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Communication

Workability and mechanical properties of alkali activated slag concrete

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Abstract

This paper reports the results of an investigation on concrete containing alkali activated slag (AAS) as the binder, with emphasis on achievement of reasonable workability and equivalent one-day strength to portland cement concrete at normal curing temperatures. Two types of activators were used: sodium hydroxide in combination with sodium carbonate and sodium silicate in combination with hydrated lime. The fresh concrete properties reported include slump and slump loss, air content, and bleed. Mechanical properties of AAS concrete, including compressive strength, elastic modulus, flexural strength, drying shrinkage, and creep are contrasted with those of portland cement concrete.

Keywords: Granulated blast-furnace slag; Alkali activated cement; Workability; Mechanical properties; Shrinkage

Slag is often used in concrete as a supplementary cementitious material and partial replacement to portland cement (OPC). The major advantages of slag replacement of OPC in making concrete is the superior durability and lower heat of hydration as compared to 100% OPC binder. However, the low early strength of these concretes is a limitation in many applications. The problem of low early strength can be overcome by using alkali activated slag (AAS) as the type of binder which can potentially yield early high-strength concrete. Talling and Brandstetr [1] provide a comprehensive state-of-the-art summary of concrete containing 100% AAS binder.

Equivalent one-day concrete strength has been achieved for OPC concrete and concrete based on AAS binder, using elevated temperature curing [2,3,4,5] and steam curing [6,7,8]. However, these curing conditions necessitate specialised equipment and facilities and require attendance by staff. The aim of this investigation was to evaluate the use of AAS concrete which would yield one-day strength equivalent to OPC concrete at normal curing temperatures (23°C), while having reasonable workability.

A range of one-day strength results have been reported [6–17] for sodium silicate activated slags cured at normal curing conditions. Workability and early strength are sensitive to dosages of NaOH, M_s (SiO_2/Na_2O, i.e., silicate modulus), and the composition and fineness of the slag. In most cases high one-day strengths were accompanied with rapid loss of workability beyond 45 min [13,15]. Similarly, a range of one-day strengths of sodium hydroxide activated slags are reported [9,10,11,12,13,18]. The combination of $NaOH + Na_2CO_3$ as the slag activator (H/C) yields comparable one-day strength for the AAS and OPC pastes and concretes [5,11,18].

1. Experimental programme

The chemical composition and properties of the cementitious binders are summarised in Table 1. The binders used are ground granulated blast furnace slag (Slag) and OPC. The term water/binder (w/b) ratio is used instead of the conventional water/cement ratio to include both the binders mentioned above. The slag is supplied with gypsum (2% SO_3) that is blended with the slag. The activators and adjuncts investigated were: (1) powdered and liquid sodium silicate; (2) hydrated lime (L); (3) liquid sodium hydroxide (NaOH); and (4) sodium carbonate (Na_2CO_3).

The dry powdered sodium silicate activator was preblended with the slag in the dry form prior to use for concrete manufacture. The liquid sodium silicate was treated with addition of NaOH to achieve identical chemical composition to the dry powdered sodium silicate activator. The liquid sodium silicate, NaOH, and the hydrated lime (1% lime in water slurry form) were added to the mix with the mixing water.

The coarse aggregate consisted of 14-mm maximum size basalt with a specific gravity of 2.95 and 24-h water absorption of 1.2%. The fine aggregate consisted of river sand with a specific gravity of 2.65, 24-h water absorption of 0.5%, and a fineness modulus of 2.19.

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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 sulphur as SO_3 (%)	2.43	2.56
Sulphide sulphur 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 (h)	N/A	2.0
Strength (MPa) of 75 × 75 × 75 mm mortar cubes (MPa)		
3 Days	N/A	32.7
7 Days	N/A	42.0
28 Days	N/A	54.1

The concrete mixture proportions are summarised in Table 2. The materials used for concrete making, the method of preparing concrete mixes in the laboratory, and the tests for fresh and mechanical concrete properties reported in this paper were in accordance with the Australian standard AS1012. Samples were made for subsequent laboratory testing as follows:

- Cylinders in accordance with AS1012, Parts 8 and 9 (100-mm diameter and 200-mm height) for compressive strength testing in triplicate at 1, 3, 7, 28, 56, and 91 days (following demoulding, subject to “bath” curing at 23°C, “exposed” curing at 23°C and 50% RH, and “sealed” curing involving storage in two polythene bags and a sealed container at 23°C).
- Shrinkage prisms tested in accordance with AS1012, Part 13 (75 × 75 × 285 mm). The exposure conditions following demoulding for a triplicate set of samples were seven days of bath curing followed by exposed curing at 23°C and 50% RH.
- Cylinders in accordance with AS1012, Part 8 (100-mm diameter and 200-mm height) for creep testing in accordance with AS1012, Part 16. Following demoulding, a duplicate set of specimens were subject to seven days of bath curing followed by 21 days of exposed curing at 23°C and 50% RH prior to loading at 40% of the 28-day compressive strength.
- Flexural strength prisms in accordance with AS1012, Part 8 (150 × 150 × 500 mm). Following demoulding, a triplicate set of specimens were subject to bath curing for 28 days. Flexural strength testing was conducted in accordance with AS1012, Part 11.
- Cylinders in accordance with AS1012, Part 8 (100-mm diameter and 200-mm height). Following demoulding, a triplicate set of specimens were subject to bath curing for 28 days and tested for elastic modulus in accordance with AS1012, Part 17.

Properties of the fresh concretes including slump and air content were also determined in accordance with AS1012, Parts 3 and 4, respectively.

Table 2
Summary of concrete mixture proportions (kg/m^3)

Constituents	OPC	H/C	AAS1	AAS2
OPC	360	—	—	—
Slag	—	360	360	360
Free water*	180	180	180	180
w/b	0.5	0.5	0.5	0.5
Fine aggregate	830	830	830	830
Coarse aggregate				
14 mm	1130	1130	1130	1130
Air content %	0.5	1.2	1.2	1.1

*Adjustments made for water in aggregates (to saturated surface dry condition), NaOH, Na_2CO_3, lime slurry, and sodium silicate.

2. Fresh concrete properties

Slump loss versus time is summarised in Fig. 1 Slag activated by powdered sodium silicate and lime slurry (AAS1) demonstrates considerably better workability than the other concrete mixes, including OPC. At 30 min, AAS1 demonstrates better slump than the initial slump; this is most likely due to further dissolution of the powdered sodium silicate into the mixing water. At 120 min, the slump loss of the AAS1 concrete is minimal compared with the other concretes. This result contrasts with slag activated by liquid sodium silicate and lime slurry (AAS2), also reported elsewhere [6–16], that were based on liquid rather than powdered sodium silicate activators. It is postulated that the powdered sodium silicate has a slower release of alkali into the cement system (as opposed to liquid sodium silicates) and leads to a slower rate of initial reaction. Similar to AAS2, H/C concrete showed significant loss of workability, with minimal slump at 60 min. The activated slag concretes entrain more air than OPC concrete, as shown in Table 2. The bleed of the acti-

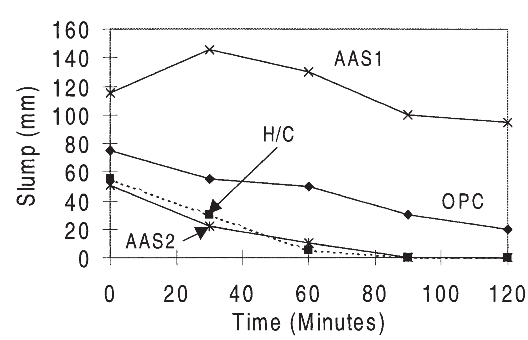

Fig. 1. Slump loss versus time; w/b = 0.5.

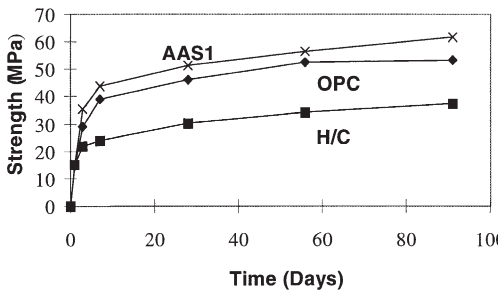

Fig. 2. Compressive strength development of concrete subject to bath curing, w/b = 0.5.

vated slag concretes was measured as zero at 2 h from the time of mixing. The OPC concrete had a bleed of 0.45% (expressed as % of mixing water). Due to rapid loss of workability, further work with AAS2 was discontinued.

3. Compressive strength

Fig. 2 shows strength development with time following bath curing. All concrete types show almost identical one-day strength. The H/C concrete show rapid early strength development, followed by lower strength than AAS1 and OPC concrete at later ages. AAS1 concrete shows higher strength than OPC concrete at all ages. Between 56 and 91 days, the strength of OPC concrete levels out, whereas AAS1 concrete continues to gain strength. Fig. 3 and Fig. 4 show the effects of various curing environments on the development of compressive strength. There is a significant difference in strength between samples subjected to exposed curing and sealed/bath curing, with AAS1 showing greater sensitivity to lack of curing.

Beyond 28 days, AAS1-exposed concrete strength levels out. Further work is currently underway to assess the longer term strength of AAS concrete subjected to exposed curing.

4. Drying shrinkage

Results of drying shrinkage is summarised in Fig. 5. AAS1 concrete shows a minor expansion during the first seven days

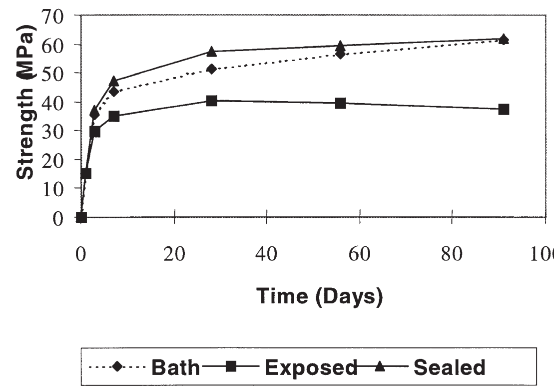

Fig. 4. AAS1 concrete subject to different curing, w/b = 0.5.

bath curing followed by a considerably higher rate of drying shrinkage when exposed, as compared with OPC concrete. 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. Drying shrinkage of H/C concrete is similar to OPC concrete up to 56 days; however, it is considerably greater beyond 56 days. It is worth noting that the Australian Standard for determination of drying shrinkage is based on 56-day test results; this would lead to a false indication of drying shrinkage in the case of H/C concrete. Further investigation is underway on AAS1 concrete to compare drying shrinkage of prisms with that measured in larger structural members and also to determine appropriate means of mitigation of drying shrinkage.

5. Flexural strength, elastic modulus, and creep

The 28-day flexural strength and elastic moduli of various concretes are shown in Table 3. Overall strain due to creep following 112 days loading is shown in Fig. 6. OPC concrete shows higher initial creep than AAS1 concrete during the first three days. However, after 112 days loading AAS1 shows a slightly higher creep strain (42 microstrain/MPa compared with 36.7 microstrain/MPa). The net effect of greater creep, greater flexural strength, and lower elastic modulus of AAS1 may be reduction of the risk of cracking

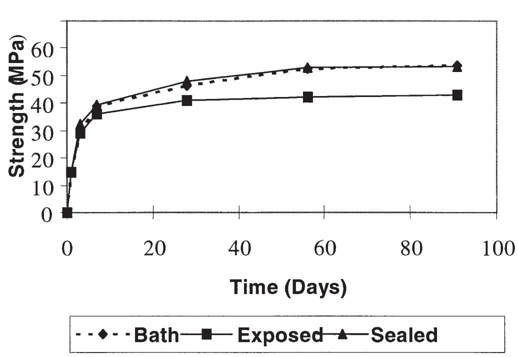

Fig. 3. OPC concrete subject to different curing, w/b = 0.5.

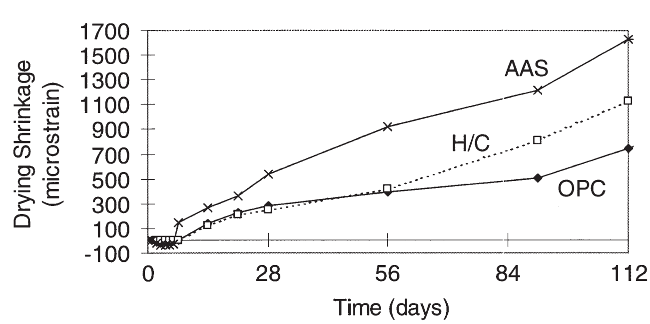

Fig. 5. Drying shrinkage of various concretes.

Table 3
28-Day flexural strength and elastic modulus of various concretes

Parameter	OPC	H/C	AAS1
Flexural strength (MPa)	5.57	4.77	7.18
Flexural strength/ compressive strength	0.12	0.14	0.15
Elastic modulus (×1000 MPa)	41.7	36.5	36.7

due to drying shrinkage under restrained conditions and this is currently being investigated.

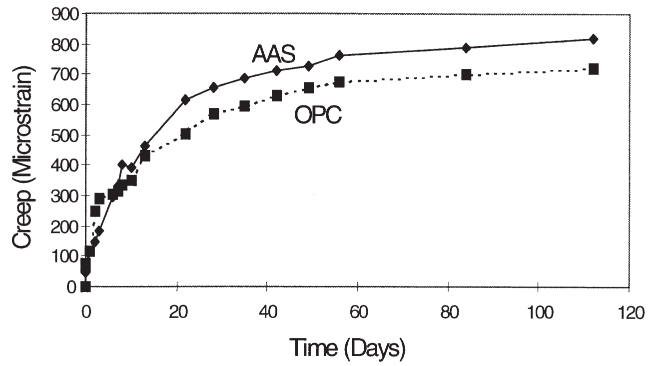

Fig. 6. Creep of OPC and AAS1 concretes.

6. Conclusions

The results of this investigation indicate:

1. At w/b = 0.5, concrete containing slag activated by powdered sodium silicate showed minimal slump loss over 2 h, whereas concrete containing slag activated by liquid sodium silicate shows considerably less initial workability and demonstrates significant slump loss. H/C concrete also showed significant slump loss over 2 h.
2. Activated slag concrete shows similar one-day strength to OPC concrete, with AAS1 showing superior strength at later ages. The H/C concrete had modest strength gain beyond three days.
3. AAS1 concrete shows a greater strength difference between bath/sealed cured cylinders to exposed cylinders when compared with OPC concrete.
4. AAS1 and H/C concrete show greater drying shrinkage than OPC concrete. However, the net effect of higher flexural strength, lower elastic modulus, and greater creep of AAS1 concrete may be reduction of the risk of cracking due to drying shrinkage under restrained conditions and this is currently being investigated.

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