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Communication

Effects of ultra-fine materials on workability and strength of concrete containing alkali-activated slag as the binder

Frank Collins *, J.G. Sanjayan

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

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Abstract

This paper presents the results of an investigation into the effects of ultra-fine materials on workability and strength development of concrete containing alkali-activated slag (AAS) as the binder. It was found that partial replacement of slag with ultra-fine fly ash significantly improves the workability; however, the strength development is similar to ordinary portland cement (OPC). Partial replacement of slag with condensed silica fume (AAS/CSF) and ultra-fine slag (AAS/UFS) show significantly greater strength than AAS at ages greater than one day. However, AAS/CSF has high water demand whereas AAS/UFS has minimal loss of workability compared with AAS. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Granulated blast furnace slag; Alkali-activated cement; fineness; workability; Compressive strength

Strength improvement by partial replacement of portland cement binder (OPC) with condensed silica fume (CSF) has been extensively reported [1,2]. However, this can be at the expense of increased water demand [1]. Use of alternative ultra-fine materials based on by-products such as ultra-fine ground granulated blast furnace slag (UFS) and ultra-fine flyash (UFA) has been less widely reported. Partial replacement of OPC with UFS with Blaine fineness 800–1500 m^2/kg shows concrete strength enhancement [3,4] with improvement of concrete workability compared with OPC concrete [4,5]. Partial replacement of OPC with fly ash, mechanically processed to <5 μm particle size, has been shown to improve concrete strength while maintaining workability, whereas equivalent samples containing CSF show reduced workability [6,7,8].

The performance of concrete with partial replacement of 100% alkali-activated slag (AAS) binder with ultra-fine materials such as CSF, UFS, and UFA has seldom been reported. Improvement of concrete strength has generally been reviewed in terms of fineness of the total ground granulated blast furnace slag binder (slag), which is normally 400–550 m^2/kg for basic slag and 450–650 m^2/kg for acidic and neutral slag [9], rather than partial replacement of slag with ultra-fine materials. Strength of AAS concrete increases with increasing slag fineness [10,11,12], but at the expense of reduced workability and causing false setting [11,12]. Roy and Silsbee [13] report high early and later strength of AAS pastes containing <4% CSF addition. Douglas and Brandstetr [14] report slightly greater compressive strength of mortars containing 8% CSF compared with identical mortars containing 5% fly ash of normal fineness. Clark and Helal [15] discuss grout applications of AAS containing binder with 98% passing 7-μm sieve and containing CSF, although the use of fine particle size was for improving permeation properties at high water/binder ratio rather than strength. The effects of partial replacement of slag with UFS and UFA appear not to have been reported in the open literature.

The aim of this investigation was to compare the performance of OPC and AAS control concretes with the performance of concretes containing partial replacement of the Slag binder with CSF, UFS, and UFA, with emphasis on the achievement of equivalent one-day strength to OPC concrete at normal curing conditions.

1. Experimental programme

The chemical composition and properties of the cementitious binders that were provided by the manufacturers are summarised in Table 1. The binders used are slag and OPC as control binders, and replacement of the slag binder with 10% CSF, 10% UFS, or 10% UFA, referred to as AAS/CSF, AAS/UFS, and AAS/UFA respectively.

* Corresponding author. Tel.: 61-3-9905-4957; Fax: 61-3-9905-4944; E-mail: frank.collins@eng.monash.edu.au.

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Table 1
Properties of cementitious materials

Oxide composition/property	Slag	OPC	UFS	UFA	CSF
SiO_2 (%)	35.04	19.9	33.2	67.6	93.5
TiO_2 (%)	0.42	*	*	0.86	*
Al_2O_3 (%)	13.91	4.62	14.6	23.4	0.06
Fe_2O_3 (%)	0.29	3.97	0.4	3.41	0.18
MnO (%)	0.43	*	*	*	*
MgO (%)	6.13	1.73	5.5	0.6	0.09
CaO (%)	39.43	64.27	42.4	1.01	0.01
Na_2O (%)	0.34	—	0.3	0.53	0.14
K_2O (%)	0.39	0.57	0.44	1.49	0.05
P_2O_5 (%)	<0.1	*	*	0.12	0.03
Total sulphur as SO_3 (%)	2.43	2.56	0.2	*	0.13
Sulphide sulphur as S^{2-}	0.44	*	*	*	*
Cl (p.p.m.)	80	*	*	*	*
Fineness (m^2/kg)	460	342	1496	90% $<$ 13.7 mm	18,300
Loss on ignition (%)	1.45	2.9	—	1.19	2.4
Time to initial set (hours)	N/A	2.0	N/A	N/A	N/A
Strength of 75 $\times$ 75 $\times$ 75 mm mortar cubes (MPa)					
3 Days	N/A	32.7	N/A	N/A	N/A
7 Days	N/A	42.0	N/A	N/A	N/A
28 Days	N/A	54.1	N/A	N/A	N/A

* Not supplied.

The term water/binder (w/b) ratio is used instead of the conventional water/cement ratio to include all the binder types mentioned above. The slag is supplied with gypsum (2% SO_3 by mass of slag) that is blended with the slag. The activators and adjuncts utilised were powdered sodium metasilicate and hydrated lime. The powdered silicate activator was preblended with the slag in the dry form prior to use for concrete manufacture. The hydrated lime was added to the mix in the form of slurry. Adjustments were made to the water added to the mixes to account for the free water contained in the slurry, sodium metasilicate, and aggregates. The coarse aggregate consisted of 14-mm maximum size basalt which has a specific gravity of 2.95 and 24-h water absorption of 1.2%. The fine aggregate consisted of river sand which has a specific gravity of 2.65 and 24-h water absorption of 0.5%. Proportioning of the concrete mixes was based on saturated and surface dry aggregate condition. The concrete mixture proportions are summarised in Table 2.

The concrete mixing and testing was conducted in accordance with the Australian Standard AS1012 Methods of Testing Concrete. Testing for the properties of fresh and hardened concretes (unless otherwise noted) included: slump at time of mixing and at 30, 60, 90, and 120 min after mixing; air content; and compressive strength. Compressive strengths were measured using standard 100-mm diameter $\times$ 200-mm long cylinders.

2. Fresh concrete properties

Slump loss versus time for each of the concrete types is summarised in Fig. 1. AAS concrete demonstrates considerably better workability than OPC concrete (115-mm initial slump compared with 75-mm initial slump for OPC concrete). At 30 min, AAS concrete demonstrates better slump than the initial value and at 120 min the slump loss of AAS concrete is minimal compared with OPC concrete, which loses 73% of the original slump.

AAS/CSF concrete has significantly less workability than AAS concrete, with a reduction in initial slump from 115 to 37 mm. This type of concrete requires use of a superplasticiser to overcome low workability. There was a minor improvement in slump at 30 min; however, considerable

Table 2
Summary of concrete mixture proportions (kg/m3)*

	Concrete type				
Binder	OPC	AAS	AAS/CSF	AAS/UFS	AAS/UFA
OPC	364	—	—	—	—
Slag[†]	—	347	313	314	308
CSF	—	—	34.8	—	—
UFS	—	—	—	35	—
UFA	—	—	—	—	34.3
Activator	—	78.4	78.5	78.5	77.5
Free water	182	173.5	174	174.5	171.5
w/b	0.5	0.5	0.5	0.5	0.5
Fine aggregate	841	801	802	805	791
Coarse aggregate	1145	1090	1091	1096	
14 mm					1077
Air content %	0.5	1.2	1.3	1.1	0.6

* All proportions adjusted for the yield volume.
† Slag activated by addition of powdered sodium metasilicate and lime slurry activator.

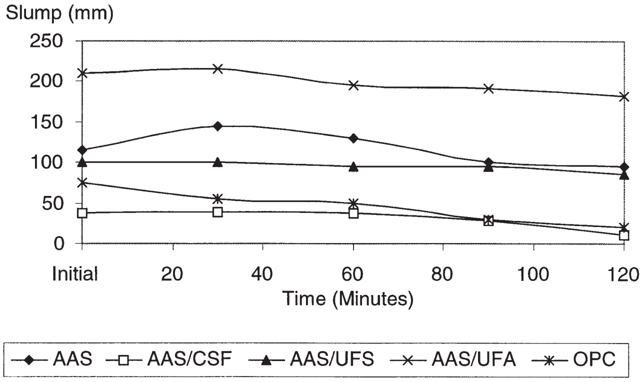

Fig. 1. Slump versus time.

slump loss was measured between 60 to 120 min. Nevertheless, the rate of slump loss was not as high during this period as for the OPC concrete. AAS/UFS concrete was slightly less workable than AAS (13% reduction in initial slump), but better than OPC concrete and showed minimal slump loss over 2 h. AAS/UFA concrete showed the best workability, with 83% increase in the initial slump, followed by 13% slump loss over 2 h. Following the elapse of 2 h the slump is superior to the initial slump of all of the mixes.

3. Compressive strength

3.1. One-day strength

Compressive strength at one day is summarised for each of the concrete types in Fig. 2. Each data set is the average of three test results. AAS concrete shows almost identical one-day strength as OPC concrete (15.1 and 14.9 MPa, respectively). AAS/UFS, AAS/UFA, and AAS/CSF concretes show improvement in one-day strength, with 28%, 24%, and 10% increases, respectively. In the case of AAS/CSF, use of a superplasticiser may have improved compressive strength. However, the one-day strength may not reflect the pattern of strength gain with age.

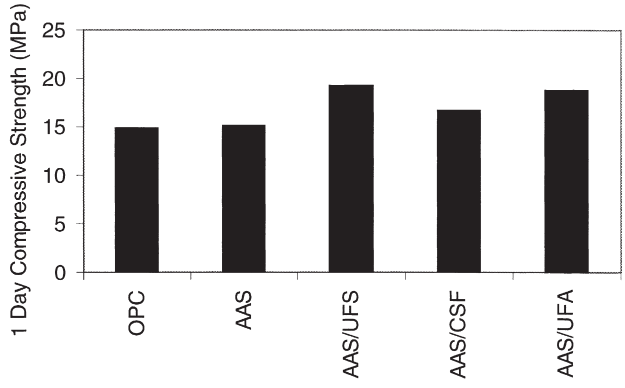

Fig. 2. One-day compressive strength; w/b = 0.5.

3.2. Strength development

Fig. 3 shows the strength development of the various concrete mixes with time. Each data set for compressive strength at 1, 3, 7, 28, 56, and 91 days is the average of three test results. AAS concrete shows higher strength than OPC concrete at all ages beyond one day. Between 56 and 91 days, the strength gain of the OPC control concrete levels off, whereas AAS concrete continues to gain strength. AAS/UFS shows marginally higher strength at all ages than both OPC and AAS concretes. Although the strength improvement of AAS/UFS concrete is significantly better than AAS concrete between 7 and 56 days (10% higher than AAS concrete at 28 and 56 days), the improvement declines to 5% at 91 days. AAS/CSF concrete demonstrated the best strength development at all ages beyond three days. The 91-day strength of AAS/CSF concrete is 74.2 MPa, which is the highest strength achieved on all the mixes and is 12% higher than the corresponding strength of the AAS concrete. Between 28 and 91 days, the slope of the strength-growth curve for AAS/CSF concrete is almost identical to AAS concrete, indicating the improvement in strength is mostly due to the improved hydration of the binder.

Although one-day strength of AAS/UFA concrete is higher than OPC and AAS concretes, the later age strengths are not as high as those for AAS/CSF and AAS/UFS concretes. At 56 days and beyond, the strength of the AAS/UFA concrete was identical to OPC concrete. This may be due to the lack of $Ca(OH)_2$ in the binder to promote the pozzolanicity of the UFA.

4. Conclusions

The results of this investigation indicate:

1. AAS concrete demonstrates considerably better workability than OPC at the time of mixing and shows minimal slump loss over 2 h. Strength at ages beyond one day is superior to OPC.

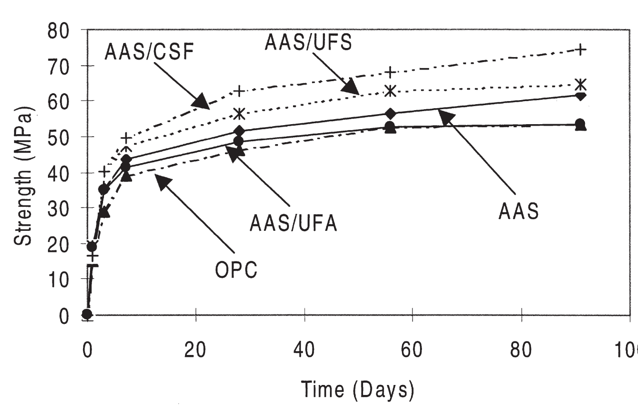

Fig. 3. Compressive strength with 10% replacement of slag with ultrafine materials; w/b = 0.5.

2. AAS/UFA concrete shows significantly improved slump compared to AAS concrete and 24% better one-day strength; however, compressive strength of concrete at ages beyond 28 days is less than AAS concrete and identical to OPC concrete.
3. AAS/CSF and AAS/UFS concretes show significantly greater strength than AAS concrete at ages beyond one day. However, AAS/CSF concrete has significant loss of workability whereas AAS/UFS has minimal loss of workability compared with AAS concrete.
4. AAS/CSF concrete achieved the highest strength development over the 91 days of curing and use of a superplasticiser may overcome its lower workability than AAS concrete.

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