

EFFECTIVENESS OF GRANULATED BLASTFURNACE SLAG IN PREVENTING ALKALI-SILICA REACTION

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ABSTRACT

In a programme covering a wide range of mixtures, three portland cements and two ground granulated blastfurnace slags (ggbfs) have been used to investigate the relationship between alkali content and ASR expansion. Length changes were monitored, for several years, on concrete prisms made with a reactive natural aggregate; the prisms were moist stored at 20°C and 38°C. Storage at 38°C was found to be an accelerated test which correlated well with storage at 20°C. At 20°C the rate of expansion was some four times slower than at 38°C. Nonetheless, there was very good consistency between the two temperatures in classifying mixtures as either 'expanding' or 'non-expanding'. Current indications are that the magnitude of ultimate exposure is less with 20°C storage than 38°C.

The mixtures containing ggbfs, tolerated much greater alkali contents in the concrete, without expansion. This effect was more pronounced for higher proportions of ggbfs. The results of the programme are discussed in relation to various rules which have been proposed to take advantage of the effectiveness of ggbfs in preventing ASR.

KEYWORDS: Accelerated tests, alkali-silica reactions, expansion, regulations, slag

INTRODUCTION

Ground granulated blastfurnace slag (ggbfs) is used as a within-mixer addition or as a component of a factory-blended portland blastfurnace cement. Its ability to prevent Alkali-Silica Reaction is well established worldwide (1). Evidence of the effectiveness of ggbfs in preventing ASR has come from numerous laboratory investigations which, almost without exception, have confirmed its ability to prevent deleterious expansion at high levels of slag content. In general the tendency for expansion reduces with increasing ggbfs content. Additional and possibly even more convincing evidence, has come from experience of actual structures. Countless structures throughout the world have been constructed using portland blastfurnace slag cement. It is the world's second most commonly used cement type and has been extensively employed for over one hundred years. However, ASR in concrete containing ggbfs is virtually unknown to us.

Regulations and advice on the avoidance of ASR vary from country to country (2). In those countries with relevant regulations and where slag cements are available, rules have evolved for the use of ggbfs as a preventative measure against ASR. Table 1 summarises these. The common factor of these approaches is that, at slag percentages greater than about 50%, more alkali is permitted in a slag cement than is allowable in a portland cement (typically nearly twice as much).

Recommendations for slag levels lower than about 50% are less well developed.

In the UK, the approach parallels a procedure for normal portland cement concretes, which limits the calculated alkali content of the concrete to less than 3.0kg/m^3 . (It should be noted that calculations are based on average alkali contents and statistical fluctuations may lead to actual contents up to about 3.5kg/m^3). For normal portland cement, the full alkali content (expressed as the sodium oxide equivalent) is included in the calculation, but for any slag present, only a proportion of its alkali is included. There are two views in the UK on the appropriate proportion of the slag alkali to include. A Concrete Society Technical Report (3) recommends that only the water-soluble alkali content of the ggbs need be counted as the reactive alkali contribution. The water-soluble alkali in ggbs is normally very small, typically less than 0.05%, and the calculated contribution from this is of little significance. However, Building Research Establishment Digest 330 (4) recommends that the contribution should be one half of the acid-soluble alkali content of the ggbs. The acid-soluble alkali content of ggbs is essentially the total alkali content, and one half of this is significant (typically 0.3%, expressed as sodium oxide equivalent).

The present programme of research was designed to try to resolve this conflict of advice. Expansion measurements are being carried out on concrete prisms containing natural UK aggregates. The chosen aggregates were a combination of flint-bearing sand and crushed limestone coarse aggregate; these were selected because ASR damage in UK structures has occasionally resulted when high-alkali portland cement has been used with such a combination. The following parameters have been varied:

- | | |
|--------------------------------------|---|
| 1) Cementitious content | (420kg/m^3 to 1000kg/m^3) |
| 2) percentage ggbs | (0% to 70%) |
| 3) alkali content of portland cement | (0.54% to 1.15%) |
| 4) alkali content of ggbs | (0.58% and 0.83%) |
| 5) added alkali | (0 to 3.8kg/m^3) |
| 6) storage temperature | (20°C and 38°C) |

Nearly three hundred specimens, corresponding to 136 different combinations of the above are being monitored.

Since a primary aim of the programme was to test the hypothesis that ggbs contributes one half of its total acid-soluble alkali to the alkali-silica reaction, the matrix of mixture designs was based on this assumption. However, a sufficiently wide range of mixtures was included to enable alternative hypotheses to be tested.

METHOD OF TEST

Prisms ($75 \times 75 \times 285\text{mm}$) were cast with stainless steel inserts for length measurement. Expansion testing followed the method given in the draft British Standard (5), with the following exceptions and additions:

Two pairs of specimens were cast from each combination; one pair was stored at $20 \pm 2^\circ\text{C}$ and the other at $38 \pm 2^\circ\text{C}$.

The specimens were wrapped in moist towelling or cloth, and then placed inside 500 gauge polythene tubing which was sealed at each end; this was then placed into a protective net and the specimens were stored horizontally.

The specimens were initially measured and weighed at 1 and 28 days. For the first two years, the 38°C specimens were measured at monthly intervals and the 20°C

specimens at 3 monthly intervals. Subsequently the time span between measurements has been increased.

The concrete mixtures were designed to produce nominal reactive alkali contents generally either 5, 6, 7 or 8kg/m³, using 3 combinations of portland cement alkali contents and 2 ggbs alkali contents. These high alkali contents, which resulted in very high cement contents were chosen to insure that at least some of the mixes containing slag expanded which would not have been the case if lower alkali levels were used. It was assumed for the purpose of calculation that 50% of the acid-soluble alkali in the ggbs was available for reaction. Details of the materials are given in Table 2 and the concrete mix proportions are detailed in a previous report (8). Mixtures that required in excess of 1000kg/m³ of cement used a total cement content of 1000kg/m³ and potassium sulphate was added to bring the total alkali to the required level. After the programme had commenced, it was found that the measured alkali content of some of the cementitious materials did not coincide exactly with the values originally indicated by the manufacturers. It is for this reason that the actual alkali contents of the mixtures do not always precisely align with the nominal values.

In all the concretes, 25% of the flint-bearing sand (ex Thames Valley) was included by volume of the total aggregate based on a mixture with a cement content of 700kg/m³. The combination of aggregates chosen has a wide 'pessimism' and it has been separately reported that similar expansions are obtained with between 20 and 40% Thames Valley sand (6) and with between 15 and 35% Thames Valley sand (7).

The results for the mixtures which have shown any significant expansion (greater than 0.05%) have previously been reported (8).

The prisms were visually examined and the crack type described, the crack width was also measured using a crack microscope.

Table 1 - Requirements under which slag cements can be used as precaution against ASR (Equivalent to low-alkali cement)

	% ggbs	Maximum sodium oxide equivalent of cementitious phase	Maximum sodium oxide equivalent of Portland cement component only
Germany	> 50	1.1%	-
	> 65	2.0%	-
Belgium	> 50	0.9%	-
	> 50	1.1%	-
France	> 60	1.1%	-
	> 80	2.0%	-
UK	> 50	1.1%	-
Japan	> 40	-	0.8%
	> 50	-	-
South Africa	> 40	-	-

'-' indicates no requirement

Table 2 - Alkali content of cementitious materials

	Sodium oxide equivalent content	
	Nominal	Measured
Portland cement 'H'	1.20%	1.15%
Portland cement 'M'	0.87%	0.87%
Portland cement 'L'	0.60%	0.54%
GGBS 'h'	0.87%	0.83%
GGBS 'l'	0.45%	0.58%

DISCUSSION

Crack Measurement and Visual examination

The smallest expansion at which cracking was noted was 0.06 and 0.09 % for the 20°C and 38°C specimen respectively. However while the 20°C specimen exhibited cracking in numerous combinations at below 0.1% expansion only two of the 38°C series exhibited cracking at below 0.1% expansion. The remainder exhibited cracking at above 0.09%. With the exception of where single large cracks were noted, the 38°C specimen exhibited larger crack widths than the 20°C specimen.

Expansion Criterion

An expansion of 0.1% was taken as a limit, above which the specimen was considered to have expanded. If the appearance of cracking is taken as an indication of deterioration, then the value 0.1% is valid of specimens cured at 38°C but may not be valid for specimens cured at 20°C.

In the 38°C specimens the shortest time to reach this expansion was 2 months, the longest time to date is 45 months. In the 20°C specimens, the shortest time to reach 0.1% expansion was 9 months. The specimens were cast over a period of time and are currently between 4.5 and 6 years old.

Effect of Temperature

Storage at 38°C accelerates ASR expansion and is advantageous for obtaining results within a realistic timescale in the laboratory. Fig 1 compares testing at 38°C with results for 20°C, which is more representative of normal ambient temperature.

For the mixtures which have expanded, the age at which they achieve 0.1% expansion at 38°C is plotted against the age to achieve this expansion at 20°C. The points with an arrow are mixtures which have achieved 0.1% at 38°C but not as yet at 20°C.

It can be seen that there is good correlation between 20°C and 38°C; the specimens at 20°C take about four times longer to reach 0.1% than those at 38°C and the

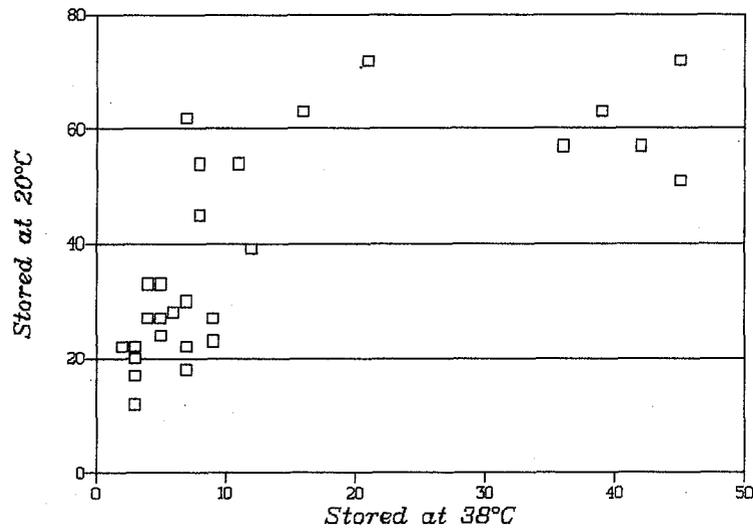


Fig 1 Months to 0.1% expansion

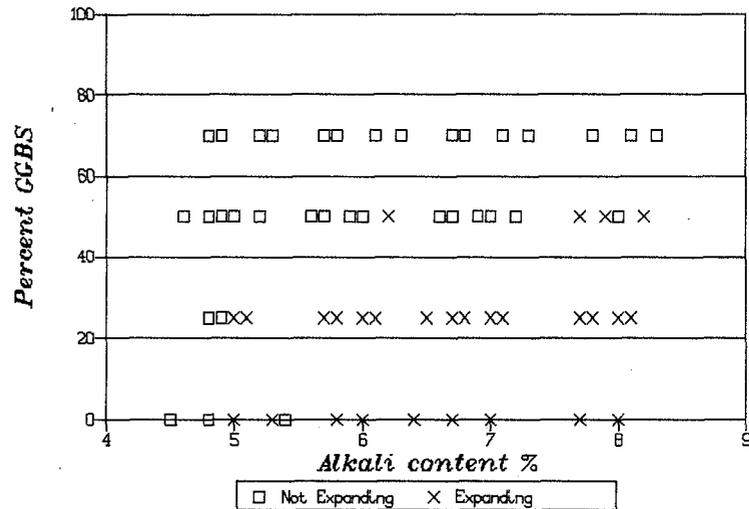


Fig 3 Reactive alkali calculated assuming half contribution from CCBS.

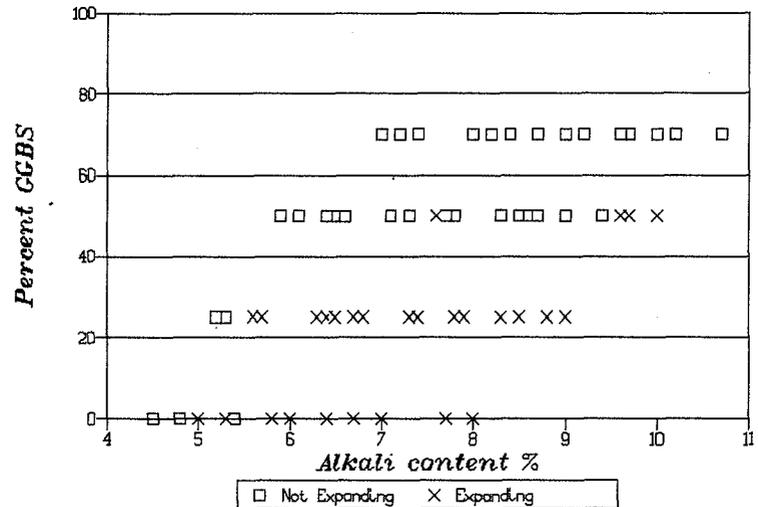


Fig 2 Reactive alkali calculated assuming full contribution from CCBS.

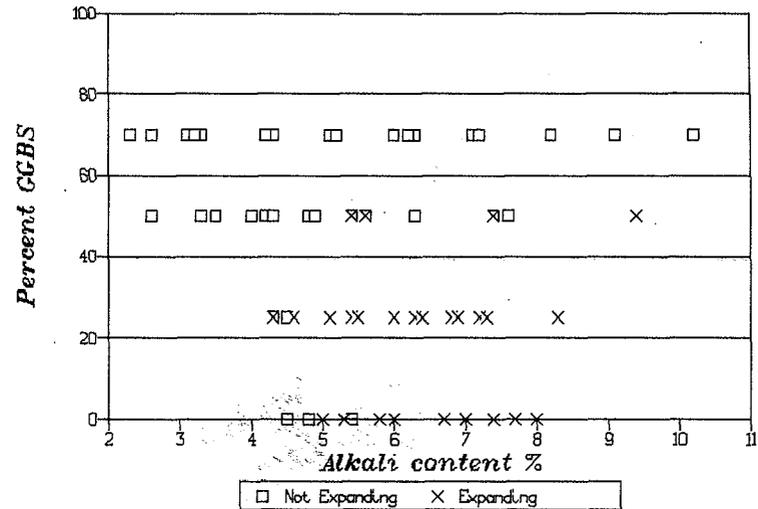


Fig 4 Reactive alkali calculated assuming no contribution from CCBS.

mixtures which have not expanded at 38°C have not expanded at 20°C either.

The magnitude of ultimate expansion varies for the various mixes. However, generally the ultimate expansion at 38°C is greater than that achieved at 20°C.

Cementitious Content and Alkali Level required for Expansion

Of the mixtures which expanded, the one with the lowest cementitious content was a mixture without ggbs, containing 458kg/m³ of high-alkali (1.15%) cement. It is worthy of note, that in terms of cementitious content, cement alkali and aggregate combination, this mixture is similar to concrete mixtures known to have suffered ASR damage in actual UK structures. For the mixtures without ggbs, the lowest alkali level for expansion was 5.0kg/m³ under laboratory conditions.

The mixtures with 25% ggbs had increased resistance to expansion. The lowest cementitious content to expand was 595kg/m³ and the lowest concrete total-alkali content was 5.6kg/m³. Even greater resistance was shown by the 50% ggbs mixtures. The lowest cementitious content to expand was 856kg/m³ and the lowest concrete total-alkali content was 8.5kg/m³. None of the 70% ggbs mixtures have expanded, even with cementitious contents of 1000kg/m³ and concrete total-alkali contents over 10kg/m³.

Reactive Proportion of Slag Alkali

The results were used to test the hypothesis that a fixed proportion of the total alkali in the ggbs might be taken as its contribution to the 'reactive' alkali in concrete.

Fig. 2, 3 and 4 are graphs of calculated 'reactive' alkali content of concrete against % ggbs and the squares indicate specimens which have not expanded and the crosses, indicate specimens which have expanded. The 'reactive' alkali content is the sodium oxide equivalent in kg/m³ and was calculated assuming: Figure 2 : full contribution from ggbs, Figure 3 : 'half' contribution from ggbs, Figure 4 : no contribution from ggbs.

If the 'reactive' alkali content is actually that calculated, then it should be possible to draw a straight vertical line separating the expanding from the non-expanding specimens. This is not possible on any of the three graphs which suggests that the concept of taking a fixed proportion of the alkali in the ggbs as reactive, is not valid. The assumption of a full contribution from the ggbs underestimates the effectiveness of ggbs in all cases. The assumption of no-contribution from the ggbs underestimates the effectiveness at ggbs levels above 35%; at 25% there can be a slight overestimate.

However, it should be noted that this slight overestimate is of the same order as the reproducibility in measuring the alkali content of OPC combined with the uncertainty in defining the critical alkali content for the normal portland cement mixes.

Benefits of ggbs

As has been discussed elsewhere (6), it is unlikely that the benefits of ggbs are simply due to a restricted availability of its alkali. Indeed, when ggbs hydrates, its alkali

will inevitably be released into the pore solution and thereafter be indistinguishable from that released from portland cement.

Several investigators have attributed the reduced ASR susceptibility of ggbs concrete, to modifications in the chemistry and permeability of the cementitious paste. They suggest (1 that the reduced permeability to alkali and/or the increased ability of the cementitious paste to bind alkali, result in ggbs concretes being able to tolerate high levels of alkali without expansion. As shown in Table 2 this is an approach taken by Germany, Belgium and France in their Regulations.

Fig 2, which takes into account the full contribution of alkali from all sources (including the ggbs), demonstrates this increased tolerance to alkali. At 50% ggbs, no expansion has occurred with mixtures containing as much as 8kg/m^3 of alkali. At 70% ggbs, no expansion has occurred even with approaching 11kg/m^3 of alkali. By comparison, normal portland cement mixtures expanded with as little as 5kg/m^3 of alkali.

UK Rules for the Avoidance of ASR

It appears that the concept of taking a proportion of the ggbs alkali as reactive, is not valid. This being the case, it will never be possible to sensibly determine the correct proportion to consider as reactive. The basic philosophy of UK rules, therefore, needs to be reconsidered. Nonetheless, for UK materials, the assumption of a zero (or water-soluble only) contribution of alkali from the ggbs appears to err on the safe side, particularly for a ggbs percent of 35% or more.

CONCLUSIONS

1. The concrete prism test produced expansion in the laboratory with a mixture similar to that known to have suffered ASR damage in the UK, in actual structures.
2. Storage of prisms at 38°C gave similar expansion behaviour to storage at 20°C but in a shorter timescale (about four times faster).
3. Storage of concrete prisms at 38°C is an accelerated test which appears to correlate well with practical situations.
4. The results are not consistent with the concept of taking a fixed proportion of the alkali in the ggbs as reactive. At 25% ggbs, an assumed contribution of either 0% or 50% of ggbs alkali would fit within the accuracy of the results. At 35% and 50% ggbs, an assumed contribution of 0% of ggbs alkali is more appropriate. At 70% ggbs there is an apparently negative contribution.
5. The concretes containing ggbs, tolerated greater alkali contents without expanding. This effect was more pronounced for higher proportions of ggbs.

6. UK Design Rules for the use of ggbs to avoid ASR, appear to be based on an incorrect hypothesis, and underestimate the effectiveness of ggbs, particularly at higher replacement percentages.

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