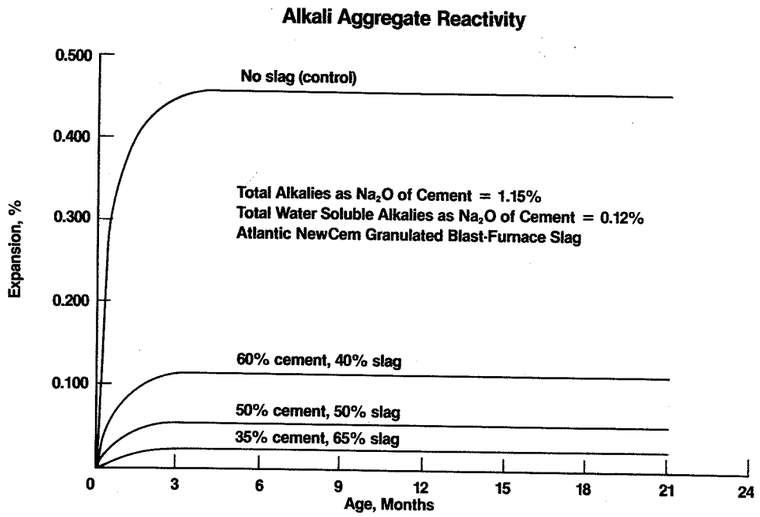

Figure 1.

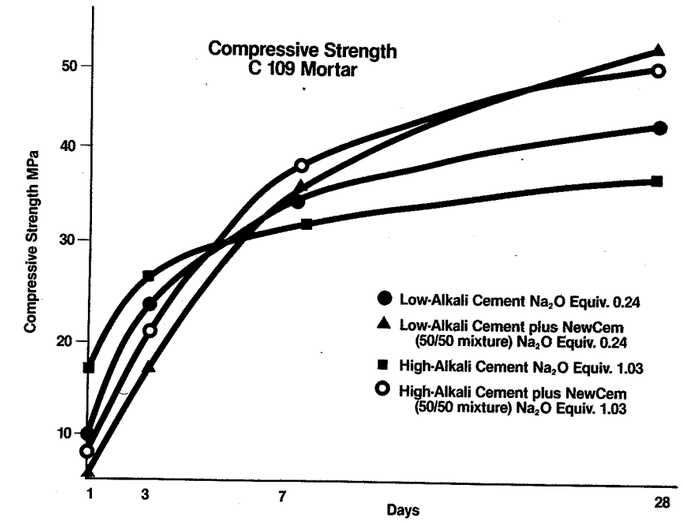

Figure 2.

THE EFFECTIVENESS OF FLYASHES AND GRANULATED BLASTFURNACE SLAGS IN PREVENTING AAR

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1. ABSTRACT

The effectiveness of slags and flyashes in preventing AAR causing damaging expansion of mortars and concretes has been assessed at BRE in a number of ways. Mortar bar expansion tests have been used with pyrex glass, beltane opal or crushed chert rock as the reactive aggregate and tests have also been carried out using concrete prisms containing a flint fine aggregate. All the tests showed that expansions were considerably reduced if sufficient flyash was used to replace the Portland cement. When beltane opal was used as the aggregate the alkali level of the ash was important and small replacement levels of high alkali ashes could increase the expansion of some mixes. The expansion of concretes containing flint aggregates may not be so sensitive to the alkali in the ash however. The more limited information on the effects of slags suggests that with UK materials a 50% replacement level is sufficient to prevent damage from AAR.

KEY WORDS - FLYASH, SLAG, AAR

2. INTRODUCTION

Since the discovery in the UK in the late 70's of deterioration due to alkali aggregate reaction there has been much interest in and debate about the possible benefits and dangers of using flyashes and granulated blastfurnace slags to reduce the possibility of damaging AAR developing in new construction.

At BRE we have assessed the effectiveness of slags and flyashes in reducing the expansion caused by AAR in a number of ways; mortar bar tests in which the reactive aggregate was pyrex glass, beltane opal or crushed chert rock and tests using concrete prisms containing flint fine aggregate. In this paper we summarise this work, concentrating on the results of the work with beltane opal and the concrete prisms which have not been presented before, and we comment on the different methods of assessment.

3. TESTS USING MORTAR BARS

In these tests 275 x 25 x 25 mm mortar bars were stored in a water saturated atmosphere at temperatures of either 38, 20 or 5°C. Length measurements recorded are the mean of two bars.

3.1 Mortar bars containing pyrex glass as reactive aggregate

The results of these tests were reported at the Cape Town conference in 1981(1). Eleven flyashes and a granulated blastfurnace slag were tested broadly according to ASTM C441 using storage temperatures of 38, 20 and 5°C. The eleven flyashes covered a wide spectrum of properties, from good to poor pozzolanas and with total alkali contents up to 4.57% equivalent Na_2O. When

used as partial replacements for a high alkali (1.06% equiv. Na_2O) Portland cement all the flyashes and the slag were found to produce significant reductions in expansion of the mortar bars compared with bars containing the Portland cement only and the extent of the reduction increased as the replacement level increased. At a storage temperature of 38°C 20% of any of the ashes or 50% of the slag reduced the expansion to a level below that produced by a low alkali (0.58% equiv. Na_2O) Portland cement. The effectiveness of the flyashes at this storage temperature was therefore greater than would be produced by an equivalent dilution of the Portland cement alkalis. The effects of the different ashes were not greatly different. Such differences as there were correlated best with a measure of pozzolanic activity and the alkali content of the ash had only a secondary effect.

3.2 Mortar bars containing chert aggregate

The main reactive component of the aggregates in concrete affected by AAR in the UK has been found to be chert. It has only been possible, however, to produce damaging expansion of mortar bars containing chert aggregates by increasing the total alkali level over and above that produced by a high alkali cement(2). The effects of partially replacing this high alkali cement plus alkali by 20, 30 or 40% of a low alkali flyash or 70% slag were also reported at Cape Town(1). Significant reductions in expansion of mortar bars stored at 38°C were produced by both the flyash and slag and 30 or 40% ash or 70% slag reduced the expansion to negligible levels.

3.3 Mortar bars containing beltane opal aggregate

In these tests the reactive aggregate was Beltane opal, a porous opaline rock from the Beltane quarry, California, which is distributed as a standard alkali reactive material by Purdue University, USA. It was used in the 150 to 300 micron fraction of the aggregate which was otherwise composed of inert basalt. The water/cement ratio of the mortars was 0.43 and the aggregate/cement ratio 2.75.

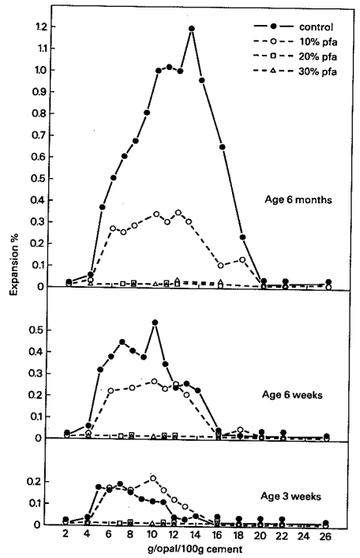

Figure 1 Mortar bars containing high alkali opc/high alkali flyash with beltane opal aggregate. 38°C

The same high alkali (1.06 equiv. Na_2O) Portland cement used in the tests with pyrex and chert aggregates was used here. In the main series of tests it was partially replaced by either 10, 20 or 30% by weight of flyash 178 (Table 1) which has a high alkali level (both total and available) and is classed as a good pozzolana. We have not yet carried out any tests in which the Portland cement is replaced by granulated blastfurnace slags in mortars with beltane opal. It was known that the expansion of mortar bars containing beltane opal varied markedly with the proportion of opal (the 'pessimum' effect) so in order to obtain a clear interpretation of the effects of the flyash a series of mixes containing different proportions of opal was made for the control Portland cement and each of the replacement levels. The results for a storage temperature of 38°C are shown in Figure 1 at ages of 3 weeks, 6 weeks and 6 months by which time expansion was effectively complete. It can be seen that at this storage temperature replacement of the high alkali cement by 20 or 30% of the ash reduces the expansion to negligible levels at any proportion of opal. With only 10% ash the mortars containing the higher proportions of opal expand more than the control at early ages but after 6 weeks storage the control expansion is greater for all amounts of opal. Overall there is a less marked pessimum for the mixes containing pfa. It can also be noticed that the control mixes containing the higher proportions of opal expand more slowly so with time the pessimum moves to higher amounts of opal.

TABLE 1 PROPERTIES OF THE FLYASHES USED

Flyash	Pozzolanicity by Lea Test[5] Strength difference MN/m^2 20–50°C 30% ash	Rating	45 μm residue	Specific surface area (m^2/kg)	Total alkalis 1)K_2O 2)Na_2O
178	17.6	Good	3.77	386	3.84 0.82
233	18	Good	5.4		3.71 0.96
237	17.4	Good	12.5	423	0.87 0.18
185	7.9	Poor	27.36	258	3.81 1.48
198	7.5	Poor	25.88	584	1.0 0.13

The expansions at 8 weeks, 3 months, and 1 year at a storage temperature of 20°C are illustrated in Figure 2. Features noticed at 38°C are now more exaggerated. The mixes containing the lower proportions of opal expand much sooner so the apparent pessimum of the control moves from 12 g opal/100 g cement at 3 months to 18 g, and as the higher opal mixes are still expanding

it may move to higher values yet. Some of the lower opal content mixes containing 10 and 20% flyash expand more quickly than the control so that at ages up to 6 months they may have equal or greater expansions to the control mixes but in most cases the control mixes then overtake them. At the lowest end of the pessimum curve however the mixes with 10 or 20% flyash equal or exceed the expansion of the control even at age 1 year. The pessimum moves to lower proportions of opal as the amounts of flyash increase; 12 g opal/100 g cement for 10% flyash and 8-12 g for 20% flyash compared with the 18 g of the control.

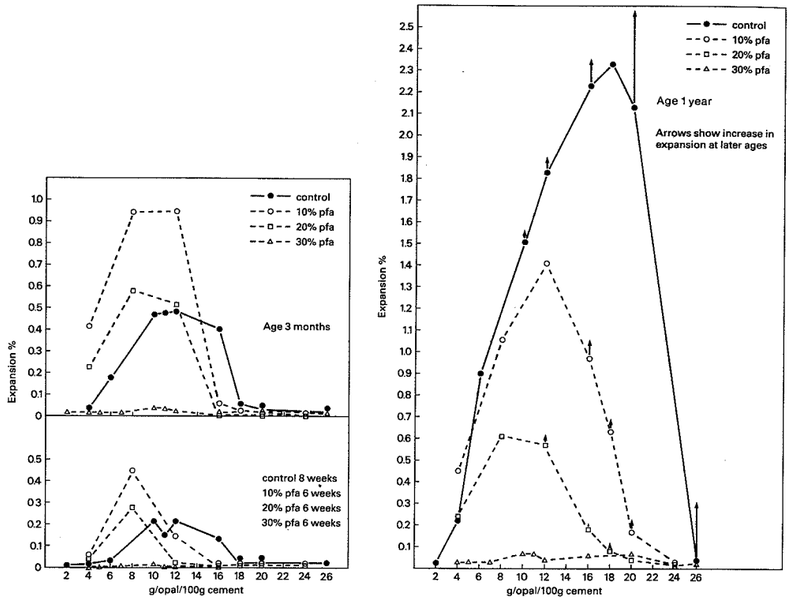

Figure 2 Mortar bars containing high alkali opc/high alkali flyash with beltane opal aggregate. 20°C

With 30% ash the expansions are small (less than 0.1% at 1 year) but definite. There is no sharp pessimum, however, and all the mixes between 10 and 20 g opal 100 g cement have similar small expansions.

The effect of the alkali level in the ash and its pozzolanicity were also investigated using three other ashes at the 20 and 30% replacement level in the mix containing 12 g opal/100 g cement. A storage temperature of 20°C was used. The properties of the ashes are given in Table 1 and the results in Figure 3.

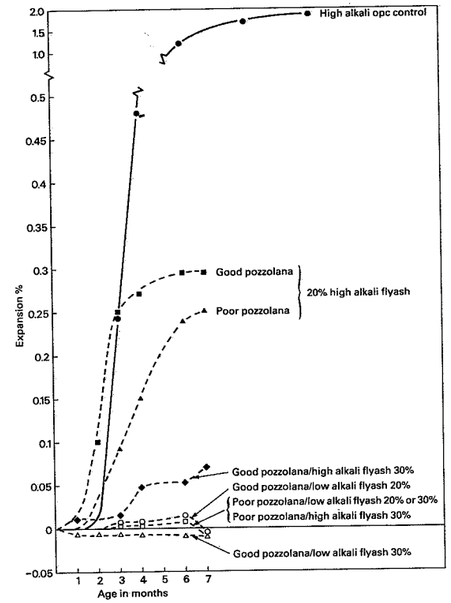

Figure 3 Effect of flyash properties on expansion of mortar bars containing 12 g opal/100 g cement. 20°C

At the 30% replacement level only the bars containing the high alkali ash 178 have expanded significantly by 7 months. Those containing the highly pozzolanic, low alkali ash 237 have shown a consistent shrinkage.

At the 20% replacement level the bars containing the high alkali ashes have expanded whereas the expansion of the bars with the low alkali ashes is insignificant.

In mortars containing beltane opal therefore, the alkali content of the flyash does seem to have a significant influence on the effectiveness of the ash in reducing expansion.

4. TESTS USING CONCRETE PRISMS

A series of experiments is in progress in which the expansion of 75 x 75 x 200 mm concrete prisms stored at 38°C either in water or in a saturated atmosphere is being used to study the reactivity of British aggregates(2). Cracking and expansion has been produced within a few months in prisms containing 20, 30 or 40% Thames Valley sand as a proportion of the total aggregate and a high content (740 kg/m^3) of the same high alkali cement (1.06 equiv. Na_2O) used in the mortar bar tests. The reactive material in this sand is flint in the coarser size fractions, the rest being mainly quartz

5, 20 and 30% of this Portland cement have been replaced by a flyash in a set of prisms containing 30% of the Thames Valley sand. For each mix duplicate prisms were made. The flyash (233) is from the same power station as ash 178 used in the mortar bar tests and similarly has a high alkali content and is a good pozzolana. A further duplicate set of prisms has been made with 600

kg/m^3 of the Portland cement giving an alkali level (from the Portland cement) equivalent to dilution of the 740 kg/m^3 mix by 20% flyash.

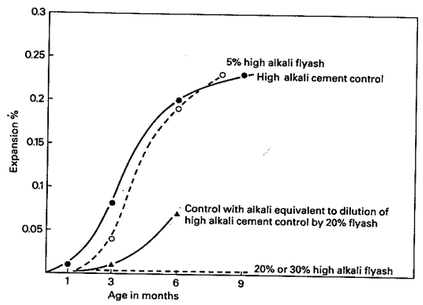

Figure 4 Concrete prisms containing high alkali opc/high alkali flyash with 30% flint/quartz fine aggregate. 38°C

It can be seen from Figure 4 that 5% replacement by flyash had little effect on the expansion but 20 and 30% replacement suppressed the expansion completely. It can also be seen that the effect of the flyash is more than is produced by an equivalent reduction in the alkali level in the concrete.

5. DISCUSSION

Comparison of the results of the different test methods described reveals both important similarities and differences. All the test methods show that expansion is reduced very significantly if a sufficient quantity of the flyash is used and where tests were carried out at both 38°C and 20°C those at 38°C show the flyashes to be more effective in reducing expansion. Tests carried out at 38°C on mortars containing beltane opal(3) or pyrex or on concrete prisms containing the Thames Valley sand show that the reductions are greater than would be produced by dilution of the cement alkalis. It may be that the pozzolanic action of the flyash which is favoured by the high storage temperature and moist conditions is playing a part in combating the alkali aggregate rection under these conditions.

The effectiveness of granulated blastfurnace slags has so far only been assessed by us using mortar bars made with either pyrex or crushed chert aggregate. The reductions in expansion seem to be approximately equivalent to the dilution of the Portland cement alkalis and with British Portland cements and slags, 50% replacement is therefore sufficient to reduce expansion to negligible levels.

The use of beltane opal in mortars produces two important results. Firstly there are some mixes, at the lowest end of the pessimum, where the replacement of the high alkali Portland cement control by 10 or 20% of the high alkali flyash results in a greater expansion. Secondly the amount of alkali in the ash seems to be important in determining the relative effectiveness of different ashes in reducing the expansion. This suggests that for the most effective control of alkali aggregate reaction involving opaline aggregates some limit should be placed on the alkali level of the

ash. It should however be noted that this result was not obtained with mortars containing pyrex aggregate.

Interpreting the results of the mortar bar tests, especially those with pyrex and beltane opal as reactive aggregates and flyash as the cement replacement, in terms of appropriate specifications for concrete is not straightforward. Mortars containing those aggregates expand by amounts which can produce cracking in concrete prisms (more than about 0.05%) inspite of quite large amounts of flyash. If the aggregate in the concrete contains an opaline or other highly reactive constituent then these results from mortars may be directly applicable to concrete. It may then be necessary to regard the ash as simply a diluent to the alkalis from the Portland cement and to restrict the alkalis in the concrete to less than 3 kg of equivalent Na_2O per cubic metre even if ash is used. If the total alkali level of the ash is restricted, however, the results suggest that 20% replacement by ash will be an adequate safeguard against AAR even with an opaline aggregate.

In the case of the aggregates such as those containing chert which have reacted in the UK however, the tests with concrete prisms show that 20 or 30% of even a high alkali ash suppressed the expansion completely. For such aggregates therefore it seems more sensible to take note of the very considerable reductions in expansion in both mortars and concrete compared with the opc controls produced by the use of flyash.

6. CONCLUSIONS

1 In all the test methods expansions caused by alkali aggregate reaction were reduced very significantly if sufficient flyash (about 30%) was used to replace the Portland cement.

2 When beltane opal is used as the reactive aggregate in mortars there are some mixes where 10 or 20% replacement by a high alkali flyash produces greater expansion than the control. Low alkali ashes were much more effective and 20% of low alkali ash suppressed expansion to negligible levels.

3 The expansion of concrete containing chert aggregate is effectively suppressed by 20% of a high alkali flyash. It may not therefore be necessary to consider the alkali level of the flyash for its use in suppressing AAR in concrete in the UK but this is being investigated further.

4 The limited amount of informtion on the effects of granulated blastfurnace slags on AAR suggests that with British Portland cements and slags a 50% replacement level is sufficient to prevent damage from AAR. More information on the effects of the alkali level in the slag on the effectiveness of the slag in preventing damaging AAR expansion is needed however.

7. ACKNOWLEDGMENT

The work described has been carried out as part of the research programme of the Building Research Establishment of the Department of the Environment and this paper is published by permission of the Director.

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THE INFLUENCE OF GROUND GRANULATED BLASTFURNACE SLAG ON THE ALKALI-REACTIVITY OF FLINT AGGREGATE CONCRETE IN THE UNITED KINGDOM

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1. ABSTRACT

A limited programme of mortar-bar testing has been carried out to evaluate the reportedly beneficial effect of adding ground granulated blastfurnace slag (ggbfs) to concrete mixtures potentially capable of deleterious alkali-reactivity. Realistic aggregate blends were used in the testing, mainly involving aggregates containing flint. Attempts were made to reproduce aggregate combinations similar to those which have sometimes proved to be alkali-reactive in the United Kingdom, including dilution of the flint component in the total aggregate by the addition of limestone. The use of ggbfs will be shown apparently to be effective at reducing expansion caused by alkali-reactivity in concrete exhibiting a high alkali content. The possibly variable influence of the slag mineralogy will be briefly considered.

Key Words: Concrete, Aggregate, Alkali-Reactivity, Blastfurnace Slag.

2. INTRODUCTION

Flint*-bearing aggregates in the UK are often found to give positive results in chemical tests for alkali-silica reactivity, and this is widely regarded as being unduly pessimistic /1/2/3/. Mortar-bar tests usually indicate only small expansions with flint aggregates, and concretes made with flint aggregates rarely show evidence of deleterious reactivity. However, a small number of examples in the United Kingdom have recently demonstrated that, in some circumstances, flint-bearing aggregates can give rise to concrete expansion as a result of alkali-reactivity /4/5/6/. These prejudicial conditions would seem to include combinations with high-alkali cement, exposure to additional alkalies, and dilution of the flint by mixing with other innocuous aggregates (such as crushed limestone), but there are possibly other factors also involved /7/.

Partial cement replacement by ground granulated blastfurnace slag (ggbfs) has been suggested by a number of research projects to be effective in preventing or reducing expansion due to alkali-silica reactivity, although the reason for the beneficial influence is uncertain /8/9/. Hobbs concludes that the principal effect is the dilution of water soluble cement alkalies /9/. Bakker suggests that the improved impermeability of concretes with cement-ggbfs binders is the main advantage /10/. Oberholster et al. believe that the effect of ggbfs is greater than can be ascribed to dilution and that chemical reaction must also be involved /11/.

In the UK to date, much of the published research on the effect of ggbfs on alkali-reactivity has been carried out using Beltane opal /9/, which is very rapidly reacting. Other experiments have used Pyrex glass /8/, which is artificial and also contains its own alkalies. It is less clear whether or not ggbfs could be expected to be effective in preventing expansion due to reactions involving flint aggregates.

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* 'Flint' is the name given to chert occurring in the Cretaceous Chalk deposits of England and nearby parts of Northern Europe.

3. OBJECTIVES

3.1. Determination of the alkali-reactivity potential of the flint aggregate samples, according to the ASTM mortar-bar method /12/, and variously using ordinary Portland cements from 'low-alkali' and 'high-alkali' UK sources.

3.2. Investigation into the effects on any alkali-reactivity of replacing the flint gravel coarse aggregate with an innocuous crushed limestone coarse aggregate, and then of varying the proportions of flint-bearing sand and limestone coarse aggregate.

3.3. Assessment of the effectiveness of ground granulated blastfurnace slag in preventing or reducing any expansion due to alkali-reactivity involving the submitted flint aggregates, with or without dilution by limestone coarse aggregate.

3.4. Brief comparison, in terms of effectiveness in preventing alkali-reactivity expansion, of ggbfs from different sources and exhibiting differing mineralogical characteristics.

4. EXPERIMENTAL DETAILS

4.1. Aggregate Samples

A supply of flint-bearing aggregates, dredged from the North Sea off the coast of East Anglia, was used for the test programme. Petrographic examination confirmed that the coarse aggregates were around 70 to 80% flint, and the fine aggregate was approximately 20% flint. These materials were considered to be petrographically similar to the flint-bearing aggregates, both land-based and sea-dredged, which are used throughout the South-East of England.

In addition, a supply of crushed Carboniferous limestone aggregate, from the Mendips in South-West England, was also used in the test programme.

4.2. Cement and Slag Samples

Two types of ordinary Portland cement were used, one being from a works typically producing 'low-alkali' Portland cement in the London area (Northfleet), and the other being from a works typically producing 'high-alkali' cement in the South-West of England (Plymstock). Two types of ggbfs were used, one designated A and being freshwater-quenched, and the other designated B and being seawater-quenched. Both of the ggbfs samples had been ground to a fineness of 350 m^2/kg as a cement replacement material for concrete.

4.3. Chemical Analyses

The two cement samples, and the two slag samples, were each chemically analysed for acid soluble and water soluble sodium, potassium and total alkalies expressed as soda equivalent. The acid soluble analyses were carried out in accordance with BS.4550:Part 2:1970 /13/, and the water soluble analyses were carried out in accordance with ASTM C114-77 /14/.

The aggregate samples, and the two ggbfs samples, were each chemically analysed for total chloride and equivalent sodium chloride. The limestone samples were analysed using the acid soluble method given in BS.1881:Part 6: 1971 /15/, whereas the flint aggregates were analysed by the water extraction

method given by the GLC /16/.

The chemical analysis results are given in Appendix A.

4.4. Potential Alkali-Reactivity Testing

4.4.1. Test programme

A total of twenty-four mortar-bar tests were carried out in accordance with the unmodified method given in ASTM C227-81 /12/.

Six tests were carried out using a blend of flint aggregates (36% 20mm, 24% 10mm, and 40% sand), and varying the cement type (Northfleet or Plymstock) and the percentage replacement by slag A (Nil, 30% or 70%).

Twelve tests were carried out using blends of crushed limestone coarse aggregate and flint-bearing sand, varying the cement type and slag replacement as above, and also varying the limestone:sand proportions (60:40, 50:50 or 70:30).

Two 'control' tests were carried out using only crushed limestone aggregates and varying the cement type (Northfleet or Plymstock).

Four tests were repeated using slag B, instead of A, in combinations employing 70% slag replacement. Two of the tests were carried out using the blend of flint aggregates, and varying cement type. The other two tests were carried out using the 60:40 blend of limestone and flint-bearing sand, and varying the cement type. In all four cases using slag B (seawater-quenched), the chloride content was deliberately enhanced by the addition of sodium chloride until the total chloride ion content of the mortar mix was equivalent to the maximum permitted by CP110:Part 1:1972 /17/; that is 0.50% chloride ion by weight of cement.

The test programme is summarised in Appendix B.

5. TEST RESULTS

The mortar-bar test results are detailed in Appendix C. The mortar-bar length change curves are shown in Figures 1 to 9 inclusive. Additional Figures 10 to 22 inclusive have also been prepared in order to make specific comparisons or to illustrate certain relationships.

6. DISCUSSION OF FINDINGS

Note: All references to 'slag' may be assumed to mean ground granulated blastfurnace slag (ggbfs).

6.1. General Considerations

The expansions recorded at 3 and 6 months in all the mortar-bar tests carried out were significantly lower than the levels of +0.05% and +0.10% respectively suggested by ASTM C227-81 /12/ as representing the levels normally exceeded by cement:aggregate combinations capable of harmful expansion.

Although measurable differences of expansion were achieved by varying the cement type, the cement:slag binder proportions, and the flint:crushed limestone aggregate blend, it seems clear that the alkali-reactivity potential of these materials is relatively low, at least as assessed by the unmodified mortar-bar test. Of course, these tests do not take into account the possible effects of exposure conditions or the local enhancement of alkali content from

external sources or by migrational movements within the concrete.

The interpretation which follows has been based largely upon the mortar-bar measurements up to 6 months. The additional mortar-bar length change readings up to 12 months have not indicated any substantive changes to the position recorded at 6 months. In fact, most of the length change curves show a small reduction in expansion between 6 and 12 months.

6.2. Flint Aggregates - Effect of Cement Type

Irrespective of whether the cement content of the binder was 100%, 70%, or 30%, the mortar-bar set made with high-alkali cement (Plymstock) always showed the greater expansion, when compared to that made with Northfleet cement. However, the numerical differences between the results for high-alkali and lower-alkali cements were not very great (see Figs. 10, 11, 12).

Comparison of the expansion curves produced by Northfleet and Plymstock cements with the limestone aggregate alone, showed a significant expansion with Plymstock, but virtually nil expansion with the Northfleet. Assuming that the limestone is totally non-reactive, this may suggest that a degree of expansion should be expected for combinations made with this high-alkali cement irrespective of the aggregate type and performance (see Fig. 7).

The relationships described above may be summarised as follows:

Binder:	100% OPC	70% OPC	30% OPC	100% OPC
Aggregate:	Flint	Flint	Flint	Limestone
Expansion at 6 months (%)				
- Plymstock	0.014	0.018	0.020	0.020
- Northfleet	0.007	0.002	0.018	-0.005

6.3. Flint Aggregates - Effect of Varying the Flint Content by Diluting with Limestone

The concentration of flint aggregate was varied by dilution with crushed limestone aggregate. In the flint:crushed limestone blends, only flint-bearing sand was used in combination with limestone coarse aggregate.

In the case of mortar-bar sets using Northfleet cement, only 3 blends were tested: 100% flint, 60% limestone:40% flint-bearing sand, and 100% limestone. In these cases, the 100% flint aggregate blend produced the higher expansion, when compared to the 40% flint-bearing sand blend, in each case. However, the expansion values were all rather low and the numerical differences between the results for different aggregate blends were hardly significant (see Figs. 13, 14 and 15).

In the case of mortar-bar sets using Plymstock cement, two additional blends were tested: 50% limestone:50% flint-bearing sand, and 70% limestone: 30% flint-bearing sand. The results were more complicated than those for Northfleet (see Figs. 16, 17 and 18).

The results for the three binder blends were not consistent. In the 30% cement:70% slag test, the results compare with those for Northfleet, with the 100% flint showing the greatest expansion, and the lower percentages of flint

aggregates showing reductions in expansion in order. The other two tests were quite different, with the 100% flint aggregate showing the lowest expansion and the lower percentages of flint aggregates showing higher expansions but with insignificant differences between them.

It may be possible to explain this behaviour by consideration of the alkali contents of the various combinations (cf. Figs. 15 and 18). Blastfurnace slag has an alkali content which is mainly acid soluble (see Appendix A). The effect of the contribution of alkalies from the slag is to increase the acid soluble alkali contents of the Northfleet blends, but to decrease the acid soluble alkali contents of the Plymstock blends; water soluble alkalies are reduced in both cases. Consequently, when 70% slag replacement is used, the acid soluble alkali contents are quite similar (0.65% and 0.80%) for Northfleet and Plymstock blends respectively. Comparison of the expansions for these mortar-bar sets (cf. Figs. 15 and 18) shows reasonable agreement, with the 100% flint aggregate test having greatest expansion. With lower alkali contents (Figs. 13 and 14) the relationship is the same but the expansion values are increased. With higher alkali contents (Figs. 16 and 17) the relationships change and expansion values slightly increase with alkali content.

If this is so, then it follows that the dilution of the flint aggregate content only has a worsening effect at higher (acid soluble) alkali contents. Conversely it is true that reducing the percentage of flint aggregate could have a beneficial influence when using lower alkali cements or when adding a high percentage (70% replacement) of slag. These tests have not identified the dilution that causes the greatest expansion increase at higher alkali contents; that is, no distinct 'pessimum' has emerged.

This suggests that the (acid soluble) alkali content has a controlling effect more important than that of alkali/silica ratio.* In the tests with alkali contents of 0.80% and lower (Figs. 13, 14, 15 and 18), increasing alkali/silica ratio leads to reduced expansions. By contrast, at higher alkali contents, increasing alkali/silica ratio seems to increase expansions.

The two tests in which 100% flint aggregate produced the highest expansions also showed the highest water soluble alkali content (by far), which may mean that water soluble alkalies have a similar controlling influence. However, comparison of the Northfleet and Plymstock combinations showing the closest water soluble alkali contents (cf. Figs. 13 and 18) did not show close similarity of expansion values.

The possible relationships between alkali contents and flint aggregate contents may be summarised as follows:

Acid sol. alkali content (%)	0.54	0.59	0.65	0.80	0.92	1.02
Water sol. alkali content (%)	0.12	0.09	0.05	0.18	0.39	0.55
	Expansion at 6 months (%)					
100% Flint aggregates	0.007	0.002	0.018	0.020	0.018	0.014
40% Flint aggregates	0.004	0.001	0.006	0.010	0.025	0.034

* Here the concept of 'alkali/silica ratio' refers only to the crude ratio between alkali content of the binder and the proportion of flint (mainly silica) aggregates in mixtures with limestone (non-silica) aggregates.

6.4. The Effect of Slag Addition - Percentage Replacement

The effect of adding ground granulated blastfurnace slag varies according to the cement type being replaced and the aggregate blend being tested. Again, the influence of adding slag is most easily studied in the combinations made with high-alkali cement. The use of slag was clearly beneficial when the alkali content was high and when the flint aggregate was diluted with limestone aggregate.

In the tests using Plymstock cement and various blends of crushed limestone:flint-bearing sand (70:30, 50:50, 60:40), the combination using 100% cement always produced the greatest expansion, and additions of slag reduced the expansion in order of percentage replacement. As explained earlier, addition of slag to the high-alkali cement reduces the (acid soluble) alkali content, so that expansion is also seen to reduce with reducing (acid soluble) alkali content. These findings would agree with the generally accepted conclusions regarding the effectiveness of blastfurnace slag in preventing deleterious alkali-reactivity, and would appear to support the notion that the principal effect is one of dilution of alkalies /9/ (see Figs. 4, 5 and 6).

In the tests using Plymstock and 100% flint aggregates, the beneficial effect of adding slag is less obvious. The expansion curves for 0%, 30% and 70% replacements are all very similar (see Fig. 2).

As discussed earlier, the result of adding slag to the Northfleet cement is marginally to increase the (acid soluble) alkali content. Consequently, the effect of adding slag to the mixes using Northfleet cement (100% flint and 60% limestone:40% flint) is to increase the expansion, so that the 70% slag replacement produces the greatest expansion. The 30% slag replacement showed lower expansion than the 100% cement but the numerical differences and the expansion values were both very small. This suggests that the addition of slag may prove less beneficial to mixes made using low-alkali cement (see Figs. 1 and 2).

The acid soluble alkali figures had a closer relationship to the expansions than did the water soluble alkali figures. In the case of the mixes using Northfleet cement, the highest expansions corresponded with the highest acid soluble alkali contents, but the lowest water soluble alkali contents. In the case of the mix using Plymstock cement and 100% flint aggregates, both lowest acid soluble and lowest water soluble alkalies corresponded with the highest expansion, but the relative numerical difference between the highest and lowest water soluble alkali contents was very much greater than that for the acid soluble alkalies. In the mixes using Plymstock cement and limestone:flint aggregate blends, the highest water soluble alkalies, like the acid soluble, corresponded with highest expansions.

6.5. The Effect of Slag Addition - Type of Slag

Slag sample A (freshwater quenched) was used in all of the testing discussed above. Repeat tests were carried out to investigate the effect of using instead the B (seawater quenched) slag sample with NaCl added to bring the total NaCl to 0.50% by weight of cement.

The comparison was only made at 70% replacement level. Where the aggregates in the mix were 100% flint, the B slag produced lower expansions than the A slag, for both Northfleet and Plymstock cements, irrespective of the higher alkali contents of the B (+NaCl) material. Indeed, the mix using Plymstock cement displayed a marginally lower expansion than that using Northfleet (Fig. 8), which could suggest that the slag itself enters a reaction with the alkalies in the cement and that this effect is more

pronounced as the alkali content of the cement rises (see Figs. 19, 20, 21 and 22).

Where the aggregates in the mix were a 60% limestone:40% flint blend (Figs. 21 and 22), the situation was reversed. The B slag produced higher expansions than the A with both Northfleet and Plymstock cements, and the latter showed a marginally greater expansion than the former.

Thus it is clear that the performances of the A and B slags were different, although the few comparative tests carried out have not fully characterised the differences. The contrasting performances appear to be sensibly independent of alkali content and could perhaps be explained as differences in the chemical activities of the slags themselves. This may indicate that some slags at least are not only inert diluents of the alkali content of the binder, but may also exhibit chemical activity.

No attempt has been made to correlate the mineralogy of the slag materials with their apparent effectiveness in preventing or reducing expansion due to alkali-reactivity. However, it seems reasonable to suppose that the mineralogical composition and texture could exercise an influence.

6.6. The Influence of Alkali and Sodium Chloride Contents

It has been shown above that there is a general relationship in most cases between alkali content and expansion. High-alkali cement produced greater expansion than low-alkali cement, even when using only limestone aggregate. The alkali content controlled the influence of altering the concentration of siliceous sand present in the aggregate; a 'pessimum' effect appeared to operate at higher alkali levels (0.92%, 1.02%), but expansion increased with proportion of flint-bearing sand present at lower alkali levels (0.80% and lower). In the blends of cement and slag, the resultant total alkali content of the binder seemed to control the expansion is most cases.

In these tests, the acid soluble alkalies seemed to have a better correlation with expansion than did the water soluble alkalies, even including the acid soluble alkalies deriving from the slags.

The effect, if any, of adding NaCl to the B slag mixes was unclear. Certainly there was no obvious increase in expansion due to the small increase in sodium. The effect of adding chloride is not known.

6.7. The Influence of Alkali/Silica Ratios

The above discussion has been based upon consideration of empirical findings or calculated alkali contents. In fact, the expansions recorded may be controlled principally by the ratio of available alkalies to reactive silica.

The 'available' alkalies are probably not adequately represented either by acid soluble or by water soluble values, but instead by a less easily defined value involving solubility in the unique conditions of a concrete pore solution and over a period of time that will vary according to the reactive aggregate component involved. The alkali portion of the alkali/silica equation is affected by the cement and by the slag (and sometimes also by the aggregates and the mixwater). The silica portion is affected by the proportion of flint aggregate in combination with limestone (assuming the sand to be totally siliceous and the limestone to be totally carbonate), and by the slag, and by the 'reactive' component of both of these. Hence the true available alkali/reactive silica ratio is difficult to ascertain, but could explain more precisely the relationships identified in the above discussion.

6.8. Other Considerations

The mortar-bars all produced expansions well below the criteria given by ASTM C227-81 /12/. Therefore, the differences of expansive behaviour discussed are all within the levels normally regarded internationally as being harmless. In this respect, it is worth noting that recent research work suggests that the unmodified mortar-bar test may not be a reliable means of predicting the potential alkali-reactivity of UK flint-bearing aggregates. It is possible, for example, that a test procedure employing concrete prism specimens may prove to be more satisfactory for British aggregates, but this is still in the process of development and evaluation /18/.

The effect of adding sodium chloride to mortar-bars is not the same as adding sodium hydroxide, although it seems likely that the addition of sodium chloride would give rise to a modest increase in the content of alkali hydroxyl ions available for reaction with silica. It is thought probable that the influence of minor contamination by sodium chloride, due to the use of seawater-quenched slag, would be subordinate to the influence of differing slag composition.

7. SUMMARY

7.1. All the mortar-bar tests carried out have suggested that the flint aggregates have a relatively low alkali-reactivity potential, even when blended with limestone aggregate and/or high-alkali cement. The additional effect of exposure conditions has not been assessed.

7.2. The high-alkali cement typically produced greater mortar-bar expansion than the lower alkali cement, even with supposedly inert limestone aggregate.

7.3. Dilution of the concentration of flint aggregate by addition of a limestone aggregate only had a worsening effect at higher alkali content levels. At total acid soluble alkali contents (of the binder) of 0.80% or less, reduction of the flint aggregate content seemed to have a beneficial effect.

7.4. The addition of ground granulated blastfurnace slag had a beneficial effect in reducing expansion when the total alkali content was high, and particularly when the flint aggregate content was diluted by the addition of limestone aggregate.

7.5. The addition of ground granulated blastfurnace slag may prove less beneficial to mixes made using lower alkali cement.

7.6. In these tests, the acid soluble alkali contents seem to have a closer correlation to mortar-bar performance than do the water soluble alkali contents.

7.7. The B (seawater-quenched) granulated blastfurnace slag behaved differently to the A slag which was used for most of the tests, but the differences have not been fully characterised.

7.8. The beneficial action of ground granulated blastfurnace slags with higher alkali content mixes seems to support the notion that the principal effect is one of dilution of alkali content. Also, the results using B slag may indicate that some slags at least could also exhibit chemical activity.

7.9. No expansive effects were ascribed in these tests to the addition of sodium chloride.

Acknowledgements

The author is most grateful to the clients of Messrs. Sandberg who have kindly given their permission to use some of the data originally produced on a commercial basis. Thanks are also due to the long-suffering Mrs. Carol Prince for typing the script and to Mr. Simon Bladon for preparing the diagrams.

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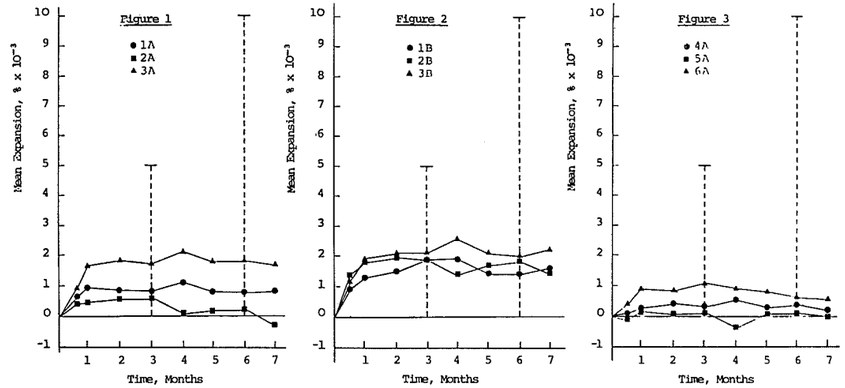


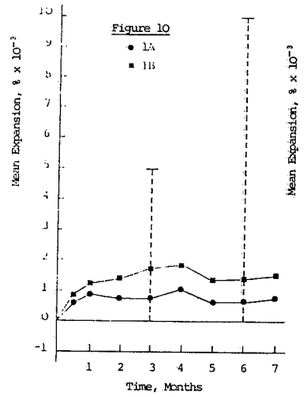
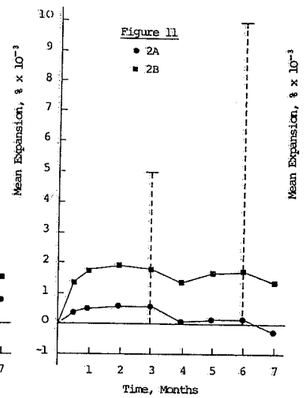


Figure 10
1A
1B
Mean Expansion, % x 10⁻³
Time, Months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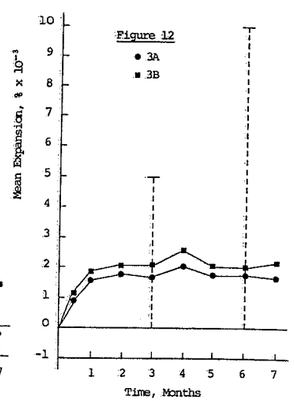
2A
2B
Mean Expansion, % x 10⁻³
Time, Months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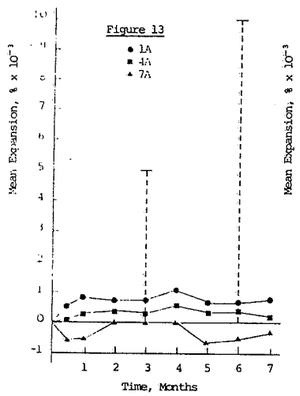
3A
3B
Mean Expansion, % x 10⁻³
Time, Months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1A
4A
7A
Mean Expansion, % x 10⁻³
Time, Months

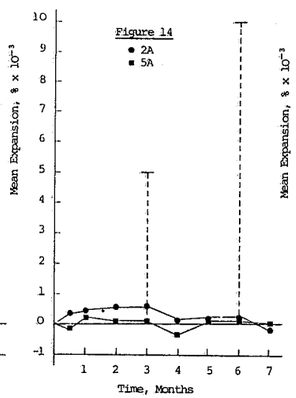
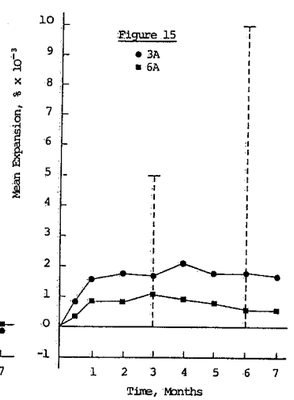


Figure 14
2A
5A
Mean Expansion, % x 10⁻³
Time, Months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3A
6A
Mean Expansion, % x 10⁻³
Time, Months

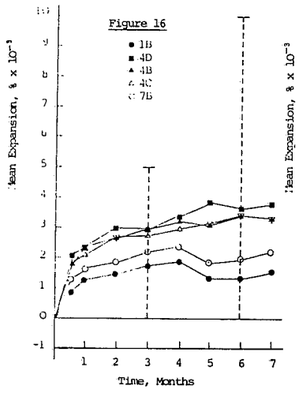
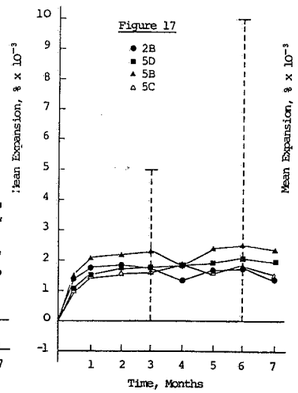


Figure 16
1B
4D
4B
4C
7B
Mean Expansion, % x 10⁻³
Time, Months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2B
5D
5B
5C
Mean Expansion, % x 10⁻³
Time, Months

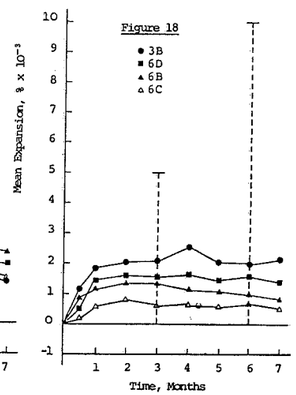
Figure 18
3B
6D
6B
6C
Mean Expansion, % x 10⁻³
Time, Months

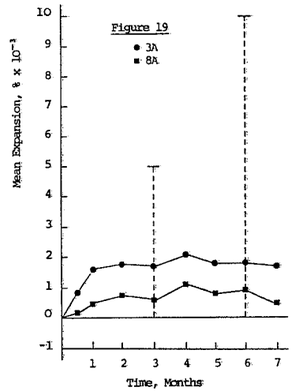
Figure 19
3A
8A
Mean Expansion, % x 10⁻³
Time, Months

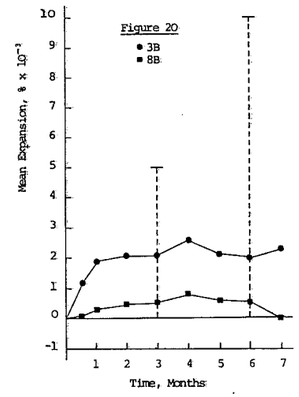
Figure 20
3B
8B
Mean Expansion, % x 10⁻³
Time, Months

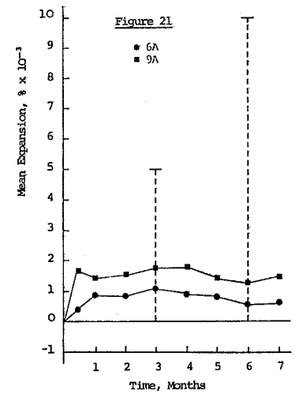
Figure 21
6A
9A
Mean Expansion, % x 10⁻³
Time, Months

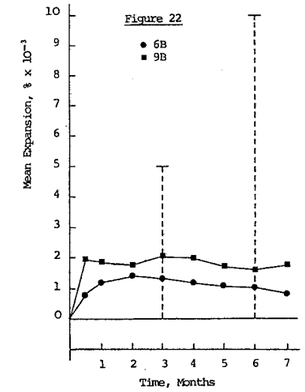
Figure 22
6B
9B
Mean Expansion, % x 10⁻³
Time, Months

APPENDIX A

Chemical Analysis Results - Alkalies and Chlorides

Sandberg Sample Ref.	Sample Details	Acid Soluble Alkalies		Water Soluble Alkalies			Total Chlorides	
		Sodium, Na_2O	Potassium, K_2O	Sodium, Na_2O	Potassium, K_2O	Total as equiv. soda	As Cl^-	As equiv. NaCl
		% by weight of dry sample						
6582	Ordinary Portland cement, ex-Northfleet	0.26	0.42	0.03	0.13	0.12	-	-
6246	Ordinary Portland cement, ex-Plymstock	0.28	1.12	0.03	0.79	0.55	-	-
4372	Ground granulated blastfurnace slag, B	0.44	0.42	0.06	0.004	0.06	0.10	0.16
4375	Ground granulated blastfurnace slag, A	0.44	0.40	0.02	0.004	0.02	0.04	0.07
6386	20-10mm flint coarse aggregate	-	-	-	-	-	0.02	0.03
6387	10-5mm flint coarse aggregate	-	-	-	-	-	0.02	0.03
6388	Flint-bearing sand	-	-	-	-	-	0.01	0.02
6389	14mm crushed limestone aggregate	-	-	-	-	-	0.02	0.03
6390	6.3mm crushed limestone aggregate	-	-	-	-	-	0.01	0.02
6391	0-5mm crushed limestone aggregate	-	-	-	-	-	0.01	0.02

APPENDIX B

Mortar Bar Programme

	BINDER			AGGREGATES***			
Mix	OPC Cement		Slag	Fine		Coarse	
Ref.*	Source**	%	%	Source	%	Source	%
			(A)				
1A	N'fleet	100	Nil	Flint	40	Flint	60
1B	P'stock	100	Nil	Flint	40	Flint	60
2A	N'fleet	70	30	Flint	40	Flint	60
2B	P'stock	70	30	Flint	40	Flint	60
3A	N'fleet	30	70	Flint	40	Flint	60
3B	P'stock	30	70	Flint	40	Flint	60
4A	N'fleet	100	Nil	Flint	40	L'stone	60
4B	P'stock	100	Nil	Flint	40	L'stone	60
4C	P'stock	100	Nil	Flint	30	L'stone	70
4D	P'stock	100	Nil	Flint	50	L'stone	50
5A	N'fleet	70	30	Flint	40	L'stone	60
5B	P'stock	70	30	Flint	40	L'stone	60
5C	P'stock	70	30	Flint	30	L'stone	70
5D	P'stock	70	30	Flint	50	L'stone	50
6A	N'fleet	30	70	Flint	40	L'stone	60
6B	P'stock	30	70	Flint	40	L'stone	60
6C	P'stock	30	70	Flint	30	L'stone	70
6D	P'stock	30	70	Flint	50	L'stone	50
7A	N'fleet	100	Nil	L'stone	40	L'stone	60
7B	P'stock	100	Nil	L'stone	40	L'stone	60
			(B)				
8A(3A)	N'fleet	30	70	Flint	40	Flint	60
8B(3B)	P'stock	30	70	Flint	40	Flint	60
9A(6A)	N'fleet	30	70	Flint	40	L'stone	60
9B(6B)	P'stock	30	70	Flint	40	L'stone	60

* Where repeat tests using B are shown, the test mix repeated is shown in parentheses.
** N'fleet = Northfleet, P'stock = Plymstock.
*** Flint = Flint gravel/flint-bearing sand,
L'stone = Limestone crushed aggregate.