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Communication

Strength and shrinkage properties of alkali-activated slag concrete containing porous coarse aggregate

Frank Collins *, Jay G. Sanjayan

Department of Civil Engineering, Monash University, Clayton, Victoria 3168, Australia

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Abstract

An investigation was conducted that examined the effects of internal curing of alkali-activated slag concrete (AAS) by replacing normal weight coarse aggregate with fully saturated blast-furnace slag coarse aggregate. The slow release of moisture from the porous aggregate provides ongoing internal curing of concrete. The study showed that, under drying conditions, the compressive strength was improved and the drying shrinkage was significantly less (40% less than AAS containing normal weight coarse aggregate).

Keywords: Mechanical properties; Shrinkage; Aggregate; Alkali-activated cement

The influence of curing on the strength development and drying shrinkage of alkali-activated slag concrete (AAS) is significant. However, structural concrete receives minimal curing during typical construction. This paper reports the results of an investigation in which the characteristics of AAS were examined after internal curing by incorporation of saturated porous coarse aggregate into the concrete.

The strength development of AAS is sensitive to the type of curing environment. Little difference in strength is recorded after air storage at 95% and 70% relative humidity (RH) [1]. However when stored below 50% RH the strength development stops after 28 days, and the strength can be 10% to 35% that of samples cured in air at 70% to 95% [1–3]. Hakkinen [4] showed that dry-exposed AAS displays a size effect whereby the strength of larger samples (up to 150-mm diameter cylinders) is less affected than smaller samples by surface microcracks caused during drying. For RH >70% the drying shrinkage for AAS concrete is similar to ordinary Portland cement (OPC) concrete [2], whereas, at RH of 33% and 50%, the drying shrinkage is significantly greater [2,5].

Weber and Reinhardt [6,7] report that 25% replacement of coarse aggregates by saturated porous expanded clay aggregates significantly improves the strength and reduces drying shrinkage of high-strength OPC concrete during exposure to air. The slow release of moisture from the saturated porous aggregates provides ongoing curing of concrete from the inside. Reduction of drying shrinkage from 7% to 30% has been reported [8–10] for OPC concrete, which incorporates air-cooled blast-furnace slag (BFS) as the coarse aggregate. The general use of lightweight coarse aggregate in AAS was reported by Talling and Brandstetr [11], although not in relation to strength development and shrinkage under drying conditions.

1. Experimental programme

The chemical composition and properties of the cementitious binders are summarised in Table 1. The binders used are ground granulated BFS (slag) and OPC cement. The term water-to-binder (w/b) ratio is used instead of the water-to-cement ratio (w/c) to include both the binders mentioned. The slag is supplied with gypsum (2% SO_3), which is blended with the slag. The activators and adjuncts utilised were powdered sodium metasilicate and hydrated lime.

The dry powdered silicate activator was preblended with the slag in the dry form before use in concrete manufacture. The hydrated lime was added to the mix (1% mass of slag) in the form of slurry. The slurry was added as a 1:3 parts water mixture.

The normal weight aggregates consisted of 14-mm maximum size basalt and river sand. The porous coarse aggregate consisted of air-cooled BFS. The properties of the aggregates are shown in Table 2.

Proportioning of the BFS concrete was based on achievement of very similar total grading curve to concrete contain-

* Corresponding author. Tel.: 61-3-990-54958; Fax: 61-3-990-54944; E-mail: frank.collins@eng.monash.edu.au.

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Table 1
Properties of cementitious materials

Constituent/property	Slag	OPC
SiO_2 (%)	35.04	19.9
Al_2O_3 (%)	13.91	4.62
Fe_2O_3 (%)	0.29	3.97
MgO (%)	6.13	1.73
CaO (%)	39.43	64.27
Na_2O (%)	0.34	—
TiO_2 (%)	0.42	—
K_2O (%)	0.39	0.57
P_2O_5 (%)	<0.1	—
MnO (%)	0.43	—
Total sulfur as SO_3 (%)	2.43	2.56
Sulfur as S^{2-}	0.44	—
Cl (p.p.m)	80	—
Fineness (m^2/kg)	460	342
Loss on ignition (%)	1.45	2.9
Time to initial set (hs)	N/A	2.0
Strength of 70 × 70 × 70 mm mortar cubes (MPa)		
3 days	N/A	32.7
7 days		42.0
28 days		54.1

Table 3
Summary of concrete mixture proportions (kg/m^3)

Constituents	OPC-basalt	AAS basalt	AAS-BFS
OPC	360	180	—
Slag	—	180	360
Free water	180	180	180
w/b	0.5	0.5	0.5
Fine aggregate	830	830	830
Basalt coarse aggregate (14 mm)	1130	1130	—
BFS coarse aggregate (14 mm)	—	—	990
Air content (%)	0.5	1.2	1.6

ing normal weight aggregate, and corrections to the mixture proportions were based on the different densities of the coarse aggregate types. The BFS aggregate was stored in sealed drum containers and presaturated with water for 4 weeks before use in concrete making. At 24 hours before concrete mixing, the excess water was drained from the containers, followed by resealing until concrete manufacture.

The concrete mixture proportions are summarised in Table 3. Allowance for moisture content in the aggregates (based on saturated and surface dry conditions), powdered sodium silicate activator, and hydrated lime slurry was made to ensure correct free-water content in the mix.

Samples were made for laboratory testing as follows:

1. Cylinders (100-mm diameter × 200-mm length) were made in accordance with AS1012 for compressive strength testing. The cylinders were tested in triplicate sets for each of the different types of curing at 1, 3, 7, 28, and 56 days (subjected to bath curing at 23°C, exposed curing at 23°C, and 50% RH, and sealed curing involving storage in two polythene bags and in a sealed container at 23°C).
2. Shrinkage prisms (75 × 75 × 285 mm) were made in accordance with AS1012. The prisms were made in triplicate sets for exposure to each of the three conditions, namely, exposed, sealed, and according to AS1012, Part 13 (i.e., 7 days bath cured followed by exposed curing at 23°C and 50% RH).

Table 2
Properties of aggregates

Aggregate type	Specific gravity	24-h water absorption (%)
14-mm basalt	2.95	1.2
14-mm BFS	2.71	4.4
River sand	2.65	0.5

Testing to determine fresh concrete properties including slump and air content also was conducted.

2. Fresh concrete properties

Fig. 1 shows the slump loss over 2 h for concretes composed of both aggregate types. For AAS, considerable workability was lost when utilising the BFS aggregate (i.e., initial slump loss from 115 to 60 mm). It is likely that the surface texture, shape, and porosity of the BFS aggregate contributed to the reduced workabilty. Nevertheless, compared with OPC concrete composed of basalt coarse aggregate, the slump at 30 min and beyond is higher.

3. Strength development

The strength development of concrete composed of the two aggregate types subjected to bath, sealed, and exposed curing for up to 91 days of age is summarised in Figs. 2, 3, and 4, respectively. The AAS-BFS has higher 1-day strength than concrete containing basalt aggregate (17.5 vs. 15.0 MPa). Between 1 and 28 days the compressive strength of bath cured AAS-BFS is lower than AAS-Basalt, although it is higher than that of OPC-Basalt. The curves for AAS-BFS and AAS-Basalt, shown in Fig. 2, are parallel, indicat-

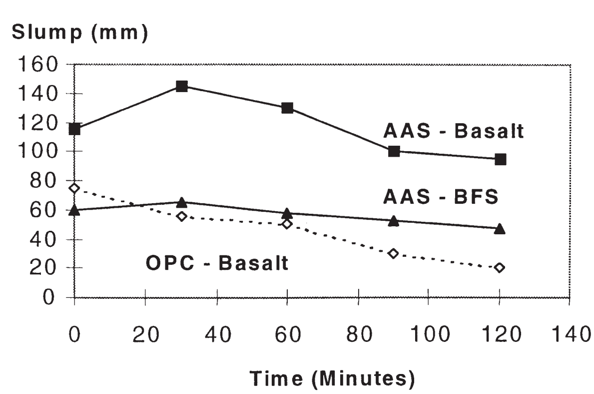

Fig. 1. Slump loss vs. time

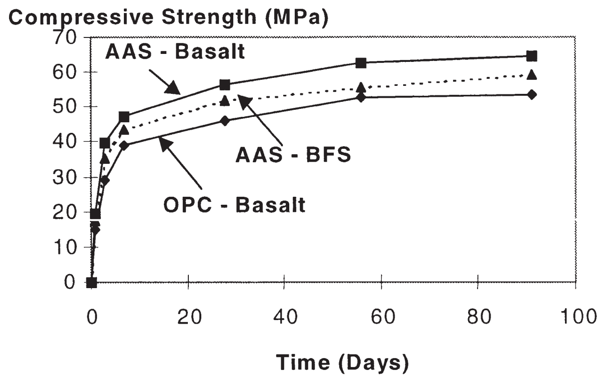

Fig. 2. Compressive strength vs. time for bath-cured cylinders at 23°C.

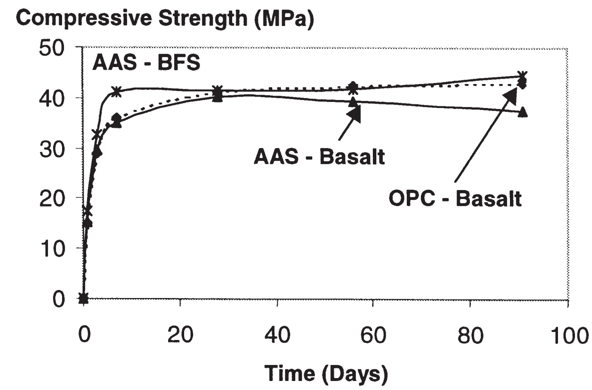

Fig. 4. Compressive strength development for cylinders exposed at 23°C and 50% RH.

ing that the difference in strength is primarily due to change in aggregate type. The effects of sealed curing are shown in Fig. 3. There is little difference between the strength of bath-cured and seal-cured concrete. Fig. 4 shows almost identical strength development during exposed curing for AAS and OPC concretes containing basalt coarse aggregate. At ages beyond 1 day the AAS-BFS concrete demonstrates higher compressive strength than the control concretes. This can be attributed to the internal curing effect whereby water from the aggregate is gradually released into the concrete to further hydrate the paste.

4. Drying shrinkage

AAS concrete has considerably higher drying shrinkage than OPC (Fig. 5). The implications of higher drying shrinkage are that under restrained conditions it may lead to a higher incidence of cracking. Adequate provision for joints and minimization of restraints should be allowed, although this is not always practical.

Fig. 5 shows an initial expansion for the concretes containing AAS and subjected to 7 days of initial bath curing. Subsequently, AAS-BFS shows significantly less drying shrinkage than AAS-Basalt after 7 days of exposure to 23°C and 50% RH. At 56 days, AAS-BFS shows 17% higher drying shrinkage to OPC-Basalt.

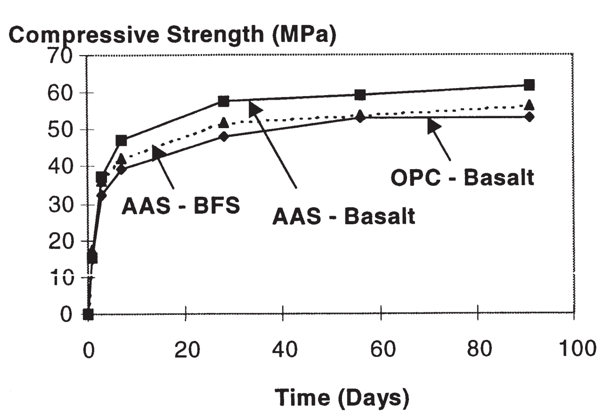

Fig. 3. Compressive strength vs. time for seal-cured cylinders at 23°C.

A separate set of prisms were made in an identical manner, but were exposed to 23°C and 50% RH from day 1 onward. The test results are presented in Fig. 6, which show:

1. AAS-BFS has slightly less initial shrinkage than OPC within the first 2 days.
2. AAS-BFS shows significantly less drying shrinkage than its counterpart containing normal weight aggregate. The drying shrinkage is 19% higher than OPC.

The overall shrinkage strains are higher than the prisms subjected to 7 days of initial curing.

Fig. 7 shows little difference in autogeneous shrinkage between AAS concrete composed of normal weight and BFS aggregate. This resulted due to significant reduction in shrinkage of AAS-Basalt when sealed cured. This indicates that improvement to the overall shrinkage behaviour of AAS by incorporation of BFS aggregate into the concrete is most likely due to the "internal curing" influence caused by moisture release from the aggregate during drying rather than a chemical effect.

5. Conclusions

The results of this investigation indicate the following:

1. After 7 days of exposure to 23°C and 50% RH, AAS-BFS concrete shows significantly less drying shrinkage than AAS-Basalt.

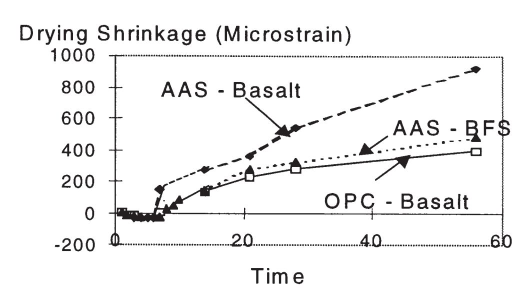

Fig. 5. Drying shrinkage: 7 days of bath curing followed by exposure to 50% RH and 23°C.

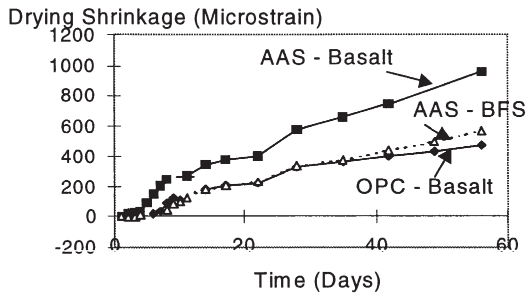

Fig. 6. Drying shrinkage: exposure to 50% RH and 23°C from day 1 onward.

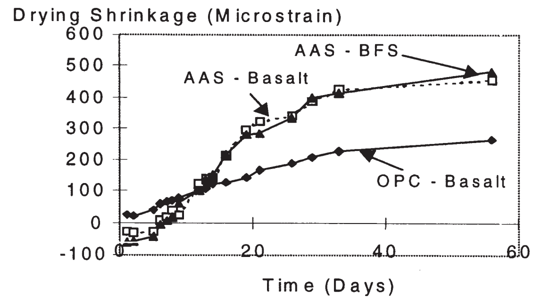

Fig. 7. Shrinkage after sealed curing at 23°C.

2. At ages beyond 1 day, under drying conditions of 50% RH and 23°C, AAS-BFS demonstrates higher compressive strength than AAS-Basalt and OPC-Basalt. The improved strength and reduced drying shrinkage can be attributed to the internal curing effect whereby water from the aggregate is gradually released into the concrete to further hydrate the paste.
3. AAS incorporating BFS as coarse aggregate (AAS-BFS) displays less workability than equivalent concrete incorporating normal weight coarse aggregate (AAS-Basalt).

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