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ALKALI-SILICA REACTION (ASR) AND ALKALI-CARBONATE REACTION (ACR) IN ACTIVATED BLAST FURNACE SLAG CEMENT (ABFSC) CONCRETE

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ABSTRACT

This paper examines the dimensional change of concrete prisms that were fabricated using concrete made with either sodium silicate or sodium carbonate ABFSC binder incorporating either an innocuous control aggregate, an aggregate that is known to be reactive by way of ASR or ACR in ordinary Portland cement (OPC) concrete or an aggregate that contains reactive silica although a good service record has been exhibited. The concrete prism test procedures detailed in the Canadian Standards Association (CSA A23.2-14A-94) specifications were used. The results of a parallel study of the early dimensional stability of ABFSC concrete which involved petrographic examination of concrete thin sections are discussed. It was found that, although ABFSC concrete is more vulnerable to ACR, it is less susceptible to expansion due to ASR than OPC concrete, however, expansions after one year can still be unacceptable. Unlike OPC, many large cavities form within the paste structure of ABFSC mixtures at early ages which is accompanied by shrinkage. This behaviour must be considered in the analysis.

Introduction

Activated blast furnace slag cement (ABFSC) contains only vitreous slag of the type suitable for use in blended Portland cement and a chemical activator, usually sodium silicate ($Na_2O \cdot xSiO_2$, silicate modulus $x = 0.5 - 1.5$ molar) or sodium carbonate (Na_2CO_3). Although ABFSC has been in use in Russia [1] and China [2] for many years, it is new to North America. Slag glass structure [3-8], reactivity [5,9] and the kinetics of the hydration reactions [10-15] have all yet to be adequately worked out. Generally, hydrated ABFSC consists of finer-grained C-S-H with a lower basicity and a higher degree of crystallinity [1,16] than hydrated OPC. The solubilities of the characteristically sodic reaction products are significantly lower than those of the calcic varieties common to hydrated OPC [15,17]. Consequently, hydrated ABFSC is chemically more stable and generally should be more durable. However, since the activators that are used in ABFSC result in highly alkaline pore solutions in the hardened mixtures, concern has been expressed in regards to alkali-aggregate reaction (AAR) [2,18]. Notwithstanding, experimental results are surprisingly scant [18].

This paper presents the experimental results from standard dimensional change tests

TABLE 1
Chemical and Physical Properties of Type 10 Cement and BFS

Oxides (%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	LOI	Total
Cement	20.8	4.1	2.8	62.1	4.0	0.64	0.16	2.3	1.5	98.6
BFS	33.5	12.5	0.17	39.3	11.7	0.45	0.48	1.59	0.8	100.5

Properties	Blaine Fineness (m^2/kg)	Density (kg/m^3)	Bogue Compounds (%)	C_3S	C_2S	C_3A	C_4AF
Cement	425	3150	Cement	56.1	17.4	6.1	8.5
BFS	340	2900	BFS contains no such compounds				

performed on both ABFSC and OPC concretes using aggregate from six sources in Canada. The examination of the early volume stability of hydrating ABFSC mixtures is detailed and the results are incorporated in the dimensional change analysis.

Experimental Program

Materials, Mixture Proportions and Specimen Preparation. The chemical and physical properties of the cement and slag that were used are presented in Table 1. The concrete mixture designs were specified [19] to contain 420 kg/m^3 cement at a water-to-cement ratio of 0.43 and three equal reactive coarse aggregate fractions by mass at a coarse-aggregate-sand ratio of 60/40. The sand that was used complies with ASTM C778 and the attributes of the coarse aggregate employed are presented in Table 2.

The alkali content in the OPC mixtures was boosted to 1.25% Na_2O_{equ} (by mass of cement) by dissolving NaOH in the mixing water. The alkali content in the ABFSC mixtures is attributed to the quantity and alkalinity of the activators that were used and was nominally 6% Na_2O_{equ} (by mass of slag). In all of the ABFSC mixtures the activator was dissolved in the mixing water so as to provide a saturated activator solution. As is commonly the case, sodium silicate was found to be the most effective activator whereas sodium carbonate proved to be only marginal in terms of strength development [20]. Since it has been reported that the use of a 50 : 50 lime slurry at a rate of 2% by mass of slag provides a much-needed delay in the setting time of the characteristically sticky ABFSC mixtures, the procedure was adopted. The lime slurry was blended in with the activator solution just prior to mixing. The water and solid constituents from the slurry and the activator were included in the total specified mass of mixing water and binder, or "cement", respectively.

For each mixture, duplicate 75 × 75 × 305 mm concrete prisms fitted with embedded stainless steel end-studs for comparator measurements were cast for either heat curing for 6h at 70°C or normal moist curing. The workability as determined by the slump of the concrete mixtures and the compressive strength for each mixture are presented in Table 3.

TABLE 2
Characteristics of the Coarse Aggregate

Code (Source)	Reaction Mechanism	Description (Active Phases)
N (Ontario)	Control	Crushed dolostone (innocuous)
P Kingston, Ontario)	ACR	Crushed fine-grained dolomitic limestone (dedolomitization, clay minerals)
S1 (Sudbury, Ontario)	ASR	Partly crushed gravel (≈75% reactive quartz-bearing particles)
S2 (Ottawa, Ontario)	ASR	Crushed siliceous limestone (small amount of microscopic chalcedony, black chert)
V (Edmonton, Alberta)	ASR	Crushed gravel (small amount of chert particles)
B (Calgary, Alberta)	ASR	Crushed gravel (small amount of chert particles)

Testing and Test Results. As specified for the AAR testing program and commencing at the age of 1d, the initial reading and the dimensional change was determined for each prism after a period of thermal stabilization. All of the prisms were stored in a common sealed, insulated and heated cabinet maintained at 38°C and 100% relative humidity. Duplicate sodium silicate ABFSC and OPC concrete prisms incorporating graded coarse aggregate (V type) were stored in covered lime-saturated water baths for the purpose of length measurement for the determination of early dimensional stability and a similarly-stored companion cylinder was used for petrographic purposes. These prisms were fitted with gauge points for the use of a demountable measuring device. The measurements were determined to the nearest 10 $\mu\epsilon$ per division using either this method or the comparator. The dimensional stability behaviour is presented in Fig. 1.

The dimensional change results after one year of storage for the alkali-aggregate reaction study are presented in Table 4. All of the moist-cured ABFSC mixtures exhibited a short period of shrinkage due to desiccation with the net amount (0.03% to 0.04%) and duration (14d to 28d) depending on the activator that was used and the reactive nature of the aggregate and expansive response of the concrete. In each case the initial measurement for the purpose of calculating expansion was taken at the age of maximum net shrinkage (shrinkage removed). No significant curing-related difference in expansion was found. Results for heat curing are omitted.

Thin sections were prepared using a low temperature method from solvent-treated and vacuum-dried wafers that had been sawn from the central portion of the companion specimens for the stability study. Unlike the case of OPC concrete, microscopic examination revealed that the ABFSC concrete exhibited large empty voids or cavities (≤0.9 mm) at the age of 14d which were filled during hardening at later ages.

TABLE 3
Workability and 28d Compressive Strengh[1] of OPC and ABFSC Mixtures

Mixture →	N	P	S1	S2	V	B
OPC						
Slump (mm)	75	80	50	40	90	95
f'c (Mpa)	31.8	32.4	31.5	34.6	33.6	33.8
Na_2CO_3 ABFSC						
Slump (mm)	60	60	50	55	80	75
f'c (Mpa)	31.8	24.9	28.4	27.8	29.1	27.7
Na_2SiO_2 ABFSC						
Slump (mm)	180	180	140	120	collapse	collapse
f'c (Mpa)	58.4	35.4	41.5	36.3	51.7	43.1

1 ⇒ duplicate moist-cured 100 mm (diameter) × 200 mm cylinders

Discussion

The CSA specification suggests a maximum limit of 0.04% after one year of storage. From the results obtained from the OPC concrete prisms, all of the reactive aggregate types lead to excessive expansions well beyond the recommended maximum value. In particular, the ACR specimens (P type) exhibited excessive cracking. ABFSC concrete incorporating this aggregate not only displayed nominally twice the expansion than that of the OPC concrete, but exhibited excessive cracking within a few weeks of storage. This suggests that the increased alkalinity of the ABFSC mixtures leads to increased reaction and expansion which is thought to involve dedolomitization and the exposure to water and subsequent swelling of sites consisting of dry clay minerals [21,22].

Attention should be drawn to the results of aggregates V and B. These aggregates have a good service record and have been used in practise in Alberta for many years. Local Alberta cements are considered to be low in alkalis since the current alkali equivalent is less than the commonly used 0.6% limit, but alkali contents continue to rise. Also, as the cement content in concrete increases, the alkali concentration increases. Concretes with a high cement content containing these aggregates could become susceptible to deleterious ASR expansions and, under severe exposure conditions, they may become more vulnerable to other destructive mechanisms.

In all cases of ASR, the ABFSC concretes exhibited expansions significantly lower than those displayed by the OPC concretes. In the cases of S1 and V, the expansions were found to be below the recommended limit of 0.04%. However, the S1 aggregate is a known slow/late-expanding alkali silica/silicate reactive aggregate when used in OPC concrete and could exhibit similar behaviour in ABFSC concrete at later ages. In the cases of S2 and B, the limit was

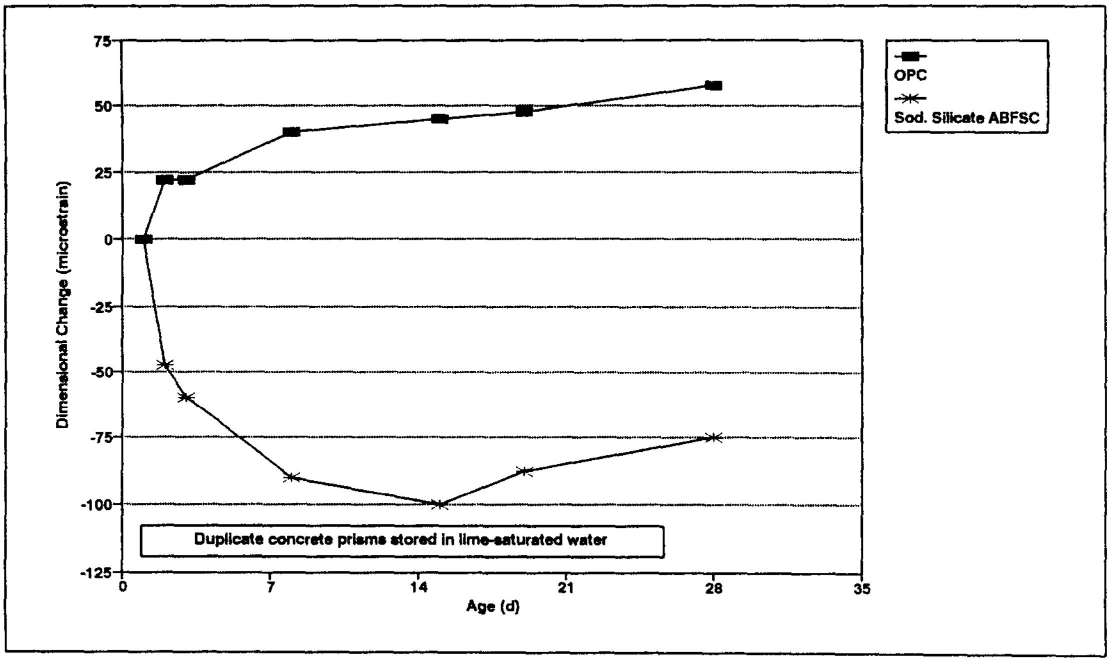

FIG. 1.
Dimensional stability of OPC and sodium silicate ABFSC concrete.

TABLE 4
Concrete Expansion Due to AAR (Shrinkage Removed)
After 1y of Storage at 38°C

	Dimensional Change (%)					
Aggregate →	N	P	S1	S2	V	B
OPC	0.033	0.305	0.125	0.192	0.089	0.124
95% Confidence Interval, ±	0.003	0.043	0.059	0.017	0.041	0.022
Na_2CO_3 ABFSC	0.023	0.720	0.024	0.085	0.032	0.042
95% Confidence Interval, ±	0.001	0.004	0.006	0.005	0.001	0.003
$Na_2O \cdot SiO_2$ ABFSC	0.030	0.617	0.021	0.082	0.028	0.059
95% Confidence Interval, ±	0.002	0.237	0.004	0.013	0.002	0.007

exceeded. Nothing can be said about the effect of activator type. With all binder contents being equal, it would appear that the markedly increased alkali content from 1.25% Na_2O_{equ} for the OPC concretes to nominally 6% Na_2O_{equ} for the ABFSC concretes leads to a higher rate of consumption of reactive silica in the aggregates during the early period of hardening. Due to the different silica-to-soda ratio in ABFSC mixtures, the pessimum effect, which is unknown in ACR, may play a part in the expansion of the concrete subject to ASR. Also, as revealed earlier, there exists an excess of large voids or cavities during the first few weeks of curing at which time the viscous alkali silica gel that is produced and expansion, if any, could be accommodated more easily than in the case of OPC concrete.

Conclusions

From the study it can be concluded that in comparison with OPC concretes, and probably due to the markedly increased alkali content, ABFSC concretes are:

1. more susceptible to deleterious expansion due to ACR and
2. less susceptible to deleterious expansion due to ASR.

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