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The Effect of Slag Addition on Strength Development of Class C Fly Ash Geopolymer Concrete at Normal Temperature

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Abstract. This paper presents the effect of slag addition on strength development and workability of fly ash/slag based geopolymer (FASLG) concrete cured at normal temperature. Class C fly ash with high ferrite (Fe) content was used as the primary material. The proportions of fly ash (FA) to slag (SL) are: 1 FA : 0 SL, 0.9 FA : 0.1 SL, 0.7 FA : 0.3 SL, and 0.5 FA : 0.5 SL. The workability and strength properties were determined by slump, vikat, and compressive strength tests. The result shows that the highest compressive strength was achieved by FASLG-3 concrete with 30% slag addition and exhibited a comparable strength to that normal concrete at 28 days. The 30% slag addition also improve the workability and increase the setting time of FASLG concrete specimens. It can be concluded that the slag inclusion on fly ash will improve the performance of geopolymer concrete at normal temperature.

INTRODUCTION

The utilization of fly ash as cement replacement material has been widely used in concrete. This is due to the environmental problems caused by the cement manufacturing process. According to Davidovits [1], the production of 1 ton cement releases between 0.6-1 ton CO₂, with cement production also contributes about 5-7% of anthropogenic CO₂ emissions, which has led to global warming issues [2, 3]. Fly ash, a by-product of coal combustion process in Steam Power Plant, is categorized as "pozzolan" material which has cementitious characteristic material as Portland Cement [4]. Concrete with 100% fly ash material, known as geopolymer, is an alternative replacement of normal concrete that conventionally use cement based material. The term of geopolymer itself was introduced by Davidovits [5]. However, the hardening process of fly ash-based geopolymer concrete takes longer time than normal concrete due to the high temperature requirement for the polymerization process. According to Vijay et al. [6], the early age strength of fly ash-based geopolymer concrete cured at room temperature reached a lower compressive strength compared to that heat cured geopolymer specimens. This might be attributed to the low content of calcium (Ca) in the fly ash raw material.

The addition of material with high Ca content is an alternative to overcome the heat cured issues on fly ash-based geopolymer concrete. Slag, a by-product of the metal ore smelting process, contains important materials such as silica and alumina which can be used as building materials [7]. In addition, a raw slag material also provides a good Ca composition up to 40% [8]. It can be used as an addition material with fly ash to overcome the problem of high temperature requirement in geopolymer concrete production.

This research presents the effect of slag addition on the strength development of fly ash-based geopolymer concrete cured at normal temperature. The strength properties are measured by compressive strength, while the workability performance and setting time are identified by slump and vikat tests. Class C fly ash with a high ferrite (Fe) content is used as base material to develop the fly ash/slag-based geopolymer concrete.

EXPERIMENTAL PROCEDURE

Material

The primary materials used for this research were class C fly ash with high ferrite (Fe) content from Paiton Power Plant, Indonesia. High calcium (Ca) content slag materials were provided from steel mill waste from PT. Ispat Indo, Indonesia. The chemical composition for both fly ash and slag materials were determined by X-Ray Fluorescence (XRF) test. The XRF test was carried out on analytical calibrated equipment, type Minipal 4. The chemical composition of the class C fly ash and slag are shown in Table 1.

TABLE 1. Chemical composition of class C fly ash and GGBS (mass %)

Composition	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	K ₂ O	TiO ₂	Mn ₂ O ₃	SO ₃
Fly ash	4.75	17.89	59.11	12.65	0.00	0.65	0.92	0.55	0.86
Slag	7.76	1.47	4.23	76.24	5.42	0.00	0.61	1.23	0.00

The fly ash used in this research was class C fly ash. It had CaO of 12,65% (> 10%), SiO₂+Al₂O₃+Fe₂O₃ of 93,39% (> 50%) and SO₃ of 0,86% (<5%) in accordance with ASTM C618 [9]. A mix of sodium silicate and 10 Molar sodium hydroxide (NaOH) were used as alkaline activators. Ratio of SiO₂ to Na₂O on sodium silicate was 3.30. A sodium silicate to NaOH ratio of 1.5 was employed in accordance with previous research [10].

Mix Proportions

The details of fly ash and slag based geopolymer (FASLG) concrete mix proportions are shown in Table 2. The FASLG concrete mix design developed from the previous research [10] with a design strength of 22.5 MPa. A water solid ratio (w/s) of 0.25 was used rather than a water binder ratio (w/b) due to a solid content on sodium silicate and NaOH. The quantity of water in FASLG concrete mix was calculated as the sum of water contained in the added water, NaOH and sodium silicate. The quantity of solid was taken from the mass of fly ash, slag and the solid content of activator solution.

TABLE 2. Mixture proportions of FASLG concrete

Mixture	Portland	Fly Ash	Slag	Aggregate		Activators		Added
	Cement			Fine	Coarse	Sodium Silicate	NaOH	
OPC (Control)	1.0	---	---	1.63	3.02	---	---	0.40
FASLG-1	---	1.0	0.0	1.63	3.02	0.24	0.16	0.02
FASLG-2	---	0.9	0.1	1.63	3.02	0.24	0.16	0.02
FASLG-3	---	0.7	0.3	1.63	3.02	0.24	0.16	0.02
FASLG-4	---	0.5	0.5	1.63	3.02	0.24	0.16	0.02

Testing Specimens

The compressive strength of 100 x 200 mm² cylinder FASLG specimens were determined in accordance with ASTM C39 [11]. Three concrete cylinders were tested for each data point. The concrete specimens were tested at 3, 7, 14, and 28 days after casting. The test was considered complete until the collapse of concrete specimens.

The workability performance of FASLG concrete specimens were performed by slump test value, while the setting time test are measured by depth penetration test (Vikat tests). The slump test was tested using Abrams Cone (300 mm height, 100 mm diameter on top and 200 mm diameter on the bottom) for each fresh FASLG concrete mixture in accordance with ASTM C143 [12]. The depth penetration test (Vikat tests) was performed in accordance with ASTM C191 [13]. This test was carried out to identify the effect of slag addition on fly ash geopolymer paste setting time. Both tests were performed for each mixture data point.

RESULTS AND DISCUSSIONS

Workability and Setting Time

Workability or freshness level of fresh concrete are obtained from slump test value in accordance with ASTM C143 [12]. The following is a discussion of the results of workability of FASLG concrete specimens that are measured by slump test using Abrams Cone as shown in Figure 1.

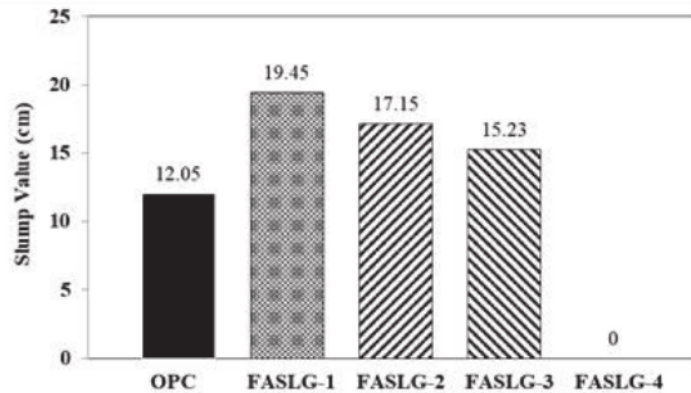


FIGURE 1. The effect of slag addition on workability of FASLG specimens measured by slump test value

The result of the slump test demonstrates that standard slump test was not a suitable measure as the liquid characteristic of the FASLG concrete results in collapses as soon as slump cone is lifted, as shown in FASLG-1 (0% slag) with slump value of 19.45 cm. The collapse was attributed to the spherical shape of fly ash particles, coupled with a lubricant effect of the sodium silicate and the added water, resulting in a high flow ability and high slump value for the FASLG specimens [14, 15]. However, the slump test of FASLG concrete specimens were significantly affected by the inclusion of slag material.

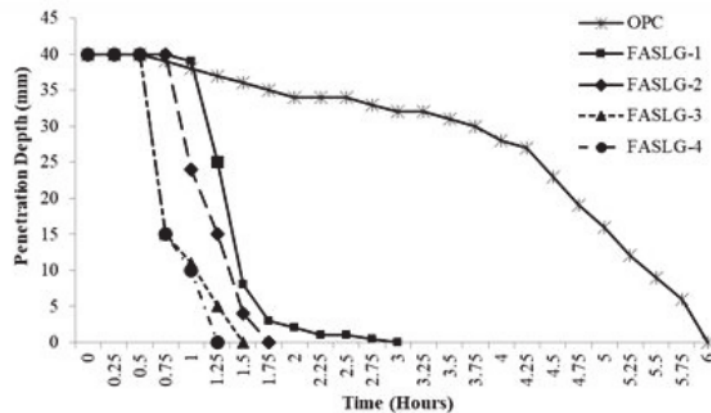


FIGURE 2. The effect of slag addition on penetration depth of FASLG specimens measured by Vikat test

Figure 1 shows that FASLG-1 concrete (0% slag) demonstrated the highest slump value (19.45 cm) compared to all FASLG concrete specimens. This value was also significantly higher than the normal concrete with the slump value design of 12.05 cm. However, the addition of slag significantly reduced the slump value of FASLG concrete specimens. The addition of 10% slag reduced the slump value 12% from 19.45 cm (0% slag addition) to 17.15 cm (10% slag addition). Further slag addition to 30% also decreased the slump value up to 11% to 15.23 cm (30% slag addition). Although FASLG-3 specimens (30% slag) showed a comparable slump value to that OPC (slump value of 12.05 cm), the low slump value made FASLG specimen to hardened very rapidly and caused difficulty during moulding. The FASLG specimens actually became more rigid, unlike the OPC and made it difficult to mould. This might be attributed to the high Ca content in raw slag material at higher ratio of slag addition (FASLG-4 with 50% slag). Similar finding was also reported by Nath and Sarker [16]. According to the authors, fly ash-based geopolymer concrete showed a lack of workability rather than OPC concrete with the same slump value. They also suggest that the decrease of slump value was influenced by the addition of slag as a binder in a concrete mixture. The addition of slag makes the slump value decrease to some extent [16].

Test result of depth penetration test of FASLG specimens are shown in Figure 2. Figure 2 displays the effect of slag addition of FASLG specimens on setting time by depth penetration test using Vikat test. The test was performed at room temperature between 20°C - 40°C. The result shows the setting time of OPC 6th hour at 40 mm depth penetration, while FASLG specimens setting time were started at 3rd hour (FASLG-1 with 0% slag). Despite having a faster setting time value, FASLG specimens has a slower early setting time. The first setting time of FASLG specimens occurred at 0.75th hours compared to that OPC setting time at 0.5th hours.

Further, the addition of slag to FASLG specimens significantly increased the setting time of FASLG specimens. The addition of 10% slag significantly increased the setting time from 3rd hours (FASLG-1) to 1.75th hours (FASLG-2). The increase of setting time from 1.75th hours (FASLG-2) to 1.5th hours (FASLG-3) occurred at the 30% slag addition. Moreover, 50% slag addition gave a setting time of 1.25th hours. This finding corroborated the previous finding on workability of FASLG specimens.

Strength Development

Table 3 and Figure 3 give the compressive strength results reported for the FASLG concrete specimens for all mixes. The FASLG specimens demonstrate a low strength at early age with all mixes producing compressive strength under 10 MPa during the first three days after casting, with the exception of FASLG-3 mix with a strength of 13.18 MPa. FASLG-1 with no slag addition (0% slag) shows the worst performance. It failed to test due to the soft form of the specimens. However, all mixes demonstrate a continual improvement of strength throughout 28 days.

TABLE 3. Compressive strength and standard deviation test result at 28 days

Mix	Compressive strength test (MPa)			
	3 days	7 days	14 days	28 days
OPC (Control)	8.13 + 0.96	11.74 + 1.09	14.88 + 0.51	22.72 + 1.31
FASLG-1	0.00 + 0.00	8.85 + 0.81	11.60 + 0.74	12.62 + 0.82
FASLG-2	5.41 + 0.63	8.92 + 0.85	12.66 + 1.13	14.49 + 0.91
FASLG-3	13.18 + 0.27	14.83 + 0.59	19.10 + 0.24	23.40 + 0.94
FASLG-4	8.41 + 0.63	10.12 + 1.18	11.28 + 0.52	13.08 + 0.43

The strength development of FASLG-3 mix (30 % slag addition) demonstrates the highest initial strength with 13.18 MPa at 3 days age (56.32% of final strength) and significantly increased from 7 to 14 days age to 14.83 MPa and 19.10 MPa, respectively. This might be attributed to Ca content in slag addition material. FASLG-3 also shows a comparable compressive strength to that OPC concrete at 28 days age with strength of 23.40 MPa. On the contrary, other mixes (FASGL-1, FASGL-2 and FASGL-4) does not display any significant increase with time, but shows a slight increase (10% to 16%) in strength from 14 days to 28 days.

Figure 3 shows that the addition of slag significantly affects the strength development in fly ash/slag-based geopolymer specimens. All FASLG mixes for each data point demonstrate a continual improvement in strength throughout 28 days along with the slag addition. The highest compressive strength was achieved by FASLG-3 with 30% slag addition for all 3, 7, 14 and 28 days age. The slag addition also improved strength performance of FASLG specimens as shown in FASLG-1 (0% slag) and FASLG-2 (10% slag). There was a significant increase of strength from 0 MPa (FASLG-1, fail to be tested) to 5.41 MPa (FASLG-2) at 3 days age. However, a slag addition more than 30% FASLG-4 (50% slag) tend to reduce the strength of FASLG specimen. A significant strength reduction occurred in all ages of FASLG-4 specimen compared to FASLG-3. The highest strength reduction was 44.12% from 23.40 MPa (FASLG-3 with 30% slag) to 13.08 MPa (FASLG-4 with 50% slag) at the age of 28 days age.

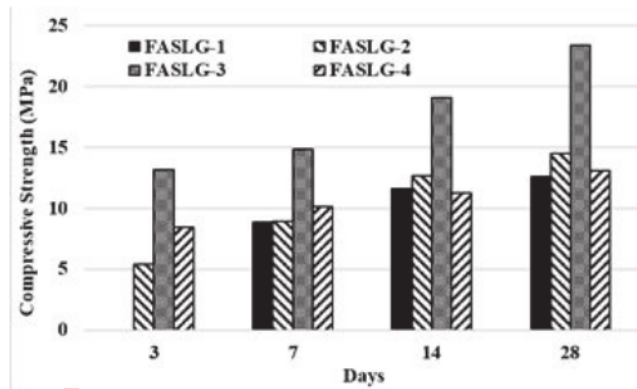


FIGURE 3. The effect of slag addition on compressive strength of FASLG specimens

Different performance was found in a previous study using a different type of fly ash [17]. The authors found that the use of class F fly ash with 50% slag addition (ratio of fly ash to slag was 50% to 50%) exhibits the highest compressive strength at 28 days. However, it should be noted that class F fly ash has low Ca content. In the previous study, the Ca content was only 2.03 compared to 12.65 in class C fly ash in this study. The effect of the slag addition is significantly influenced by the type of fly ash material. The slag addition on class F fly ash with high silicate (Si) and low Ca content can provide additional strength. The polymeric reaction of geopolymer concrete involves Si and aluminate (Al). A high Si content of fly ash tends to have un-reacted Si remaining from the fly ash [18]. This un-reacted Si reacts with Ca (from slag addition) creates a hydration reaction similar to that OPC.

In contrast, the slag inclusion on class C fly ash with low Si and high Ca content tend to have an un-reacted Ca component. Most of Si has reacted with Al to form the geopolymer matrix. The addition of slag (with high Ca

content) coupled with high Ca content in class C fly ash results un-reacted Ca. This un-reacted Ca undergoes a hydration reaction forming $\text{Ca}(\text{OH})_2$ which might lead to expansion of the concrete and cracking. Thus, the more slag addition on class C fly ash (FASLG-4 with 50% slag) will provide more Ca content which significantly decreases the strength with time.

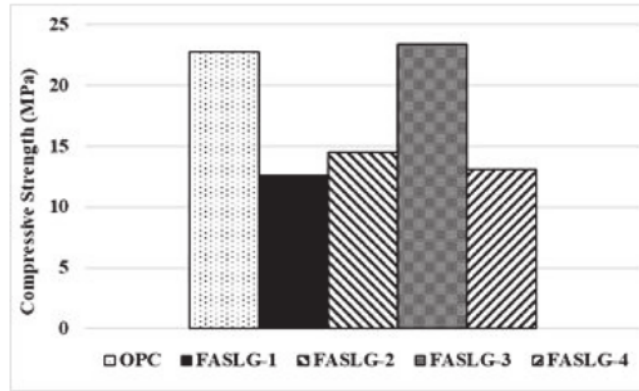


FIGURE 4. Strength comparison of OPC and FASLG specimens at 28 days

Overall the results show a comparable compressive strength of FASLG-3 (30% slag) to that OPC concrete at 28 days age (Figure 4). This would suggest that the slag inclusion is the primary contributor to the strength gain with time. This is consistent with the previous reported data for fly ash/slag mix geopolymer specimens, which have been observed to give an initial strength, which generally gains further strength before showing a reduction in strength with time [17]. While 100% fly ash geopolymer specimens generally required heat curing to achieve high strength, the use of slag on fly ash geopolymer can provide a solution to the requirement for heat curing of geopolymer concrete production providing structural integrity at ambient temperatures.

The data suggests that the hydration reaction of fly ash/slag geopolymer specimens has two possible mechanisms: (1) The polymerization of fly ash and the hydration reaction of slag are occurring separately. It is hypothesized that the slag reacts first to form a matrix gel around the fly ash and the fly ash then fills in the pores, to provide the increased strength. (2) Both reactions are occurring simultaneously with the slag reaction activating the fly ash at the ambient temperature [17].

SUMMARY

The compressive strength test, slump test value and depth penetration tests (Vikat test) for FASLG concrete specimens were studied experimentally up to 28 days. The primary conclusions may be drawn based on this study are:

- The workability of fly ash-based geopolymer specimens was significantly affected by slag inclusion, indicated by a decrease of slump value with increased slag addition. The slump test cannot be performed on 50% slag addition due to the flash setting time of FASLG specimens.
- The addition of slag to fly ash-based geopolymer specimens significantly increased the setting time rate of FASLG specimens from 3th hours (0% slag) to 1.25th hours (50% slag).
- The highest compressive strength was achieved by the fly ash/slag based geopolymer concrete with 30% slag addition. However, the addition of 50% slag tend to reduce the strength at 28 days.
- The fly ash/slag-based geopolymer concrete with 30% slag addition showed a comparable compressive strength to that normal concrete at 28 days.
- The addition of slag on fly ash-based geopolymer concrete can provide a solution on heat curing treatment requirement of geopolymer concrete production. The fly ash/slag-based geopolymer concrete can be cured at room temperature.

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