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THE USE OF FLYASH AND GRANULATED BLASTFURNACE SLAG TO REDUCE EXPANSION DUE TO ALKALI-AGGREGATE REACTION

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SYNOPSIS

A number of flyashes and a granulated blastfurnace slag which are available in the UK have been assessed for their usefulness in reducing the expansion caused by the alkali aggregate reaction. Pyrex glass and chert rock have been used as the reactive aggregate and tests using Beltane opal are in progress. The factors influencing the effectiveness of flyashes and granulated blastfurnace slags in reducing expansion are discussed and the way in which the temperature of the reaction and the nature of the reactive aggregate may influence the results of the assessment are described.

SAMEVATTING

'n Aantal soorte poeierkoolas en hoogoondkorrelslak wat in die VK beskikbaar is, is geëvalueer vir hul nut om die uitsetting wat deur die alkali-aggregaatreaksie veroorsaak is, te verminder. Pyrexglas en chertrots is gebruik as reaktiewe aggregaat en toetse, waarin Beltaanopaal gebruik word, is aan die gang. Die faktore wat die doeltreffendheid van poeierkoolas en hoogoondkorrelslak beïnvloed om uitsetting te verminder word bespreek en die wyse waarop die temperatuur van die reaksie en die aard van die reaktiewe aggregaat die resultate van die waardebepaling mag beïnvloed, word beskryf.

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1. INTRODUCTION

Soon after Stanton discovered that alkali aggregate reactivity (AAR) was the cause of damage to concrete in the USA[1] he found that such damage could be alleviated by adding finely ground reactive material to the concrete mix. Since then it has been claimed that a wide variety of natural and artificial pozzolanas and materials such as granulated blastfurnace slags with latent hydraulic properties can mitigate damage due to AAR. Since the deterioration of concrete due to AAR has been found in some structures in the UK in recent years, there is much interest here in the possibility of using such pozzolanic materials where the particular cement/aggregate combination is suspect. The materials most readily available in the UK which would be used in this way are flyashes, the fine residue from the combustion of pulverised coal, and granulated blastfurnace slags. There is also currently much interest in the UK in the use of these cement replacement materials for other reasons such as the reduced costs of concrete, savings in energy of manufacture of cement and the possible greater durability of concrete containing them.

The effectiveness of flyashes and granulated blastfurnace slags in reducing expansion due to AAR has been examined by a number of workers[2,3,4,5]. In most of the investigations Pyrex glass was used as the reactive aggregate although Lenzner and Ludwig[4] used an opaline sandstone. The work of the US Army Engineers Waterways Experiment Station[2,3] suggested that flyashes with a low alkali content are more effective than those with a high alkali content in reducing expansion due to AAR and that although a high alkali flyash will increase the expansion of an otherwise innocuous combination of Pyrex and a low alkali cement, the resulting expansion will not be great enough to be considered deleterious. In line with these findings the ASTM specification for flyash for use in concrete (C 618) has a limit of 1,5 per cent as Na_2O on the available alkalis where the flyash is to be used to counteract AAR.

The use of granulated blastfurnace slag to counteract AAR has been studied in considerable detail in Germany[5] and it is concluded from this work that the expansion depends on the total alkali content and the slag content of the cement. For slag cements with at least 50 per cent slag a limit of 1,1 per cent total alkalis as Na_2O was judged to give a performance equivalent to that of a low alkali (less than 0,6 per cent equivalent Na_2O) Portland cement. For slag cements with at least 65 per cent slag the alkali content was found to have practically no influence on the expansion, so a rather arbitrary high limit of 2 per cent Na_2O equivalent was set for these cements. These limits have now been incorporated in the appropriate German Standard (DIN 1164) as specifying a low alkali cement. However, Lenzner and Ludwig found no correlation between the alkali content of the slag and expansion when 35 per cent slag replacement was used in the cement.

The objective of the work reported here was to decide whether British flyashes and granulated blastfurnace slags were effective in reducing expansion due to AAR and in the case of the flyashes, to establish the criteria governing the relative effectiveness of different ashes. Eleven different ashes with a wide spectrum of properties were tested, in combination with a high alkali cement. Only one Portland blastfurnace cement and one source of ground granulated slag for on-site mixing are available in the UK so the opportunity and need for extensive testing was more limited and only the granulated slag was tested.

2. TEST PROCEDURE

The method of test was basically that specified in ASTM C 441 'Effectiveness of mineral admixtures in preventing excessive expansion of concrete due to alkali aggregate reaction', ie monitoring the length change of mortar bars stored at 38 ^{o}C and made with a reactive aggregate and a high alkali Portland cement partially substituted by the particular ash or slag.

(a) *The materials tested.* Information on properties of the eleven flyashes and the granulated blastfurnace slag is given in Table 1, (page 2). The pozzolanicity rating of the flyashes according to the Lea test[6] ranged from poor to good (7 to 17 MN/m^2 difference in strength between storage at 20^o and 50 ^oC using the same Portland cement) and their total alkali levels ranged from 0,75 to 4,57 per cent equivalent Na_2O. The high alkali Portland cement contained 1,06 per cent alkalis as equivalent Na_2O (1,3 per cent K_2O and 0,21 per cent Na_2O) while the low alkali Portland cement contained 0,58 per cent equivalent Na_2O (0,47 per cent K_2O and 0,27 per cent Na_2O). Pyrex glass as specified in ASTM C 441 was used as the reactive aggregate in most of the tests. In a few of the tests a chert aggregate was used and some tests using Beltane opal are underway.

Chert is the aggregate type found to be attacked in the majority of concrete structures in which deterioration due to AAR has been identified in the UK. In laboratory experiments, however, it has been found possible to produce deleterious expansion in mortar bars containing chert aggregate only by increasing the alkali level artificially above that found in the British Portland cement with the highest alkali content (about 1,1 per cent equivalent Na_2O). The particular sample of chert used in these tests would be classed as 'deleterious' by the ASTM chemical method for the potential reactivity of aggregate (C 289).

Beltane opal is a porous opaline rock from the Beltane quarry in California and is being distributed, as a standard alkali reactive material for use in research, by Purdue University, USA.

(b) *Tests carried out.* Using the Pyrex aggregate the following investigations were carried out:

The relative effectiveness of different flyashes.
The effect of different levels of ash substitution.

(continued on page 5)

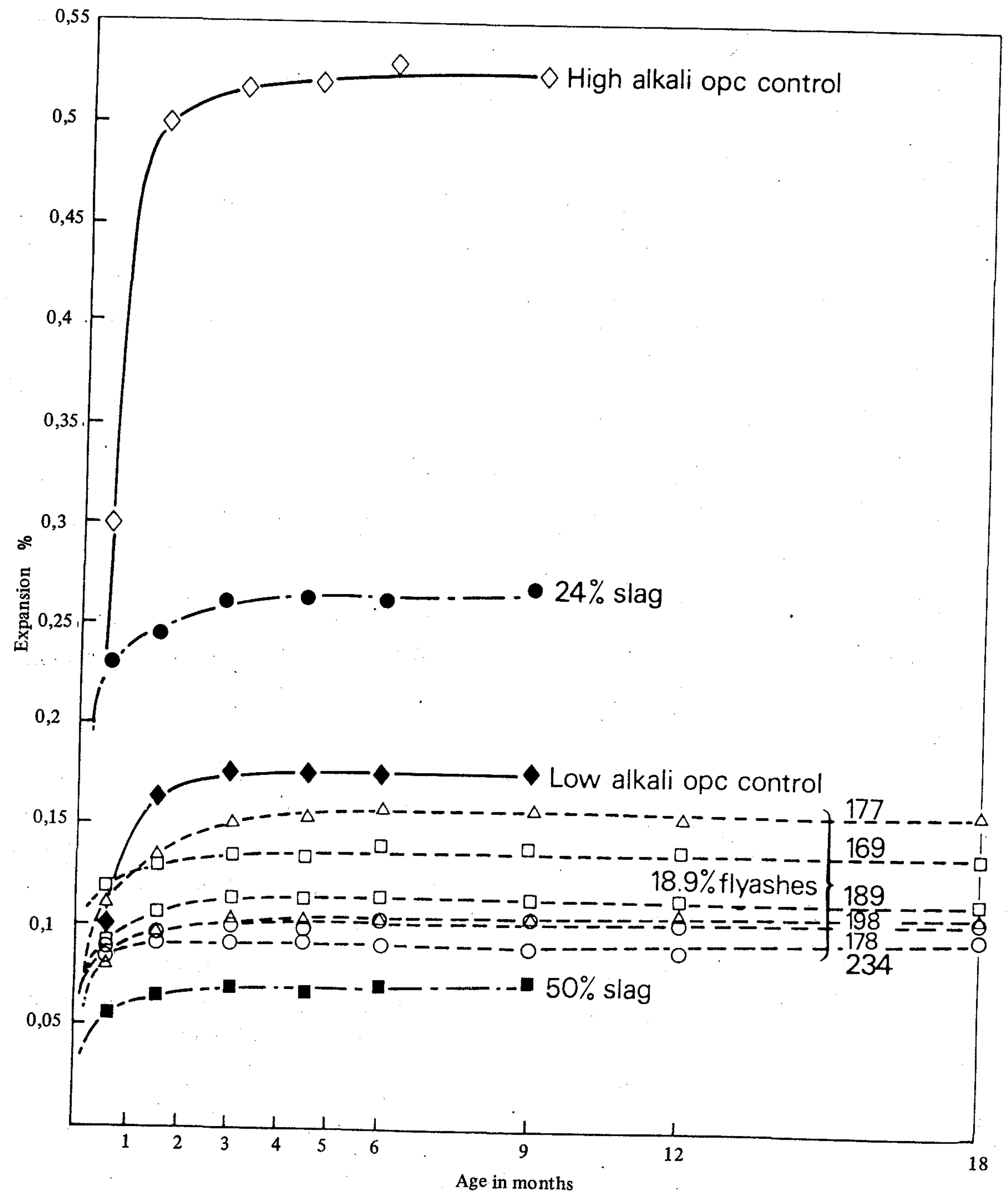

FIGURE 1 : Expansion of mortar bars containing high alkali opc and Pyrex aggregate with replacement by flyashes or slag; 38 °C storage

TABLE 1 : Properties of the cement replacement materials used

Flyashes	Pozzolanicity by Lea Test: Strength differences (MN/m^2) 20 - 50 °C	Pozzolanicity by Lea Test: Rating	45 µm residue % (m/m)	Specific surface area (m^2/kg)	Total alkalis: 1) K_2O 2) Na_2O % (m/m)	Total alkalis: equiv Na_2O % (m/m)	Available[1] alkalis equiv Na_2O % (m/m)
177	7,4		28,45	593	2,98 0,68	2,64	1,39
185	7,9	Poor	27,36	258	3.81 1,48	3,99	1,08
187/90	7,3		35,33	266	2,45 0,54	2,15	0,59
198	7,5		25,88	584	1,0 0,13	0,79	0,12
169	12,9		26,09	302	3,04 1,40	3,40	1,16
173	13,0	Moderate	20,29	383	3,16 1,33	3,41	1,34
189	13,5		25,89	296	3,76 2,10	4,57	1,30
174	13,40		25,09	399	2,78 1,26	3,09	1,16
178	17,6		3,77	386	3,84 0,82	3,35	1,58
234	17,4	Good	16,33	nd	1,56 0,29	1,32	0,48
237	17,4		12,50	423	0,87 0,18	0,75	0,28
Gran.slag 286	nd		nd	330	0,9 0,36	0,95	nd

nd - not determined
1 - according to ASTM C311

The effect of different storage temperatures on the effectiveness of flyash.

The effectiveness of ground granulated blast-furnace slag.

These tests were complemented by those using the chert aggregate at different substitution levels and different temperatures.

3. TESTS USING PYREX GLASS

(a) *The relative effectiveness of different flyashes.* The expansions obtained after up to 18 months in mortar bars containing Pyrex aggregate together with the high alkali Portland cement and 18,9* per cent m/m of the different ashes stored at 38 °C are shown in Figure 1, together with the expansions from low and high alkali Portland cement controls.

All the ashes tested reduced the expansion below that produced by the low alkali Portland cement. Such a cement would normally be regarded as having a sufficiently low alkali content to be safe for use with reactive aggregates.

The differences between the expansions produced with the various ashes were small but the most effective ashes were in general those with the best pozzolanicity rating. There was little correlation either with total or available (soluble in 28 days in $Ca(OH)_2$ solution) alkali content of the ashes except that ash 198 which was one of the most effective ashes in reducing expansion, although classed as a poor pozzolana, had a particularly low alkali content.

(b) *Different levels of ash substitution.* Two ashes, 178 and 185, both with relatively high alkali levels but one rated as a poor pozzolana and one as a good pozzolana were substituted for 10, 20 and 30 per cent of the high alkali Portland cement in mortar bars made with the Pyrex aggregate and stored at 38 °C. At the 30 per cent substitution level an ash (237) of good pozzolanicity but low alkali content was also used.

The results shown in Figure 2 show that at all levels of substitution the expansion is reduced compared with a high alkali Portland cement alone. At the 20 and 30 per cent substitution the expansion is reduced below that produced by the low alkali Portland cement.

In all cases the ash rated as a good pozzolana was more effective than the poor pozzolana. At the 30 per cent level the low alkali ash was also marginally better than the high alkali ashes but the differences were very small.

(c) *The effect of different storage temperatures on the effectiveness of ashes.* The results quoted above showed that the effectiveness of the ash in reducing expansion due to AAR correlated with a measure of its pozzolanicity. The pozzolanic reaction is particularly sensitive to temperature, more so, for example, than is the hydraulic reaction of Portland cement, so that the 38 °C storage might be thought to be favouring the flyash. The effect of storage at 5 °C and 22 °C as well as 38 °C was therefore investigated. Two ashes, 178 and 237, both rated good pozzolanas but with high and low alkali contents respectively were used substituted at the standard 18,9 per cent m/m level for a high alkali Portland cement in mortar bars with Pyrex aggregate. The results are shown in Figures 3, 4 and 5, page 6.

The most noticeable effect is that increasing the temperature produces a more rapid expansion but a reduced level of final expansion. This is the case for both the high alkali Portland cement controls and the mortar bars containing ash. Thus although the expansion of the bars containing flyash is greater at 22 °C than at 38 °C, the reduction in expansion compared with the controls is virtually the same in both cases. The expansions at 5 °C are still increasing but it can be seen that the bars containing flyash are expanding at a lower rate than the controls.

The behaviour of the high and low alkali flyashes at different temperatures was almost the same, with the low alkali ash producing slightly lower expansions.

(d) *The effect of brief periods of higher temperature curing and storage.* The results reported above showed that storage at 38 °C produced lower final expansions than storage at 22 °C. It is known that in many structures concrete will reach at least 38 °C for some hours[7], the temperatures reached being dependent on cement type and content, concrete section and type of formwork. Some experiments have therefore been carried out to see if brief periods of exposure to a higher temperature during curing would be effective in reducing the expansion due to AAR. The experiments were carried out using a flyash (178) mixed with the high alkali Portland cement at the standard 18,9 per cent m/m replacement level. This was because at the time it was thought that the temperature sensitivity of the pozzolanic reaction was influencing the effectiveness of the flyash in reducing expansion. As described above it subsequently became apparent that temperature influenced the expansion whether or not flyash was present so these experiments on the usefulness of brief exposure to higher temperatures can be assumed to have a wider applicability than just to systems containing flyash.

The curing and initial storage regimes are shown on page 6:

* ASTM C 441 specified the replacement of 100 g of Portland cement by an equal volume of admixture. Because the variation in the density of the ashes was small the level of replacement was standardised to 18,9 per cent m/m.

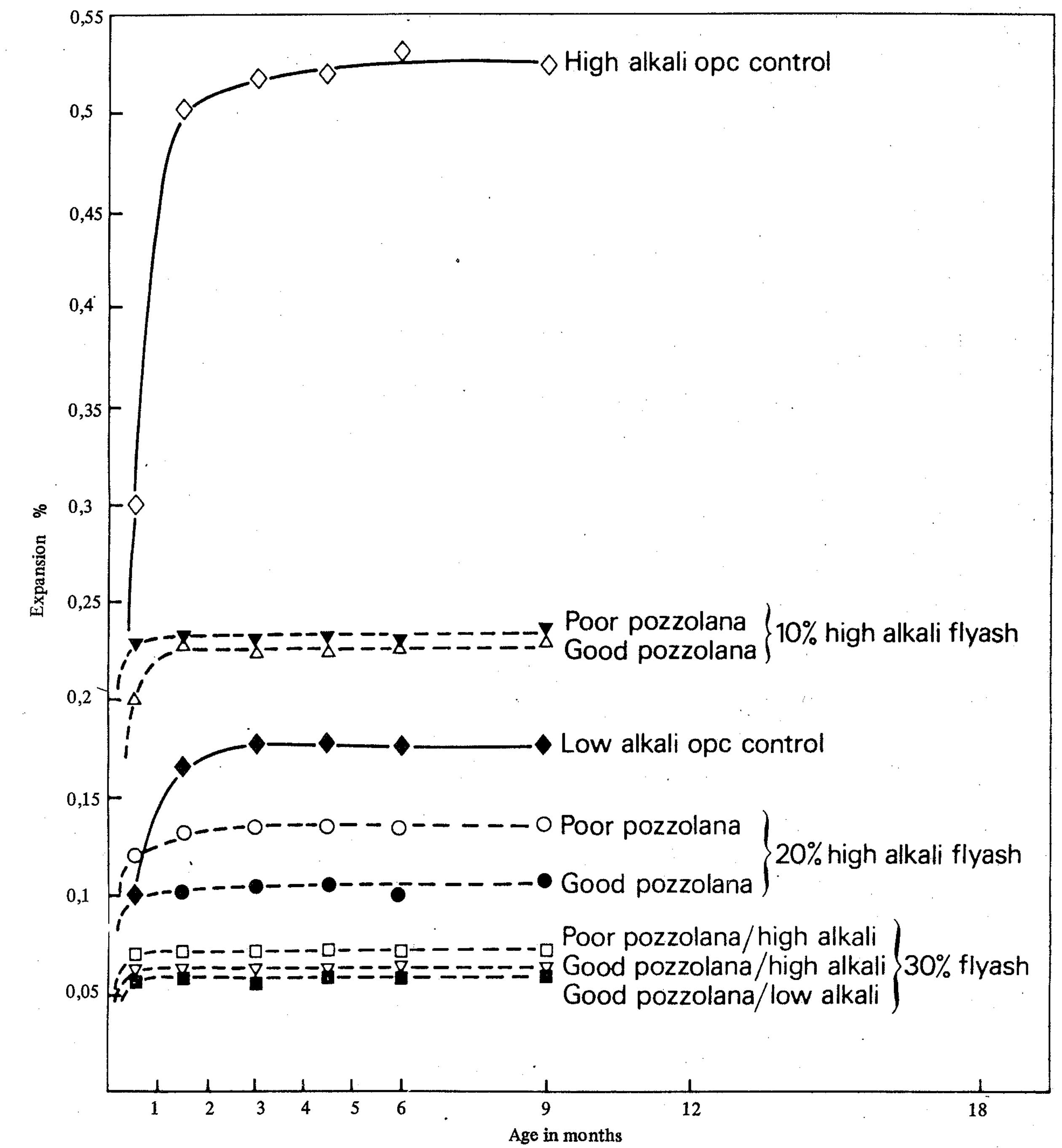

FIGURE 2 : Expansion of mortar bars containing high alkali opc and different levels of flyash substitution, 38 °C. Pyrex aggregate

Mix no	24 h cure temperature	38 °C storage days
T12	22 °C	12
T6	22 °C	6
T2	22 °C	2
T1	22 °C	1
T24 h	38 °C	0
T6 h	6 h 38 °C 18 h 22 °C	0

After this initial storage subsequent storage and measurements were at 22 °C.

The expansions produced are shown in Figure 6. It can be seen that the longer the bars are stored at the higher temperature the lower the expansion. Brief periods of exposure at the curing stage are more effective than equivalent periods later. However the effects are relatively small and it seems unlikely that it could be put to practical use.

(e) *The effectiveness of ground granulated slag.* Ground granulated slag was used to replace the high alkali cement at two levels, 24 per cent which was the level which accrued from the specified volume replacement in ASTM C441, and 50 per cent.

The expansions obtained are shown in Figure 1. The 24 per cent replacement can be seen to be relatively ineffective but at the 50 per cent level, which is a more normal replacement level for a slag cement, a very considerable reduction was obtained, well below the expansion produced by the low alkali Portland cement.

4. THE USE OF FLYASH AND SLAG TO REDUCE EXPANSION WITH CHERT AGGREGATE

Flyash 237, a good pozzolana with a low alkali level was tested at 40, 30 and 20 per cent replacement levels with a high alkali Portland cement and a chert aggregate. Ground granulated slag at 70 per cent replacement was tested in the same way. The alkali level of the mortar was increased by adding NaOH in the mixing water equivalent to 1,4 per cent Na_2O so that the total alkali in the high alkali Portland cement control was 2,5 per cent.

The expansions produced in mortar bars stored at 38 °C are shown in Figure 7. Similar experiments are being carried out at 22 ° and 5 °C but so far no significant expansion has been recorded at these temperatures.

Significant reductions in expansion are produced by both the flyash and slag. Flyash at the 30 and 40 per cent replacement level and the slag at the 70 per cent level reduced the expansion to that produced with this aggregate

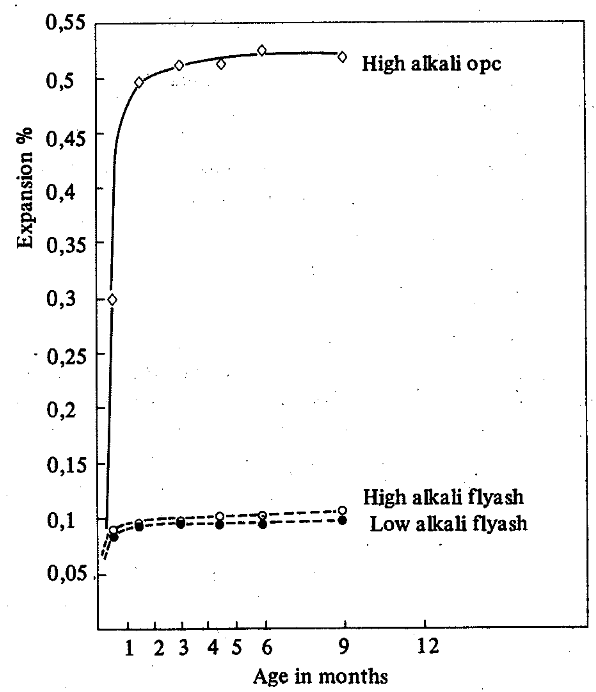

FIGURE 3: Expansion of mortar bars at 38 °C, high alkali opc, 18,9 mass % flyash, Pyrex aggregate.

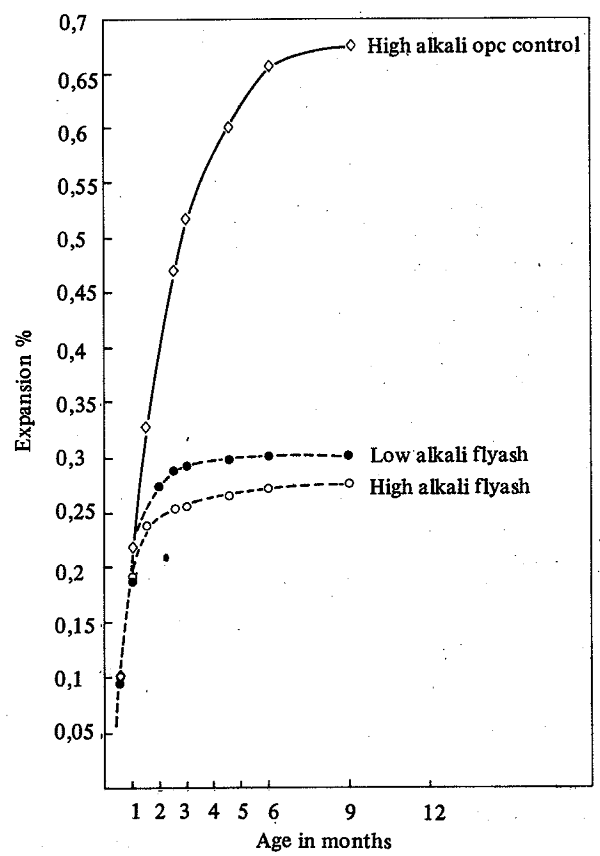

FIGURE 4: Expansion of mortar bars at 22 °C, high alkali opc, 18,9 mass % flyash, Pyrex aggregate.

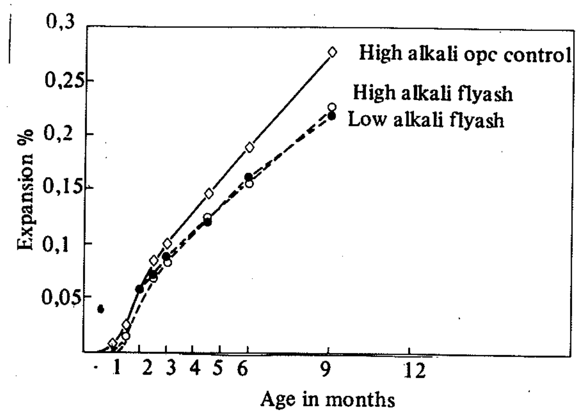

FIGURE 5: Expansion of mortar bars at 5 °C, high alkali opc, 18,9 mass % flyash, Pyrex aggregate.

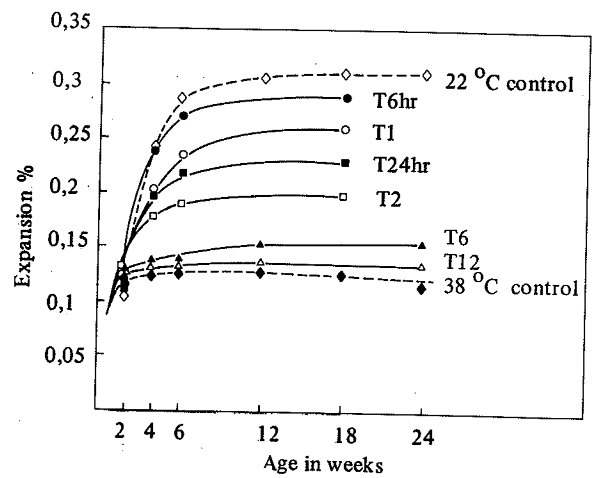

FIGURE 6: Expansion of mortar bars with different curing regimes, high alkali opc + 18,9 mass % flyash, Pyrex aggregate.

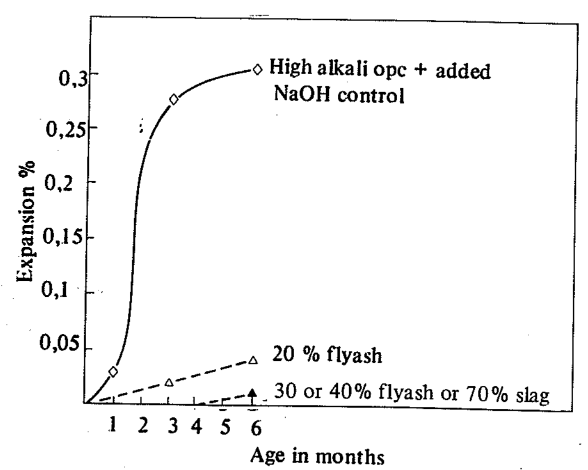

FIGURE 7: Expansion of mortar bars containing chert aggregate with high alkali opc + added NaOH (total of 2,5% equiv Na_2O) and 20, 30 or 40% flyash or 70% slag. 38 °C storage.

by a Portland cement with only 0,5 per cent equivalent Na_2O. In all cases the reduction was greater than could be accounted for by simple reduction of the alkali level by dilution.

5. DISCUSSION

When Pyrex glass is used as the reactive aggregate the partial replacement of a high alkali Portland cement by a flyash or by granulated blastfurnace slag produces a significant reduction in expansion of mortar bars at all replacement levels tested (10, 20 and 30 per cent flyash and 24 and 50 per cent slag). The reductions are greater than could be accounted for by simple dilution of the alkali content of the Portland cement.

Weight for weight the flyashes are more effective in reducing expansion. However, at the normally used cement replacement levels, 20 to 30 per cent for flyashes and about 50 per cent for the slag the two materials perform similarly and both would be expected to reduce the expansion to below that produced by a low alkali (less than 0,6 per cent equivalent Na_2O) Portland cement.

Only small differences were found between the effectiveness of different ashes. These differences could be best correlated with a measure of the pozzolanicity of the ash. The ashes with lower alkali content did, on the whole, seem to perform slightly better than those with high alkali but this effect was secondary to the pozzolanicity. The available alkali content of the ashes gave no better correlation with the observed expansions than did the total alkali content. Only one of the ashes exceeded the limit of 1,5 per cent available alkali in ASTM C618 but this was one of the most effective ashes in reducing expansion. On the basis of the ashes tested here, therefore, this alkali limit cannot be justified.

Insufficient slag samples were tested to comment on the DIN specifications for low alkali slag cements. The 50 per cent slag sample just met the 1,1 per cent Na_2O DIN limit and in fact reduced the expansion well below that produced by a low alkali Portland cement so slag cements meeting these specifications would certainly be effective.

The tests carried out using the chert aggregate support the results obtained with the Pyrex glass although here 30 per cent flyash was needed to reduce the expansion to that produced by a low alkali Portland cement. Seventy per cent replacement of cement by slag was equivalent to the sample in which 30 and 40 per cent of the cement was replaced by flyash.

Lowering the storage temperature of the Pyrex mortar bars reduced the rate of expansion but increased the final level of expansion. This effect was evident in both the Portland cement controls and when flyash was added. Thus the temperature dependence of the pozzolanic reaction does not seem to be an important factor in determining the effectiveness of flyashes. Brief periods of curing or possibly because the Na_2O/SiO_2 ratio in the gel is now such that the gel is too fluid to cause expansion. There is support for this from the work of Vivian[9] who observed a pessimum when he added NaOH to a system containing 10 per cent reactive silica.

The water soluble alkali content of flyash is very small (usually less than 0,1 per cent equivalent Na_2O). However Gutt, Nixon and Gaze[10] found that in a model $C_3A/Ca(OH)_2/K_2SO_4$ system the addition of flyash accelerated the increase in alkalinity. They concluded that the alkalis were not dissolving from the flyash but rather that the flyash was acting as a surface catalyst to the precipitation of ettringite, the removal of calcium from solution and the consequent increase in the hydroxyl ion concentration of the solution. When Pyrex glass is used its lower surface area means that the Na_2O/SiO_2 ratio is already above the pessimum and any addition of alkali reduces the expansion.

The effects of adding pozzolanas can also be interpreted in terms of adding reactive silica which reacts with the alkalis at such an early stage that the reaction products can be accommodated by the mortar during the setting and hardening. The beneficial effects of adding ground glass for example would seem only to be explainable in this way. If there is a pessimum Na_2O/SiO_2 ratio for the particular reactive aggregate/cement combination then it is again possible that expansion could be increased by addition of more reactive silica in the form of the pozzolana.

A particular pozzolana may be adding both alkali and reactive silica so the effect on the Na_2O/SiO_2 ratio may not be simple. Moreover the marked reduction in the level of calcium in the pore solution which is the most clear cut result of adding flyash probably also plays a part, perhaps by altering the composition of the silicate gel. Significant effects on expansion due to AAR when the amount of lime in solution is reduced have been noted at BRE and by other workers[11, 12]. The important conclusion seems to be that if the particular aggregate/cement combination shows a pessimum Na_2O/SiO_2 ratio there is then the possibility that the addition of a pozzolana could have a deleterious as well as a beneficial effect. The existence of such a pessimum ratio in the case of very reactive opaline aggregates is well established whereas no such critical ratio has been observed with Pyrex glass. From a practical point of view it has therefore to be decided whether or not the particular aggregates being used in concrete are going to behave like Beltane opal or like Pyrex. The chert aggregate investigated here seems to be behaving like Pyrex glass and so far none of the UK aggregates which have been investigated have shown a 'pessimum'. Nevertheless the observations made on the Beltane opal system point out the need for care in the use of pozzolanas to control AAR. Ideally the particular cement/aggregate/pozzolana should be tested before use although time pressure will probably make this impossible in many cases. Investigations of concrete as distinct from mortar are also needed to establish whether these small-scale accelerated-test results can be scaled up.

In spite of these difficulties in interpretation, the indications are that the use of cement replacement materials such as slags and flyashes can give useful protection against expansion due to AAR provided they are used in large enough proportions, 30 per cent or more with flyashes and 50 per cent with slags.

6. CONCLUSIONS

(a) All the flyashes and the one ground granulated blastfurnace slag tested have been found to produce significant reductions in the expansion of mortar bars when these materials replace a proportion of a high alkali Portland cement. Such reductions have been found both when Pyrex glass and chert have been used as the reactive aggregate.

(b) 30 per cent flyash or 50 per cent slag is judged to be sufficient to reduce the expansion to a level equivalent to that produced by a low alkali Portland cement.

(c) There were only small differences between the effectiveness of the flyashes. These differences correlated best with a measure of pozzolanic activity. The alkali content of the ashes may have a secondary effect but the results do not support the ASTM limit on available alkalis of 1,5 per cent equivalent Na_2O.

(d) These results are consistent with the DIN limits on the alkali content of slags for use in low alkali slag cements ie:

1,1 per cent equivalent Na_2O when the cement contains at least 50 per cent slag
or 2,0 per cent equivalent Na_2O when the cement contains at least 65 per cent slag.

Insufficient samples were tested to give further guidance on these limits.

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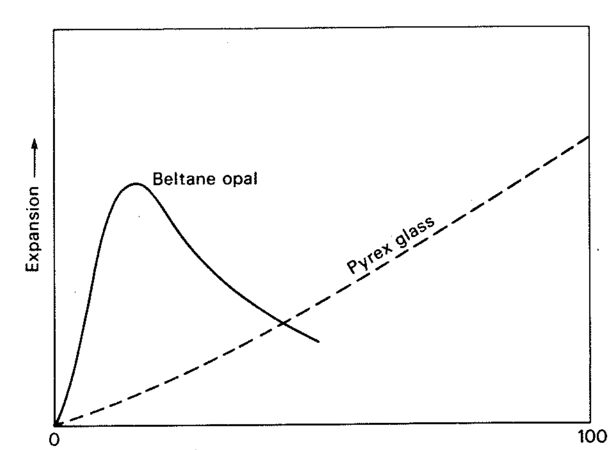
storage at higher temperature produced some reduction in expansion but probably not enough to be useful in practice. Moreover as no information has yet been obtained on the effect of temperature on the expansion of bars made with the more slowly reacting chert aggregate it is difficult to extrapolate the results of the experiments with the Pyrex aggregate to concrete made with natural aggregate.

The uncertainties inherent in drawing conclusions on the behaviour of concrete structures made with natural aggregates from laboratory experiments with a fast reacting 'standard' aggregate such as Pyrex are central to the problem of interpreting these results. In his paper to this symposium Dr Hobbs has presented results showing that when Beltane opal is used as the reactive aggregate the addition of flyash can, under some circumstances, increase expansion. Some consideration of this difference in results from the two aggregates is therefore necessary.

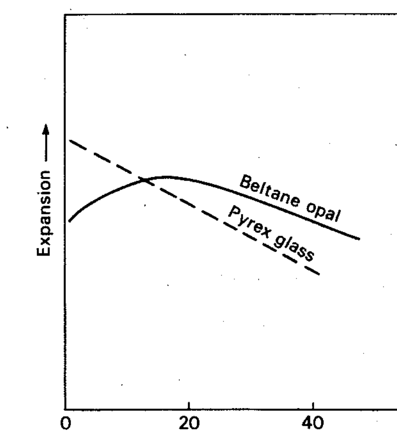
In experiments involving Pyrex or Beltane opal as alternative reactive aggregates there seem to be fundamental differences in behaviour:

(a) When, at a fixed alkali level, the amount of reactive aggregate is increased, bars containing Beltane opal show a pessimum expansion, whereas the expansion of bars containing Pyrex is proportional to the amount of Pyrex as shown below.

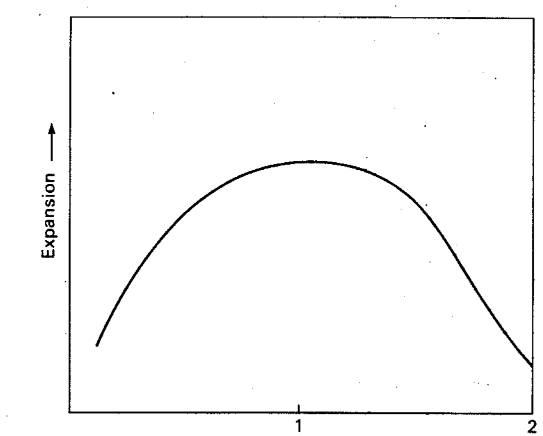


Percentage reactive aggregate

For the Beltane opal there is therefore a critical Na_2O/SiO_2 ratio at which the expansion is greatest. The existence of this critical Na_2O/SiO_2 ratio must depend on the high surface area of reactive silica in Beltane opal, which at higher reactive aggregate contents is in excess of the available alkalis. The surface area of the Pyrex glass on the other hand is low and the critical Na_2O/SiO_2 ratio is not reached even when the aggregate is 100 per cent Pyrex. If however the surface area of Pyrex is increased by grinding then the expansion is reduced and this could be regarded as a sort of artificial pessimum.



Percentage flyash



Percentage added alkali
Effect of added alkali on expansion (after Vivian[9])

(b) When flyash is added the expansion of bars containing Pyrex glass is reduced in proportion to the amount of ash added whereas with Beltane opal there is again a pessimum.

Dr Hobbs finds that the water soluble alkali content gives the best correlation with expansion of bars containing Beltane opal[8] and he also interprets the effect of adding flyash in terms of the total water soluble alkali content of the system. Thus the addition of more alkali to a mix containing Beltane opal which is at a Na_2O/SiO_2 ratio below the pessimum would initially increase the expansion. Beyond the pessimum the expansion will be reduced,

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