

REPORT ON REACTIVE CONCRETE AGGREGATE
FROM THE CAPE PENINSULA, SOUTH AFRICA

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ABSTRACT

Several concrete structures in the Cape Peninsula show serious cracking and deterioration due to dimensional change. The common factor in all the structures has been found to be the coarse aggregate, commonly known as Malmesbury shale or Malmesbury hornstone. The deterioration apparently occurs both where low-alkali and high-alkali cements have been used. X-ray data were obtained for the reaction product in the concrete but attempts to index it were unsuccessful. The main reaction product produced in the laboratory by adding saturated lime water to Malmesbury shale could, however, be indexed and was found to agree closely with calcium silico-aluminate (7).

Introduction

In South Africa the existence of a serious and widespread problem arising from the excessive shrinkage of concretes and mortars containing certain Karroo aggregates was first demonstrated by Stutterheim (1) in 1954. He concluded that the general cracking pattern observed in reinforced concrete structures could only be explained on the basis of excessive shrinkage and expansion of the concretes. Although it was at this stage known that alkali-aggregate reaction could cause expansion, it was concluded from both field and laboratory evidence that expansion was not the cause of deterioration. Detailed investigations subsequently carried out by Roper (2) led to the conclusion that problems encountered with the dimensionally unstable Karroo aggregates were due to shrinkage.

In 1971, during an investigation of aggregate generally known as Malmesbury shale or Malmesbury hornstone intended for use in concrete for a proposed civic centre in Cape Town, the NBRI expressed concern about the possibility of this type of aggregate being dimensionally unstable in the presence of calcium, magnesium and sodium ions. The investigation revealed that the aggregate contained illite and that the potassium of the illite could be quite easily replaced by magnesium, calcium and sodium, resulting in a vermiculite type of mineral.

Oberholster and Brandt (3) in 1974 examined concrete from a structure in Cape Town that showed serious cracking and found signs of cement-aggregate reaction which resembled alkali-aggregate reaction. Malmesbury shale was used as the coarse aggregate.

Incidence of Problem

Following on the above finding of cement-aggregate reaction in a concrete structure which showed distress, the NBRI was informed of several other structures which displayed similar signs of deterioration. These structures were visited and examined.

No attempt was made to conduct a systematic survey to determine the number of structures showing the same type of cracking. Eleven bridges and one dam, which showed the same pattern of cracking, were examined. In addition, a concrete road was also beginning to show signs of deterioration that could be associated with cement-aggregate reaction.

The following is a brief description of some of the structures that were inspected and of the concrete of which samples are being investigated in the laboratory.

The Steenbras Dam

The original Steenbras Dam (4) was a gravity concrete structure consisting of a curved portion and two straight flanks, in which precast concrete blocks were used as forms. The extreme length of the wall was 428 m and the length of the spillway 67 m. It was completed in 1921.

During the early 1950s it was decided to strengthen the existing dam and raise it by 1,8 m. In essence the process was one of placing vertical cables through the wall of the existing dam from the crest into the foundation and stressing the cables to produce stabilizing compressive forces on the upstream face. Construction of the raised portion was completed in 1954.

Table Mountain sandstone was used as coarse aggregate for the original dam while Malmesbury shale coarse aggregate was used for the 457 mm-thick raised section.

Recent inspection has revealed deterioration of the components associated with the heightening of the wall. The raised portion of the wall is leaning forward by an amount varying from 16 mm in 1 m to 42 mm in 1 m (5). Cracks, similar to those shown in Figure 1, were seen in the southern wall and other tie heads. The 100 mm-thick reinforced walkway slabs are under considerable compression; it is not clear whether this is due to dimensional change of the walkways or to dimensional change of the tie heads on which they rest.



FIG. 1

Cracking in right flank terminal
tie head, Steenbras Dam

Pirow Street Bridge

Construction of the Pirow Street Bridge took place between February and July 1961. The piers, transoms, longitudinal beams and deck were all cast in situ. The coarse aggregate used was Malmesbury shale, the fine aggregate Cape Flats sand and the cement was one with a low alkali content, i.e. less than 0,60 per cent alkali calculated as Na_2O . Cracking of the transom beams became noticeable in 1965 and the bridge deteriorated to such an extent that remedial action had to be taken only nine years after its completion. Figure 2 shows the cracks in the end of a transom beam. It is important to note that the stringer (longitudinal) beams of two adjacent spans rest on the transom beam and that water from the deck finds its way down between the joints of the deck and the stringers and collects on the surface of the transom beam.



FIG. 2

South-west end of transom beam showing serious cracking, Pirow Street Bridge

N2 National Road

The N2 concrete road was opened in 1971. The coarse aggregate used was Malmesbury shale while Cape Flats sand with a shell content of about 28 per cent was used as fine aggregate. A high alkali cement was used. A cursory examination of the road surface revealed fine cracks. However, it is not clear whether this is due to expansion or shrinkage.

Foot of conductor mast

Cores of the concrete from the foot of a conductor mast are also being examined in the laboratory. The concrete displayed severe cracking which appeared to be due to expansion. Malmesbury shale coarse aggregate was used.

Factors common to all the structures that were inspected and which displayed cracking are that they contain Malmesbury shale coarse aggregate, the cements used had either a low

alkali or a high alkali content and obvious cracking was usually observed about five years after completion of the structures.

Appearance of the Concrete

Hand specimens of pieces of the concrete and of concrete cores have a characteristic appearance on freshly fractured surfaces.

The general impression is that there is a dark reaction rim, 0,5 to 1 mm wide, around the periphery of the aggregate. Closer inspection, however, reveals that a white reaction product occurs as a deposit on the fracture surfaces. The deposit is thickest 0,5 to 1 mm away from the periphery, forming a distinct white ring 1 to 1,5 mm wide around the inside of the periphery, decreasing abruptly to approximately a uniform thickness over the rest of the surface (see Figure 3). It appears that the reaction product has been drawn by capillary action into cracks in the aggregate.

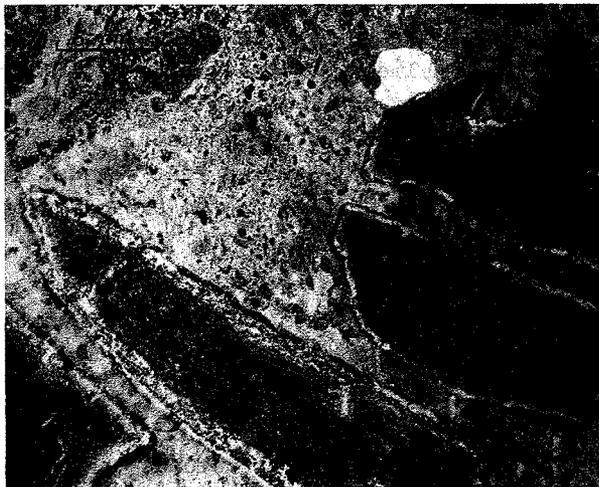


FIG. 3

White deposit of reaction product occurring
on fracture surface of coarse aggregate.
Concrete from foot of conductor mast

White deposits are also seen filling voids in the mortar, occurring on the impression surfaces of aggregate on the mortar and also on the surfaces of aggregates, where the aggregate and mortar have broken away from each other.

Malmesbury Shale Aggregate

The coarse aggregate in Cape Town generally known as Malmesbury shale or Malmesbury hornstone in the main consists of spotted hornfels, argillaceous quartzite, feldspathic quartzite, phyllite and baked shale.

There are nine quarries producing some $2,4 \times 10^6 \text{ m}^3$ of this type of aggregate annually. The aggregate produced by the various quarries can differ greatly in mineralogical composition and physical properties. Even in the same quarry there can be extreme variations as shown by the data in Table 1, which shows the chemical composition of aggregate collected from three different quarries.

TABLE 1
Chemical Composition of Malmesbury Shales

Sample No	Chemical Composition (%)							
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	H ₂ O ⁺
E1	72,66	13,36	3,34	1,53	1,30	3,38	3,04	0,75
E2	57,39	20,92	7,09	4,16	1,13	2,36	3,86	2,64
E3	57,86	21,32	7,05	4,05	1,21	2,19	3,89	2,73
E4	59,27	19,88	6,50	3,95	1,70	2,74	4,05	2,66
E5	73,73	13,17	3,20	1,40	1,41	2,77	2,67	1,22
E6	74,05	13,08	3,23	1,40	1,32	2,85	2,27	0,98
B1	70,62	15,06	3,71	1,89	0,87	3,04	2,49	1,21
B2	66,66	16,76	4,89	2,59	1,68	2,49	3,28	1,34
B3	61,07	19,59	6,24	3,52	1,33	2,18	3,80	1,77
T3	64,64	17,74	5,03	2,70	1,71	2,97	3,18	1,37
P1	64,80	17,05	4,92	2,69	1,11	2,78	3,23	1,68

- E1 : argillaceous quartzite
- E2 : spotted hornfels
- E3 : spotted hornfels
- E4 : spotted hornfels
- E5 : feldspathic quartzite
- E6 : argillaceous quartzite
- B1 : argillaceous quartzite
- B2 : spotted cordierite hornfels
- B3 : argillaceous quartzite
- T3 : run of quarry aggregate
- P1 : run of quarry aggregate from E

A characteristic feature of the Malmesbury shales is the presence of illite which gives a peak on the X-ray diffractometer trace at approximately $10,1 \text{ \AA}$. After treatment with calcium containing solution, the height of the illite peak is greatly reduced and new or stronger peaks appear at approximately $14,9 \text{ \AA}$ and $7,2 \text{ \AA}$ (see Figure 4).

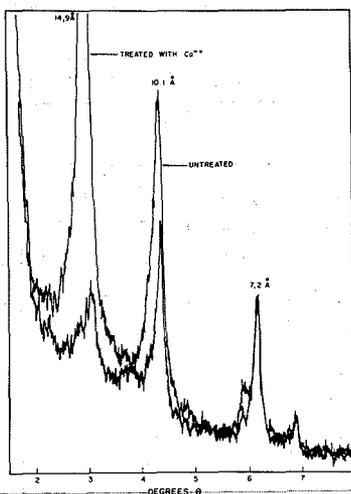


FIG. 4

X-ray diffraction trace of $< 2 \mu\text{m}$ fraction of Malmesbury shale, untreated and treated

Davis (6) estimates that 90 per cent of the coarse aggregate used for concrete in Cape Town is Malmesbury shale. As the shale does not readily crush to a good cubical particle shape, the particle shape quality of the aggregate produced by most of the crushers in the Cape Peninsula varies from poor to fair.

Fine Aggregate

The fine aggregate used in most of the concrete in Cape Town is known as Cape Flats dune sand. In the past this sometimes contained shell and sometimes was free of shell. However, almost the only dune sand now being used for concrete contains 25-30 per cent shell. The sand has a narrow grading, 95 per cent being in the fractions between 180 and 150 μm (6).

Cements

Ordinary portland cements from three factories are being used in the Cape Peninsula. Two of these are high-alkali cements and one is a low-alkali cement. The chemical analyses of the three cements are given in Table 2.

TABLE 2
Chemical Composition of Cements

Cement No	Chemical Composition, %									
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	SO ₃	loi*
a	20,58	4,92	3,52	0,09	0,97	63,60	0,27	0,55	2,77	0,85
b	20,58	5,19	3,56	0,10	1,31	62,96	0,21	0,88	2,57	1,23
c	20,45	5,05	2,22	0,05	1,10	63,22	0,21	0,27	2,75	2,46

* loi = loss on ignition

Laboratory Investigations

Examination of concrete

Figure 5 shows a polished specimen of concrete from the Pirow Street Bridge as seen under reflected light. A reaction product occurring between the contact of the aggregate and the mortar has a gel-like appearance and shows desiccation cracks. Figure 6 is a scanning electron micrograph of this reaction product.

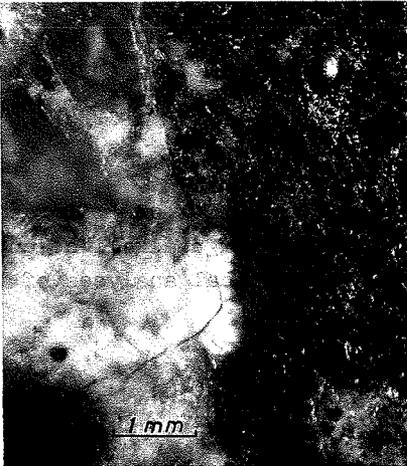


FIG. 5

Photomicrograph of concrete from Pirow Street Bridge showing reaction product

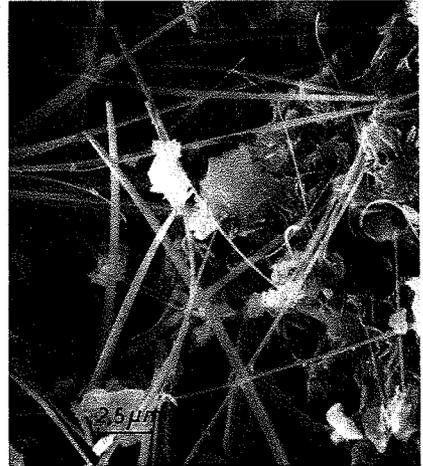


FIG. 6

Scanning electron micrograph of reaction product, Pirow Street Bridge

Reactivity of Malmesbury Shale

Based on the premise that the illite in the shale could react with calcium ions of the portland cement as follows



thus releasing potassium ions which would be available for alkali-aggregate reaction, ASTM test C 227-71 was carried out

on two Malmesbury shales and a quartzite control aggregate, using a low-alkali cement from the Transvaal. The maximum linear expansion recorded after nine months was 0,027 per cent, the average for the control being 0,022 per cent.

Results of the same test repeated with Malmesbury shale and the two high-alkali and one low-alkali cement from the Cape are still inconclusive. The results for the control of Pyrex glass with the same cements gave values of 0,041 per cent for cement a, 0,060 per cent for cement b and 0,011 per cent for cement c after four weeks.

Of nine Malmesbury shales tested for potential reactivity by the chemical method ASTM C 289-71 five were shown to be potentially deleterious. All the hornfelses, except one, were shown to be innocuous, while all the argillaceous and felspathic quartzites, except one, were shown to be deleterious by the chemical method.

Malmesbury shales were put in stoppered conical flasks with saturated lime water at 22°C. In time a white gel appeared. All the samples shown to be innocuous by ASTM test C 289-71 produced the reaction product within three days after the addition of lime water while all the samples shown to be deleterious by the test produced the reaction product only after 19 days. The amount of reaction product increases with time. Almost no reaction product is produced at 38°C, and a fair amount at 10°C.

Water extracts of cements a, b and c (Table 2) were prepared and added to the Malmesbury shale aggregate E2. A reaction product appeared first with the extract of cement c and the amount produced after six weeks was more than twice the amount produced with the extracts of cements a and b.

Reaction product

Examination with the SEM of the reaction product produced by adding saturated lime water to Malmesbury shale showed a mat of long slender fibres occurring together with a gel-like mass (Figure 7). Calcium carbonate and an

occasional perfectly developed crystal resembling hydrogarnet were also present.

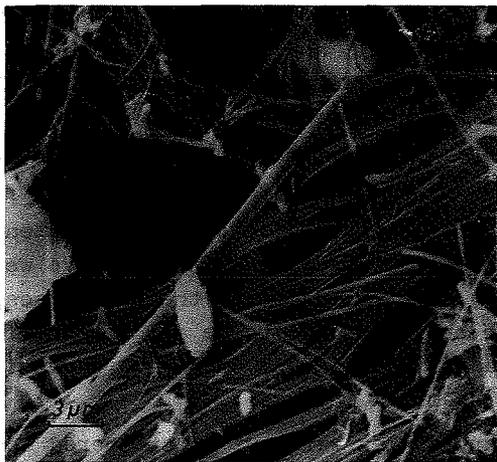


FIG. 7

Scanning electron micrograph of reaction product of Malmesbury shale with $\text{Ca}(\text{OH})_2$

X-ray diffraction analysis done on the reaction product of Malmesbury shale with saturated lime water gave values that agreed fairly well with the values reported by Carlson and Berman (7) for calcium silicoaluminate. The reaction product in the concrete gave d-values that varied from structure to structure, the only resemblance being that in all the samples d-values of $9,4 \text{ \AA}$ and higher are recorded. The results for the reaction product of Malmesbury shale with saturated lime water are compared with the values given for calcium silicoaluminate by Carlson and Berman in Table 3.

TABLE 3.

X-ray diffraction values of reaction product and calcium silicoaluminate (7)

1		2	
dÅ	Relative intensity	dÅ	Relative intensity
9,58	100	9,69	100
5,54	20	5,56	25
4,91	18	4,94	10
4,65	18	4,68	8
3,85	41	3,85	14
3,57	12	3,57	6
3,45	15	3,44	14
3,19	18	3,20	6
3,01	12	3,00	4
-	-	2,88	10
2,77	5	2,77	8
2,74	16	2,74	10
2,67	5	2,66	6
2,58	6	2,58	10
2,54	45	2,54	16
2,18	18	2,157	4
2,13	10	2,130	8

1 : Malmesbury shale + saturated lime water

2 : Calcium silicoaluminate (7)

Conclusions

The cracking observed in the Cape Peninsula for structures built with concrete containing Malmesbury shale as coarse aggregate has not so far been simulated in the laboratory. No expansion of mortar bars made with Malmesbury shale and either low-alkali or high-alkali cements and tested in accordance with ASTM C 227-71 was observed. The ASTM C 289-71 chemical test for reactivity yielded anomalous results in the case of Malmesbury shale.

A reaction product was observed in all the affected structures. In all instances X-ray diffraction data give high d-values for the product. It could not be proved that the reaction product is the cause of the deterioration of the concrete.

A gelatinous reaction product is produced when saturated lime water is added to Malmesbury shale. X-ray diffraction data for the crystalline component agree closely with the values reported by Carlson and Berman (7) for calcium silicoaluminate.

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