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Drying shrinkage of slag blended fly ash geopolymer concrete cured at room temperature

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Abstract

Recent studies have shown that blending of ground granulated blast furnace slag (GGBFS) with low-calcium fly ash can have significant effects on the setting and early strength development of geopolymers cured at room temperature. This paper presents the shrinkage behaviour of geopolymer concrete mixtures in which class F fly ash was replaced with 10% or 20% GGBFS and the sodium silicate to sodium hydroxide (SS/SH) ratio was either 1.5 or 2.5. Shrinkage of 4 geopolymer and 1 ordinary Portland cement (OPC) concrete mixtures cured at room temperature were studied. Comparisons are made between the shrinkage behaviours of geopolymer concretes with different mixture proportions and those of the OPC concrete. It was found that shrinkage decreased with the increase of slag content and decrease of SS/SH ratio in geopolymer concrete cured at room temperature. The shrinkage of geopolymer concrete up to the age of 180 days was found to be comparable to that of OPC concrete of similar compressive strength. Thus, shrinkage of geopolymer concrete could be reduced to values within the limit recommended in the Australian Standards for normal OPC concrete.

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Keywords: GGBFS; fly ash; geopolymer; room temperature curing; shrinkage .

1. Introduction

Utilization of geopolymer as an alternative binder to OPC adds sustainability to concrete by reducing the CO_2 emission associated with cement production [1-4]. Geopolymer is termed as a polymer as it can transform,

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polymerize and harden at low temperature [5]. Geopolymerization of fly ash occurs through a conjoined reaction of destruction and condensation of the largely amorphous aluminosilicate phase. Alkali metal (Na or K) silicate, hydroxide or the combination of hydroxide and silicate solution is commonly used in the synthesis of fly ash based geopolymers [6, 7].

Compressive strengths of fly ash- based geopolymers depend on a number of factors such as the ratio of the gel phase to undissolved Al–Si particles and the amorphous nature of geopolymer materials [8]. Kumar et al. [9] noticed that mechanically activated fly ash based geopolymer displayed higher compressive strength when cured at high temperature. However, early moisture evaporation from the geopolymeric gels might obstruct the satisfactory strength development. Nath and Sarker [10] found that the addition of water improves the workability of the geopolymer concrete with the cost of strength. Similar geopolymer concrete mixtures without extra water exhibited higher compressive strength than the mixtures with additional water.

Shrinkage of concrete at early age is generally considered as a critical parameter for durability design of concrete structures [11, 12]. Drying shrinkage is a time-dependent deformation due to loss of water by hydrostatic tension from the small capillary pores of the hydrated concrete specimens and may cause severe cracking in concrete that eventually allow the ingress of aggressive agents inside the concrete.

The rate of moisture loss at early ages in concrete depends upon several factors such as relative humidity, temperature, water to binder ratio, size and shape of the specimen [6, 7, 12]. However, most of the shrinkage strain is observed during the first few months after the casting of concrete. Several factors such as aggregate properties, alkaline liquid and water content, binder materials and the curing environment are considered to affect shrinkage behavior of geopolymer concrete [13, 14, 15]. Wallah and Rangan [12] reported that the ambient-cured geopolymer concrete based on fly ash only as the binder showed much higher shrinkage than the heat cured geopolymer concrete. Collins and Sanjayan [16] also noticed relatively high drying shrinkage in slag based geopolymer concrete than the OPC concrete.

Most of the previous studies reported the strength and drying shrinkage properties of heat-cured geopolymer concrete, which is considered to be ideal for precast concrete members. Geopolymer concrete suitable for curing at room temperature is necessary to widen its application beyond precast concrete. Slow strength development and high drying shrinkage are considered as some drawbacks of fly ash based geopolymer concrete when cured at room temperature. The effects of the blending of GGBFS with fly ash on the strength development and early drying shrinkage of geopolymer concrete have been presented in this paper. The results of the GGBFS blended fly ash geopolymer concrete are compared with those of OPC concrete.

2. Experimental work

2.1. Materials

Low calcium fly ash was used as the main aluminosilicate source and a small percentage of GGBFS was blended with it in making the geopolymer binder. The chemical compositions of fly ash and GGBFS are given in Table 1. The alkaline liquid was a mixture of 14M sodium hydroxide and sodium silicate solutions. The mass ratio of SiO_2 to Na_2O of the sodium silicate solution was 2.61 (SiO_2 = 30.0%, Na_2O = 11.5% and water = 58.5%). Crushed granite aggregates with nominal sizes of 7, 10 and 20 mm were used as coarse aggregates. The combined aggregate volume was a combination of 41% 20mm, 9% 10mm, 15% 7mm and 35 % sand.

Table 1. Chemical composition of fly ash and GGBFS

Sample	SiO_2	Al_2O_3	Fe_2O_3	SiO_2+ Al_2O_3+Fe_2O_3	CaO	Na_2O	K_2O	SO_3	P_2O_5	TiO_2	LOI[a]
Fly ash	53.71	27.20	11.17	92.08	1.90	0.36	0.54	0.30	0.71	1.62	0.68
GGBFS	29.96	12.25	0.52	-	45.45	0.31	0.38	3.62	0.04	0.46	2.39

[a]Loss on ignition

2.2. Concrete mixtures and test specimens

The mix design parameters of the geopolymer concrete mixtures used in this study were selected based on the previous works of the authors [10, 17]. Two mix variables were used in the geopolymer concrete mixtures. They are the percentage of GGBFS and the sodium silicate to sodium hydroxide ratio (SS/SH). The amount of alkaline liquid was 40% of the total binder. The percentage of GGBFS was either 10% or 20% of the total binder, and the SS/SH ratio was either 1.5 or 2.5. The mixture proportions of the concrete are given in Table 2. The geopolymer concrete mixtures were designated with their variable constituents. For example, R1.5S20 represents a geopolymer concrete mixture with hydroxides/SH ratio (R) of 1.5 and 20% GGBFS (S). The other mixtures are designated in a similar way. An OPC concrete mixture was designed as per the procedure of ACI 211.1-91 [18].

Table 2. Mixture proportions concrete.

Mixture id	Mixture ingredients							
	CA[a]	Sand	Fly ash	GGBFS	Cement	SH[b]	SS[c]	Water
R2.5S10	1209	651	360	40	-	45.7	114.3	-
R2.5S20	1209	651	320	80	-	45.7	114.3	-
R1.5S10	1209	651	360	40	-	64	96	-
R1.5S20	1209	651	320	80	-	64	96	-
OPC	1054	768	-	-	446	-	-	165

[a] Coarse Aggregate, [b] Sodium hydroxide, [c] sodium silicate

Geopolymer and OPC concrete cylinder specimens of 100 mm in diameter and 200 mm in height were cast and used for compressive strength test. Specimens of 75 × 75 × 285 mm prism were cast for the drying shrinkage tests. All the specimens were demoulded at one day after casting. After demoulding, the geopolymer concrete specimens were wrapped tightly with plastic to prevent any loss of moisture and the OPC concrete specimens were immersed in water. At the age of 7 days, the plastic wrapping of the geopolymer concrete specimens was removed and the OPC concrete specimens were brought out of water. The length measurements of the shrinkage specimens were started from this age. The specimens of both types of concrete were cured in room condition at 20±2 ^{O}C and 70±10% relative humidity for the subsequent period. The change in length of the specimen was measured at specific intervals with a digital micrometer and the shrinkage values were determined until 180 days.

3. Results and discussion

3.1. Compressive strength

The compressive strengths of the concrete specimens up to the age of 180 days are given in Table 3. It is noted from the table that compressive strengths of fly ash based geopolymer concrete increased with the increase of GGBFS in the mixtures.

Table 3. Compressive strength results

Age (days)	Geopolymer series				OPC
	R2.5S10	R2.5S20	R1.5S10	R1.5S20	
7	27	31	25	29	36
28	40	47	43	54	48
56	45	50	50	63	56
90	47	54	52	68	62
180	49	59	54	70	65

For example, the strength value of mixture R2.5S10 containing 10% GGBFS gained 40 MPa compressive strength at 28 days. The compressive strength of the mixture further increased to 47 MPa by increasing the slag content to 20%. Similarly, the 28-day compressive strength of the mixtures with SS/SH ratio of 1.5 increased from 43 MPa to 54 MPa by increasing the slag content from 10% to 20%. This increase in strength by the increase of the slag content is attributed to the increase of calcium in the binder. The higher compressive strength of the mixtures containing higher slag content can be observed from 7 days to 180 days of age. It is noteworthy that the reduction of SS/SH ratio from 2.5 to 1.5 also effected the strength development. Mixture R1.5S10 achieved 8% higher strength than the mixture R2.5S10 at 28 days. The strength development was the highest when GGBFS was increased to 20 % the SS/SH ratio was decreased to 1.5. The compressive strength of the mixture R1.5S20 was found 16% higher than that of mixture R2.5S20.

3.2. Drying shrinkage

The mean drying shrinkage values of the geopolymer concrete specimens are plotted in Figs. 1 and 2. It can be seen from these figures that the rate of shrinkage was high during the early ages up to 28 days and the rate decreased after this age. The 180-day drying shrinkage of the geopolymer concrete specimens varied between 482 and 722 microstrain. It is noteworthy that the 56-day drying shrinkage values of the geopolymer specimens were below the limit of 1000 microstrain as recommended by the AS1379-2007 standard [17] for normal concrete.

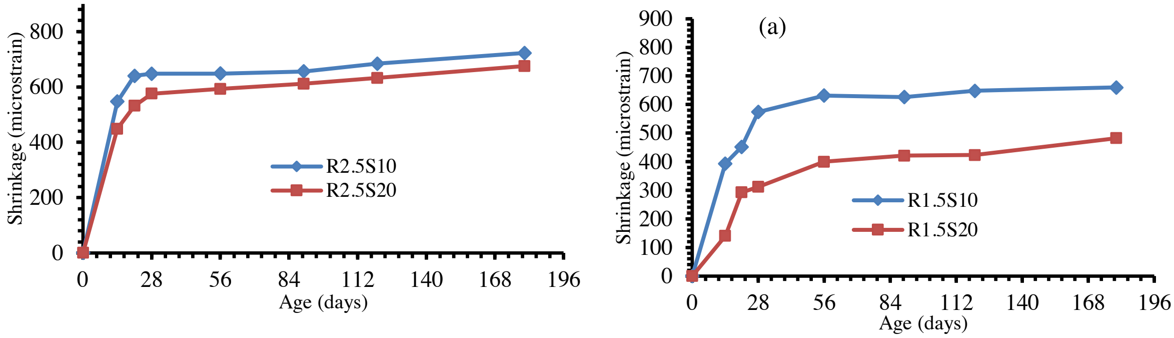

Fig. 1 Drying shrinkage of geopolymer concrete with different slag content: (a) SS/SH ratio = 2.5, (b) SS/SH ratio = 1.5

It can be seen from Fig. 1 (a) that for a constant SS/SH ratio of 2.5, drying shrinkage decreased with the increase of GGBFS. The 180-day drying shrinkage values of the mixtures R2.5S10 and R2.5S20 were 722 and 675 microstrain respectively. The effect of the slag appears to be more pronounced for the SS/SH ratio of 1.5, as shown in Fig. 1(b). The 180-day drying shrinkage values of the mixtures R1.5S10 and R1.5S20 were 660 and 482 microstrain respectively. Thus, the drying shrinkage decreased with the increase of slag content for both the SS/SH ratios.

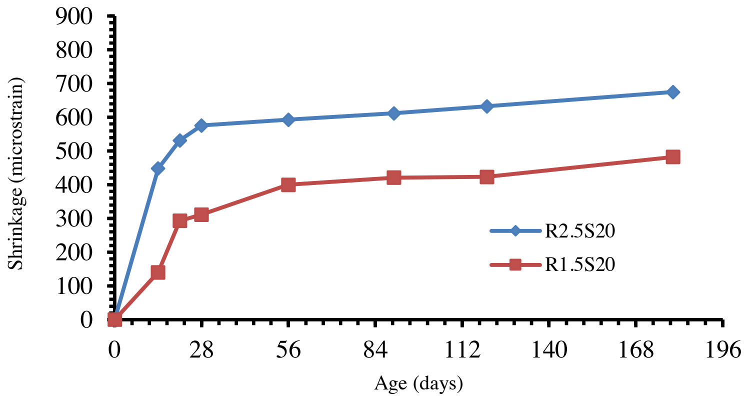

Fig. 2 Drying shrinkage of geopolymer concrete with different SS/SH ratio

A comparison of the drying shrinkages of the mixtures containing 20% slag and different SS/SH ratios are shown in Fig. 2. It can be seen that a reduction of SS/SH ratio from 2.5 to 1.5 significantly reduced the drying shrinkage value. Mixture R1.5S20 exhibited 30% less shrinkage than mixture R2.5S20 at 180 days. It is noted from Fig. 2 that blending of GGBFS with fly ash and using lower SS/SH ratio can reduce the shrinkage of geopolymer concrete cured at room temperature. Among all the geopolymer mixtures, R1.5S20, with 20% slag and SS/SH ratio of 1.5 showed the lowest value of shrinkage.

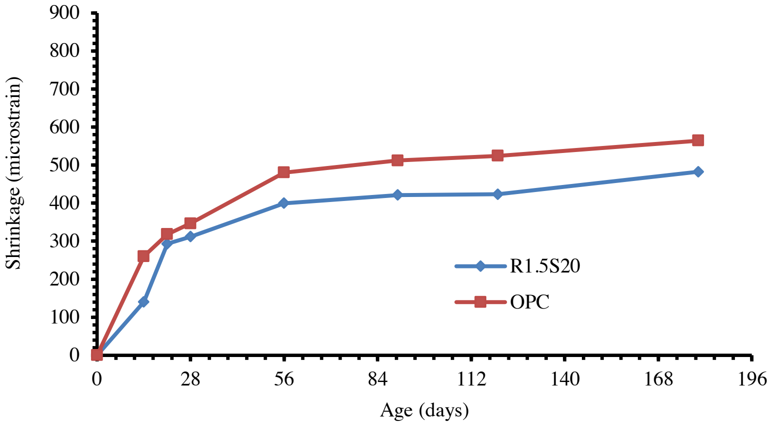

Fig. 3 Drying shrinkage of geopolymer concrete and OPC concrete of similar strength grade

The drying shrinkage values of the OPC concrete specimens are plotted in Fig.3. The shrinkage values of the geopolymer concrete mixture R1.5S20, which has a similar compressive strength of the OPC concrete, are also plotted in this figure. It can be seen from the figure that the OPC concrete exhibited 11% higher shrinkage at 28 days. The drying shrinkage value of R1.5S20 at 28 days was found 311 macrostrain compared to the value of 346 macrostrain of OPC concrete specimens. The corresponding values at 180 days were 482 and 562 microstrain respectively. Thus, it can be seen from Fig.3 that blending of GGBFS with fly ash and reducing the SS/SH ratio can reduce the shrinkage of geopolymer concrete to be comparable to that of OPC concrete of similar strength. The lower drying shrinkage of the GGBFS blended fly ash geopolymer concrete is attributed to the presence of less interconnected capillary network of the geopolymer matrix. This observation is consistent with the finding reported by Ma and Ye [18].

3.3. Comparison with the design shrinkage calculated by the Australian Standard

Concrete shrinkage models are intended to provide an estimate of shrinkage strain at different ages. Clause 3.1.7.2 of the Australian Standard AS 3600 [19] describes a procedure for calculating the design shrinkage of OPC concrete. The calculation is based on the characteristic compressive strength of concrete, thickness of the member, the surrounding environment and the age of concrete. The value calculated using the standard has a range of ±30%. This procedure was used to calculate the design shrinkage of the geopolymer and OPC concrete specimens of this study. The measured mean 28-day shrinkage value and the corresponding calculated value for each mixture are given in Table 4. It can be seen that the experimental values for the geopolymer concrete mixtures are higher than the calculated value except for the mixture R1.5S20. The measured values for the OPC concrete mixture and the geopolymer concrete mixture R1.5S20 are smaller than the calculated value. However, the measured values are within the ±30% range of the calculated value for all the mixtures except for mixture R1.5S20. The measured shrinkage of this mixture is the lowest among all the geopolymer concrete mixtures. A comparison of the calculated and experimental shrinkage values of mixture R1.5S20 up to the age of 180 days is shown in Figure 4. It can be seen that the measured values of shrinkage for this mixture are smaller than the calculated values up to 180 days.

Table 4. Drying shrinkage values at 28 days

Series	Mixture Id	Experimental	AS3600
geopolymer	R2.5S10	647	578
	R2.5S20	575	557
	R1.5S10	574	524
	R1.5S20	311	493
OPC	OPC	346	453

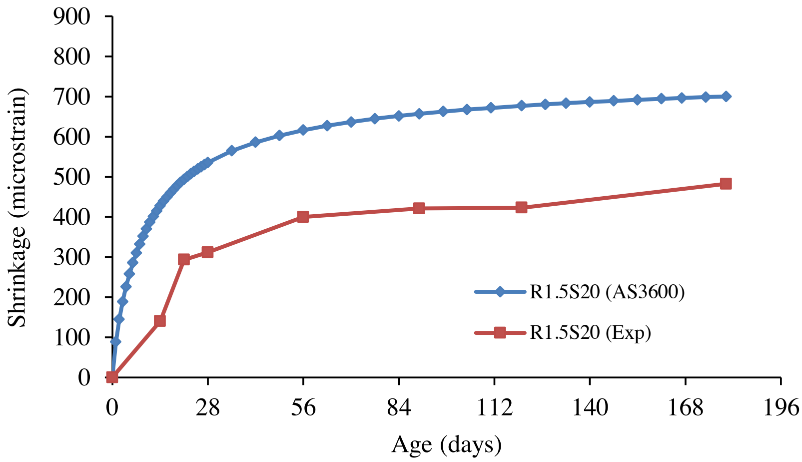

Fig. 4 Shrinkage of geopolymer concrete (Experimental and AS3600 model)

Castel et al. [15] studied the shrinkage behaviour of fly ash geopolymer concrete mixtures with an alkaline liquid to binder ratio of 0.6 and curing at different temperatures. It was shown in their study that curing at 40 ^{O}C for 3 days was necessary for the shrinkage of fly ash geopolymer concrete to meet the design shrinkage requirement of AS 3600. The results of this study, as presented in Table 4 and Fig.4, show that shrinkage of geopolymer concrete cured at 20 ^{O}C could be reduced by the addition of GGBFS with fly ash, and the reduction of the SS/SH ratio. Therefore, these mix design considerations of can reduce shrinkage geopolymer concrete to meet the required design values when cured at lower temperatures.

4. Conclusions

Four geopolymer concrete mixtures based on fly ash blended by GGBFS as the binder were studied. The percentage of GGBFS was either 10% or 20% and the sodium silicate to sodium hydroxide ratio was either 1.5 or 2.5. The alkaline liquid was 40% of the binder in all the mixtures. An OPC concrete mixture was used for comparison with the results of the geopolymer concretes. The geopolymer concrete specimens were cured at 20 ^{O}C. Compressive strength and shrinkage behaviour of the concrete mixtures were determined. The results of the study are summarized below:

- Compressive strength of GGBFS blended fly ash geopolymer concrete increased with the increase of slag content. The 28-day compressive strength of the geopolymer concretes varied between 40 and 54 MPa. The highest compressive strength was found in the mixture with SS/ SH ratio of 1.5 and 20% slag.
- The 180-day shrinkage of the geopolymer concrete mixtures varied between 482 and 722 microstrain.

Shrinkage was found to decrease with the increase of the percentage of slag and decrease of the SS/SH ratio. The lowest shrinkage was observed in mixture R1.5S20. The shrinkage of the OPC concrete mixture at 180 days was 564 microstrain. The 56-day shrinkage values were below 1000 microstrain, which is a general specification for normal OPC concretes.

- The measured 28-day shrinkage values of all the mixtures except the OPC and R1.5S20 were higher than the design shrinkage calculated by the procedure of AS 3600. However, the shrinkage of the room temperature-cured geopolymer concrete could be reduced within the range of the calculated design values by increasing the slag content and reducing the SS/SH ratio.

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