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Communication

Resistance of alkali-activated slag concrete to alkali–aggregate reaction

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Abstract

This paper presents an investigation into durability of alkali-activated slag (AAS) concrete exposed to alkali–aggregate reaction (AAR). In the concrete prism test method (ASTM C 1293), reactive aggregates introduced in the AAS matrix reacted with alkali–silica gel formed around aggregates. The expansion of AAS concrete prisms was 0.04% after 50 days and 0.1% after 22 months. The expansion in OPC concrete was about 0.03% after 22 months of experiment. It was found that AAS concrete had lower resistance to alkali–aggregate attack than that of OPC concrete of similar grade. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Ground granulated blast furnace slag; Alkali-activated cement; Durability; Acid attack

1. Introduction

Durability of alkali-activated slag (AAS) concrete is being investigated due to some advantages that arise from its use in construction, such as utilisation of industrial by-products, low energy consumption and low greenhouse gas emission [1]. In the previous papers, durability of AAS concrete when exposed to sulfate attack and carbonation were reported [2,3]. AAS concrete had a superior durability to OPC in sulphate attack, but was more exposed to carbonation. The possibility of alkali–aggregate reaction (AAR) in AAS concrete must be investigated before its use in concrete manufacturing. AAS concrete may be susceptible to AAR due to the use of significant amounts of alkali for slag activation. Previous investigations indicated that the expansion in the AAR test was very different for two different slags, activated by the same amount of alkali [4]. For one slag, the expansion was low, comparable to that of low-alkali Portland cement, while in the other case, it was comparable to the expansion of Portland cement with high alkali content. This paper presents the study of the durability of AAS concrete produced using Australian slag when exposed to AAR.

2. Experimental

2.1. Materials

The chemical composition and properties of slag are summarised in Table 1. The blast furnace slag is a granulated product ground to fineness of about 460 m^2/kg, with the particle size range of 1–10 μm, and is neutral with the basicity coefficient K_b=(CaO + MgO)/(SiO_2 + Al_2O_3) equal to 0.93. The slag is supplied with 2% blended gypsum. The chemical composition and properties of ordinary Portland cement used in OPC concrete preparations are also detailed in Table 1.

AAS concrete was prepared using as activator a mix of sodium silicate[1] and sodium hydroxide[2] solutions with the modulus of solution (mass ratio of SiO_2 to Na_2O), M_s, equal to 0.75. The prepared AAS concrete contained 4% Na by mass in proportion to slag. The mix designs for AAS and OPC concrete specimens were shown in Refs. [2,3]. The AAS concrete had a nominal strength of 40 MPa at 28 days. The water to binder (w/b) ratio for AAS was fixed to 0.5. Performance of AAS concrete samples was compared to OPC samples with a nominal compressive strength of 40 MPa at 28 days, and w/b = 0.5.

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[1] PQ Australia. Sodium silicate solution grade D, wt. ratio SiO_2/Na_2O = 2, %Na_2O = 14.7, %SiO_2 = 29.4.

[2] Ajax Chemicals, 60% w/v water solution.

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Table 1
Composition of slag

Oxide (%)	Slag[a]	Cement[b]
SiO_2	35.04	19.9
Al_2O_3	13.91	4.62
Fe_2O_3	0.29	3.97
CaO	39.43	64.27
MgO	6.13	1.73
K_2O	0.39	0.57
Na_2O	0.34	0.67
TiO_2	0.42	
P_2O_5	<0.1	
MnO	0.43	
SO_3	2.43	2.56
Sulphide sulphur as S^{2-}	0.44	
Cl	80 ppm	
Loss on ignition	1.45	2.9
Bogue compounds (%)		
C_3S		64.2
C_2S		9.3
C_3A		5.7
C_4AF		12.2
Fineness (m^2/kg)	460	342

[a] Steel Cement, Port Melbourne, Australia.

[b] Type I/II, Geelong, Victoria, Australia.

2.2. Test procedures

A number of tests are available for an evaluation of the potential alkali reactivity of aggregates, and the reactivity of a particular cement–aggregate combination, such as the mortar prism test (ASTM C 227), the concrete prism test (ASTM C 1293–95), the quick chemical test (ASTM C 289) and the rock cylinder test (ASTM C 586). The concrete prism test is regarded as a more suitable and accurate indicator of the performance of the material in actual concrete, since the same mix can be used in laboratory specimens as for a proposed structure [5]. Thus, in this study, the concrete prism test was used to assess the susceptibility of AAS concrete to AAR.

In the concrete prism test, the concrete prisms of 285 × 75 × 75 mm in size are cast, and their expansion is measured. In this test, nonreactive sand is used when evaluating a coarse aggregate. The concrete prisms have to be stored in moist conditions at 38 ± 2°C. The expansion has to be monitored up to 18 months. The current experience is that a testing period of 2 years (with a 0.04% expansion limit) is sufficient for evaluation of concretes containing fly ash or slag, but a particular attention should be paid to the rate of expansion toward the end of the testing period [6].

Reactive coarse aggregates from Queensland, Australia were used in the experiment, which was carried out according to the concrete prism test, ASTM C 1293–95. The concrete prisms (285 × 75 × 75 mm) were cast from mixes of OPC or AAS, sand and the reactive coarse aggregates, and their expansion was measured periodically. For comparison, OPC and AAS concrete prisms with nonreactive aggregates were prepared. A minimum of three prisms were used for each type of concrete. The prisms were demolded 24 h after casting and placed in plastic containers with sealed lids, and a certain amount of water at the bottom. The containers were held at 38°C; the prisms were kept in a vertical position, without touching the water. The expansion was monitored up to 22 months.

Microstructures of samples exposed to tests were studied by a SEM (JEOL JSM-840 A) equipped with an EDS analyser (Oxford Image Analysis). The studies utilised backscattered electron imaging (BEI) of polished cross section. Specimens were cut from the concrete and polished for examination of the surface and subsurface region for evidence of deterioration.

3. Results

Alkali–aggregate reactivity was tested in AAS and OPC concrete specimens over 22 months. Throughout this period, no visual signs of deterioration in OPC samples were observed. To the end of this period, some map cracking on the surface of AAS samples became evident.

Figs. 1 and 2 show the expansion measured for AAS and OPC concretes over 22 months of storage. The expansion in AAS concrete was high from the start of the experiment, and reached 0.04% after first the 50 days. Then the rate of expansion was slowed down up to 300 days probably due to increased strength of AAS concrete, and after 12 months, it was approximately 0.045%. In the next 10 months, expansion renewed its growth and reached 0.1% at 22 months. Thus, the expansion in AAS concrete was above the limit of 0.04% at 12 months set by the standard ASTM C 1293–95. On the contrary, expansion in OPC concrete was slow and did not reach 0.03% after 22 months, which was within the limit set by the standard. The measurements of the length evolution of

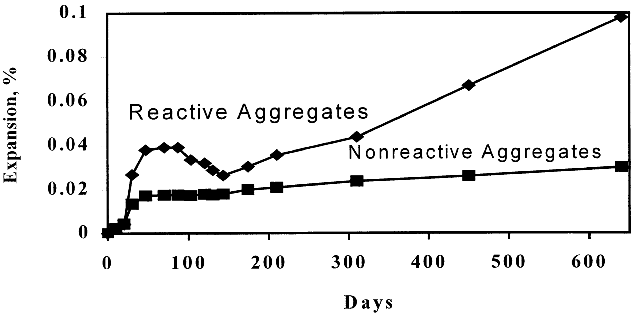

Fig. 1. Expansion measured in AAS concrete in the concrete prism test of AAR (ASTM C 1293-95).

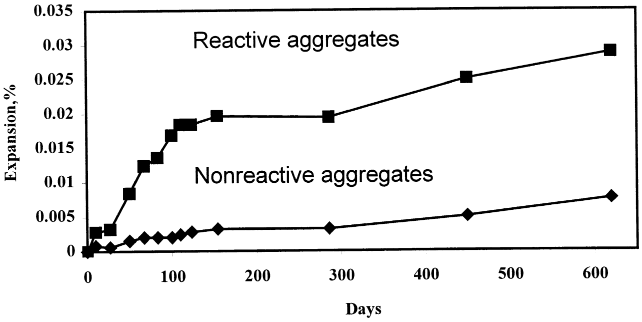

Fig. 2. Expansion measured in OPC concrete in the concrete prism test of AAR (ASTM C 1293-95).

the concrete prisms showed that expansion in AAS concrete was higher than that in OPC concrete, especially during the first month of the experiment. The high expansion in AAS concrete was attributed to the high content of alkali in the system. The decreased expansion rate in AAS specimens after the second month of the experiment was associated with the continuing hydration and the increase in the compressive strength of the concrete samples.

Four samples of AAS concrete of different age with reactive aggregates were examined using SEM BEI. The samples showed formation of silica gel around some aggregates (Fig. 3). There were only few microcracks in areas of gel accumulation. The EDS analysis of the areas around the aggregates (Fig. 4) showed presence of Si, O and small amounts of Ca, Na, Mg and Al. There were few microcracks in the paste not associated with alkali–silica gel formation. The detected cracks were probably the result of shrinkage. Only few microcracks were caused by alkali–silica reaction.

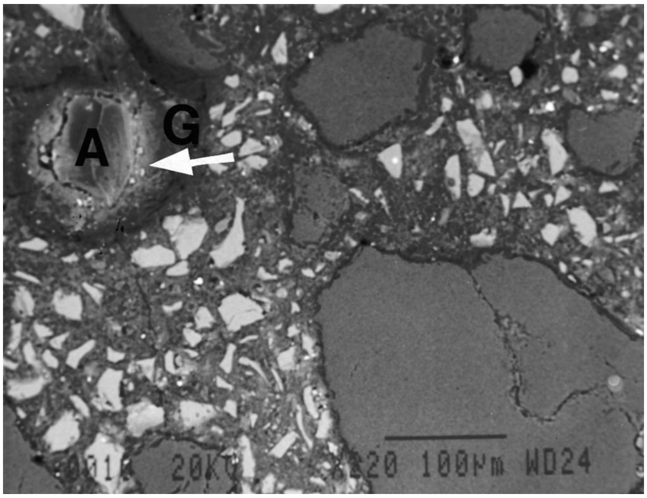

Fig. 3. BEI of the interior region of AAS concrete with the reactive aggregates after 10 months from the start of experiment. A, Reactive aggregate; G, alkali–silica gel. The arrow shows the region analysed by EDS (Fig. 4).

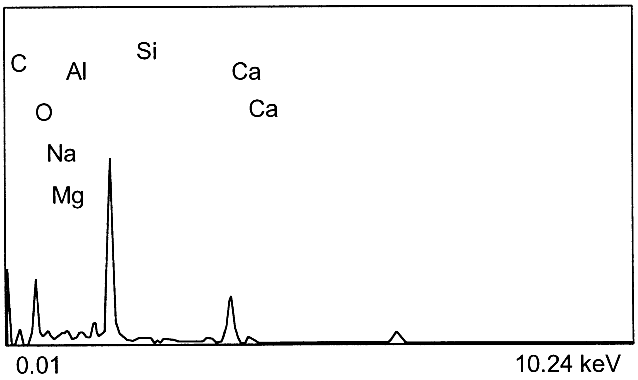

Fig. 4. EDS spectrum of the interior region of AAS concrete with the reactive aggregates shown in Fig. 3.

4. Discussion

There are evidences of AAR in AAS concrete. The expansion in AAS concrete was above the limit set by the standard, and the examination in the SEM showed formation of an alkali–silica gel near the aggregates. The AAS concrete pore solution has a high content of alkalis from slag activators, and the aggregates containing reactive silica used in AAS concrete were attacked by alkalis from the pore solution. This reaction induced the formation of the alkali–silica gel (Fig. 3), which led to the destructive expansion in the concrete. Fig. 3 shows some microcracks developed in the area of gel accumulation. On the concrete surface, pop-outs and weeping out of silica gel were not evident, but map cracking started to develop towards the end of the experiment.

The expansion in OPC concrete after 12 months was low, and it was about 0.03% after 22 months (Fig. 2), showing that the aggregates used in the experiment were not very reactive. This sets a direct contrast to AAS concrete that was found to be susceptible to deterioration from AAR. The previous investigation by Metso [4] revealed very different susceptibility to AAR of two AASs having the same level of alkali. In AAS, strength increases with the content of alkali in activator (approximately up to 8% of Na_2O equivalent) [7,8]. However, the increase in the Na content rises the possibility of AAR. Thus, durability of AAS concrete with reactive aggregates depends on these two processes. The deterioration of concrete from AAR also depends on reactivity of aggregates. In some cases, concrete may not deteriorate due to high concrete strength and low reactivity of aggregates.

The investigation of AAR reaction in F-cement (slag + F-admixture, containing about 2% Na of the slag weight) showed that increasing sodium concentration in the activator of slag strengthens the alkali reaction sensitivity of mortars [9]. However, the alkali reactivity of F-cement did not appear greater than that of ordinary Portland cement.

5. Conclusions

The investigation of durability of AAS concrete examined the performance of AAS concrete exposed to AAR. It was found that AAS concrete is more susceptible to deterioration from AAR than OPC concrete of similar grade. The mechanism of deterioration involved formation of alkali–silica gel near reactive aggregates, expansion and cracking of concrete. The experiments showed that expansion in slag concrete may be mitigated by rapid strength development; thus, observation of slag samples over a 2-year period is essential.

Acknowledgments

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