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Use of different industrial and agricultural by – products in formulation of one – part geopolymer binder

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Abstract

A one – part geopolymer binder is produced by combining solid aluminosilicate materials with solid alkali activators, which can be activated with water, akin to ordinary Portland cement. The current study investigated the potential use of different silica – rich industrial or agricultural by – products to formulate a one – part fly ash – based geopolymer binder. For this purpose, aluminosilicate by – products comprising fly ash, silica fume, rice husk ash or glass waste, were each blended with sodium hydroxide at a ratio of 1.8, then fused at temperatures of 600, 650, 700, 750 and 800 °C for 1 hour to obtain the fused material. In each case, the one – part geopolymer binder was prepared by mixing the fused material and fly ash as geopolymer precursors. The geopolymer binder was mixed with fine aggregate and water to prepare mortar mixtures, which were subjected to workability measurements as well as compressive strength testing. Cubes of 50 mm size were cast and cured at 80 °C in an oven for 24 hours, then they were stored at ambient temperature for six days until compressive strength testing. Results show that regardless of the fusion material type, an increase in the ratio of silicate source to sodium hydroxide in fusion material led to strength loss along with increases in workability. Overall, the glass waste fusion material fused at 600°C, resulted in the best 7 – day compressive strength of 33.6 MPa along with a flow workability of 185 mm.

Keywords: one – part geopolymer, fusion, silica source, compressive strength, fly ash

1. INTRODUCTION

Portland cement – based concrete is extensively employed in global construction practice, owing to its cost – effectiveness and engineering properties in comparison to other building materials. However, there are some disadvantages of ordinary Portland cement (OPC) that mainly relate to its adverse effects on the environment. Intensive carbon emissions and energy consumption resulting from the manufacture of OPC cement, are among the most negative aspects of utilising the binder. Cement production uses 4.7 million British thermal units (BTUs), equivalent to approximately 180 kilograms of coal, and produces almost a ton of

CO_2 for every ton of cement produced [1]. The resulting CO_2 emissions significantly contribute to global warming.

The geopolymer binder presents a potential alternative to OPC and offers a more environmentally sustainable binder option by comparison. A wide range of aluminosilicate materials can be used to produce geopolymer binders through their activation by strong alkali – activators. In order to produce geopolymer binders, aluminosilicate resources used are typically either natural pozzolans, such as volcanic ash, laterite soil, kaolin clay, zeolite or industrial by – products including fly ash (FA), ground granulated blast – furnace slag (GGBS), rice husk ash (RHA), metakaolin, silica fume (SF), etc. [2-7]. Dissolution of aluminosilicate raw materials in alkali activator solution generates Al and Si monomers in the aqueous environment, which subsequently form a polymeric structure with Si, Al, and O components through a polycondensation process. The final geopolymer microstructure contains alkalis, such as sodium (Na) and potassium (K), to maintain the charge balance [8].

The vast majority of research conducted on geopolymer binders has been done using binary alkali – activator solutions consisting of sodium/potassium silicate and sodium/potassium hydroxide. Although the use of concentrated alkali – activator solution results in the production of a hardened geopolymer binder system with appropriate properties, the practical application of strong alkali solution poses a risk due to their high pH values, which can be harmful to human health. As such, the incorporation of highly concentrated alkali solutions into geopolymer binder mixtures may potentially elicit some resistance from industry stakeholders with regard to replacing conventional cement with these alkali – activated materials [8].

The formulation of a one – part geopolymer binder system is a means of eliminating alkali – activator solutions from among the ingredients of geopolymer mixtures. The one – part geopolymer binder system is activated by only adding water, which is more advantageous for commercial use [10,11].

Similar to OPC, the one – part geopolymer binder is prepared by mixing solid aluminosilicate (silica source) materials with solid alkali activators that can be activated by only adding water [10,12]. Any substance that provides alkali cations, raises the mixture's pH, and stimulates the dispersion of silica and alumina within the system can be used as an activating agent in a one – part geopolymer binder [13]. Various studies have been reported in the literature, on the formulation of one – part geopolymer binders using various starting materials.

Yang [14] utilized a sodium silicate powder combined with FA or GGBS as the raw materials to formulate a one – part geopolymer binder cured at ambient temperature. It was reported that the highest 7 – day compressive strength results of the FA – based and GGBS geopolymer mortars, were 3.2 MPa and 48.46 MPa, respectively. Nematollahi [10] reported 7 – day compressive strengths of 33.9 MPa and 37.3 MPa for the combined 75% FA / 25% GGBS geopolymer binder cured at ambient temperature and 60 °C in the oven, respectively.

The present study investigated the effects of various fused materials made using different silica – rich materials and solid sodium hydroxide (NaOH), on the properties of fresh and hardened geopolymer mortars. Silica – rich materials comprising glass waste (GW), FA, RHA and SF, were employed in the experiment. This study also investigated the effect of different fusing temperatures on the flow workability and compression strength of geopolymer mortar samples. The benefits of employing this fusion approach are threefold: firstly, it generates a powder product instead of a liquid solution; secondly, it significantly reduces the production costs associated with activator synthesis, thereby lowering the price of alkali – activated concrete; and thirdly, the utilization of a low – temperature fusion methodology results in a reduced carbon footprint [15].

2. EXPERIMENTS

2.1 Materials and Methods

The silica – rich materials used for fusion were FA, RHA, SF and GW. The low calcium (Class F) FA obtained from Lethabo power station of Eskom SOC Ltd in South Africa, was used as the aluminosilicate raw material, which was fused with the silica – rich materials at 600 to 800 °C. SF was obtained from Mapei South Africa (Pty) Ltd, while GW was supplied by Consol Glass (Pty) Ltd. The coarse GW particles were crushed to powder and sieved through a 150 µm sieve, to obtain fine material for fusing with NaOH. RHA was burned in a laboratory electric furnace at a temperature of 400 °C for 1 hour at a rate of 3 °C per minute, in order to reduce the unburned carbon content of its composition. The chemical compositions of GW, SF, FA and RHA are given in Table 1. Kiran Global (pty) Ltd, supplied the industrial grade NaOH flakes used in the study. The silica sand of sizes 0.8 to 1.4 mm was used as fine aggregate for the preparation of mortar mixtures. The silica sand was supplied by Sallies Silica (Pty) Ltd.

Table 1: Chemical compositions of glass waste, silica fume, fly ash and rice husk ash.

Oxides	Glass waste (%)	Silica Fume (%)	Fly Ash (%)	Rice Husk Ash (%)
SiO_2	83.21	97.56	56.46	89.20
CaO	10.73	1.04	3.14	0.73
Al_2O_3	3.72	0.28	34.93	0.37
Na_2O	3.52	0.23	0.07	0.10
Fe_2O_3	1.97	0.12	3.24	0.60
MgO	1.09	0.29	1.87	1.53
K_2O	0.22	0.48	0.31	1.71
TiO_2	0.20	-	0.83	0.03
P_2O_5	0.06	-	0.48	1.08
SO_3	0.05	-	0.34	3.88
Mn_2O_3	0.04	-	0.02	0.14
Loss of ignition	4.55	-	0.71	3.88

The fusion process consisted of mixing each of the silica sources with NaOH flakes at a ratio of 1.8. The constant aluminosilicate/alkali ratio used in the experiment was based on optimum Na_2O and SiO_2 rates in FA geopolymer mixes adapted from previous studies [6,16,17]. The peak fusion temperature was varied at 600, 650, 700, 750 and 800 °C, while the heating rate and

peak durations were kept constant at 3 °C per minute and one hour, respectively. The temperature variation range, and peak duration of 60 minutes used were adapted from other studies [18,19]. Afterwards, the fused material was finely ground using a laboratory ball – mill, for a duration of 1 hour to obtain powder. The fused materials were stored in sealed containers, to avoid possible carbonation.

To prepare mortar mixtures, the fused materials were mixed with FA and sand using a laboratory mortar mixer. The dry materials were mixed for two minutes, then water was added, while the mixer was running, and mixing continued for an additional two minutes. The ratios of sand to FA, fused material to FA and water to FA, were kept constant at 2.25, 0.25, and 0.4, respectively. In the control sample, only NaOH was used without any additional silica – rich material. Table 2 provides the mix proportions used.

Table 2: Mix proportions of one – part geopolymer mortars prepared using the different silica source / NaOH fused materials and fly ash (FA).

Mix ID	Fusing Temp (°C)	Silica Source in Fused Mat	Fused Mat/ FA	Sand/ FA	Water/ FA	Solid NaOH (g)	Fused Mat (g)	FA (g)	Sand (g)	Water (g)
Control	-	-	0	2.25	0.4	63	0	450	1013	180
GW600	600	Glass Waste	0.25	2.25	0.4	-	113	450	1013	180
GW650	650	Glass Waste	0.25	2.25	0.4	-	113	450	1013	180
GW700	700	Glass Waste	0.25	2.25	0.4	-	113	450	1013	180
GW750	750	Glass Waste	0.25	2.25	0.4	-	113	450	1013	180
GW800	800	Glass Waste	0.25	2.25	0.4	-	113	450	1013	180
FA600	600	Fly Ash	0.25	2.25	0.4	-	113	450	1013	180
FA650	650	Fly Ash	0.25	2.25	0.4	-	113	450	1013	180
FA700	700	Fly Ash	0.25	2.25	0.4	-	113	450	1013	180
FA750	750	Fly Ash	0.25	2.25	0.4	-	113	450	1013	180
FA800	800	Fly Ash	0.25	2.25	0.4	-	113	450	1013	180
RHA600	600	Rice Husk Ash	0.25	2.25	0.4	-	113	450	1013	180
RHA650	650	Rice Husk Ash	0.25	2.25	0.4	-	113	450	1013	180
RHA700	700	Rice Husk Ash	0.25	2.25	0.4	-	113	450	1013	180
RHA750	750	Rice Husk Ash	0.25	2.25	0.4	-	113	450	1013	180
RHA800	800	Rice Husk Ash	0.25	2.25	0.4	-	113	450	1013	180
SF600	600	Silica Fume	0.25	2.25	0.4	-	113	450	1013	180
SF650	650	Silica Fume	0.25	2.25	0.4	-	113	450	1013	180
SF700	700	Silica Fume	0.25	2.25	0.4	-	113	450	1013	180
SF750	750	Silica Fume	0.25	2.25	0.4	-	113	450	1013	180
SF800	800	Silica Fume	0.25	2.25	0.4	-	113	450	1013	180

* GW600, FA600, RHA600 and SF600 stands for glass waste, fly ash, rice husk ash and silica fume, mixed with alkali of Silica Source / NaOH ratio of 1.8 and fused at 600 °C.

After mixing, the fresh mortars were subjected to flow table testing to measure the flow workability, in accordance with ASTM C230 [20]. For compressive strength testing, 50 mm mortar cubes were cast, according to ASTM C109 [21]. To prevent the mixture's liquid components from evaporating, plastic sheets were used to enclose the fresh mortar cubes, which were then oven – cured at 80 °C for 24 hours. They were removed from the oven, then demoulded once having cooled down to room temperature. After demoulding the cubes were

sealed again, then stored for ambient curing at room temperature. The cube samples were tested for compressive strength at the age of 7 days.

3. RESULTS AND DISCUSSIONS

3.1 Flow Workability

Figure 1 shows the effect of fusion temperature on flow workability of the fresh mortar mixtures made using different silica – rich based fused materials. The flow for mortars made using GW, increased with an increase in fusion temperature from 600 to 800 °C. The highest flow workability of 247 mm was given by the mixture made using the GW that had been fused at 800 °C. At the lower fusion temperature of 600 °C, the flow workability of GW mortar were also lower giving 185 mm. This observation can be attributed to the higher conversion of GW to solid sodium silicate at 600 °C, whereas an increase in fusing temperature to 800 °C reduces the conversion rate [19]. The presence of higher sodium silicate content in the fused material, gives higher dissolved Si which leads to an increase in viscosity of the fresh mixture upon introduction of water, in turn reducing flow workability. While the lower conversion rate of GW in relatively higher fusing temperatures, results in a higher content of non – soluble phase responsible for improving workability.

In the mixtures made using fused materials based on FA, RHA or SF, there was no observed significant relationship between fusion temperature and flow workability. This observation can be attributed to the less effectiveness of the fusion process to enhance reactivity at the employed fusion temperatures, as similarly observed for the compressive strength results; discussed later in section 3.2.

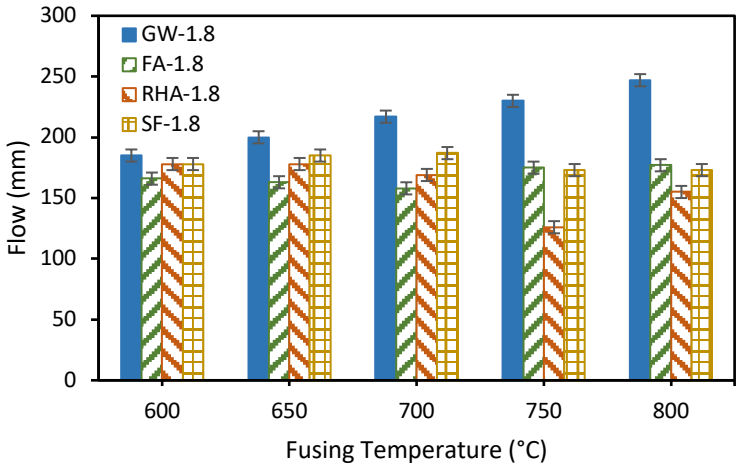

Figure 1: Effects of fusion temperature on flow workability results of one – part fly ash geopolymer mortars made with the different silica source / NaOH fused materials.

3.2 Compressive Strength

Figure 2 depicts the impact of fusion temperature on the 7 – day compressive strength results of mixtures containing a range of fused materials derived from different sources of silica. The curing conditions for all the mixes consisted of one day of storage in the oven at

80 °C, followed by 6 days of ambient curing. The mixture exhibiting the highest compressive strength of 33.6 MPa was the fused material derived from GW as the silica source, and subjected to a fusion temperature of 600°C. Furthermore, a reduction in compressive strength is evident upon elevating the fusion temperature in mixtures utilizing GW as the silica source in the fused material. This can be explained by the higher conversion rate of GW particles to sodium silicate and higher solubility of the fused material in water, when produced at the optimum fusion temperature of 600 °C [19]. The less soluble the fused material is in water, the lower the compressive strength of the sample. All the other mixes made with the other different silica sources in the fused materials, gave very low compressive strengths compared to the results of the GW material. Mortars prepared using GW/NaOH materials, fused at 600 to 700 °C, gave compressive strengths higher than the 16 MPa of the control mixture prepared using NaOH without any silica source in the activator. The significant difference between compressive strengths of the control mixture and the results of the mortars prepared using GW – based fused material, confirms the effectiveness of the employed fusion method.

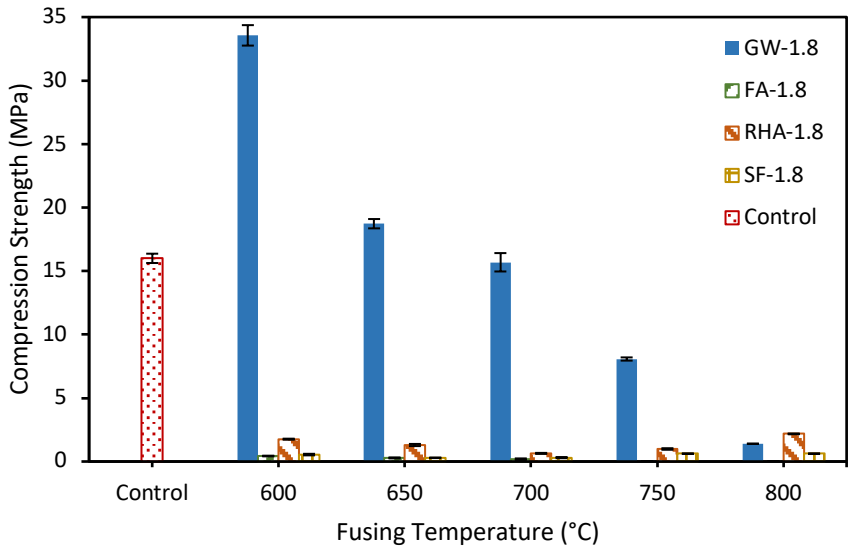

Figure 2: Effects of fusion temperature on compression strength results of one – part fly ash geopolymer mortars made with the different silica source / NaOH fused materials

4. CONCLUSIONS

The current study focussed on use of the different silica – rich industrial or agricultural by – products to formulate a one – part fly ash – based geopolymer binder. The silica – rich materials that were used in the present study were fly ash, rice husk ash, glass waste and silica fume. These silica – rich materials were combined with alkali at a silica source to NaOH ratio of 1.8 and fused at temperatures of 600, 650, 700, 750 and 800 °C. The study evaluated the effects of different fusion temperatures on flow workability and compressive strengths of mortars containing each of the silica rich fused materials. The conclusions drawn from findings of the present study are as follows:

- The flow workability of mortar mixtures containing glass waste fused material, increased with an increase in fusion temperature.
- Changes in the fusion temperature showed no significant changes on flow workability results of the mixtures containing fused materials based on silica fume, rice husk ash or fly ash.
- The compressive strengths of mortar mixtures containing glass waste fused material, decreased with an increase in fusion temperature.
- The compressive strengths of mortar mixtures containing fused materials based on silica fume, rice husk ash and fly ash, were very low and remained constant with an increase in fusion temperature.
- The fusion temperatures of 600 to 650 °C, gave the highest compressive strength results of one – part fly ash based geopolymer mortars made using glass waste – based fused material.

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