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A REVIEW OF TEST METHODS FOR ALKALI-EXPANSIVITY OF CONCRETE AGGREGATES

by Dr P E Grattan-Bellew*

SYNOPSIS

The aim of these test procedures is the prediction of the performance of a given cement-aggregate combination in a particular environment. The problem of identifying potentially expansive rock types is complicated by the fact that, in some cases, the reactive component of the rock is of secondary origin and that there are several types of alkali-aggregate reaction, each with its own characteristics and reaction rate.

SAMEVATTING

Die mikpunt met hierdie toetsprosedures is die voorspelling van die gedrag van 'n bepaalde sement-aggregaatkombinasie in 'n besondere omgewing. Die probleem om potensieel uitsetbare rotstipes te identifiseer word bemoeilik deur die feit dat, in sommige gevalle, die reaktiewe komponent van die rots van sekondêre oorsprong is en dat daar verskeie tipes alkali-aggregaatreaksies bestaan, elk met afsonderlike eienskappe en reaksietempo.

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Secretariat: NBRI of the CSIR
P O Box 395, Pretoria 0001, South Africa
Telephone (012) 86-9211 Telegrams Navorsbou
Telex SA 3-630

Sekretariaat: NBNI van die WNNR
Posbus 395, Pretoria 0001, Suid-Afrika
Telefoon (012) 86-9211 Telegramme Navorsbou
Teleks SA 3-630

* *Division of Building Research, NRC, Ottawa, Canada*

1. INTRODUCTION

There are four accelerated test methods that are frequently used to determine the potential alkali-expansivity of various types of concrete aggregates: the mortar bar method, the concrete prism method, the rock cylinder method and the chemical method.

Accelerated tests cannot simulate exactly the conditions to which concrete is exposed in the field, where it may be subjected to cycles of wetting and drying, and possibly also to freezing. There is, however, ample evidence that a reasonable estimate of the durability of a cement-aggregate combination can be obtained from accelerated tests. To obtain the maximum acceleration of the expansion of mortar or concrete samples in tests requires control of factors such as humidity, temperature, alkali content of the cement and grain size of the material.

One of the problems that confronts the inexperienced, and at times even the experienced, investigator is how to differentiate between normally and excessively or deleteriously expansive mortar, concrete or rock cylinders. The expansion limit of 0,1 per cent after six months, specified in the mortar bar method ASTM C227[1] as the maximum permissible expansion, has been shown to be not applicable to certain aggregates[2]. Frequently, the expansivity of mortar bars or concrete prisms is reported as a percentage expansion at the termination of the experiment. In the literature, the time reported varies considerably and frequently insufficient data are given to determine what the expansion would have been for some other period of time. In the chemical method ASTM C289[3], the ratio of the amount of dissolved silica to the reduction in alkalinity, indicative of a deleteriously expansive aggregate, will vary for different types of silica or even for one silica mineral of different densities.

In this paper, the applicability of the various standard tests for alkali-aggregate expansivity is reviewed. It is also shown that the rate of expansion during the main expansive phase of the reaction is a good measure of the expansivity of the samples and one which is relatively independent of the length of time for which the measurements were made.

2. TEST METHODS

The optimum test method depends on the type of alkali-aggregate reaction. These are: *classical alkali-silica reactivity* found with aggregates containing opal, chert and volcanic glass; *alkali-carbonate expansivity* found in impure dolostones containing clay; and *slowly expanding siliceous aggregates* consisting of greywackes, quartzites, quartz-arenites, argillites and phyllites. The type of reaction depends on the type of aggregate and is evaluated by petrographic examination, according to the recommended practice, ASTM C295[4], although in some cases it may be necessary to extend the scope of the method by X-ray diffraction and SEM studies.

(a) *Mortar Bar Method, ASTM C227.* The mortar bar method, which was designed for use with classical alkali-silica reactive aggregates, is the most commonly used method of detecting potential expansivity of cement-aggregate combinations. The mortar bars, which have an effective length of 250 mm, are cast in steel moulds. They are cured at 100 per cent relative humidity and 38 °C; their length change is monitored periodically.

Swenson and Gillott[5] showed that the mortar bar method was not applicable to alkali-carbonate expansive aggregates. It has also been shown[2] that the method cannot be applied satisfactorily to some slowly expanding siliceous aggregates. In these two types of reactions, expansion is not due to the formation of a gel that absorbs water and swells, as is the case with alkali-silica reactive aggregates.

When the expansion of concrete and mortar is due, in part, to expansion of aggregate, the coarser the aggregate the greater will be the expansion. Hence, concrete prisms expand more than mortar bars. The published results of many expansion experiments on mortar bars made with alkali-silica aggregates are shown in Table 1, pages 2 and 3; the rates of expansion calculated from these data are also included. Some results from mortar bars made with slowly expanding siliceous aggregates, recorded by Mukherjee[6] and Grattan-Bellew[7], are shown in Table 2, page 4.

(b) *Concrete Prism Test, CSA 23.2-14A.* The concrete prism test[8] is similar to the mortar bar test, ASTM C227, except that the samples are larger, 75 mm by 75 mm by 350 mm, and the grading of the aggregate is different. Normal grading used for concrete test cylinders is specified but the author uses stone up to 19 mm. For alkali-carbonate and the slowly expanding siliceous aggregates, this test is the optimum one although the rock cylinder method is also satisfactory. The results of many concrete prism expansion measurements made on slowly expanding siliceous aggregates, found in the literature, and those recorded by the author, are shown in Table 3, pages 5 and 6. The results of tests using alkali-carbonate aggregates are shown in Table 4, page 7.

(c) *Rock Cylinder Test, ASTM C586, and the Proposed Miniature Rock Prism Test.* In the rock cylinder test[9], cylinders 35 mm long by 9 mm in diameter are stored in 1N NaOH solution and the change in their length monitored. The procedure for the miniature rock prism test[2] is similar but the prisms are much smaller, 3 mm by 6 mm by 30 mm, with the result that they become saturated with alkali in a much shorter time than do the rock cylinders.

The rock cylinder test was designed to detect the deleterious expansion of alkali-carbonate expansive aggregates. Newlon and Sherwood[10] found a correlation of 0,9853 between the expansion of rock cylinders in NaOH and the expansion of concrete made with the same aggregate and high alkali cement. This test has also been applied to siliceous aggregates by Duncan[11] and Dolar-Mantuani[12] but with less success. Duncan's results show a correlation coefficient of only 0,5703 between the expansion of rock

TABLE 1 : Expansion of mortar bars made with reactive aggregates and cements of various alkali contents, reported in the literature. The rate of expansion at 140, 300 and 600 days are shown

Author, sample, rock type	Alkali content of cement, % Na_2O equivalent	Rate of expansion $\times 10^3$ days$^{-1/2}$	Expansion at: 140 days	300 days	600 days
Alderman[30] Australia	0,57	7,0	0,025	0,04	0,09
opal	1,04	34,0	0,18	0,22	0,305
Sims[31] Cyprus	0,64	12,0	0,021	0,08	-
chert	1,16	35,0	0,25	0,32	-
Bonzel[32] Germany	0,7	1,3	0,30	0,34	0,34
opaline sandstone	1,06	25,0	0,122	0,124	0,125
	1,4	29,0	0,022	0,025	0,027
Jagus[33] India	0,55	2,0	0,021	at 98 days	
quartzite	0,85	5,0	0,049		
	1,15	11,0	0,084		
Stark[34] New Mexico	0,48	27,0	0,036	-	-
andesites &	0,57	28,0	0,060	-	-
rhyolites	0,92	47,0	> 0,16	-	-
Lenzner[35] Germany					
opaline sand 0,5 - 1 mm	0,9	72,0	0,20	0,37	0,57
0,09 - 0,5 mm	0,9	42,0	0,30	0,32	0,31
1 - 3,5 mm	0,9	10,0	0,10	0,14	0,2
Alsinawi[36] Iraq	0,48	2,6	0,04	-	-
chert	1,06	22,0	0,21	-	-
Mielenz[37] USA - alkali-silica reactive sands					
Idaho Falls	1,38	33,0	0,5	0,68	0,75
Cowlitz	1,38	30,0	0,4	0,56	0,68
Depo Mwt-2	1,38	28,0	0,2	0,3	0,38
Brotschi[24]	0,66	129,0	0,55	at 28 days	
opal	0,80	163,0	0,79		
	0,95	156,0	0,70		
	1,02	149,0	0,57		
Kelly[38]					
2,5% opal in sand	0,83	66,0	0,067	1,1	1,16
Bayano river[2] Panama	0,06	0,7	0,03	0,035	-
volcanic glass sand	1,08	11,6	0,120	0,125	-
McConnell[23] USA					
opal Virgin Valley (5%)	1,38	110,0	1,43	2,1	-
chert Kimball	1,38	45,0	0,6	0,8	-
chalcedony Brazil	1,38	19,0	0,16	0,22	-
chalcedony Oregon	1,38	108,0	0,8	0,85	-
chalcedony California (20%)	1,38	61,0	0,8	0,90	-
novaculite Arkansas	1,38	55,0	0,45	0,47	-

TABLE 1 (continued)

Author, sample, rock type	Alkali content of cement, % Na_2O equivalent	Rate of expansion $\times 10^3$ days$^{-1/2}$	Expansion at: 140 days	300 days	600 days
Stanton[19] USA	0,45	0,3	- 0,001	- 0,005	-
sand 4A	0,77	19,0	0,03	0,16	-
silica reaction	0,90	21,0	0,052	0,18	-
	0,92	24,0	0,054	0,20	-
	0,92	23,0	0,064	0,20	-
	1,14	31,0	1,10	0,24	-
Hobbs[39]					
opal (3%)	1,15	108,0	0,24	at 60 days	
(2%)	1,15	55,0	0,18		
Houston[22] USA					
Republican River Sand	0,54	18,0	0,03	0,11	-
Republican River Sand	1,02	28,0	0,16	0,196	-
Louisiana Sand	0,59	2,1	0,013	0,02	-
Louisiana Sand	1,02	3,8	0,012	0,04	-
Davis[20] Australia					
opal	0,20	- 0,2	0	1,2	1,35
	0,40	28,0	0,08	1,2	1,47
	0,60	56,0	0,6	1,3	1,7
	0,85	73,0	1,1	0,95	1,29
	1,0	62,0	1,0	0,18	0,32
	1,18	58,0	1,0	- 0,02	- 0,01
Gogte[40] India					
quartz sandstone	1,15	23,0	0,19	-	-
basalt 5T	1,15	23,0	0,126	-	-
phyllite	1,15	20,0	0,158	-	-
chlorite sandstone	1,15	17,0	0,121	-	-
basalt 3T	1,15	16,8	0,067	-	-
phyllite sericitic	1,15	3,3	0,03	-	-
charnockite	1,15	1,9	0,019	-	-
argillaceous sandstone with chert	1,15	8,3	0,040	-	-
Duncan[11] Nova Scotia	0,34	1,4	0,016	0,016	0,015
calcareous argillite	0,71	1,7	0,019	0,02	0,023
AP 14A	0,08	2,5	0,02	0,045	0,065
	1,04	4,5	0,04	0,076	0,085
quartzite AP 14C	0,34	5,8	0,04	0,08	0,110
	0,71	1,4	0,017	0,017	0,025
	1,04	1,4	0,016	0,012	0,012
phyllite AP 24/S9B	0,34	3,6	0,035	0,05	0,080
	0,71	2,1	0,02	0,019	0,020
	1,04	2,1	0,017	0,015	0,019

TABLE 2 : Expansion after 140, 300 and 600 days of curing at 38 °C and 100% R.H. of mortar bars made with the slowly expanding siliceous aggregates and one sample of volcanic glass

Sample and reference*	Alkali content of cement, % Na_2O equivalent	Rate of expansion x 10^3 days$^{-1/2}$	Expansion, % at: 140 days	300 days	600 days
Argillite†					
Lady Evelyn Lake	0,68	2,3	0,031	0,034	0,036
Grattan-Bellew[7]	1,08	8,4	0,081	0,088	0,088
Dolar-Mantuani[41]	0,93	14,7	0,035	0,05	0,12
James Bay granodiorite	0,60	0,95	0,024	0,029	0,031
# 73-13	1,08	0,77	0,020	0,023	0,024
Ottawa Valley	0,60	1,6	0,024	0,031	0,034
reference sand	1,08	0,84	0,014	0,016	0,018
Sudbury series**					
Dark red quartz†	0,6	2,9	0,034	0,029	0,032
arenite # 74-53	1,08	3,1	0,032	0,032	0,047
White quartz-arenite†	0,6	3,4	0,038	0,040	0,051
# 74-54	1,08	6,7	0,066	0,067	0,078
Green cherty quartz-argillite†	0,6	4,4	0,090	0,044	0,050
# 74-55	1,08	8,8	0,072	0,090	0,099
Purple quartz-arenite	0,60	3,5	0,023	0,030	0,035
# 74-56	1,06	1,8	0,020	0,019	0,030
Medium grey quartz-argillite	0,60	3,6	0,028	0,043	0,050
# 74-57	1,08	3,3	0,04	0,043	0,050
Dark grey quartz-argillite†	0,60	1,8	0,026	0,029	0,039
# 74-45	1,08	2,4	0,021	0,031	0,035
Pagnutti sand	0,60	0,92	0,018	0,031	0,036
# 72-95	1,08	0,65	0,28	0,021	0,023
Pale green quartz-arenite					
# 74-50	1,08	3,0	0,03	0,035	0,045
# 74-51	1,08	3,5	0,04	0,036	0,055

* When no reference is given: unpublished results by the author.
** Sudbury series, unpublished results but petrology and composition of the rocks given by Grattan-Bellew[7]
† Material shown to be expansive by the concrete prism test.

cylinders and concrete prisms made with high alkali cement. This poor correlation may be due to a combination of factors: an insufficient number of samples may have been used to account for the variability of composition of the rock and difficulties encountered in making accurate length measurements of the expansive samples due to gel deposition on the surfaces of the prisms.

The miniature rock prism test has been used to evaluate the expansivity of a suite of slowly expanding siliceous aggregates from the Sudbury region of Ontario[7]. The correlation coefficient between the rates of expansion of the rock prisms in 2N NaOH and of concrete prisms made with high alkali cement was 0,7845. Although the correlation was only moderately good, it indicates that, with these types of

TABLE 3 : Rates of expansion and percentage expansion after 300, 600 and 1000 days, moist curing at 38 °C of concrete prisms made with slowly expanding siliceous aggregates. A number of non-expansive samples are also included. (Grattan-Bellew unpublished data from Sudbury)

Sample* and author	Alkali content of cement, % Na_2O equivalent	Rate of expansion x 10^3 days$^{-1/2}$	Expansion, % at: 300 days	600 days	1000 days
Lady Evelyn Lake	0,68	10,0	0,07	0,111	0,170
argillite # 76-15	1,05	45,0	0,219	0,245	0,248
White vein quartz					
# 77-8	1,0	3,2	0,053	0,053	-
Granodiorite	0,68	1,8	0,018	0,020	-
James Bay # 73-13	1,08	0,62	0,012	0,015	-
Rhyolite (purple)					
Nova Scotia # 73-53	1,08	13,5	0,093	-	-
Pale pink quartz-arenite	0,68	1,3	0,019	-	-
# 74-52	1,08	1,2	0,019	-	-
Greywacke					
Nova Scotia # 73-50	1,08	24,0	0,070	0,09	0,092
Granophyre					
# 72-72	1,08	0,96	0,013	0,019	0,019
Composite sand & stone					
from Sudbury pit					
# 72-95	1,08	5,4	0,043	0,056	0,06
Norite					
# 72-84	1,08	0,41	0,009	0,012	0,010
Pink quartz-arenite					
# 72-89	1,08	2,7	0,024	0,044	0,051
Grey quartz-argillite					
# 72-85	1,08	16,6	0,096	0,144	0,143
Dark grey quartz-argillite	0,68	3,2	0,038	0,044	0,053
# 74-45	1,08	7,8	0,075	0,112	0,117
# 74-46	0,68	2,0	0,026	0,040	0,060
	1,08	11,9	0,093	0,140	0,160
Pale grey quartz-argillite	0,68	2,6	0,028	0,036	0,038
# 74-47	1,08	10,0	0,103	0,117	0,200
Dark red quartz-arenite	0,68	3,3	0,032	0,041	0,048
# 74-53	1,08	7,8	0,072	0,093	0,096

* When author's samples are not from Sudbury, the location is listed.

continued on page 6

TABLE 4 : Rates of expansion of concrete made with alkali-carbonate expansive aggregates and cements of varying alkali content

Sample, location, author	Alkali content of cement, % Na_2O equivalent	Rate of expansion x 10^3 days$^{-1/2}$	Expansion after: 300 days	600 days	1000 days
Kingston					
Grattan-Bellew* # 78-13	0,68	3,2	0,061	-	-
	1,08	4,9	0,085	-	-
# 78-14	0,68	0,36	0,006	-	-
	1,08	1,0	0,020	-	-
# 78-15	0,68	1,7	0,028	-	-
	1,08	4,7	0,075	-	-
# 78-16	0,68	21,6	0,360	-	-
	1,08	35,1	0,880	-	-
# 78-17	0,68	0,66	0,006	-	-
	1,08	2,08	0,042	-	-
# 78-18	0,68	0,63	0,001	-	-
	1,08	1,5	0,022	-	-
Swenson[5]	0,99	43,0	0,6	-	-
	1,05	48,0	0,9	-	-
Smith[29] Ontario	1,1	8,1	0,06	-	-
Newlon[10] # 1-8	0,95	6,3	0,082	-	-
Buck[28] # 1-8	1,0	5,5	0,08	0,09	0,101
Hadley[25] St Louis #20007	0,60	6,09	0,08	-	-
	0,89	10,6	0,14	-	-
North Vernon # 200024	0,60	3,4	0,04	-	-
	0,89	4,0	0,055	-	-
Elgin	0,89	0,45	0,009	both considered expansive by Hadley	
	0,60	0,40	0,006		
Osgoode # 2000	0,60	1,4	0,015		
	0,89	1,8	0,025		

* Unpublished results.

aggregates, the miniature rock prism method gives more reliable results than the rock cylinder test.

Neither the rock cylinder nor the miniature rock prism test gives a good indication of the expansivity of classical alkali-silica reactive aggregates because the samples either dissolve completely or break up owing to the dissolution of the bonding between the grains[2, 13]. The samples dissolve, indicating they are reactive, but this test gives no indication of the expansivity of the rock.

(d) *Chemical method, ASTM C289-77.* In this test[3], the aggregate is crushed to pass a No 50 screen. The -50 + 100 mesh fraction is retained and heated with a 1N NaOH solution in a reaction vessel at 80 °C for 24 h. The amount of dissolved silica and the reduction in the alkalinity are then determined. This test was developed by Mielenz et al[14] to evaluate the potential expansivity of classical alkali-silica reactive aggregates; good correlation was found between the results from the chemical method and those from the mortar bar test. The main advantage of this method is that

TABLE 3 (continued)

Sample* and author	Alkali content of cement, % Na_2O equivalent	Rate of expansion x 10^3 days$^{-1/2}$	Expansion, % at: 300 days	600 days	1000 days
White quartz-arenite # 74-54	0,68	4,6	0,044	0,054	0,058
	1,08	8,1	0,079	0,093	0,097
Purple grey quartz-arenite # 74-56	0,68	2,2	0,021	0,025	0,030
	1,08	2,6	0,028	0,035	0,036
Fine grey quartz-arenite # 74-57	0,68	4,1	0,041	0,060	0,064
	1,08	14,1	0,124	0,163	0,170
Pale green quartz-arenite composite sample # 72-92	1,08	21,0	0,204	1,212	0,212
Medium green cherty quartz-arenite # 74-55	0,68	1,9	0,022	0,035	0,037
	1,08	19,0	0,136	0,148	0,150
Pale green quartz-arenite # 74-50	0,68	2,0	0,022	0,026	0,029
	1,08	5,5	0,068	0,087	0,089
# 74-51	0,68	4,7	0,049	0,062	0,060
	1,08	11,3	0,110	0,118	0,118
Greywacke James Bay # 76-1	0,68	2,9	0,025	0,033	-
	1,08	5,3	0,064	0,070	-
Amphibolite James Bay # 73-14	0,68	0,7	0,018	0,021	0,021
	1,08	0,9	0,019	0,019	0,020
Oberholster[27]	0,29	1,8	0,002	0,002	-
Malmesbury	0,77	0,2	0,04	0,08	-
Hornfels	0,97	17,0	0,15	0,20	-
Gillott[26] Alert					
Subgrewacke Q3	0,99	20,0	> 0,12	-	-
Q4	0,99	9,5	1,10	-	-
Duncan[13] Nova Scotia	-	-	0,02	0,024	-
Calcareous	0,71	0,3	0,005	0,006	-
Phyllite AP 14A	1,00	6,5	0,049	0,10	-
Quartzite AP 14C	0,71	1,0	0,017	0,026	-
	1,00	6,0	0,067	0,10	-
Phyllite AP 24/S9B	0,71	2,1	0,021	0,047	-
	1,00	12,2	0,10	0,185	-

* When author's samples are not from Sudbury, the location is listed.

the results can be obtained within three days. A disadvantage is that the ratio of the amount of silica dissolved to the reduction in alkalinity, indicative of excessively expansive aggregates, varies with the type of aggregate and shows poor correlation between results obtained by different workers (eg, Gudmundsson[15]). The results reported in the literature indicate that this test should not be used unless it has first been evaluated with aggregates of known expansivity taken from the area where aggregate deposits are to be tested. The chemical method is not applicable to alkali-carbonate aggregates where the expansion does not involve silica. Duncan and Foran[13] found only a 50 per cent agreement between the results of this test, applied to slowly expanding siliceous aggregates, obtained in two laboratories. It may be possible, by further research, to improve the results of the chemical test when applied to slowly expanding aggregates.

3. THE RATE METHOD OF EVALUATING THE EXPANSIVITY OF CEMENT-AGGREGATE COMBINATIONS

Figure 1 shows a typical expansion curve for mortar bars containing an opal sand. From the shape of this curve it is apparent that the rate of expansion during the main expansion phase of the reaction largely determines the total expansivity of the sample. In the expansion mechanism of classical alkali-silica reactive aggregates[16 - 18], diffusion appears to be the rate-controlling mechanism of the reaction. In a diffusion-controlled reaction the rate of reaction is proportional to the square root of time. If the expansion during the main expansion phase of the alkali-silica reaction is diffusion controlled then there should be a linear relationship between the percentage expansion and the square root of time during this period. To test this hypothesis, expansion values of a series of mortar bars made with cements of varying alkali contents, recorded by Stanton[19] (for sand No 4A), were replotted against the square root of time (Figure 2). The mean correlation coefficient for the regression lines fitted to the points is 0,9840. Similar results, obtained from those recorded in the literature, confirm that, during the main expansive phase of the reaction, diffusion is the rate-controlling process. The rates of expansion are shown on the regression lines in Figure 2; from these it is evident that the rate of expansion expressed in terms of the square root of time is proportional to the total expansivity of the samples. To test the validity of this hypothesis, sets of data recorded in the literature[6, 7, 20 - 25] were replotted to yield the rates of expansion and these were compared with the percentage expansion after various lengths of time. Nine sets of data of mortar bar and concrete prism expansion measurements from sources in the USA, Australia, USSR and Canada were used. A number of typical graphs are shown in Figure 3. The mean correlation coefficient for the straight lines fitted to the points on the graphs is 0,9693. This indicates that the rate of expansion during the main expansive phase of the reaction is linearly related to the expansivity of the sample. This correlation was found to hold for mortar bars and concrete prisms made with all types of aggregates. The time before the onset of the main expansive phase of the reaction varied, however, from a few days for the alkali-carbonate aggregates to 150 days for the slowly expanding siliceous aggregates (Figure 4).

It was not possible from the available data to establish that the rate of expansion of rock cylinders was proportional to the expansivity of the samples. It was established, however, that during the main expansive phase of the reaction a linear relationship existed between the percentage expansion and the square root of time. It seems probable, therefore, that the rate of expansion should be proportional to the expansivity.

4. THE MINIMUM RATE OF EXPANSION FOR THE DELETERIOUS EXPANSION OF SAMPLES

An estimate of the rate of expansion corresponding to the cut-off between deleteriously expansive and normally expansive samples can be obtained from results reported in

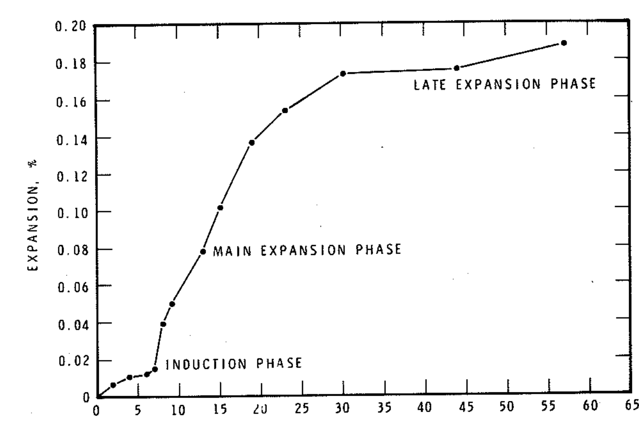


FIGURE 1: Typical expansion curve of mortar bars made with sand containing opal.

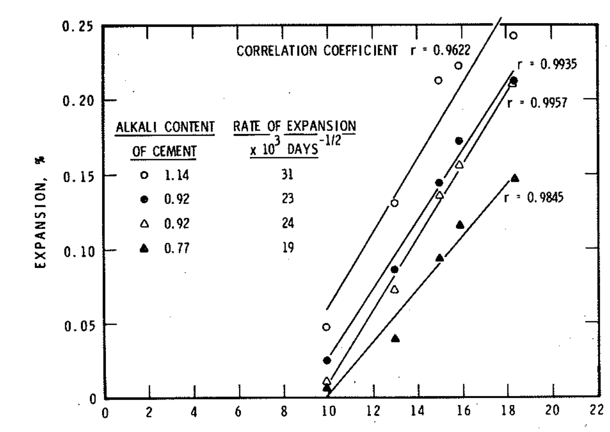
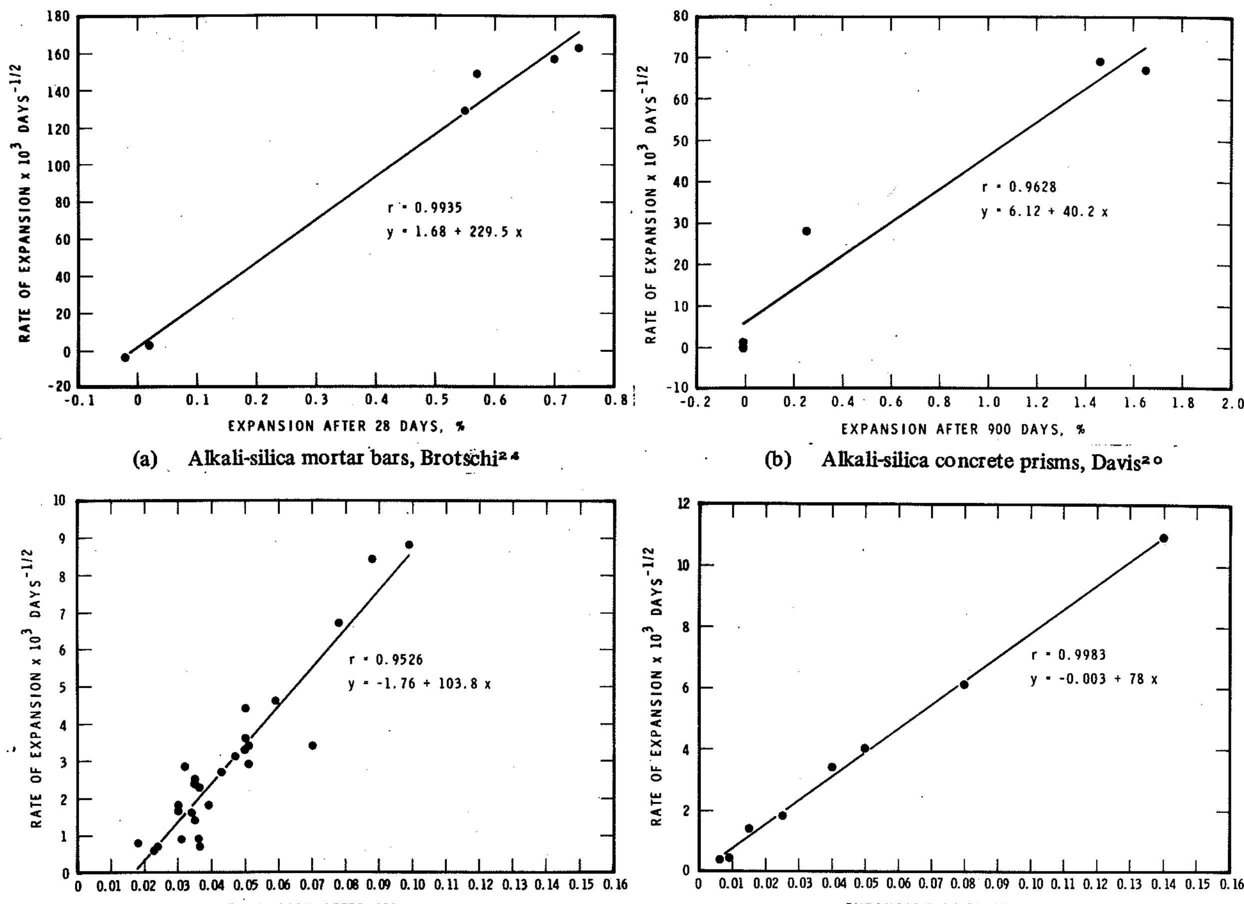


FIGURE 2: Linear relationship between the percentage expansion of mortar bars made with reactive sand and cements with varying alkali contents (after Stanton[19]).



(a) Alkali-silica mortar bars, Brotschi[24]

(b) Alkali-silica concrete prisms, Davis[20]

(c) Alkali-siliceous mortar bars. Sudbury (unpublished)

(d) Alkali-carbonate concrete prisms, Hadley[25]

FIGURE 3 : Percentage expansions after varying times vs rates of expansion of mortar bars and concrete prisms showing the correlation between rate of expansion and the final expansion of the samples. Also included are the correlation coefficient *r* and the equation for each line fitted to the points in the graphs.

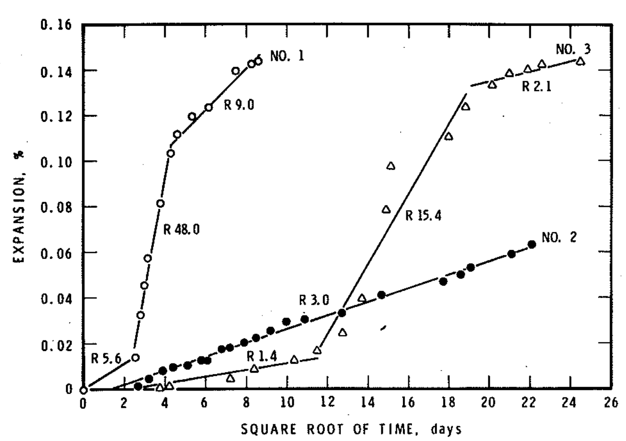


FIGURE 4: Characteristic expansions of concrete prisms made with alkali-silica reactive aggregate No 1, alkali-carbonate expansive aggregate No 2 and slowly expanding siliceous aggregate No 3. The rates of expansion 'R' x 10³ are indicated for the three phases of the expansions.

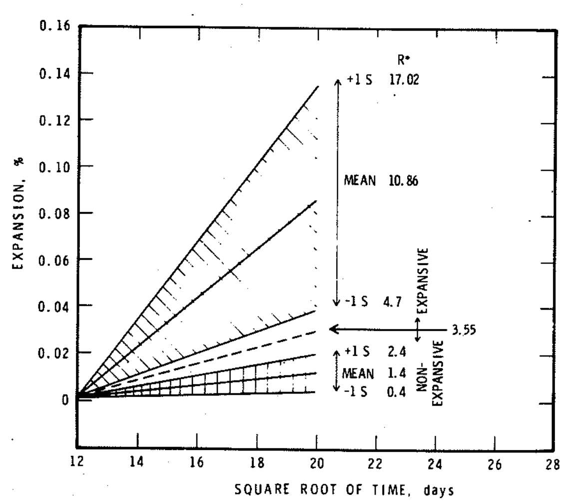


FIGURE 5: One standard deviation (s) time-expansion envelopes about the mean expansion, of *expansive* and *non-expansive* concrete prisms. The cut-off rate, 3,55 x 10⁻³ days^-½, used to differentiate between expansive and non-expansive concrete prisms. * R is the rate of expansion expressed as days^-½ x 10³.

the literature for the various types of reactive samples as follows. The mean rate of expansion and its one standard deviation time expansion envelope for both normal and deleteriously expansive concrete samples are plotted on a graph (Figure 5). A line is positioned mid-way between the lower boundary of the one standard deviation time expansion envelope for the expansive aggregates and the upper boundary of the one standard deviation time expansion envelope of the non-expansive samples. The slope of this line gives an estimate of the rate of expansion corresponding to the cut-off between deleteriously expansive and normally expansive samples. This procedure is expected to give only a rough estimate of the cut-off between expansive and innocuous samples; it should be checked against known expansive and innocuous material from a particular area under investigation.

(a) Mortar bar test.

The mean rate of expansion for deleteriously expansive mortar bars obtained from data in the literature is 35,5 x 10^{-3} days$^{-1/2}$ with a standard deviation of 26 x 10^{-3} days$^{-1/2}$. The mean rate of expansion and its one standard deviation for non-expansive aggregates is 2,0 x 10^{-3} $\pm$ 1,3 x 10^{-3} days$^{-1/2}$. Using the procedure already outlined, a cut-off of 6,4 x 10^{-3} days$^{-1/2}$ is found to differentiate between deleteriously expansive and normally expansive samples. Mortar bars made with Louisiana sand[22] expanded 0,04 per cent in 300 days and are considered non-expansive. The rate of expansion calculated for this sample is 3,8 x 10^{-3} days$^{-1/2}$ which is lower than the cut-off value. Mortar bars made with volcanic glass sand expanded 0,125 per cent in 600 days and cracked. This sample would be considered expansive. The rate of expansion for this sample was 11,2 x 10^{-3} days$^{-1/2}$. These two results indicate that the cut-off rate of expansion to differentiate between deleteriously expansive and innocuous samples lies between 3,8 and 11,2 x 10^{-3} days$^{-1/2}$, which is in reasonable agreement with the suggested value of 6,4 x 10^{-3} days$^{-1/2}$. It must, however, be emphasized that this is not a unique value and its validity should be checked for a particular area, with a particular suite of rocks.

Using the same logic and the results of Mukherjee et al[6], a cut-off rate of expansion of 4,0 x 10^{-3} days$^{-1/2}$ was found to differentiate between deleteriously expansive and innocuous mortar bars made with slowly expanding siliceous aggregates, but the value for a suite of quartzose aggregates from the Sudbury area was 1,9 x 10^{-3} days$^{-1/2}$. As correlation between the expansion of mortar bars and that of concrete prisms for the Sudbury area was poor, the values from the latter method are probably unreliable. The lower cut-off value for the slowly expanding siliceous aggregates is to be expected as these rocks expand more slowly than the classical alkali silica aggregates.

(b) Concrete prism test.

(i) *Siliceous aggregates.* The mean rate of expansion of expansive concrete prisms made with high alkali cement and slowly expanding siliceous aggregates listed in Table 2 is 10,86 x 10^{-3} days$^{-1/2}$ with a standard deviation of 6,16 x 10^{-3} days$^{-1/2}$. The mean rate of expansion of the non-expansive samples is 1,4 x 10^{-3} days$^{-1/2}$ with a standard deviation of 1,15 x 10^{-3} days$^{-1/2}$; using the same logic as previously, a cut-off rate of expansion of 3,55 x 10^{-3} days$^{-1/2}$ is obtained. The lowest rate of expansion calculated for a known expansive concrete is 9,5 x 10^{-3} days$^{-1/2}$ for a sample made with greywacke, Q4, from Alert[26]. Most expansive samples have much higher rates of expansion, eg, 17 x 10^{-3} days$^{-1/2}$ for a hornfels from Cape Province[27] or 45 x 10^{-3} days$^{-1/2}$ for an argillite from Lady Evelyn Lake, Ontario[2]. From these results, it would appear that the cut-off value of 3,55 x 10^{-3} days$^{-1/2}$, to differentiate between deleteriously expansive and innocuous, is probably too low. A value of about 6 x 10^{-3} days$^{-1/2}$, as was found for mortar bars made with classical alkali-silica reactive aggregates, might be more realistic but in practice a cut-off should be determined for a particular suite of rocks in a given area.

(ii) *Alkali-carbonate expansive aggregates.* If the highly expansive aggregate No 78-16 from Kingston (Table 3) with a rate of expansion of 48 x 10^{-3} days$^{-1/2}$ is omitted, the mean rate of expansion for expansive aggregates is 6,39 x 10^{-3} $\pm$ 2,16 x 10^{-3} days$^{-1/2}$. The mean rate of expansion of the non-expansive samples is 1,37 x 10^{-3} $\pm$ 0,61 x 10^{-3} days$^{-1/2}$. Using the same logic as before, a cut-off rate of expansion to differentiate between deleteriously expansive and innocuous samples of 3,1 x 10^{-3} days$^{-1/2}$ was obtained. Expansion data for sample No 1-8 listed by Buck[28] gave a rate of expansion of 5,5 x 10^{-3} days$^{-1/2}$. The sample expanded by 0,101 per cent in 1 000 days and is hence expansive. Expansion data on an alkali-carbonate aggregate from the Utinoff quarry, Ontario[29], yielded a rate of expansion of 8,1 x 10^{-3} days$^{-1/2}$. This sample expanded by 0,06 per cent in 300 days. These low rates of expansion for moderately expansive concretes indicate that a cut-off of 3,1 x 10^{-3} days$^{-1/2}$ may be about correct. Because these samples start expanding after a few days, a lower rate of expansion may give rise to more expansion than would be obtained, for example, with concrete made with slowly expanding siliceous aggregate with the same rate of expansion.

(c) Rock-cylinder and miniature rock prism tests.

(i) *Alkali-carbonate expansive aggregates.* From a survey of rock-cylinder test results, it was not possible to determine a cut-off value to differentiate between expansive and innocuous samples. Different authors reported widely divergent results. It is thought that this may be due to variations in the samples and also to limitations of the method. The miniature rock prism method tends to give more reproducible results but not enough measurements have been made to differentiate between expansive and innocuous samples and it appears the cut-off value may be about 10 x 10^{-3} days$^{-1/2}$.

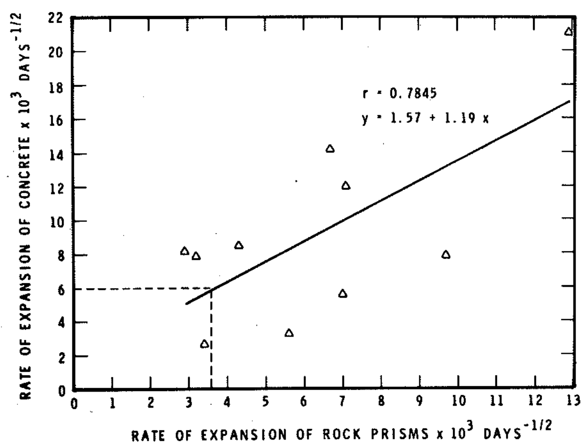


FIGURE 6: Correlation between expansion of miniature rock prisms in 2 N NaOH and concrete prisms made with high alkali cement made with Sudbury aggregates. The correlation coefficient is 0,7845.

(ii) *Slowly expanding siliceous aggregates.* As the correlation coefficient between the expansion of rock cylinders in alkali and the expansion of concrete prisms made with the same aggregates and high alkali cement is only 0,5703, no attempt was made to find a cut-off value to differentiate between deleteriously expansive and normally expansive samples. Using the miniature rock prism method, a correlation coefficient between the rates of expansion of rock prisms and concrete prisms from the Sudbury area was found to be 0,7845 (Figure 6). Assuming a cut-off rate of 6 x 10^{-3} days$^{-1/2}$ for the concrete prisms, a corresponding rate of about 3 x 10^{-3} days$^{-1/2}$ as the cut-off to differentiate between expansive and innocuous rock prisms may be read off the graph (Figure 6). From these results, it is evident that the cut-off rate of expansion is about the same for miniature rock prisms as it is for concrete prisms made with slowly expanding siliceous aggregates. This is not unexpected as a large part of the expansion of the concrete made with these aggregates is due to the expansion of the aggregate and not due to gel formation.

5. SUMMARY

The optimum test method for alkali expansivity of concrete aggregates depends on the type of aggregate. For classical alkali-silica reactive aggregates, opal, chert and volcanic glass, the mortar bar method is the best. The concrete prism test is the optimum method for testing alkali-carbonate expansive rocks, but the rock-cylinder and miniature rock prism methods can also apply. The concrete prism test is also optimum for evaluating slowly expanding siliceous aggregates, quartzites, argillites, quartz arenites and greywackes. Poor correlation is found between the expansion of rock cylinders and concrete prisms made with slowly expanding siliceous aggregates; better results seem to be obtained with the miniature rock prism test.

The chemical method is applicable to classical alkali-silica reactive aggregates but the interpretation of the results is not easy. This method also has some potential for the evaluation of slowly expanding siliceous aggregates, but more research on its application to these types of aggregates is needed.

6. CONCLUSIONS

The expansion of mortar bars and concrete prisms was found to be diffusion controlled. The rate of expansion, expressed as the square root of time, during the main expansive phase of the reaction was shown to be linearly related to the ultimate expansion of the sample. Approximate minimum rates of expansion, above which samples would be considered deleteriously expansive, were determined for mortar bars made with alkali-silica reactive aggregates and for concrete prisms made with slowly expanding siliceous aggregates and alkali-expansive carbonate aggregates.

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DISCUSSION

Dr H B Poole (Queen Mary College, London, England), referred to the results obtained by Dr Hobbs with Beltane opal, which showed an induction period of a few days, which was understandable and easily envisaged. However, the induction period Dr Grattan-Bellew proposed for some of the rocks, was of the order of a 100 days. He asked if there was any explanation as to why it took so long to react. He added that if the rate of expansion equation as calculated from the rate of expansion curve was used, it was essential to know when this had commenced because an error of at least a few days could be made in deciding where the slope of the curve had become steeper.

Dr Grattan-Bellew replied that when data was fed into the computer and the expansion was plotted against the square root of time, there was usually quite a sharp break if the measurements had been made frequently enough. However, one had to be very careful that one was actually measuring the steep part and consequently some experience was required of the length of time expected for the type of rock being studied. For example, the rock encountered in the South Western Cape, South Africa, and also that near Sudbury, Canada, had a long induction period of about 150 days. In addition when one was dealing with concrete prisms, the aggregate particles were larger, i.e. 19 mm. It would consequently take some time for the alkali to work its way into the aggregate to react and cause expansion, whereas in the mortar prism method the aggregate was much smaller. However, when working with opal, it had to be remembered that it reacted almost instantaneously with the alkali.

Dr L Dolar-Mantuani (Toronto, Canada), commented that the rock cylinder test had actually been developed for the testing of alkali reactive carbonate rocks. Studies in Nova Scotia had shown that it could also be used for rock types such as argillites, but could not be used for opal as this would just dissolve in the 1N NaOH. When comparing the rock cylinder and the rock prism tests one had to keep in mind that the rock prism was much smaller and, although very useful, it was not as representative of the rock as the rock cylinder which was approximately three times larger.

Dr Grattan-Bellew mentioned that it was possible to do a rock cylinder test with opal. It expanded rapidly and then dissolved and disintegrated so there would be no data on the total expansivity, or any way in which to correlate between the expansivity of the cylinder and what the rock would do. If one had material which was thought to be classically alkali-silica reactive, it was possible to do a rock cylinder test which would give a result, although it would not correlate well with the concrete. The rock prism method that was applied by Duncan, Gillott and others who worked in Nova Scotia appeared to work. However, their data contained one graph which plotted the expansion of the concrete against the expansion of the rock cylinders, and the correlation was only about 0,58. In his own minature rock prism test in Sudbury there was a slightly better correlation of 0,78 which could be due partly to the methodology which had been used. It was a general tendency to use a small chunk of rock and extract either 10 cores or 10 slices which gave good reproducibility. They had at least 5 slices or 5 cores, but he felt it would probably be far more satisfactory to take 5 different pieces of rock because one then had a more representative sample. It would result in more scatter within the sample, but might correlate better with the concrete data.