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COMPRESSIVE STRENGTH OF GEOPOLYMER MORTAR USING GROUND FERRONICKEL SLAG AND FLY ASH

JHUTAN CHANDRA KURI, MD NABI NEWAZ KHAN, and PRABIR KUMAR SARKER

School of Civil and Mechanical Engineering, Curtin University, Perth, Australia

A huge amount of ferronickel slag is produced as a by-product of manufacturing ferronickel, which is used in stainless steel and nickel alloy. This paper presents the effect of using different percentages of ground ferronickel slag (GFNS) with fly ash (FA) on the workability and compressive strength of geopolymer mortar. A mixture of NaOH and Na_2SiO_3 solutions was used as the alkaline activator. It was found that the flow of fresh mortar decreased with the increase of GFNS content. This is attributed to the higher fineness and angular shape of GFNS particles as compared to spherical fly ash particles. The mortar cube specimens were heat-cured at 60 ^{o}C for 24 hours. The compressive strength of geopolymer mortar using 100% FA was 54 MPa and it increased by 17%, 21% and 36% for using 25%, 50% and 75% GFNS as fly ash replacement, respectively. The strength increase is attributed to the increase of Si/Al ratio by GFNS that favoured the production of alkali aluminosilicate reaction products.

Keywords: Alkaline activator solution, Aluminosilicate gel, Flow, Geopolymerization, Heat curing.

1 INTRODUCTION

A significant amount of CO_2 is released to the atmosphere as a consequence of the production of Portland cement. CO_2 is one of the greenhouse gases, which is responsible for global warming and environmental damage. Development of alternative binders can have a significant contribution to the reduction of energy usage and greenhouse gas emission associated with the manufacturing of Portland cement. Geopolymer is an alternative binder that utilizes industrial by-products as raw materials. Geopolymers are produced by the reaction of an alkali with a variety of aluminosilicate source materials which are usually industrial by-products such as ground granulated blast furnace slag (GGBFS) and fly ash (Davidovits 2015). It was shown that geopolymers have good mechanical, chemical and physical performance with low porosity, water absorption, permeability and shrinkage; high resistance to fire and other aggressive chemicals (Maragkos *et al.* 2009, Deb *et al.* 2013). The properties of geopolymer concrete are comparable to those of conventional concrete. Besides, the manufacturing of geopolymer needs a lower amount of energy in addition to the utilization of industrial by-products (Sakkas *et al.* 2014).

The properties of base materials have a significant impact on the characteristics of geopolymers. The activity of aluminosilicate sources highly depends on the chemical constituent, fineness, mineral content and morphology of the base materials (Deb and Sarker 2017). A good base material should possess sufficient amorphous content as well as good capacity to release silicon and aluminum (Zhang *et al.* 2018). Ferronickel slag is a by-product of the manufacturing of ferronickel, which is used in stainless steel and nickel alloy. The main components of FNS are SiO_2, FeO, and MgO, along with crystalline and noncrystalline minerals. A notable proportion of amorphous silica exists in FNS (Saha and Sarker 2019). Therefore, ground FNS (GFNS) has the potential of using as an aluminosilicate source material alone or together with fly ash, metakaolin and GGBFS for the production of geopolymer binder.

Komnitsas *et al.* (2007) conducted an investigation into the suitability of geopolymer synthesis from low-calcium electric arc furnace FNS. The authors found that the aging period has a significant effect on the development of compressive strength as compared to the heating time and temperature. Maragkos *et al.* (2009) reported that the optimal amount of solid to liquid ratio, initial SiO_2 and initial NaOH concentration for the synthesis of FNS geopolymers were 5.4 g/mL, 4 M and 7 M, respectively. Yang *et al.* (2014) investigated the influence of high-magnesium nickel slag (HMNS) on fly ash based geopolymer. They observed that the optimum proportion of HMNS was 20%, where high compressive strength and low drying shrinkage were attained. Moreover, Sakkas *et al.* (2014) found that FNS based geopolymers exhibited high strength, low thermal conductivity and water absorption, which are similar to or better than those of other fire-resistant materials.

The properties of FNS can have significant influences on the properties of geopolymers. The FNS used in this study was produced from garnierite ores found in New Caledonia, which is not yet studied as a source material for geopolymer production. Therefore, this study was carried out to investigate the influence of ground ferronickel slag as an aluminosilicate source for geopolymer mortar. The workability of fresh geopolymer mortar and the compressive strength of hardened geopolymer mortar manufactured using different proportions of GFNS together with fly ash were investigated.

2 EXPERIMENTAL WORK

2.1 Materials

Ground ferronickel slag (GFNS) and locally available Class F fly ash (FA) were used as the aluminosilicate source to prepare geopolymer mortar. The chemical compositions of fly ash and ferronickel slag are given in Table 1. The raw granulated ferronickel slag was ground by a laboratory ball mill. The photographs of raw FNS and GFNS are shown in Figure 1. The maximum size of raw FNS was about 5 mm. The characteristic particle diameters (d_{10}, d_{50} and d_{80}) of fly ash and GFNS are given in Table 2. It can be seen that the mean particle size (d_{50}) of the fly ash and GFNS were 13.62 μm and 14.37 μm, respectively. The d_{80} values of GFNS and fly ash were 37.10 μm and 45.5 μm, respectively. This implies that the fineness of GFNS was higher than that of fly ash.

Table 1. Chemical compositions of fly ash and ferronickel slag.

Constituents	Fly ash	Ferronickel slag
SiO_2	60.03	51.42
Al_2O_3	22.75	2.88
CaO	3.80	0.48
Fe_2O_3	6.78	12.85
K_2O	1.28	0.03
MgO	1.29	30.58
Na_2O	0.54	0.08
P_2O_5	0.89	0.01
SO_3	0.25	0.05
TiO_2	1.06	0.06

Table 1 (contd). Chemical compositions of fly ash and ferronickel slag.

Constituents	Fly ash	Ferronickel slag
MnO	0.07	0.46
SrO	0.05	<0.01
Cr_2O_3	0.01	1.07
ZnO	---	0.02
Loss on ignition	1.15	---

(a) (b)

Figure 1. (a) Raw ferronickel slag, (b) Ground ferronickel slag.

Table 2. Particle diameters of fly ash and ground ferronickel slag (GFNS).

Characteristic diameter	Fly ash (µm)	GFNS (µm)
d_{80}	45.50	37.10
d_{50}	13.62	14.37
d_{10}	1.42	1.43

Natural silica sand with fineness modulus of 1.95 was used as fine aggregate to produce geopolymer mortar. The alkaline activator solution was a mixture of NaOH and Na_2SiO_3 solutions. The concentration of NaOH solution was 8 molar which was prepared by dissolving pure sodium hydroxide pellets in tap water. Sodium silicate solution was collected from a local supplier which contains 29.5% SiO_2, 14.8% Na_2O and 55.7% water.

2.2 Manufacture of Geopolymer Mortar

The mixture proportions of geopolymer mortar and the Si/Al molar ratio are given in Table 3. The mixture proportions were selected based on our previous works on geopolymer mortar (Nath and Sarker 2015). Fly ash was replaced by 25% to 75% GFNS with an interval of 25%. For all the mixtures, the quantity of alkaline activator solution was 45% of the total binder and the ratio of the sodium silicate to the sodium hydroxide solution was 2.

The desired amount of NaOH and Na_2SiO_3 solutions were mixed first to prepare the alkaline activator. The alkaline solution was prepared around 30 minutes before the final mixing with other materials. The fly ash, GFNS and sand were dry mixed in a Hobart mixer for 2 to 3 minutes and then the alkaline solution was added slowly while the mixing was continued for about 3 to 5 minutes.

The workability of fresh geopolymer mortar was determined by the flow test according to ASTM C1437-07 (2007). After removing the flow mould, the flow table with geopolymer mortar was dropped 25 times in 15 seconds. The percentage of increase in diameter of the mortar as compared to the original base diameter is taken as the flow. Cube moulds (50 mm × 50 mm × 50 mm) were filled with geopolymer mortar and vibrated using a vibrating table. The samples were cured in a laboratory oven at 60 °C for 24h period. After heat curing, the geopolymer samples were demolded and left in ambient condition to reach room temperature. Compressive strength test of hardened geopolymer mortar was performed at 2 days after casting (1 day after heat curing) according to AS 1012.9 (2014).

Table 3. Mixture proportions of geopolymer mortar.

Mix ID	**Ingredients (kg/m^3)**					**Molar ratio**
	Fly ash	**GFNS**	**Sand**	**SH**	**SS**	**Si/Al**
GFNS-0	733	0	1137	110	220	2.569
GFNS-25	550	183	1137	110	220	3.184
GFNS-50	367	367	1137	110	220	4.276
GFNS-75	183	550	1137	110	220	6.749

3 RESULTS AND DISCUSSION

3.1 Workability

Flow test was conducted to measure the workability of fresh geopolymer mortar. Figure 2 shows the effect of GFNS content on the flow of geopolymer mortar. It can be seen that flow of fresh mortar decreased with the increase of GFNS content.

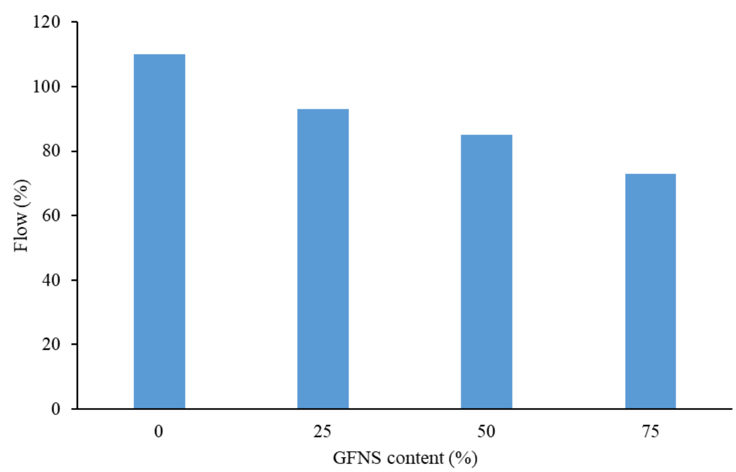

Figure 2. Influence of GFNS on the flow of geopolymer mortar.

The mortar mixture using 100% fly ash exhibited the highest flow of 110%, whereas the mortar with 75% GFNS showed the lowest flow, which was 73%. The flows of 93% and 85% were observed for 25% and 50% GFNS contents, respectively. As all the mixtures were prepared with the same liquid and sand contents, the decrease of flow with the increase of GFNS indicates a higher liquid demand of GFNS as compared to fly ash. This is attributed to the higher fineness of GFNS than fly ash. Also, the angular shape of GFNS particles contributed to reduce the flow as compared to the spherical fly ash particles. This is because the mobility of spherical fly ash particles is expected to be higher than that of angular GFNS particles.

3.2 Compressive Strength

The compressive strength of hardened geopolymer mortar was determined after heat curing at 60 °C for 24 hours. The effect of GFNS content on the compressive strength of geopolymer mortar is shown in Figure 3. The reported strengths are average values of the results obtained for three identical specimens. It is seen that the compressive strength of mortar increased with the increase of GFNS content of up to 75%. The compressive strength of control (100% fly ash) geopolymer mortar was 54 MPa, whereas those of the mortars using 25%, 50% and 75% GFNS were 63 MPa, 66 MPa and 74 MPa, respectively. Therefore, compressive strength of geopolymer mortar increased by 17%, 21% and 36% as compared to that of the control sample due to the use of 25%, 50% and 75% GFNS, respectively.

The increase of compressive strength is attributed to the formation of alkaline aluminosilicate gel. Production of alkaline aluminosilicate gel highly depends on the chemical compositions of the binder material and the alkaline activator solution. It can be seen from Table 3 that the Si/Al ratio of the mixture increased with the increase of GFNS content. In other words, compressive strength of geopolymer mortar increased as the Si/Al ratio increased from 2.569 for mixture GFNS-0 to 6.749 for mixture GFNS-75. In the geopolymerization process, dissolution of GFNS and fly ash particles by the alkaline activator solution, Si and Al contents forms Si-O-Si and Si-O-Al bonds and develops silicate oligomers and $Al(OH)_4^-$. Si plays a significant role at the time of oligomerization between silica and alumina. A higher proportion of silica enhanced the development of silicate oligomers and increased the active participation of Al that leads to the development of three-dimensional network, which increases the compressive strength (Yaseri *et al.* 2017).

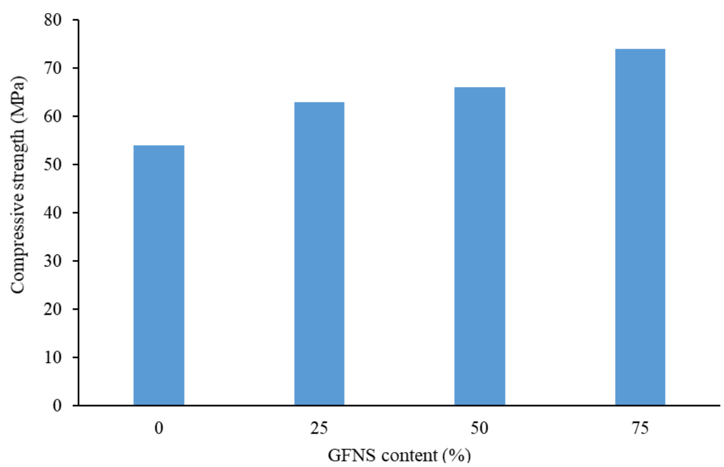

Figure 3. Influence of GFNS content on the compressive strength of geopolymer mortar.

4 CONCLUSIONS

The workability of fresh geopolymer and compressive strength of hardened geopolymer containing different proportions of GFNS as partial replacement of fly ash were investigated. The compressive strength of geopolymer mortar was determined after heat curing at 60 °C for 24 hours. The results show that the flow of fresh geopolymer mortar decreased with the increase of GFNS as partial replacement of fly ash. This is attributed to the higher fineness and angularity of the GFNS particles as compared to spherical fly ash particles. The compressive strength of heat-cured geopolymer mortar increased by the use of GFNS as a partial replacement of fly ash. Compressive strength increased from 54 MPa to 74 MPa by 75% replacement of fly ash by GFNS. The strength increase is attributed to the increase of Si/Al ratio of the binder by the use of GFNS as replacement of fly ash. Therefore, the increase of Si/Al ratio favoured the production of alkali aluminosilicate reaction products.

Acknowledgments

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