DELETERIOUS REACTIVITY OF A NUMBER OF UK AGGREGATES AND AN EXAMINATION OF THE DRAFT BS CONCRETE PRISM TEST

D W Hobbs
Concrete Performance Group, British Cement Association,
Slough, SL3 6PL, UK.

Expansion test results are reported on concretes with original alkali contents, expressed as equivalent sodium oxide, ranging from 3 to 8 kg/m^3, prepared using a number of UK aggregates. The concretes were subject to three exposure regimes - moist storage at 38°C, moist storage at 20°C and external storage. It is shown that the original alkali content above which abnormal expansion can occur is approximately 5 kg/m^3 and that expansion observations made in controlled tests are only applicable to field concretes of the same mix proportions.

INTRODUCTION

To minimise the risk of cracking due to ASR in new construction one of the following approaches may be used: i) the use of an aggregate with a good performance record, ii) testing the aggregate for reactive silica, iii) testing the cement-aggregate combination for deleterious reactivity, and iv) placing an alkali limit on the concrete or cement. This report is concerned with the third approach.

In the UK a concrete prism expansion test for establishing aggregate reactivity is currently being considered for possible adoption by BSI (1). The current draft BS Concrete Prism Test is broadly as follows:

Four concrete prisms, 75 x 75 x 250 to 300mm in size are prepared with a cement content of 700 kg/m^3. The cement alkali level is enhanced when necessary to 1.0%, expressed as equivalent sodium oxide by mass, by adding potassium sulphate to the mixing water. The concrete prisms, after demoulding, are stored moist at 20 or 38°C. At specified ages the length of the prisms is measured. An expansion criterion for distinguishing between deleterious and innocuous aggregates has yet to be established.

The main objectives of the work presented in this report were firstly to establish whether the draft BS concrete prism test was a suitable method for determining the reactivity of UK aggregates and secondly to determine the original alkali level below which abnormal expansion is unlikely to occur.

Expansion tests are reported which were carried out on concrete prisms stored moist at 38°C and 20°C and on companion concrete blocks stored externally. The concretes had original alkali contents, expressed as equivalent sodium oxide ranging from 3.0 to 8.0 kg/m^3. The test work was commenced early in 1988.

EXPERIMENTAL DETAILS

Cement

The cement used was an ordinary Portland cement with an alkali content expressed as equivalent sodium oxide of 1.00 per cent by mass. The sodium oxide and potassium oxide contents of the cement were 0.44 and 0.85 per cent by mass. This cement was selected because of its high Na_2O/K_2O ratio as limited evidence exists which indicates that at a given original alkali content, the risk of cracking due to ASR is probably greater at high Na_2O/K_2O ratios (Hobbs,2).

Aggregates

The aggregates used in the test programme were selected on the basis of the test results obtained by the sponsors of the research programme using a concrete prism expansion test procedure similar to an early version of the draft BS Concrete Prism Expansion Test (BSI,3). In the programme 14 sands and coarse aggregates were used as follows:

1. A Trent Valley sand
2. A Trent Valley coarse aggregate,from the same source as 1
3. A partially crushed chert/flint sand, Somerset
4. A coarse siliceous aggregate, from same source as 3
5. A Mendip Limestone,crushed fines
6. A Mendip Limestone,crushed coarse,from the same source as 5
7. A siliceous sand, Dorset, England
8. A Thames Valley sand
9. A sea dredged sand,Southern England
10. A partially crushed quartzite coarse aggregate,South West England
11. A sharp siliceous sand, Dorset
12. A Thames Valley coarse aggregate,20-10mm
13. A Thames Valley coarse aggregate,10-5mm
14. A Thames Valley sand,from the same source as 13 and 12.

Specimen preparation and original alkali contents

The aggregates were used in an oven dry condition and extra water was added to allow for aggregate absorption. Apart from drying, the aggregates were used in their as-received condition. The aggregate and all the water were put into the mixer pan and mixed for 2 minutes. An hour later the cement was added and the batch was mixed for 3 minutes. From each batch prisms 75 x 75 x 250mm in size with cast-in steel end inserts or alternatively blocks, 200 x 250 x 500mm in size, or alternatively both prisms and one block were cast. The concretes were compacted on a vibrating table (BSI,4). After casting the prisms were stored under a polythene sheet in a fog room. The concrete blocks were covered with a polythene sheet and stored overnight in the mixing laboratory. The original alkali content of the various concretes prepared ranged from 3 to 8 kg/m^3.

Exposure condition 1. At an age of 24 hours, two or four prisms from each batch were wrapped in a moist paper towel or cotton cloth. The wrapped prisms were placed into polythene tubing of the same length as the prisms and each wrapped prism was then placed into a polythene bag. The bagged prism was placed into a sealed container and at an age of 24 hours or 7 days the length of the prism was measured using a dial gauge comparator or occasionally a micrometer. The wrapped prisms within their sealed containers were then stored in a room maintained at 38 ± 2°C. At ages of 2,4,13,26,39 and 52 weeks after mixing the length of the prism was measured after it had been allowed to equilibrate within its closed container to 20 ± 1°C. The wrapped prism within its sealed container was then returned to the hot room.

Exposure condition 2. At an age of 24 hours or 7 days two prisms were stored vertically above water in a sealed container in a room maintained at 38 ± 2°C. At 1 or 7 days and at 2, 4, 13, 26, 39 and 52 weeks after mixing the length of the prism was measured after being allowed to equilibrate within its closed container to 20 ± 2°C. The prism within its sealed container was then returned to the hot room.

Exposure condition 3. At an age of 24 hours, two or four prisms from each batch were wrapped, stored and their length periodically monitored in the same manner as for exposure condition 1, except, firstly, the storage temperature was 20 ± 2°C throughout the length monitoring period and secondly, the length of the prisms was additionally measured at ages after mixing of 78 and 104 weeks.

Exposure condition 4. At an age of 24 ± ½ hour, 2 prisms from each batch of 12 were stored horizontally above water in sealed containers stored at 20 ± 2°C. The length of the prisms was measured at ages after mixing of 1, 2, 4, 13, 26, 39, 52, 78 and 104 weeks.

Expansion measurements and exposure conditions for the concrete blocks stored externally

The concrete blocks were cast during the summer months and demoulded and exposed externally at an age of 24 ± ½ hour (see Figure 1). Demec points were immediately fixed, with an Araldite epoxy resin, to areas cleaned with emery paper. The position and spacing of the demec points are shown in Figure 2. The first demec measurements were taken 2 days after mixing and then measurements were periodically made approximately every 6 months. Occasionally more frequent length measurements were made. During the first three years of the test programme no demec points were dislodged.

EXPANSION. 38°C

A concrete expansion of 0.05 per cent is sometimes taken as the level which distinguishes between deleterious and non-deleterious cement aggregate combinations (ASTM,5). The approximate ages at which an expansion of 0.05 per cent was reached are given in Table 1 for concretes with original alkali contents ranging from 5.2 to 8.0 kg/m^3. Data is not presented for concretes with lower original alkali contents as apart from perhaps one exception, none of these concretes have exhibited abnormal expansion. The following summarises the main observations made to date:

1. No concretes containing aggregate combinations (3,4),(5,4),(5,6),(7,6) and (14,12,13) have exhibited abnormal expansion.

2. At an original alkali content of 7 kg/m^3, seven aggregate combinations have exhibited expansions in excess of 0.05 per cent, the age at which abnormal expansion commenced ranging from 2 to 7.5 months. The seven aggregate combinations were in order of expansion (3,6),(11,6),(9,6),(8,6),(1,2),(5,2) and (1,6). At an age of one year the expansion of the concretes containing these aggregates ranged from 0.58 to 0.10 per cent.

3. At an original alkali content of 5.2 kg/m^3 only two aggregate combinations, (8,6) and (9,6) have exhibited abnormal expansions, the age at which abnormal expansions commenced being 10 and 7 months respectively.

4. Only aggregate combination, (9,6), has resulted in an expansion in excess of 0.05 per cent when the original alkali content was below 5.2 kg/m^3. This aggregate combination resulted in an expansion at one year of 0.055 per cent when the original alkali content was 4.9 kg/m^3.

It follows from these observations that aggregate combinations giving rise to abnormal expansion in concretes with an original alkali content of 7 kg/m^3, as in the draft prism test, give rise to lower expansions when used in concretes of lower original alkali content. Below an original alkali content of approximately 5 kg/m^3, abnormal expansion of the concretes is not observed. Thus the performance of the aggregate combinations in the draft Prism Test does not give a good indication of the likely performance of the aggregate combinations in concretes with high practical alkali levels, namely 4.0 to 5.0 kg/m^3.

TABLE 1 - Age at which abnormal expansion commenced (months). Prisms stored above water and wrapped

Aggregate combination		Alkali Content (kg/m^3) 5.2		6.0		7.0		8.0	
Sand	Coarse	38°C	20°C	38°C	20°C	38°C	20°C	38°C	20°C
1	2	O'K	O'K	7	23	3.5	18	3	12
1	6	O'K	O'K	12	O'K	7.5	18	7.5	18
3	6	O'K	O'K	6	14	2	10	2.5	8
5	2	O'K		11.5		4.5	19	11	12
5	10	O'K		12		O'K	18	10	10
8	6	10		4.5	21	4	15	2	13
9	6	7		3.5	17.5	3.5	13	3	12
11	6	O'K	O'K	7	18	3	12	35	11.5

TABLE 2 - Age at which abnormal expansion commenced (months). Concretes stored externally

Aggregate combination		Alkali content (kg/m^3) 6.0	7.0 *				8.0
Sand	Coarse	a	a	b	c	d	a
1	2						26
3	6	18	18	18	18	22	18
7	6						30
8	6		28	25	30(e)	28	28

* a = exposed, b = exposed upper face only,
c = exposed and partially immersed in I N salt solution,
d = reinforced and exposed,
e = placed horizontal and exposed.

In Figure 3 the mean expansion at one year for the wrapped prisms, prepared using the aggregate combinations which resulted in abnormal expansion, is shown plotted against the original alkali content. With the exception of aggregate combination (3,6), expansion increases with original alkali content. Figure 3 shows that the magnitude of the original alkali content necessary for deleterious expansion depends upon the aggregate combination employed, the minimum original alkali content necessary for deleterious expansion being about 5.0 kg/m^3.

EXPANSION. 20°C

The approximate age at which a concrete expansion of 0.05 per cent was recorded is given in Table 1. At an original alkali content of 7.0 kg/m^3, six aggregate combinations induced expansions in the concrete prisms in excess of 0.05 per cent, the age at which abnormal expansion commenced ranging from 10 to 19 months. The six aggregate combinations, in order of concrete expansion at two years, were (3,6),(9,6),(8,6),(1,2), (1,6) and (5,2). The two year expansion of the concretes containing these aggregate combinations ranged from 0.44 to 0.05 per cent. At an original alkali content of 5.2 kg/m^3, none of the aggregate combinations have to date resulted in expansions in excess of 0.05 per cent. Thus the expansions measured in the draft BS Prism Test do not give a good indication of the performance of similar concretes made with lower original alkali contents.

In Figure 4 the mean expansion at two years for the wrapped prisms prepared using the aggregate combinations which resulted in abnormal expansion, is shown plotted against original alkali content. With the exception of aggregate (3,6), expansion increases with alkali content. Examination of the data in Figure 4 shows that the magnitude of the original alkali content necessary for deleterious expansion depends upon the aggregate combination employed; the minimum original alkali content necessary for deleterious expansion being greater than 5.0 kg/m^3.

EXPANSION. EXTERNAL EXPOSURE

Thirteen of the blocks stored externally have, to date, exhibited abnormal expansion. These blocks were prepared using four aggregate combinations (1,2),(3,6),(7,6) and (8,6). The age at which abnormal expansion was observed is given in Table 2. This age is taken as the age at which an increase in expansion rate became apparent or the age at which the expansion reached a level of 0.05 per cent. The ages at which abnormal expansion occurred ranged from 18 to 30 months, aggregate combination (3,6) being the most deleterious.

The expansion results for the exposed blocks prepared using aggregate combinations (3,6) and (8,6) are shown plotted in Figures 5 and 6. These were the only two aggregate combinations which have, to date, resulted in abnormal expansion when the original alkali content was 7 kg/m^3. At an age of 3 years the expansion of the top faces of the four blocks prepared using aggregate combination (3,6) with an alkali content of 7 kg/m^3, ranged from 0.317 to 0.333 per cent, a remarkably low variation. The expansion rate at the top face of these blocks from an age of 18 months to 36 months, was about 0.02 per cent per month. In the case of aggregate combination (8,6) the expansion at 3 years of the top faces of the three vertical blocks with an alkali content of 7 kg/m^3 ranged from 0.151 to 0.168 per cent, again a low variation.

COMPARISON OF THE EXPANSION BEHAVIOUR OF THE CONCRETES SUBJECTED TO THE THREE EXPOSURE CONDITIONS

Figure 7 compares the age to abnormal expansion for concrete prisms stored at either 38 or 20°C with that for concrete blocks stored externally. During the period 1 June 1990 - 31 May 1991, the concrete blocks were subject to a mean external temperature of 9.0°C. The age to abnormal expansion for the concrete blocks stored externally is broadly eight times and double that for comparable concretes stored at 38 and 20°C respectively. This is in agreement with the common assumption that the chemical reaction rate doubles for each 10°C rise in temperature. It should be noted that few of the blocks stored externally have, to date, exhibited abnormal expansion.

Figure 8 compares the interpolated expansion at an age of 4.5 months for the concrete prisms stored at 38°C with the expansion at an age of 3 years for the comparable concrete blocks stored externally. Examination of these figures shows that the results are broadly related. It follows from this observation and the previous sub- section that the performance of a concrete under field conditions can probably be predicted from the performance of the same concrete when stored moist at either 38 or 20°C. To date, this observation is valid for a number of the concretes which when stored at 38°C exhibited abnormal expansion in 2 to 4 months and exhibited an expansion at one year in excess of 0.25 per cent. Concretes exhibiting smaller expansions when stored at 38°C have not, to date, exhibited abnormal expansions when stored externally.

CONCLUSIONS

A number of UK aggregates containing chert or flint were tested for alkali-silica reactivity. The following conclusions are applicable to the particular aggregate combinations tested and to the data obtained to date. The concretes tested had original alkali contents ranging from 3 to 8 kg/m^3.

1. The expansion results obtained in the Draft BS Concrete Prism Test are only applicable to field concretes prepared using the same mix proportions and the same original alkali content by mass, namely 7 kg/m^3. The results are not applicable to concretes with higher or lower original alkali contents by mass.

2. To date, the concretes stored externally which have shown abnormal expansion when stored at 38°C exhibited abnormal expansion in 2 to 4 months and exhibited an expansion at one year in excess of 0.25 per cent.

3. The original alkali content above which abnormal expansion can occur is approximately 5 kg/m^3.

RECOMMENDATION

In the UK, to minimize the risk of expansion due to ASR when a 'reactive aggregate' is used, an alkali limit of 3.0 kg/m^3 is often placed on the concrete. This limit is based on the certified average alkali content of the cement supplied by the manufacturer. The current work shows that this limit is unnecessarily restrictive. For the flint and chert containing aggregates used in this study it is recommended that the alkali limit be raised from 3.0 to 4.0 kg/m^3.

ACKNOWLEDGEMENTS

This work was funded by the Mineral Industry Research Organisation (MIRO) the individual sponsors being Blue Circle Industries PLC, Castle Cement, ECC Quarries Limited, RMC Technical Services Limited and Rugby Cement. The author is grateful to Mr R Belcher, Mr P Hilliard, Mr J Rochford, Mr C Slattery, Mr M Sehmar and Mr M Webster for their assistance in carrying out the test programme.

REFERENCES

1. British Standards Institution, 1990, "Testing Aggregates. Alkali-silica reactivity. Concrete prism method". BSI, London, draft BS812:Part 123.

2. Hobbs, D.W., Struct.Eng.,62A, 1984, 26.

3. British Standards Institution, 1987 "Testing aggregates. Alkali-silica reactivity:Concrete prism method". BSI London, draft BS812:Part 123.

4. British Standards Institution, 1983, "Testing concrete. Method for making test cubes from fresh concrete". BSI London, BS1881:Part 108.

5. American Society for Testing Materials, 1990, "Standard specification for concrete aggregates". Annual book of ASTM standards. ASTM, Vol.04.02. Concrete and aggregates. Section 4. Construction. C33-90, 10.

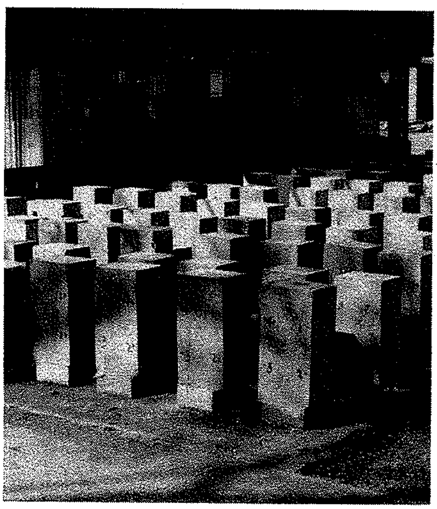

Figure 1 External blocks

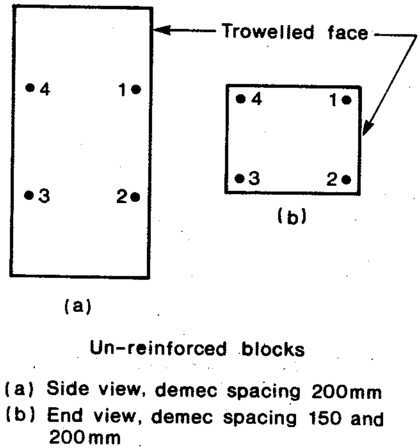

Figure 2 Position and spacing of Demec points

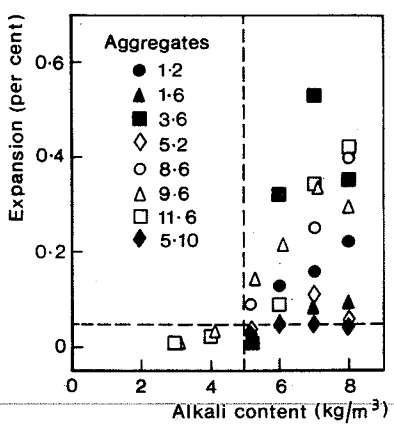

Figure 3 One year expansion v alkali content. 38°C

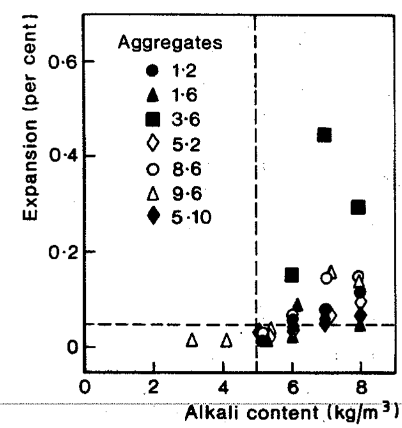

Figure 4 Two year expansion v alkali content. 20°C

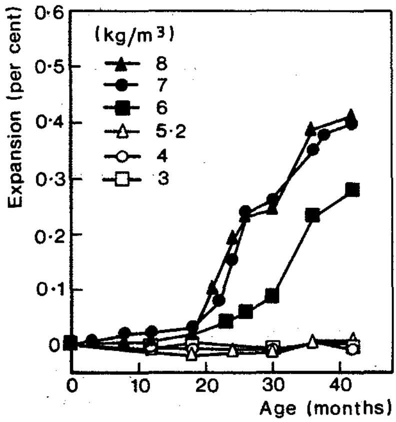

Figure 5 Expansion v age. Aggregates (3,6). Stored externally

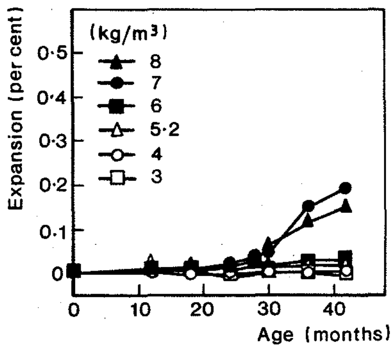

Figure 6 Expansion v age. Aggregates (8,6). Stored externally

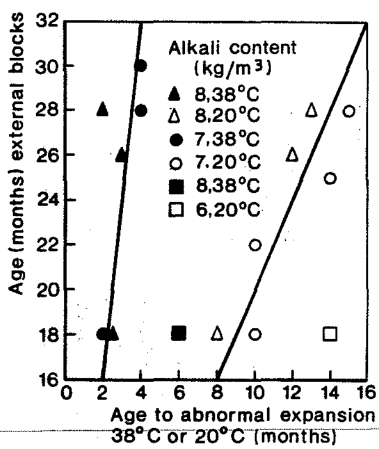

Figure 7 Age at abnormal expansion

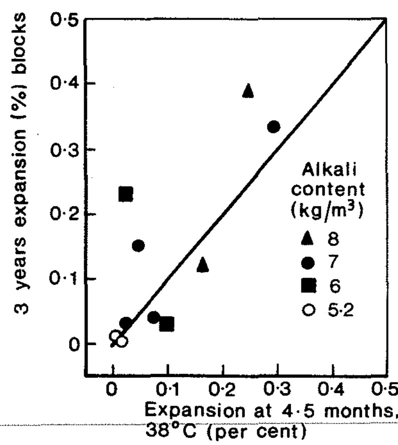

Figure 8 Expansion at equivalent ages