# The effect of glass waste as an aggregate on the compressive strength and durability of fly ash-based geopolymer mortar

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**Abstract.** Geopolymers have been introduced to limit the use of ordinary Portland cement (OPC), as its production contributes to the emission of about 7% of the world's carbon dioxide, which has a negative effect on the environment. The present study aimed to investigate the effect of glass-waste aggregate on the mechanical properties of fly ash-based geopolymer and OPC mortars. In the study, fly ash geopolymer and OPC mortars were also prepared using glass-waste as fine aggregate. In addition, geopolymer and OPC mortars were also prepared using silica sand as control mixes. A blended solution comprising sodium silicate and sodium hydroxide was used as an alkali activator in fly ash geopolymer mixtures. Fresh mixtures were subjected to workability measurements, while 50 mm cubes were made for compressive strength testing. Mortar prisms of  $25 \times 25 \times 285$  mm were prepared and subjected to drying shrinkage test. From the results, the use of glass-waste aggregate negatively affected the compressive strength of the mortars, regardless of the binder type. Geopolymer mortars made using glass-waste aggregate gave 55% lower compressive strength than those made using silica sand. However, mixtures made using glass waste aggregate exhibited better performance in drying shrinkage than those made using silica sand.

# **1** Introduction

The carbon emissions as a result of ordinary Portland Cement (OPC) production are a worldwide concern, and ways of reducing these emissions are constantly being explored. Geopolymers have been introduced as a solution to overcome this problem. Geopolymers are synthesised inorganic materials made through a reaction between aluminosilicate raw materials and highly concentrated alkali-activator solutions. The raw materials used in geopolymers should be rich in silica and alumina [1]. What makes geopolymers advantageous over OPC is their ability to use a wide variety of waste and byproducts, such as fly ash (FA), ground granulated blast furnace slag, metakaolin, bottom ash, etc., which would otherwise be disposed-of in landfills [2,3]. FA is a residual of coal burning in power plants in electricity production. Despite the millions of tons of FA produced yearly in South Africa, only about 7% of it is used in the construction industry as a pozzolan in cement or other applications. The lack of FA usage increases the demand for storage spaces such as landfills. This has a negative impact on the environment as FA is a non-biodegradable material [4].

Similarly, glass-waste also has negative effects on the environment as it is a non-biodegradable material and is not suited for landfills [5, 6]. There is an increase in glass-waste, about 7% of solid waste produced globally is made up of glass, while in South Africa, glass waste makes up 4.5% of all waste. Therefore, using glass waste and FA as construction materials may help moderate the above-mentioned environmental challenges.

Glass-waste is used in geopolymers due to its chemical and physical homogeneity and contains significant amorphous silica [6,7]. Some studies [8,9] suggest the application of glass-waste as an aggregate in geopolymer concrete or mortars, while some [10-14] use it as a raw material to formulate geopolymer binder. A study by Torres-Carrasco and Puertas [15] suggested incorporation of glass-waste as a reactive silica source in geopolymer mixtures. It was reported that blending < 45  $\mu$ m glasswaste of 15 g in 100 mL 10M NaOH to form an alkali activator led to a slight increase in 28-day compressive strength [15].

Some studies [10,16-18] reported improvement in strength development of geopolymer binders, in which glass-waste was used as a binder replacement. From the results compressive strength of fly ash geopolymers increases from 26 to 53 MPa, with an increase in glasswaste content from 5% to 30%, while some studies [8,19,20] reported the opposite. Most of the studies on the application of glass-waste as an aggregate replacement are in agreement that an increase in glass-waste content in geopolymer mixtures results in strength loss [15]. Hajimohammadi et al. [9] reported similar strengths of geopolymer mortar with natural sand and those of glass waste sand, giving 58 and 53 MPa, respectively. Reduction in strength as a result of glass-waste incorporation may be attributed to the change in Si/Al ratio of the mix, due to a high silicon content of glass [13].

Several studies have stated that geopolymers have superior behaviour in durability properties compared to OPC binder concrete. Shrinkage is a concrete property

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causing the volume stability of the material to deteriorate due to loss of water during the drying process, resulting in cracks that expose the concrete to external influences [21,22]. Drying shrinkage is responsible for early age cracking as the concrete lacks enough strength, thus it is crucial to evaluate it at early ages [23]. As a durability property, drying shrinkage in geopolymer binder systems is affected by several factors, including the type of aggregate used, the physical and chemical properties of binders, binder content, aggregate to binder ratio, activator properties, the alkaline solution to binder ratio, and curing conditions (temperature, duration and medium) [21,23-27]. Some studies have reported decreases in drying shrinkage with an increase in glasswaste content used as an aggregate [28-30].

The present study aimed to investigate compressive strength and drying shrinkage of geopolymer mortars prepared using glass-waste as an aggregate.

# 2 Experimental Methods

A low calcium (Class – F) FA was used as the main binder to prepare mortar mixtures. The chemical compositions of the FA used are in Table 1. CEM I - 52.5R ordinary Portland cement was used in addition to the geopolymer mixes, as well as the main binder for OPC control mixes. Glass-waste or silica sand were used as fine aggregates to prepare the geopolymer and OPC mortars. Both aggregates were equally used in two different sizes (50% of 0.6 - 1.18 mm referred to as coarser aggregate and 50% of 0 - 0.6 mm referred to as fine aggregate). The particle size distribution of aggregates used is shown in Fig 1.

 Table 1. Chemical composition of fly ash and glass waste aggregate

Oxides	Fly ash (%)	Glass waste (%)	
SiO <sub>2</sub>	56.46	83.21	
Al <sub>2</sub> O <sub>3</sub>	34.93	3.72	
CaO	3.14	10.73	
Fe <sub>2</sub> O3	3.24	1.97	
MgO	1.87	1.09	
TiO <sub>2</sub>	0.83	0.20	
Mn <sub>2</sub> O <sub>3</sub>	0.02	0.04	
Na <sub>2</sub> O	0.07	3.52	
K <sub>2</sub> O	0.31	0.22	
P2O5	0.48	0.06	
SO <sub>3</sub>	0.34	0.05	
LOI	0.71	4.55	

LOI\* loss of ignition



**Fig. 1.**: Particle size distribution of glass waste and silica sand, SSC – silica sand coarser SSF- silica sand fine GWSC – glass waste sand coarser, GWSF – glass waste sand fine

Commercial sodium hydroxide flakes of 98% purity of industrial-grade were mixed with water to obtain a 13M concentration, which was adopted from the findings of previous studies [31,32]. A sodium silicate solution with Ms = 3.3 (where  $Ms = SiO_2/Na_2O$ ) and solids content of 36% was used in combination with NaOH as activators. Activator-to-binder (a/b) ratios of 0.4 and Na<sub>2</sub>SiO<sub>3</sub>-to-NaOH ratio of 2 were adopted. A constant aggregate to binder ratio of 1.4 was used for geopolymer mixes in both aggregate systems. The mix samples analysed in this study are shown in Table 2.

Table 2. Mix Proportions Table

Mix ID	Binder(g)		Aggregate(g)		(g)	(g)	<sup>3</sup> (g)
	FA	OPC	SS	GWS	Water	NaOH	Na <sub>2</sub> SiO
OPC-SS	0	588	630	0	182	0	0
OPC-GWS	0	588	0	630	182	0	0
FA-SS	500	0	700	0	41	26	133
FA/OPC-SS	450	50	700	0	41	26	133
FA-GWS	500	0	0	700	41	26	133
FA/OPC-GWS	450	50	0	700	41	26	133

FA-fly ash, OPC- ordinary Portland cement, GWS-glass waste sand, NaOH-sodium hydroxide,  $Na_2SiO_3$ -sodium silicate

Flow workability measurements were carried out using a flow table, following ASTM C1437 [33]. 28-day compressive strengths were measured using 50 mm cubes, as per ASTM C109M standard [34]. The geopolymer cubes subjected to compressive strength testing were cured at ambient temperature of 23 °C. Furthermore,  $25 \times 285$  mm prisms were cast and subjected to drying shrinkage test for a duration of 91 days, as per ASTM C596 [35]. Mortar prisms were oven cured at 80 °C for 24 hours and were kept in the open at room temperature for the rest of the testing period.

## **3 Results and Discussions**

#### 3.1. Flow workability

Fig. 2 shows the flow workability results undertaken. It can be seen that specimens prepared with glass-waste aggregate and OPC binder exhibited the highest flow workability of 188 mm. The high workability of OPC samples containing glass-waste aggregate can be attributed to the impermeability and smooth surface of the glass particles [36]. However, glass-waste aggregate had an opposite effect in geopolymer specimens as they reduced flow workability. This observation may be attributed to an interaction between alkali activator and glass particles that increased the mixture's viscosity and resulted in lower workability. Replacement of silica sand with glass-waste aggregate in geopolymer mixes resulted in a reduction of flow by 18%. OPC inclusion in geopolymer mixes reduced flow workability regardless of the aggregate type. Similarly, OPC has rough and angular shaped particles, unlike FA with a spherical shape. Introducing OPC in the mix allows particles to interlock in the binder phase and results in a reduction of flow workability. The reduction in the flow workability of OPC inclusion in FA geopolymer mixtures was not as significant as that caused by the glass-waste aggregate. Overall, FA geopolymer mixes exhibited lower flowability than OPC binder mixes. This observation is attributed to the high viscosity of alkali activator compared to water, making the geopolymer mixes more cohesive and stickier [21].



**Fig. 2.** Flow workability of mixes: OPC-SS – ordinary Portland cement mortars made using silica sand aggregate, OPC-GWS – ordinary Portland cement mortars made using glass waste aggregate, FA-SS – fly ash geopolymer mortars made using silica sand aggregate, FA-GWS – fly ash geopolymer mortars made using glass waste aggregate, FA/OPC – fly ash geopolymer mortars containing 10% OPC in binder.

### 3.2. Compressive Strength

The compressive strengths of tested specimens are shown in Fig. 3. The control OPC mixes made using silica sand

as an aggregate, exhibited the highest 28-day compressive strength of 53.2 MPa. FA geopolymer mortar containing silica sand aggregate and 10% OPC replacement in binder, exhibited comparable strengths to those of the control mix, giving 28-day compressive strength of 49.5 MPa. Regardless of the aggregate type, inclusion of 10% OPC in the FA geopolymer mixes enhanced strength. Inclusion of OPC into the geopolymer made using silica sand and glass-waste aggregates resulted in 38% and 48% increase in compressive strength, respectively. The improvement in strength development in geopolymer mixtures due to inclusion of OPC can be attributed to formation of calcium-silicate-hydrates (CSH) phase along with the geopolymer framework, which in turn results in further early strength development [37]. Moreover, the heat of OPC hydration may also play a role in the acceleration of geopolymerization reaction, which can also enhance strength development [1].

Compressive strength reduced when silica sand aggregate was replaced with glass-waste aggregate, regardless of the binder system. The strength loss due to glass-waste incorporation can be attributed to the smooth surface of glass particles compared to those of silica sand. A relatively rough surface of silica sand particles results in the formation of stronger bonds between aggregate and binder, while the bond between the binder phase and the smooth surface of glass aggregates are weaker [38].



**Fig. 3**. 28-day compressive strength of OPC and fly ash geopolymer mortars (as described in Fig. 2)

#### 3.3. Drying shrinkage

Many studies have shown that type of aggregate used can significantly affect the drying shrinkage of concrete or mortar [24]. Fig. 4 shows the drying shrinkage of FAbased geopolymer and OPC concrete with two different types of aggregate. Mortars that were prepared using 100% OPC as binder and silica sand as the aggregate exhibited the highest drying shrinkage among the others. It can be seen that specimens containing glass-waste aggregates exhibited lower drying shrinkage in both binder systems compared to specimens prepared with silica sand aggregate. This is due to the stiff nature of glass particles with very low porosity, which eliminates drying shrinkage in the aggregate phase, and reduces the overall drying shrinkage in the matrix [30]. This observation is consistent with other studies [16, 19, 24].

Furthermore, the precence of glass aggregate in the mixtures can promote the occurence of alkali silica reaction (ASR), resulting in the expansion of mortars to a limited extent, which in turn may reduce shrinkage. Further studies are needed to investigate the rate and effect of ASR on shrinkage in these mixtures.



Fig. 4. Drying shrinkage results of ordinary Portland cement and fly ash geopolymer mortars (as described in Fig. 2)

## 4 Conclusion

Glass-waste aggregate was used as a replacement to silica sand in OPC binder mixes as well as fly ash geopolymer mortar mixes. The effects of glass-waste aggregate on flow, compressive strength, and drying shrinkage were determined. Findings showed that glass-waste particles in OPC and fly ash binder had opposite effects, where glasswaste in OPC binder increased workability, while glasswaste in fly ash geopolymer binder reduced workability. OPC binder with silica sand had the highest compressive strength, however, fly ash geopolymer mortar with silica sand and 10% OPC exhibited comparable results. Glasswaste had similar effects on compressive strength in both binder systems, as a reduction of up to 50% was observed. Similarly, drying shrinkage was reduced by the inclusion of glass-waste in both binder systems. A reduced glasswaste aggregate content is suggested in order to control the decline in strength gain.

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