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INFLUENCE OF PARTIAL CEMENT REPLACEMENT BY GROUND GRANULATED SLAG ON THE EXPANSION OF CONCRETE PRISMS CONTAINING REACTIVE SILICA

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ABSTRACT

This paper reports the results of an investigation into the effectiveness of ground granulated blastfurnace slag in reducing the potential for deleterious alkali silica reaction to occur. Available expansion results are reported for concrete prisms prepared from four cements and three slags. The prisms were cured throughout at 20°C and both the influence of slag level and concrete cementitious content have been investigated. The results enable the effective alkali contributed by the slags to be estimated.

1. INTRODUCTION

The specification of concrete containing ground granulated blastfurnace slag (ggbs) is recognised in several countries [1-3] as an effective measure to reduce the risk of deleterious alkali silica reaction occurring in concrete containing potentially reactive aggregates. However, the effectiveness of ggbs, particularly at levels of cement replacement below 50%, has been questioned by several workers [4-6].

The present programme of work was started in 1986 and had as its main objective the assessment of the risk of deleterious asr occurring in concrete with binder contents in the range 275 kg/m^3 to 450 kg/m^3 when specific Portland cements were partially replaced by commercially available ggbs.

2. EXPERIMENTAL DETAILS

2.1 Reactive Silica

Previous work [4] had used mortar bars containing Beltane Opal. It has a high level of reactivity which can result in prism failure before relatively slow reacting materials such as ggbs have had an opportunity to contribute fully to hydrate structure and pore solution chemistry. For this reason, coupled also with the imminent non-availability of Beltane Opal, it was decided to seek a new, less reactive reference reactive aggregate for laboratory work.

Calcined flint cristobalite (cfc), prepared by processing flint sized between 1 and 2 mm under a controlled heating and cooling regime meets most of the requirements of a reference reactive aggregate. These requirements, and the properties of cfc are reviewed in a paper to the conference [7].

2.2 Cements and Slags

Chemical and physical data relating to the four cements and three slags included in the programme are given in Table 1. Two of the cements had high alkali contents (0.86% and 1.14% eq Na_2O) whilst the remaining two had alkali levels close to the current UK mean level of 0.65%. slags L and N had been quenched by granulation, whilst slag P had been pelletised.

Blends containing 30%, 40% and 50% slag were prepared using a dry powder blender. The strength development characteristics of the blends, when tested as concretes according to BS 4550, are given in Table 2. The two granulated slags, L and N, showed higher levels of hydraulic activity, and made greater contributions to strength during 28 days curing than the more coarsely ground pelletised slag P.

Table 1 - Chemical and Physical Characteristics of Cements and Ground Slags

	Cements				Ground Slags		
	A	B	C	D	L	P	N
SiO_2	19.3	20.6	21.6	20.0	33.0	35.4	36.1
IR*	0.20	0.13	0.51	0.70	0.41	0.36	0.13
Al_2O_3	5.7	5.0	5.3	6.8	11.8	12.7	9.9
Fe_2O_3	2.0	2.1	1.7	2.2	1.6	0.3	0.79
Mn_2O_3	0.04	0.05	0.11	0.03	0.64	0.89	0.51
P_2O_5	0.28	0.04	0.04	0.15	0.01	0.01	0.01
TiO_2	0.25	0.22	0.26	0.32	0.59	0.76	0.36
CaO	62.4	65.4	64.2	64.5	41.3	41.3	41.0
MgO	2.5	1.8	2.4	1.1	9.0	6.7	9.5
SO_3	4.0	2.4	2.8	2.9	0.13	0.14	-
S^{2-}	-	-	-	-	0.86	0.76	1.1
LOI#	1.4	1.0	0.7	0.9	0.8	0.6	0.6
K_2O total	1.22	1.13	0.79	0.69	0.51	0.60	0.35
Na_2O total	0.34	0.12	0.15	0.23	0.32	0.24	0.18
K_2O ws	1.18	0.98	0.68	0.56	0.01	0.01	0.01
Na_2O ws	0.23	0.07	0.10	0.10	0.02	0.03	0.03
eq Na_2O tot	1.14	0.86	0.67	0.68	0.66	0.63	0.41
Free lime	0.4	1.4	0.8	0.9	-	-	-
% glass	-	-	-	-	81	90	96
CMØ	-	-	-	-	1.88	1.71	1.67
Particle Densities kgm^{-3}	3110	3150	3140	3110	2950	2920	2910
SSA m^2kg^{-1}	401	362	400	391	498	451	561

* Insoluble residue determined according to BS 4550

\# Loss on ignition. Corrected for S^{2-} oxidation

$$\text{Ø CM = CM = Chemical Modulus} = \frac{CaO + MgO + Al_2O_3}{SiO_2}$$

2.3 Preparation and Treatment of Test Specimens

Concrete prisms of dimensions 75x75x270 mm and containing stainless steel reference studs were cast using standard BS granite coarse aggregate and silica sand. Cement contents of 225, 275, 350 and 450 kgm^{-3} were selected according to the alkali content of the cement and slag combination, with the objective of finding the threshold concrete alkali level above which expansion occurred. To assist in the selection of the most appropriate mixes, the alkali contribution from the slags was assumed to be $^1/2$ the total alkali content.

For each material combination, five prisms were cast containing 0% cfc and 4 levels of cfc selected to cover the expected pessimum content. The cfc, which was sized between 1 and 2 mm replaced a proportion of the sand on a volume basis. The prisms were cured and stored throughout at 20°C in an atmosphere of 100% relative humidity.

Table 2 - Strength Development of OPC's and Slag Blends

			COMPRESSIVE STRENGTH MPa				
CEMENT	SLAG	% SLAG	1d	3d	7d	28d	6m
B	-	-	11.9	22.9	31.1	38.8	43.5
	L	30	6.4	17.1	27.1	42.7	47.9
	L	40	5.6	16.2	27.0	41.1	49.6
	L	50	4.8	14.5	26.8	44.9	53.4
B	P	30	5.7	15.4	21.5	37.6	46.4
		50	3.7	11.3	16.7	36.7	50.7
A	-	-	-	33.0	38.1	46.7	48.6
	N	50	-	17.0	31.0	52.3	58.8
C	-	-	11.6	22.0	29.3	41.1	44.5
	P	30	6.3	14.0	20.5	37.2	47.9
D	-	-	13.8	26.2	34.4	41.6	45.2
	P	30	6.9	15.9	22.4	39.6	50.2

3. RESULTS AND DISCUSSION

Concrete prism expansion results are summarised in Table 3. Expansions are length changes relative to the control prism and the ultimate expansion was judged to have been reached when no further change in length occurred for a period of 200 days. In every case the expansion results relate to the prisms containing the level of cfc which gave the highest expansion. Figure 1 shows a typical set of expansion curves, in this case for concrete containing 450 kgm^{-3} of cement. Note that initially the pessimum appears to be 13% cfc, but the ultimate pessimum is close to 10% cfc.

Figures 2 and 3 show respectively the influence of slag level on the age at which expansion exceeded 0.05% and the ultimate expansion of prisms prepared from cement B. It can be seen that partial replacement of cement by slag delayed expansion and also reduced the level of expansion. However, the reduction in expansion at slag levels of 30% and 40% was slight and of even greater importance, significant expansions were found in prisms containing 50% slag, a slag level considered 'safe' by some specifications. Currently the prisms containing 50% slag are still slowly expanding at ages exceeding 600 days. In concretes with 450 kgm^{-3} of cement the incorporation of 50% slag delayed the appearance of significant expansion by factors up to 5. This illustrates the danger of drawing premature conclusions regarding the effectiveness of slag as an asr suppressant.

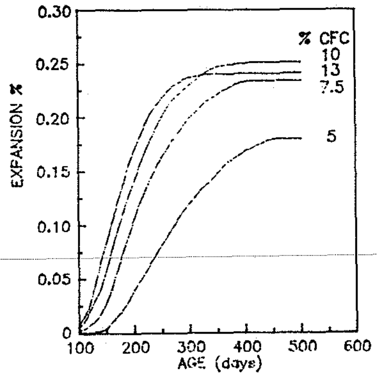

Fig 1. Concrete Exapansion Curves for various CFC Contents

Table 3 - Expansion Results

CEMENT	SLAG	% SLAG	CEMENT CONTENT kgm^{-3}	CONCRETE EFFECTIVE ALKALI LEVEL A_E kgm^{-3}		EXPANSION %		
				$k_s = ^1/_2$	$k_s = 1$	START days	ULTIMATE days	ULTIMATE %
B	-	0	450	3.87	3.87	90	330	0.32
	L	30	450	3.14	3.59	130	460	0.31
	P	30	450	3.13	3.55	160	410	0.29
	L	40	450	2.90	3.49	160	550	0.29
	L	50	450	2.66	3.40	270	$>$550	$>$0.27
	P	50	450	2.63	3.33	300	$>$600	$>$0.09
B	-	0	350	3.03	3.03	170	350	0.11
	L	30	350	2.46	2.80	180	610	0.12
	P	30	350	2.44	2.77	220	560	0.10
	L	40	350	2.28	2.74	210	600	0.12
	L	50	350	2.09	2.66	440	$>$730	$>$0.08
	P	50	350	2.06	2.61	-	-	NIL at 770 day
B	-	0	325	2.80	2.80	160	320	0.07
B	-	0	275	2.37	2.37	-	-	0.007 at 850 day
	L	30	275	1.94	2.21	-	-	0.003 at 810 day
	P	30	275	1.92	2.18	-	-	0.003 at 860 day
A	N	50	450	3.01	3.47	350	$>$650	$>$0.18
	-	0	350	4.01	4.01	70	240	0.31
	N	50	350	2.36	2.72	-	$>$750	$>$0.01
	-	0	275	3.16	3.16	140	260	0.08
	N	50	275	1.86	2.14	-	-	NIL at 720 day
	-	0	225	2.57	2.57	-	-	NIL at 570 day
C	-	0	450	3.01	3.01	100	400	0.25
	P	30	450	2.53	2.95	230	520	0.20
	-	0	350	2.36	2.36	-	-	0.03
	P	30	350	1.97	2.30	-	-	0.002 at 770 day
	-	0	275	1.85	1.85	-	-	NIL
D	-	0	450	3.05	3.05	120	310	0.21
	P	30	450	2.55	2.97	250	520	0.21
	-	0	350	2.39	2.39	-	-	0.006 at 720 day
	P	30	350	2.01	2.33	-	-	0.004 at 740 day

It is noteworthy that both the delay and the reduction of expansion was greater with slag P than with slag L. As noted earlier, slag P is less hydraulically active than slag L. What may also be significant is that slag P has a lower chemical modulus than slag L and may have a greater capacity for reducing the $Ca(OH)_2$ level in the concretes.

From examination of Table 3, it can be seen that the partial replacement of cements C and D and cement A by respectively slags P and N had a similar effect in delaying and reducing expansion. Table 3 also gives calculated values for the effective alkali contents A_E in kg/m^3 of the concretes calculated as follows:-

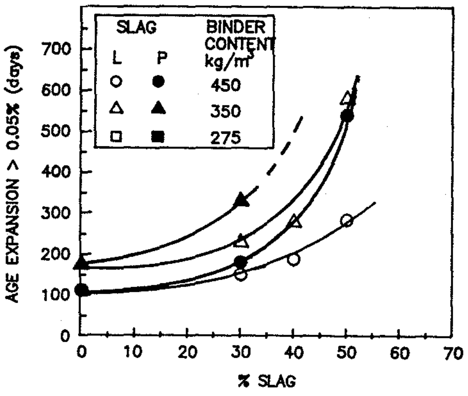

Fig 2. Influence of Slag Content on Age at which Expansion Exceeded 0.05%

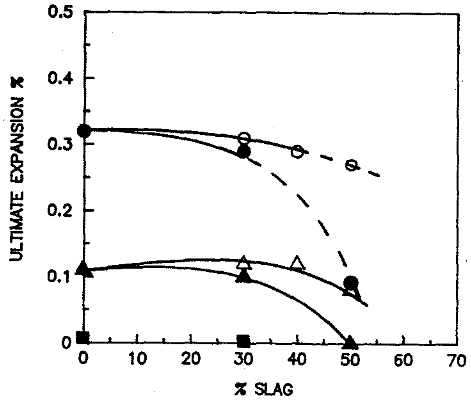

Fig 3. Influence of Slag Content on Ultimate Expansion of Prisms

$$A_E = \left[A_c\,(1-p) + k_s\,A_s\,p\right] \times \frac{\text{Cement Content kg/m}^3}{100}$$

where

A_c is the cement alkali content
p is the proportion of slag in the blend
A_s is the slag total alkali content
k_s is the proportion of slag alkalis considered to be effective.

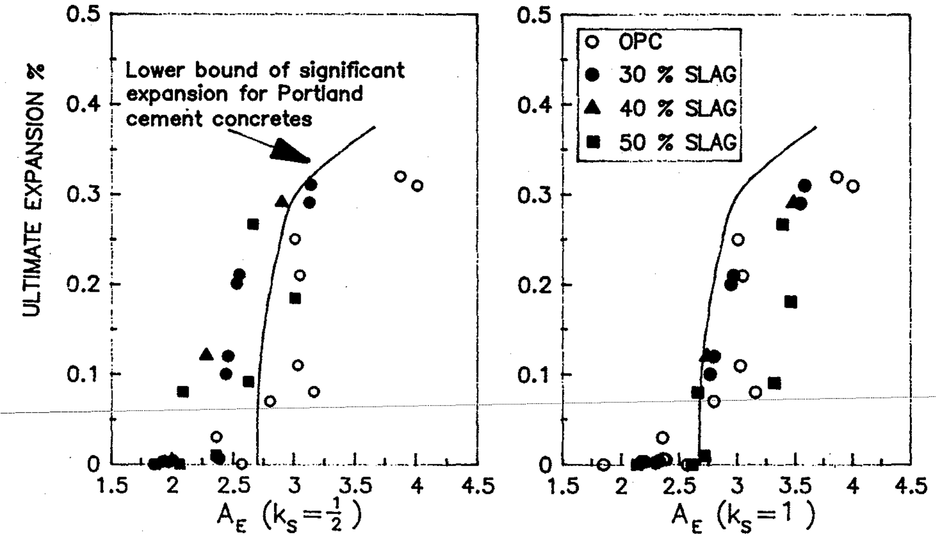

Fig 4. Relationship between Ultimate Expansion and Effective Alkali Content as Calculated by two difference values of k_s

In order to assess the proportion of slag alkalis which were effective in this investigation A_E has been calculated using K_s values of 1 and $^1/2$. Figure 4 shows the relationship between ultimate expansion and the effective alkali contents as calculated above. It can be seen that under the test conditions employed in this investigation, the effective alkali contribution from the slags was the closer to 100% than 50%.

The critical concrete alkali content above which expansion occurred was approximately 2.5 kgm^{-3} eq Na_2O. This is rather lower than that found by Hobbs [5] when using Beltane Opal in conjunction with Thames Valley aggregate, which has a higher porosity than the granite aggregate used in this investigation. Tests [7] in which the granite aggregate was replaced with a gravel aggregate have shown that the critical alkali level is increased to approximately 3.5 kgm^{-3} eq Na_2O.

4. CONCLUSIONS

1. The partial replacement of cement by ggbs significantly delayed the expansion of concretes containing calcined flint cristobalite. As a consequence, care must be taken not to draw premature conclusions regarding the effectiveness of ggbs as an asr suppressant.

2. Although expansion was delayed, the degree of expansion was little changed at ggbs levels of 30% and 40%. The prisms containing 50% ggbs have shown significant expansion and at the time of writing are still expanding slowly.

3. Under the test conditions employed, the effective alkali contribution from the sources of ggbs investigated was closer to 100% than 50%

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