THE USE OF GGBS TO PREVENT ASR EXPANSION CAUSED BY UK FLINT AGGREGATES

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In prolonged accelerated tests, cement replacement by ggbs has been found to inhibit the ASR expansion of concrete containing a reactive combination of natural UK aggregates. At 50% replacement, expansion was prevented in tests despite the addition of potassium hydroxide to compensate for any dilution of alkalis. For the conditions and materials used, the effectiveness of ggbs at controlling ASR expansion was not primarily dependent upon reactive alkali content and, for 50% replacement, the concrete alkali content does not appear to be relevant.

INTRODUCTION

It is well established that ground granulated blastfurnace slag (ggbs), either added as a separate ingredient or present as a component of the cement, has the potential to improve the durability of concrete (Douglas (1), Higgins & Uren (2), Dewar (3)). The effectiveness of ggbs in negating or reducing the detrimental effects of alkali-silica reactivity (ASR) has been recognised for more than 40 years (Cox et al (4), Barona (5)) and has been repeatedly demonstrated by practical experimentation: the literature has been reviewed by Hogan (6) and by Hobbs (7). Also, the present authors are not aware of any structures, made using concrete containing ggbs as 50% or more of the binder, which have exhibited damage resulting from ASR.

Damage attributed to ASR was first reported in the British Isles (in Jersey) in the early 1970s and examples of various concrete structures damaged by ASR in the UK mainland have been recognised from the mid 1970s (Sims (8)). The reactive aggregate constituent in most of the UK examples has been flint (ie Cretaceous chert) and most commonly when

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flint-bearing sand has been used in combination with a non-reactive coarse aggregate, such as crushed limestone. Use of 50% or more cement replacement by ggbs was recommended as one preventative measure in UK practice both by the first Building Research Establishment (BRE) digest on ASR (9) and by the first edition of the authoritative Hawkins Working Party Report (10).

The mechanisms by which ggbs inhibits the effects of ASR remain uncertain (Glasser (11), Swamy (12)). Broadly, the theories fall into three groups: i) Improved impermeability of ggbs concretes (Bakker (13)), ii) Chemical reactions which consume alkalis and/or calcium hydroxide (Smolczyk (14), Chatterji & Clausson-Kaas (15)), and iii) Dilution of the binder (and hence concrete) alkali concentration (Hobbs (16)). The effectiveness of ggbs in controlling ASR expansion could actually be a combination of these factors.

In 1982, Hobbs (16) reported experiments using mortar-bars made with high-alkali cement and opal as the reactive aggregate. He found that, "if the cement has an alkali content of 1.1% and the cement content is 550 kg/m^3, damage due to ASR may be avoided if 50% of the cement is replaced by ggbs". He concluded that ggbs acts as an 'alkali diluter' and that "ggbs may be assumed to contain no available alkalis".

Sims (17) conducted a series of mortar-bar tests using natural UK flint-bearing aggregates and similarly concluded, "the addition of ggbs 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". Sims also found that "the addition of ggbs may prove less beneficial to mixes made using lower alkali cement".

That ggbs contains variable proportions of alkalis which can be released within concrete is beyond question and has been recognised since the earliest research into the effects of ggbs on ASR expansion (4). If it is assumed that the only or principal factor involved in the suppression of ASR expansion by ggbs is the dilution of concrete alkali concentration, then the content of 'reactive' alkali in ggbs assumes particular significance.

In 1986, Hobbs (7), on the basis of a literature review and some further (concrete prism) tests, again using opal as the reactive constituent, revised his earlier conclusion and recommended that, "if tests are not possible, the effective alkali content ... of the particular slag [should be taken as] one half of its acid-soluble alkali content". This conclusion gave rise to "a strong school of thought that the alkalis in ... slag contribute to the reaction" (12).

The second BRE digest on ASR (18), which replaced the earlier digest, made unspecified reference to these research results and recommended that one-half of the acid soluble alkali content of ggbs should be included in any calculations of concrete alkali content, "until the research evidence is more complete". However, significantly, the digest added, "when a blend of OPC and ggbs containing at least 50% slag is being used the controlling factor seems to be the greatly reduced ability of hydroxyl ions to diffuse within the cement paste rather than the alkalis contributed by the cement or slag".

Pore solution analyses have also indicated that factors other than ggbs alkali content might be involved. Nixon and Page (19) found that pfa and ggbs had quite different influences on concrete pore solution chemistry, although both tended to reduce the hydroxyl ion concentration relative to mixtures with binders containing only OPC (with Na_2Oeq content of 0.6% or more): they found "little correlation" between the pore solution hydroxyl ion content and the ggbs alkali content. Similarly, Canham et al (20) concluded that "the effectiveness of ggbs's in lowering the hydroxyl ion concentrations of cement-pore liquids is not primarily controlled by the alkali content of the slag and it appears that other factors influencing the nature and composition of the CSH gel formed may be important".

Further laboratory tests were carried out by Kollek (21), again using opal as the reactive constituent, and he reached similar conclusions to Hobbs (7), that the effective alkali content of ggbs should be taken as 50% of acid-soluble alkalis. Moir and Lumley (22), using concrete prism tests and calcined flint cristobalite (cfc) as the reactive aggregate constituent, reported "significant expansion" of concretes with binders containing 50% ggbs and concluded that, "under the test conditions employed, the effective alkali contribution [as a % of the acid soluble alkalis] from the sources of ggbs investigated was closer to 100% than 50%".

Alasali (23), using concrete prism tests and fused silica as the reactive component, found that the ability of a ggbs to contribute alkali to the concrete depended upon the overall alkali content of the concrete. Alasali described a threshold concrete alkali content ("point of alkali counteraction"), which was 4.4 kg/m^3 in his tests, below which ggbs contributed alkalis and above which ggbs made no contribution.

In summary, ggbs has a variable alkali content and it seems that under certain circumstances some proportion of these alkalis might become released within concrete, especially if the concrete alkali content deriving from other sources is comparatively low. However, the extent to which any such released alkalis will promote ASR expansion remains uncertain, as all of the above cited experimental programmes using concrete specimens have employed unusually highly reactive opaline or synthetic aggregate constituents to facilitate rapid results. The expansions produced for ggbs concretes in these laboratory experiments would seem to contrast with the apparent absence of any damage reported in practice for ggbs concrete structures on a worldwide basis.

The limited test programme described in this paper was designed to investigate the performance of various ggbs concretes made using potentially expansive combinations of UK natural aggregate materials, and particularly to assess the extent to which factors other then alkali content might be involved in the suppression of ASR damage.

EXPERIMENTAL PROCEDURE AND RESULTS

General Principles

Previous investigations (17) using natural flint aggregates and ggbs were carried out using the ASTM C227 mortar-bar test (24). However, in the UK it is now recognised that the mortar-bar test can produce misleading results and a method using concrete specimens has been preferred (Sims (25)). The present laboratory programme was based upon the concrete prism test procedure issued by the British Standards Institution as a 'draft for public comment' (26).

Concrete prism test results are presented for aggregate combinations variously containing only natural marine flint aggregates and also blends of crushed limestone coarse aggregate and land-based flint-bearing sand. The marine flint aggregate mixture was selected as a combination which experience had shown to produce no deleterious expansion in practice, owing to the presence of a much greater then 'pessimum' quantity of reactive silica. It was included to provide long-term data on a control containing reactive silica but not producing ASR expansion.

In the case of the limestone/flint mixture, the intention was deliberately to create an expansive combination in order to assess the effectiveness of ggbs at preventing ASR damage.

Certain tests were repeated, with potassium hydroxide (KOH) added to the concrete mix to compensate for any alkali dilution effect of ggbs, in order further to evaluate the respective roles of alkali dilution and other factors on the efficacy of ggbs in controlling the effects of ASR. After testing, selected prism specimens were subjected to pore solution analysis and petrographical examination.

Materials

The washed marine aggregates were representatively sampled from commercial stockpiles of materials dredged from the North Sea. Compositions for these aggregates are given in Table 1.

TABLE 1 - Petrographic compositions of North Sea aggregates (Approximate %)

	20mm	10mm	Sand
Flint	91	81	35
Quartz	4	11	35
Quartzite	-	-	20
Sandstone	5	7	-
Shell	<1	1	5
Others (incl ironstone)	-	<1	5

The crushed Carboniferous limestone was from the Mendip Hills. The flint-bearing sand for use in combinations with the limestone was from the Thames Valley. These aggregates were obtained from stocks held by the BRE to ensure consistency with the earlier work using only OPC concretes carried out by Nixon and Bollinghaus (26).

The ordinary Portland cement was a 'high-alkali' cement of UK manufacture. The commercial ggbs was produced by Civil and Marine Limited (Frearson & Uren (27)). Alkali contents for these binder materials are given in **Table 2**.

TABLE 2 - Alkali contents of cement and ggbs (% by mass)

	Ordinary Portland Cement	Ground Granulated Blastfurnace Slag	
Analysis Basis:	Acid Soluble	Acid Soluble	Water Soluble
Potash, K_2O	0.90	0.39	<0.01
Soda, Na_2O	0.37	0.30	0.01
Total Alkalis as Na_2Oeq	0.96	0.56	0.01

Concrete Prism Tests

Nine concrete prism tests were carried out, using the materials combinations shown in **Table 3**. The tests were all carried out in general accordance with the BSI draft method (26) including humid storage at 38°C, except insofar as the method makes no provision for cement replacement materials.

For reference, one of the combinations [65] comprised only the high-alkali OPC and the mixture of marine flint aggregates, whilst another [55] comprised only the high-alkali OPC and the blend of limestone coarse aggregate with flint-bearing sand. Four of the combinations [56-59] comprised the same blend of limestone and flint sand, but with ggbs at various cement replacement levels from 10% to 50%.

In each of the limestone/flint sand combinations, a sand content of 40% was used, for consistency with the earlier mortar-bar work (17), whereas Nixon and Bollinghaus (26) had obtained the highest expansions with a sand content of 20%. However, in these tests, the control mix [55] yielded expansion values comparable with those reported by Nixon and Bollinghaus (ie 0.25% and 0.22% at 12 months respectively).

Finally, three selected prism tests with ggbs were repeated, with Analar grade KOH being added to the mix in compensation for the calculated dilution in concrete alkali content if it were to be assumed that the ggbs makes no contribution to the effective alkali content. In two cases [62 & 63], sufficient KOH was added to provide for complete compensation, whereas in the third case [64] KOH was added to replace about one half of the calculated dilution effect.

TABLE 3 - Concrete prism test details and results

Prism Set:	65	55	56	57	58	59	62	63	64
Aggregate Proportions, % by mass								Note 1	
North Sea	100	-	-	-	-	-	-	-	-
Mendip	-	60	60	60	60	60	60	60	60
Thames Valley	-	40	40	40	40	40	40	40	40
Binder Proportions, % by mass								Note 2	
OPC	100	100	90	70	60	50	70	50	50
ggbs	-	-	10	30	40	50	30	50	50
KOH added?	No	No	No	No	No	No	Yes	Yes	Yes
Concrete Reactive Alkali Contents, kg/m^3								Note 3	
Basis 1	7.1	7.1	6.4	5.0	4.3	3.6	7.5	7.7	5.5
Basis 2	-	-	6.4	5.0	4.3	3.6	7.5	7.7	5.5
Basis 3	-	-	6.6	5.6	5.1	4.6	8.1	8.7	6.5
Basis 4	-	-	6.8	6.2	5.8	5.5	8.7	9.7	7.5
Concrete Prism Test Results, % expansion								Note 4	
3 months	-0.01	0.00	-0.01	-0.02	-0.01	0.00	0.00	0.00	0.00
6 months	-0.01	0.14	0.01	-0.01	0.00	0.00	0.02	0.00	0.01
9 months	-0.01	0.22	0.08	-0.01	0.00	0.00	0.04	0.00	0.00
1 year	-0.01	0.25	0.09	-0.02	0.00	0.00	0.09	0.00	0.00
2 years	-0.01	0.26	0.11	-0.02	-0.01	-0.01	0.15	0.00	0.00
3 years	-0.02	0.28	0.11	-0.02	-0.01	-0.01	0.17	0.00	-0.01
4 years	-0.02	0.29	0.13	0.00	0.01	0.00	0.19	0.01	0.00
5 years	0.00	0.29	0.14	0.02	0.01	0.01	0.21	0.02	0.01
6 years	0.01	0.29	0.16	0.01	0.01	0.04	0.21	0.02	0.02

Notes

1. Crushed Carboniferous limestone coarse aggregate from the Mendip Hills and Thames Valley sand containing flint in the coarser particle size fractions.

2. The concrete mixes each contained 700 kg/m^3 binder. See Table 2 for alkali contents.

3. Basis 1: Assuming no reactive alkalis from ggbs. Basis 2: Assuming water soluble alkalis in ggbs are reactive. Basis 3: Assuming 50% of acid soluble alkalis in ggbs are reactive. Basis 4: Assuming all acid soluble alkalis in ggbs are reactive.

4. Values represent averages for sets of prisms, rounded to the nearest 0.01%.

Table 3 includes calculated concrete alkali contents for the nine combinations, variously taking the ggbs effective alkalis as nil, water-soluble, 50% of alkali-soluble or 100% of acid-soluble. The KOH compensations assume the ggbs effective to be nil (as recommended by Hobbs (16) and Hawkins (10)), so that the assumption of any higher values would mean that prism mixes 62 to 64 had been over-compensated in respect of the added KOH. The second edition of the Hawkins Working Party Report (28) considered that the water-soluble alkali content of ggbs should be taken into account, whereas the second BRE digest on ASR (18) recommended assuming 50% of the acid-soluble alkalis.

The concrete prism results up to 6 years are detailed in Table 3. Expansion curves up to 2 years for the five limestone/flint sand mixes with various ggbs contents and the three repeated limestone/flint sand mixes with added KOH are given in Figures 1 and 2.

Pore Solution Analysis

A concrete prism specimen was selected from each of three test sets 55, 62 and 63, being the non-ggbs control and the repeat tests with 30% and 50% ggbs replacement and fully compensated by KOH. The prism specimen was selected in each case to be a median in respect of expansion values measured for the set of four prisms in the test up to 2 years. These three specimens were each sub-sampled variously for pore solution analysis and petrographical examination.

The pore solution analyses were carried out at Aston University. Specimens of pore solution were expressed from the concrete, following re-saturation overnight with 15% of water relative to concrete sample mass, using a technique developed from that originally devised at Purdue University (Barneyback & Diamond (29), Nixon & Page (29)). The expressed solutions were then each chemically analysed for hydroxyl, potassium and sodium ion concentrations using titration techniques.

The pore solution analyses are given in Table 4.

TABLE 4 - Pore solution analyses (millimoles per litre)

Prism Set	Combination (see Table 3)	OH	K	Na
55	Control (no ggbs)	185	128	86
62	30% ggbs + KOH	169	118	61
63	50% ggbs + KOH	177	135	58

Quantified Petrographical Examination

A 10mm thick slice was diamond sawn from each of the three selected prism specimens, from the side and along the length of each prism. A portion from each slice was then impregnated with an epoxy resin containing a fluorescent dye and prepared as a large-area thin-section.

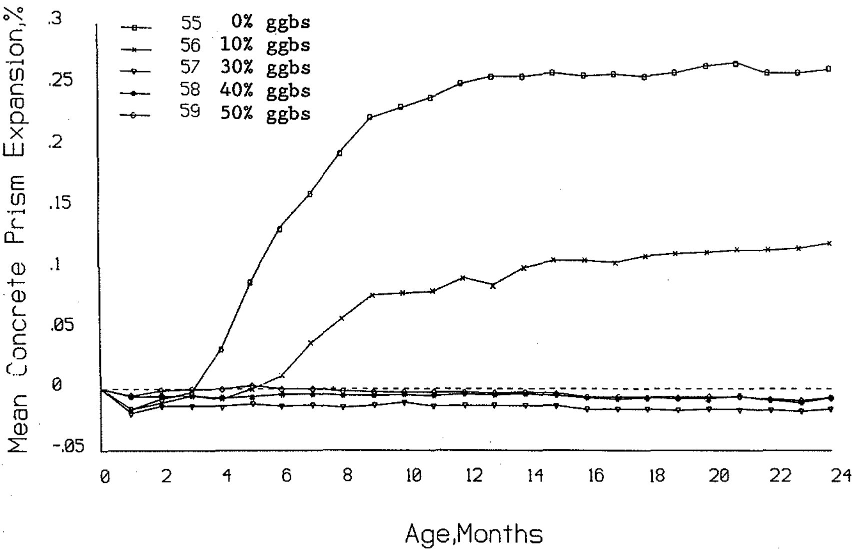

FIGURE 1 - Concrete Prism Test Expansion Curves, Mendip Limestone/Thames Valley Sand Combination

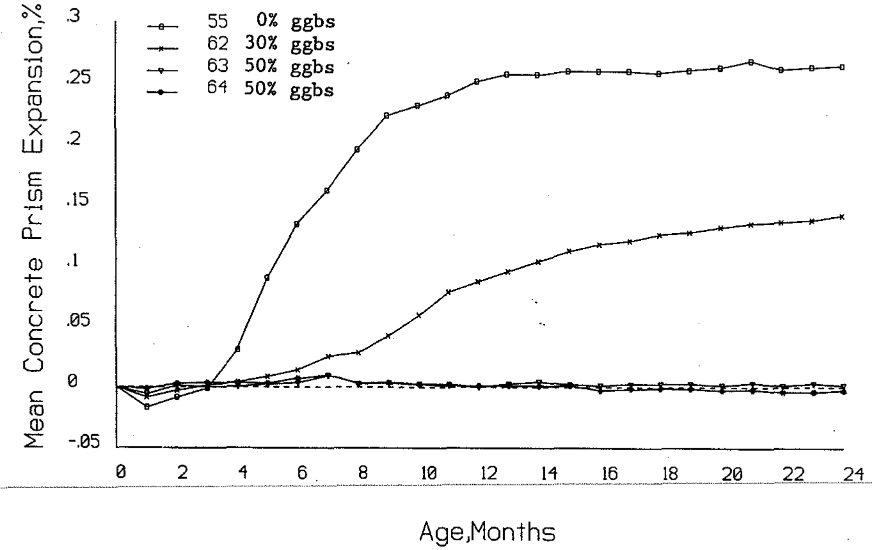

FIGURE 2 - Concrete Prism Test Expansion Curves, Ggbs Mixes Alkali-Compensated by KOH

The three thin-sections were each subjected to quantified petrographical examination in accordance with the method described by Sims, Hunt & Miglio (30). In this procedure, the large-area thin-section is divided into centimetre squares and each square is systematically examined under a high-power petrological microscope for features diagnostic or possibly indicative of ASR, including reaction sites, gel deposits and micro-cracks.

The quantified examination results are summarised in Table 5.

TABLE 5 - Quantified microscopic data (number of features per 100 cm^2)

Prism Set	Combination (see Table 3)	Reaction Sites	Gel Deposits*	Empty Cracks & Microcracks
55	Control (no ggbs)	38	399	193
62	30% ggbs + KOH	19	242	225
63	50% ggbs + KOH	11	211	91

* Total of gel deposits in cracks, microcracks and air-voids

DISCUSSION

Marine Flint Aggregate Combination

Prism set 65 represents a standard test of North Sea flint gravel (60%) and flint-bearing sand (40%) materials, using the draft BSI method (26). No expansion has been recorded even after 6 years.

Limestone/Flint Sand Combinations

Control prism set 55 represents a standard test of the crushed Carboniferous limestone (60%) and Thames Valley flint-bearing sand (40%) combination, using the draft BSI method (26). A substantial expansion of 0.25% was recorded at one year, rising to nearly 0.30% after 6 years. Such a level of movement with these natural materials is considered sufficient for assessment purposes, without having to resort to the use of highly reactive opaline or even synthetic materials which cannot be expected necessarily to behave in a manner analogous to that of natural aggregate combinations.

The three concrete mixes containing between 30% and 50% cement replacement by ggbs exhibited nil expansion at 12 months and the mix containing only 10% ggbs replacement exhibited about half the expansion of the control mix. These trends have been maintained up to 6 years. These findings confirm the potential effectiveness of partial cement replacement by ggbs at suppressing ASR expansion.

Alkali-Compensated Limestone/Flint Sand Combinations

The above findings reaffirm the conclusions of many experiments undertaken over 40 years and also seem to agree with practical experience with actual structures. However, the meaningfulness of such findings has been questioned either on the basis of "drawing premature conclusions" (22) about expansions which are only delayed, or because the reactive alkalis are not released from ggbs in concretes made using relatively high-alkali cements so that the alkali concentration is above "the point of alkali counteraction" (23).

In the latter case it is argued (Hobbs (31)) that ggbs replacement of less than 50%, for example to reduce the overall concrete alkali content to less than 3.0 kg/m^3 or to render the binder equivalent to a 'low-alkali' cement (cf various provisions of Hawkins (28)), might be less effective than expected, or even counter productive.

To investigate the first concern, over the risk of delayed expansion, the present tests have been maintained for more that 6 years, although little significant change has actually occurred since 1 year.

To assess the second concern, over the inactivity of ggbs alkalis in otherwise already relatively high-alkali concretes, additional KOH was added to certain repeat limestone/flint sand mixes made with 30% and 50% ggbs replacement levels. Providing that added KOH is as active as the alkalis deriving from OPC, these mixes were expected to show equivalent expansions to the control non-ggbs mix, if the only effect of ggbs was to dilute the concrete alkali content in a mix made using high-alkali cement. In fact, as can be seen from Figure 2, those combinations with 50% ggbs replacement continued to exhibit nil expansion, even with KOH added to equal (and probably exceed) the alkali level of the control mix. The mix with only 30% ggbs replacement did exhibit expansion when KOH was added, although it was still only about half of that exhibited by the control mix.

Only the control mix and the two fully alkali-compensated mixes were subjected to pore solution analysis and petrographical examination. The pore solution technique is not fully developed for concrete (as opposed to cement paste or mortar), also the samples had to be rehydrated and in any case were probably too few to be statistically viable. The results produced no evidence of any significant difference between the samples which had expanded and that which had not.

Quantified petrographical examination indicated substantial numbers of reaction sites and gel deposits in the control mix without ggbs. These were significantly reduced for both the mixes containing ggbs, despite the alkali-compensation by added KOH, with the 50% ggbs replacement mix exhibiting the lower values in comparison with the control, with less than one-third of the number of reaction sites and only a little more than one-half of the number of gel deposits. These reduced incidences of ASR evidence broadly correspond to the lower expansions in the prism tests, but it is notable that significant microscopic evidence of ASR is still to be found in a prism specimen which exhibited nil expansion.

CONCLUSIONS

An accelerated concrete prism test of a combination of marine flint aggregates has exhibited no expansion even after 6 years.

A control mix of crushed limestone and flint sand produced a concrete prism expansion of 0.25% after 1 year, rising to 0.3% over 6 years. This natural aggregate control mix was considered preferable to the use of unusually highly reactive and/or synthetic materials.

The effectiveness of ggbs at suppressing ASR expansion was demonstrated. Expansion was inhibited, even after 6 years of accelerated testing.

Combinations containing 50% ggbs replacement continued to exhibit nil expansion even when KOH had been added to the mix at least to equal the alkali content of the control mix.

Pore solution analyses produced no evidence of significant difference between the samples, irrespective of expansion or KOH compensation.

All the concretes exhibited microscopic evidence of ASR, even if no expansion had taken place. However, the quantities of ASR evidence were significantly reduced for the examined non-expansive mixes containing ggbs, despite the KOH compensation.

It is concluded that, for these test conditions and materials at least, the effectiveness of ggbs at controlling ASR expansion is not primarily dependent upon concrete alkali content and, for replacement levels of 50%, the concrete alkali content does not appear to be relevant.

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