deterioration of concrete structures in the Cape Peninsula, South Africa, concluded, from field investigations and laboratory experiments, that the deterioration is caused by expansive alkali-aggregate reaction similar to that encountered in Nova Scotia, Canada and described by Duncan (6).

As a result of the reports on the deterioration of concrete in the western Cape, the NBRI was approached by the Electricity Supply Commission (ESCOM) to advise them on the selection of materials for the manufacture of concrete for the Koeberg nuclear power station, which involves 400 000 m³ of concrete. This paper is based on the results of earlier NBRI experiments and on preliminary results obtained from the investigation being carried out under contract to ESCOM in accordance with ANSI N45.2 - Quality

Field survey

It has been stated by Mather (7) that none of the laboratory methods can be relied on, independently or collectively, to provide an unquestionably positive indication of potentially harmful reactivity. Consequently service record data are of critical importance and, when service records establish that deleterious reactions have occurred in a structure in which the aggregate has been used, a fine or coarse aggregate will be evaluated as potentially deleteriously reactive.

A survey (8) was undertaken of a large number of concrete structures, with a view to establishing whether a common factor is present in the structures that show the kind of deterioration generally associated with alkali-aggregate reaction. The survey took the form of a superficial inspection of the majority of structures and a detailed examination of some. The relevant details were recorded on a standard form. Where practicable, cores were taken from as many as possible of the structures that were examined in detail.

The results of the survey revealed that more than 40 per cent of the bridges examined in the Cape Peninsula and immediate environs show the type of cracking associated with alkali-aggregate reaction. Other structures, such as a dam wall, a concrete road, conductor mast foundations,

bollards and some concrete framed buildings, also display this particular type of cracking. Cracking of affected structures has usually been observed after 4 to 5 years. Furthermore, it appears as if the incidence of cracking in structures built during the last 10 years is higher than in older structures.

Structures that are relatively free to expand in all directions show typical pattern cracking of variable size, with crack widths varying from hairline to 3 to 4 mm and extending to depths of 300 mm and more. However, conditions of restraint or loading influence the cracking pattern; for instance, cracks in columns tend to run vertically while cracks in retaining walls, which are not as free to expand laterally as vertically, tend to run horizontally. Horizontal offsetting of decks and parapet walls of bridges, and closing of movement joints due to expansion have been observed.

Exposure conditions are an important factor influencing cracking of the concrete. Surfaces exposed to wetting and drying have generally been found to be more severely cracked than adjacent surfaces sheltered by overhangs or bridge decks, where cracking is either less or non-existent. Also, elements backed by wet earth, such as retaining walls, are often cracked, while parts of structures, such as transom beams over which water can flow from joints above, are often cracked in the wetted areas. The cracking pattern is not consistent in all structures. In some cases

the superstructure is cracked while the retaining walls and abutments are sound, and in others the cracking is confined to the retaining walls or abutments or to a small area of an exposed element. In the concrete road pavement the cracks occur mainly near the slab edges or where joints have been cut in the slab.

Wet-looking, greyish, surface staining at cracks has sometimes been noticed, while exudation of salts through cracks has been observed but is not very common. The use of epoxy resin or poly-sulphide to seal cracks and coat surfaces has generally not been successful and, in some cases, the coating has aggravated the concentration of salts behind the coating.

All the structures showing cracking associated with alkali-aggregate reaction contain coarse aggregate from the Malmesbury Group, i.e. mainly greywacke and hornfels, but phyllite, argillite and quartzite are also encountered. With the exception of one structure, none of those containing granite aggregate displays alkali-aggregate cracking. In the case of the one structure, it has not been established unequivocally that cracking is due to alkali-aggregate reaction.

It has not been possible to establish the source of the cement that was used in the different structures. This is unfortunate, since two of the three factories manufacturing cement in the western Cape produce high alkali cement.

All three of the cements are distributed by a central marketing organization under a single brand name and, in addition, clinker is sometimes sent from one factory to another.

Examination of cores

Cores taken from cracked structures and examined in the laboratory displayed features commonly associated with alkali-aggregate reaction, such as: a reaction rim around the periphery of the aggregate; aggregate fracture surfaces covered with white reaction product; voids filled with reaction product which is white and porcellaneous in the interior and mostly white and translucent on the exterior; cracks in the aggregate, often partially filled with reaction product or stained dark by viscous gel and cracks in the aggregate continuing into the mortar and, mostly, filled with white reaction product. In general, the features observed bear a striking resemblance to those described previously by Brown (9) for a variety of concretes showing distress.

Petrographic examination of aggregate

Aggregates submitted by ESCOM were examined petrographically, in accordance with the basic guidelines given in ASTM Designations C 294 and C 295 (10, 11), for a quick provisional evaluation.

Since it was suspected from the service record of concrete

of aggregate is potentially alkali reactive, alternate aggregates had to be found for the concrete of the Koeberg nuclear power station and these alternate aggregates had to be evaluated against the existing sources of Malmesbury aggregate. The only alternate sources of freely available aggregate were granite and granite gneiss.

The petrographic identification of reactive aggregates, other than those involved in the classical alkali-aggregate reaction, is fraught with difficulties and uncertainties. In the case of the aggregate from the Malmesbury Group, i.e. greywacke, hornfels, argillite, phyllite, quartzite, and the granite and granite gneiss, attention was given mainly to features associated with the progressive deformation of quartz, as described by Young (12) and summarized by Dolar Mantuani (13). The potential reactivity of the granite rocks was assessed on the basis of the strain effects in quartz. This feature was found by Gogte (14) to be related to the expansion of mortar prisms containing these rocks as aggregate.

The greywackes and quartzites of the Malmesbury Group have been subjected to low grade thermal metamorphism and are generally hard, well indurated and have a low porosity. Sand-size quartz and feldspar grains, rock fragments and occasional detrital muscovite grains are found in a brownish, semi-opaque groundmass composed mainly of vermiculite, chlorite, quartz, feldspar and a little

sericite. The groundmass can form up to 50 per cent of the total rock and, to some extent, is intergrown with larger sand grains. The quartz grains, which form approximately 75 per cent of the sand-size fraction, usually show undulatory extinction, have sutured margins and, occasionally, triple points. The margins of the grains are indistinct and usually appear to be intergrowing or reacting with the matrix (see Figure 1). Some of the feldspar grains show extensive alteration and distortion of twinning planes.

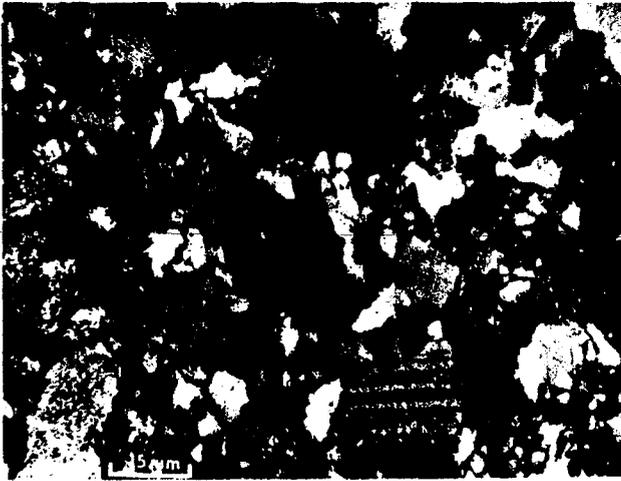


Figure 1. Metagreywacke showing strained quartz grains and reaction with matrix.

The phyllites and hornfels of the Malmesbury Group are extremely fine-grained with the result that strain effects

in the quartz grains can only be observed with difficulty. However, grain mounts in refractive index oil often show polycrystalline quartz grains. The rocks contain quartz, feldspar, vermiculite, illite and sericite and often contain "spots" of biotite and cordierite. All these rocks contain K-vermiculite which is relatively easily converted to Ca-vermiculite by ion exchange.

Macroscopic and microscopic veins, filled mainly with quartz but also with illite, sericite and calcite, are common. Many of the quartz veins contain forms of silica that are known to be alkali reactive, such as strained quartz and chert.

The essential features of three of the granitic aggregates evaluated are briefly as follows (15).

Aggregate Rh is a pale grey fine-grained granite, fresh and unweathered. Approximately one third of the feldspar grains are sericitised. Quartz is present in irregularly shaped grains with wavy contacts. As a whole there are no signs of strain.

Aggregate Ro is a medium-grained granite gneiss, slightly weathered, and veins of quartz and muscovite are encountered. The quartz consists of, mostly small, recrystallized polygonal grains; there are some triple point contacts, and slight straining occurs, amounting to approximately 20 per cent of the total rock.

Aggregate K is a medium-grained granite gneiss grading to a biotite schist. The quartz has an annealed appearance and mosaic-like texture; the contacts are commonly sutured. The quartz content can be as high as 55 per cent and evidence of strain is found throughout. The feldspars show signs of deformation in disrupted twinning, are strongly sericitised and altered and show evidence of reaction with micaceous bands along the margins and fractures where they are breaking down. Figure 2 shows a thin section of the aggregate.

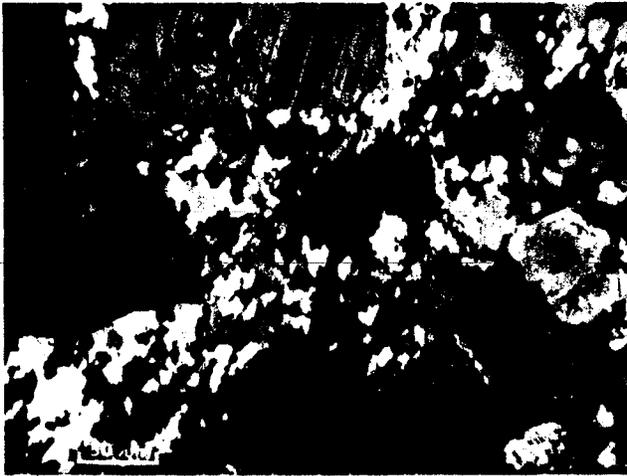


Figure 2. Thin section of Kanonkop aggregate showing strained and recrystallised quartz. Crossed nicols.

Concrete prism and mortar prism tests for potential reactivity

Initial test runs on concrete prisms made with hornfels, collected from a quarry producing aggregate from the Malmesbury Group and stored at 38 °C and 100 per cent relative humidity, showed slow but progressive expansion with high alkali cements.

The results are presented graphically in Figure 3.

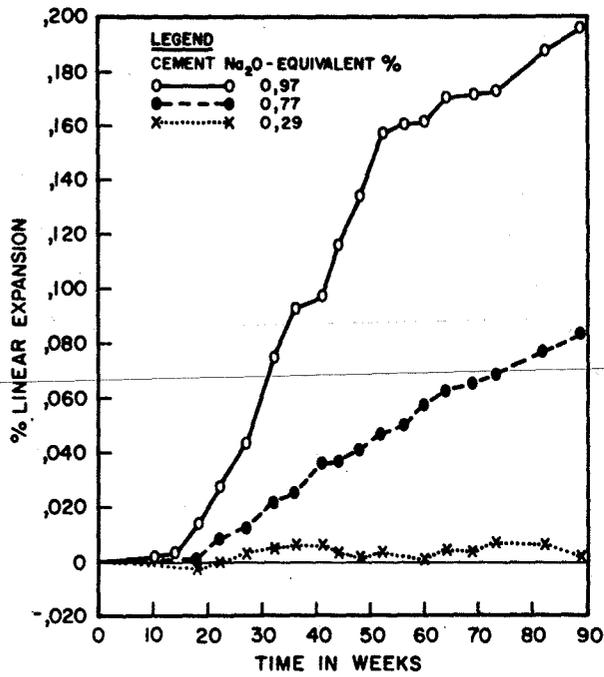


Figure 3. Linear expansion of concrete prisms containing Malmesbury hornfels E4 as coarse aggregate and stored at 38 °C and 100 per cent relative humidity.

For the evaluation of the potential reactivity of aggregates for the Koeberg nuclear power station, mortar prisms, as well as concrete prisms, were made. The mortar prisms were made and stored as described in ASTM C 227-71 (16). The concrete prisms, measuring 75 mm x 75 mm x 300 mm, had the same mix ratio as the concrete proposed for the power station, viz.,

coarse aggregate : fine aggregate : cement : water ::
3.38 : 1.87 : 1.00 : 0.50

The concrete prisms were stored in sealed containers at 100 per cent relative humidity and kept at two temperature levels, namely, 38 °C and 55 °C.

The test programme was based on a factorial design in which five coarse aggregates, three fine aggregates and four cements were used. Norite was used as control coarse aggregate and a portland cement, with a Na₂O-equivalent of 0.40 per cent, as reference cement. The high alkali cement had a Na₂O-equivalent of 0.79 per cent. Mortar prisms made with Duran 50 glass and each of the four cements were also included in the test programme. Some of the more important results obtained after 50 weeks of storage are presented in Figures 4(a) to 4(f).

ASTM C 227 specifies that expansion in excess of 0,05 per cent at three months, or 0.1 per cent at six months, should be considered deleterious. Duncan et al (7) suggested that, inter alia, the following length-change criteria be used:

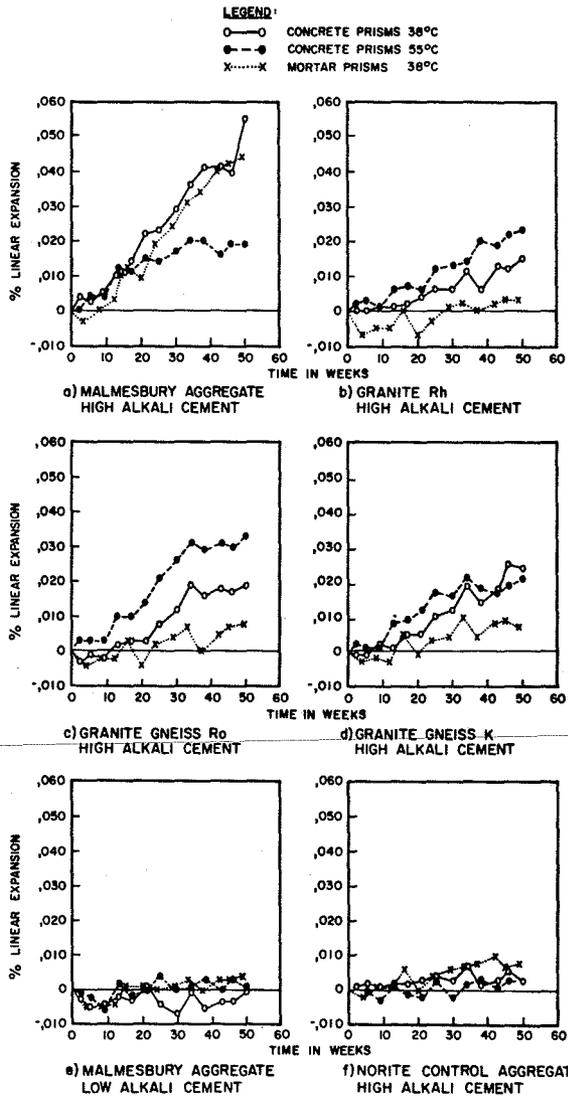


Figure 4. Linear expansion of mortar and concrete prisms stored in sealed containers.

(i) 0,88% Na₂O-equivalent, 38 °C : 0,04 per cent at 72 weeks and 0,05 per cent at 144 weeks for mortar prisms.

(ii) 0,71% Na₂O-equivalent, 38 °C : 0,05 per cent at 120 weeks for concrete prisms.

The Bureau of Reclamation (18) recommends that, for concrete prisms stored in sealed containers at 55 °C, failure be established at 0.07 per cent expansion within 120 days (17 weeks).

From Figures 4(a) to 4(f) the following can be concluded:

(i) According to ASTM C 227, none of the aggregates is deleteriously alkali reactive.

(ii) According to the Bureau of Reclamation criterion for length change of concrete prisms stored at 55 °C, none of the aggregates is deleteriously alkali reactive.

(iii) According to the criteria of Duncan et al, the Malmesbury aggregate is deleteriously alkali reactive when judged according both to the concrete prisms and the mortar prisms stored at 38 °C, even though the test has only been in progress for 50 weeks. None of the granite aggregate prisms has reached the maximum limit specified by Duncan et al. However, these limits may be reached after the

specified length of time.

- (iv) For the Malmesbury aggregate, the expansion of concrete and mortar prisms stored at 38 °C is more than twice as high as that of concrete prisms stored at 55 °C. The amount of expansion of mortar prisms is very close to that of concrete prisms stored at the same temperature, viz. 38 °C.
- (v) For the two granitic aggregates, Rh and Ro, the amount of expansion for concrete prisms stored at 55 °C is higher than that of concrete prisms stored at 38 °C. For all three of the granitic aggregates there is practically no expansion of the mortar prisms.
- (vi) Concrete and mortar prisms made with Malmesbury aggregate and low alkali cement and stored at 38 °C and also at 55 °C for the concrete prisms, show no expansion. The same applies to prisms made with norite aggregate and high alkali cement.
- (vii) Compared with the norite control aggregate, concrete prisms made with granitic aggregate and high alkali cement display an expansive trend.

The results for mortar prisms made with Duran 50 glass, are given in Table 1.

Table 1 Linear expansion of mortar prisms made with Duran 50 glass in accordance with ASTM C 227-71

STORAGE TEMP °C	ALKALI CONTENT OF CEMENT			LINEAR EXPANSION, %, AFTER				
	Na ₂ O %	K ₂ O %	Na ₂ O-eq* %	7 days	4 weeks	8 weeks	24 weeks	50 weeks
38	0,26	0,22	0,40	0	0,010	0,027	0,050	0,061
	0,21	0,88	0,79	0,011	0,021	0,027	0,030	0,033
55	0,26	0,22	0,40	0,002	0,009	0,016	0,015	0,017
	0,21	0,88	0,79	0,012	0,010	0,014	0,010	0,007

*Na₂O equivalent

It can be seen that mortar prisms, made with the cement which is regarded as a high alkali cement in terms of ASTM Specification C 150 (19), do not give the amount of expansion mentioned in ASTM C 441 (20), and furthermore that, in the long-term, the mortar prisms made with low alkali cement attain a higher expansion. In fact, after 50 weeks, the expansion obtained for mortar prisms made with Malmesbury aggregate and the high alkali cement was 0,044 per cent which is higher than the value of 0,033 per cent obtained for mortar prisms made with Duran glass and high alkali cement, but less than the expansion of 0,061 per cent obtained for mortar prisms made with Duran glass and the low alkali cement.

At 55 °C the expansion of the Duran glass mortar prisms was substantially reduced.

Discussion

From the results of the field survey and by comparing the petrography of the Malmesbury Group rocks and the results of the tests for mortar prisms and concrete prisms made with Malmesbury aggregate, with the results obtained by Duncan (6) for Nova Scotian aggregates, a decision could be taken to reject the aggregate on account of its alkali reactivity.

On the grounds of the service records of the granites in general it has been concluded that they are more acceptable than the Malmesbury aggregates. However, since it has not been possible to establish where low alkali cement and where high alkali cement has been used in particular structures, this conclusion has yet to be confirmed. On the strength of the petrographic examination, granite gneiss K was rejected; granite gneiss Ro was accepted with some reservations and granite Rh was regarded as suitable.

Compared with the reference specimens, however, concrete prisms made with the granitic aggregates, showed an expansive trend with the high alkali cement for all three of the aggregates. On account of this expansive trend and taking into account that, with a Na_2O -equivalent of 0,79 per cent, the cement can be regarded as a medium alkali cement, none of the three granitic aggregates can be accepted unconditionally after 50 weeks testing. It is therefore recommended that the granitic aggregates be used with a low alkali cement, until such time as more conclusive results can be obtained.

The investigation confirms the dilemma of research workers in general to arrive at a quick decision about the potential alkali reactivity of an aggregate. For mortar prisms made with the type of aggregate investigated the limits of ASTM C 227 do not apply. Judging the results of concrete prisms according to the criteria of Duncan et al (17) can be fairly complex because of the variables involved, viz. alkali content, temperature and time.

From the investigation it is concluded that judging mortar prisms in accordance with ASTM C 227 is subject to interpretation. As mentioned above, the specified limits do not apply to the type of aggregate examined, i.e. greywacke and hornfels. It is stated in ASTM C 33-74a that for the test the alkali content of the cement should be substantially above 0,6 per cent and preferably above 0,8 per cent, expressed as Na_2O (21). However, it would seem that not only should the alkali content of the cement be given but also the reactivity of the cement with a reference aggregate. Therefore, to limit the subjectiveness of a test such as ASTM C 227, a standard cement should be specified and should be available. A reference aggregate that is also freely available, and against which the reactivity of a cement can be evaluated, should also be prescribed. The reference aggregate should preferably not be Pyrex glass, since it is doubtful whether there is a correlation between the reactivity of a cement with Pyrex glass and its reactivity with reactive natural aggregates.

Conclusion

There is urgent need for a quick and reliable method for evaluating the potential alkali reactivity of an aggregate. To increase the objectiveness of such a method it may be necessary to have a standard reference aggregate and a standard reference cement available, though it is realised that, even then, the problem is still fairly complex because of the pessimum concept.

Acknowledgment

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