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Development of Self-Compacting Geopolymer Concrete Using Fayalite Slag Aggregates

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Abstract: Because of its high cement consumption, which limits its use in concrete construction, self-compacting concrete requires a higher cement content and various admixtures. Therefore, it is prudent to explore alternative options to minimize environmental impacts while creating environmentally friendly self-compacting concrete. This study examines the use of fly ash (FA) and ultrafine slag (UFS) in self-compacting geopolymer concrete (SGC), supplemented with fayalite slag aggregates (FSA). These aggregates, in varying quantities up to 60%, were used instead of traditional sand. The rheological properties and compressive strength of SGC were investigated. The analysis revealed that the addition of FSA improved the flowability of SGC. Notably, using a combination comprising 60% FSA, the largest slump measurement of 683.5 mm was achieved. Substituting up to 20% of FSA generally improved the properties of SGC at all ages. After one year, the mixture containing 20% FSA outperformed other compositions, with a maximum compressive strength of 49.38 MPa.

Keywords: self-compacting concrete, compressive strength, fayalite slag aggregates

1. Introduction

Concrete being the second most employed substance after water hits nearly 10 billion tons of production per year [1, 2]. To inherit the key binding features in concrete, employed cement requires a highly energy-intensive procedure for development. Yet, it results in a global environmental concern by adding dioxide (CO_2) as high as 5% to 7% to the atmosphere [3]. Materials made of alumina-silicate derived from geopolymer concrete (GPC) are recommended as a way to lessen the environmental effects of cement. These substances,

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which include fly ash (FA) and rice husk ash (RHA), are employed in place of cement to provide the required binding qualities. GPC is less harmful to the environment since it uses natural aggregates (NA) and reduces the requirement for cement, addressing issues with waste management and disposal.

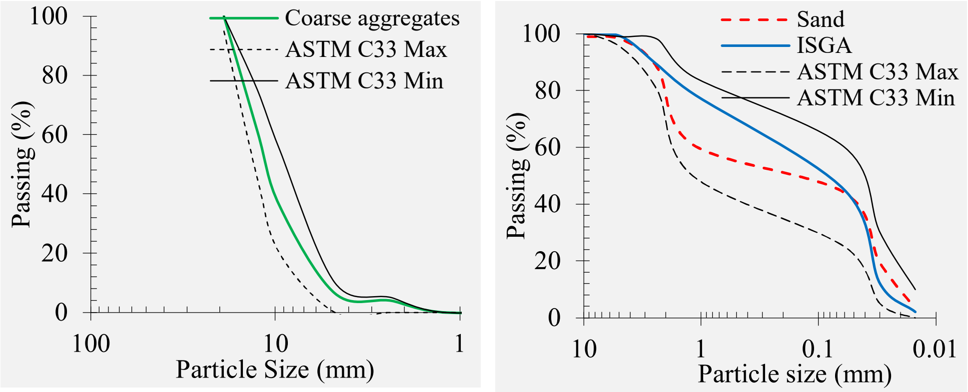
Numerous scholars have recommended the fayalite slag for the better response of GPC, which is one of the prime sources of waste obtained from copper production. Manufacturing a ton of copper results in nearly 2.2 tons of slag [4]. Generally, an enormous area is required to dump the compressive strength (CS) on the ground, whereas the limiting natural resources encourage employing the finer fayalite slag aggregates (FSA) to replace the NA materials. Previously, FSA-modified GPC successfully established the needful improvements [5]. Sreenivasulu et al. [6] examined the FSA-modified GPC and observed associated changes in flexural aspects. Researchers claimed that by substituting the fine aggregates with FSA, GPC presented an exceptional response at all dosages of substitution including 0%, 20%, 40%, and 60%. Similarly, Mahendram and Arunachalam [7] examined the FA-sourced GPC by replacing the fine aggregates with 0%, 20%, 40%, 60%, 80%, and 100% FSA. The mix subjected to room and 60 °C of curing temperature was developed with NaOH solution of concentration level as high as 14 M. Researchers claimed that not only FSA improve the bond among different ingredients, but also it notably enhanced the compression strength. Some studies [8, 9] considered the FSA-sourced modification an essential source to synthesize geopolymers. This demonstration is explained by the associated chemical composition with concerning suitable properties to replace the fine aggregates. Generally, a waste material rich in alumina and silica having enough calcium (Ca) is held responsible for developing the strength of concrete and mortar and is known as a secondary calcium silicate hydrate.

Moreover, concrete structures require sufficient durability and adequate mechanical response. Henceforth, this study employed both FSA as well as UFS to fabricate the SGC specimen to observe the corresponding improvement in durability, microstructure, and strength. After observing the fresh state features, SGC mixes were subjected to mechanical tests in their hardened state.

2. Experimental Setup

2.1. Materials and Methods

Fly ash (FA) with a lower calcium content was sourced from a coal power plant, while UFS was used as both a binding material and an additive to FA. FSA were obtained from a copper production facility. An alkaline solution was synthesized using sodium hydroxide (NaOH) pellets in combination with Na_2SiO_3. The NaOH pellets used were 98% pure. Table 1 presents the different ingredients of GPC and other relevant physical characteristics. The specific gravity test results for FSA, FA, and UFS were 3.62, 1.85, and 2.73, respectively. Similarly, sieve analysis was used to determine the gradation of coarse aggregates, FSA, and sand, following the guidelines outlined in ASTM C136 [10]. The resulting distribution of grain sizes is presented in Figure 1.



(a) (b)

Figure 1. Grain size distribution plot for tested aggregates (a) coarse aggregates (b) sand and FSA aggregates

Table 1. Physical features of SGC ingredients

Materials	Appearance	Specific gravity	Fineness modulus	Water absorption (%)	Unit weight (kg/m^3)
Coarse aggregates	–	2.66	5.48	1.09	1702
River sand	Gray	2.63	2.23	2.96	1233
FA	Light grayish	1.85	-	-	1100
FSA	Blackish	3.62	3.11	0.39	1986
UFS	Blackish	2.73	-	-	1020

The developed solution of NaOH comprised 8M of concentration, which was subjected to continuous cooling for almost 2 – 3 hours. The process of preparation was in line with the recommendations suggested by Ng et al. [11], achieving the best possible qualities for the GPC was the goal. The mixture of Na2SiO3 and NaOH produced the activator solution. After blending for five to seven minutes, the mixture was let to sit at room temperature for a full day. Na2SiO3 had a SiO2 to Na2O ratio of 2.06 and looked colorless. Depending on the percentage of sand substituted with FSA, the amount of FSA in the SGC mixes ranged from 0 to 60% for 0FSA-SGC, 20FSA-SGC, 40FSA-SGC, and 60FSA-SGC. The alkaline activator liquid to binder ratio was held at 0.45, while the ratio of Na2SiO3 to NaOH was kept at 2.50 [12]. Several trial mixes were prepared, and the presented values of different variables were derived based on their optimal performance. Also, with more than 60% addition of FSA in replacement to that of sand, the mix experienced undesirable features which were immediately discarded. Apart from Na_2SiO_3 and NaOH, all other constituents were initially subjected to dry mixing. Afterward, with the addition of the activating solution, the mixing was performed for an additional 4 minutes. Specimens were later de-molded and stored at ambient curing conditions. To accomplish the desired workability, SGC was modified by an admixture of

Polycarboxylate ether which comprised 2.50% of FA by weight [13]. Insight into the finalized composition of various mixes is presented in Table 2.

Table 2. Mix design of SGC

Ingredient	Self-Compacting Geopolymer Concrete Mix			
	0FSA-SGC	20FSA-SGC	40FSA-SGC	60FSA-SGC
FA (kg/m^3)	385	385	385	385
UFS (kg/m^3)	130	130	130	130
Sand (kg/m^3)	985	788	591	394
FSA (kg/m^3)	0	197	394	591
Coarse aggregates (kg/m^3)	780	780	780	780
Alkaline activator (kg/m^3)	231.75	231.75	231.75	231.75
NaOH (kg/m^3)	61.45	61.45	61.45	61.45
Na_2SiO_3 (kg/m^3)	153.62	153.62	153.62	153.62
Admixture (%)	9.62	9.62	9.62	9.62

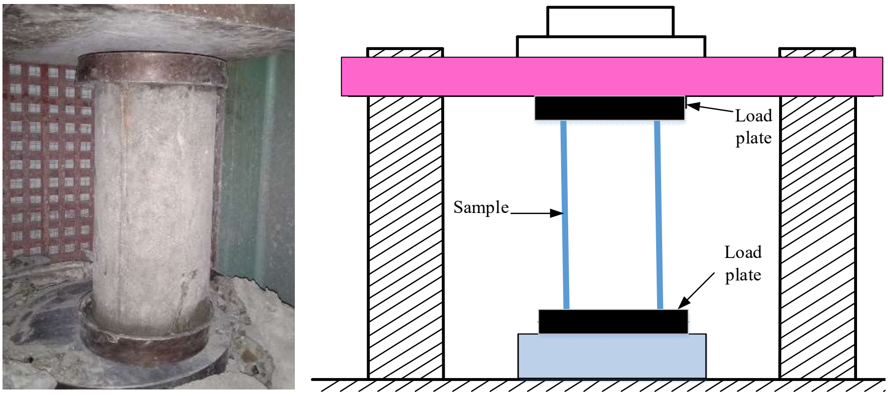
2.2. Testing of specimens

Conforming to the guidelines provided by ASTM C143 [14], different mixes were tested for slump. Mostly, the slump cone test is employed to assess the workability which ascertains the needful effort to establish a fresh mix of concrete with nominal loss inhomogeneity. Nonetheless, this study included U-box, V-funnel, sieve aggregation testing, and L-box, which were in line with the standard [15]. Several fresh state parameters of SGC, including as density, resistance to segregation, workability, and density, were also determined in addition to the main experiment. A 100 x 200 × 300 mm cone was employed to gauge the slump. To let the concrete flow freely, the specimen had to be poured in three layers and then lifted. A compression testing equipment was used to perform compression tests on 150 × 300 mm cylinders at 7, 28, 90, and one year, as shown in Figure 2. The methods adhered closely to the ASTM C39 criteria [16].

3. Results and Discussion

3.1. Rheological Properties

Table 3 outlines the findings of fresh state features of SGC specimens. Not only the FSA-sourced modification improved the workability and viscosity of the test specimen, but also it notably improved the passing ability. Enhancement in the workability is attributed to the glassy structure of FSA [17]. Mix labeled with 60FSA-SGC attained the largest slump with 683.55 mm of value, whereas the least value of 627.75 mm was noted for the 0FSA-SGC specimen. Nevertheless, FSA-sourced modifications in SGC caused a reduction in both, V-funnel time and T500 slump. Because the FSA is not capable of absorbing sufficient water (0.39%), the T500 slump was dropped. This decline is explained by the release of excessive water, which eventually induced non-homogeneity in the mix with inherited higher susceptibility to segregation and bleeding phenomenon.



(a) (b)

Figure 2. Compressive strength testing of samples (a) experimental (b) schematic

Table 3. Characteristics of fresh state SGC specimen

Specimen	0FSA-SGC	20FSA-SGC	40FSA-SGC	60FSA-SGC
Slump (mm)	627.75	660.3	669.6	683.55
V-funnel (s)	6.96	6.18	5.28	4.58
Sieve segregation ratio (%)	3.39	5.07	9.02	10.93
Passing ratio	0.73	0.77	0.86	0.91
U-box (mm)	18.6	13.95	13.95	16.74
T500 slump (s)	2.84	2.12	1.53	1.12

When FSA was introduced, the reference mix 0FSA-SGC's V-funnel time dropped to 6.95 seconds. The V-funnel time of the 60FSA-SGC mix was 34% shorter than that of the reference mix. The FSA-modified SGC specimen's decreased viscosity is the cause of this drop. The viscosity parameter influences the flow time in addition to the mix's consistency. A mixture with less viscosity therefore flows more readily. As per [15], the mix specimens were categorized as SF2 and VF1, which corresponded to slump flow and viscosity categories. FSA-modified SGC mixes accomplished a notable improvement in passing ratios which varied from 0.72 to 0.91. SGC mixes presented U-box values ranging from 13.95 to 18.6 mm, which further supported an improvement in passing characteristics [18]. 0FSA-SGC specimen accomplished 18.6 mm of difference in filling heights, however, it dropped to 13.95 mm for both 20FSA-SGC as well as 40FSA-SGC based mixes. Contrarily, this difference in filling heights was higher with 16.74 mm of value in 60FSA-SGC. Because the particles of FSA are heavier, they tend to settle at the base of the U-box which eventually causes a rise in the filling height. In addition, the mixes containing more than 40% FSA were prone to bleeding and segregation due to less water absorption and glassy features of FSA particles. Figure 3 presents the rheological properties of fabricated SGC mixes.

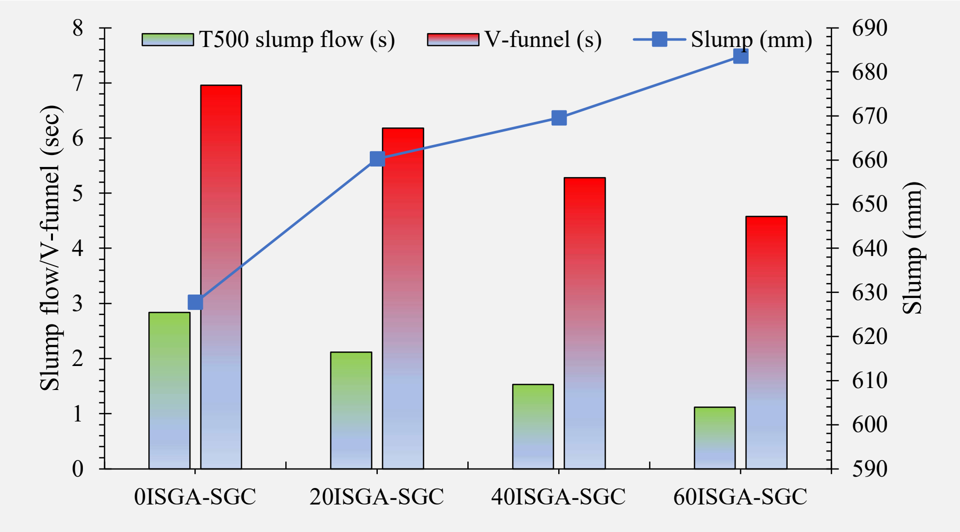


Figure 3. Rheological properties of fabricated SGC mixes.

With the increase in FSA from 0% to 60%, the resulting mixes attained the variation in sieve aggregation proportion with 3.39–10.92. Because the resulting values were less than 15%, therefore prepared mixes strongly adhered to the guidelines of [15]. Fresh state features were mainly enhanced by the combined action of FSA, FA, and UFS, which was primarily accomplished by an improved binding impact and associated homogeneity and compactness in the mix. Henceforth, up to 60% of FSA modification reported favorable changes in the fresh state features of SGC.

3.2. Relationship for Rheological Properties

A technique of linear regression was employed to evaluate the association between different variables such as workability, passing ability, resistance to withstand the segregation, and viscosity of SGC specimens. Slump with V-funnel timing and slump with T500 flow were strongly correlated by regression coefficients (R^2) of 0.9159, correspondingly (See Figure 4). The rise in the slump caused a drop in T500 flow value, which further supports the fact that viscosity and flowability are in close relationship. Nevertheless, V-funnel timing and slump were inversely proportional.

Figure 5 highlights the association between slump flow, V-funnel timing, and passing ratios. V-funnel timing with slump and V-funnel timing with passing ratio achieved the R^2 of 0.9331, correspondingly. Both V-funnel time with slump and V-funnel time with passing ratio were inversely proportional. Behera et al. [19] presented a similar fashion of association between slump with V-funnel timing and T500 flow with a slump. Likewise, V-funnel time with a passing ratio attained the R^2 of 0.97 [18]. These findings are also in close agreement with those established in this work.

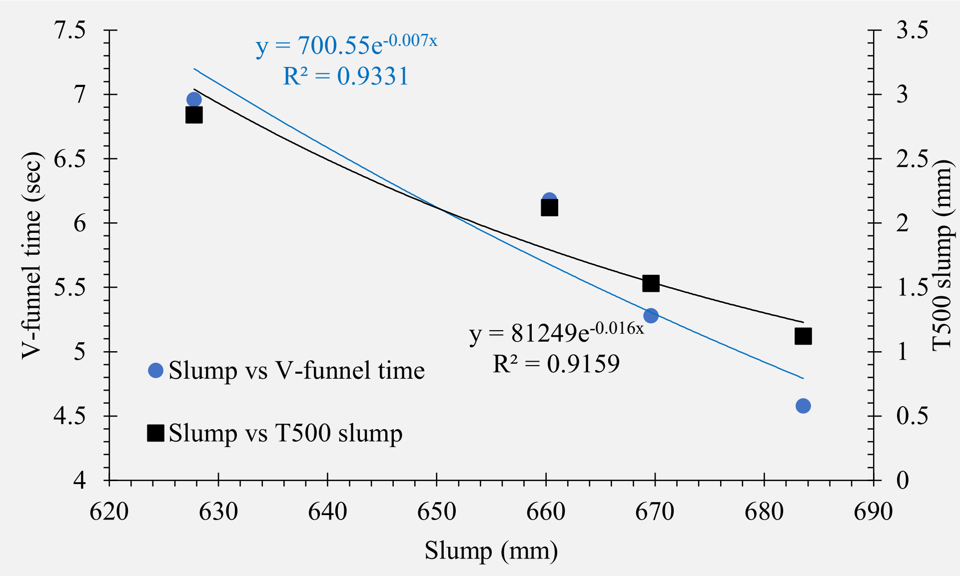


Figure 4. Relationship of slump with T500 slump flow and V-funnel time of SGC specimens.

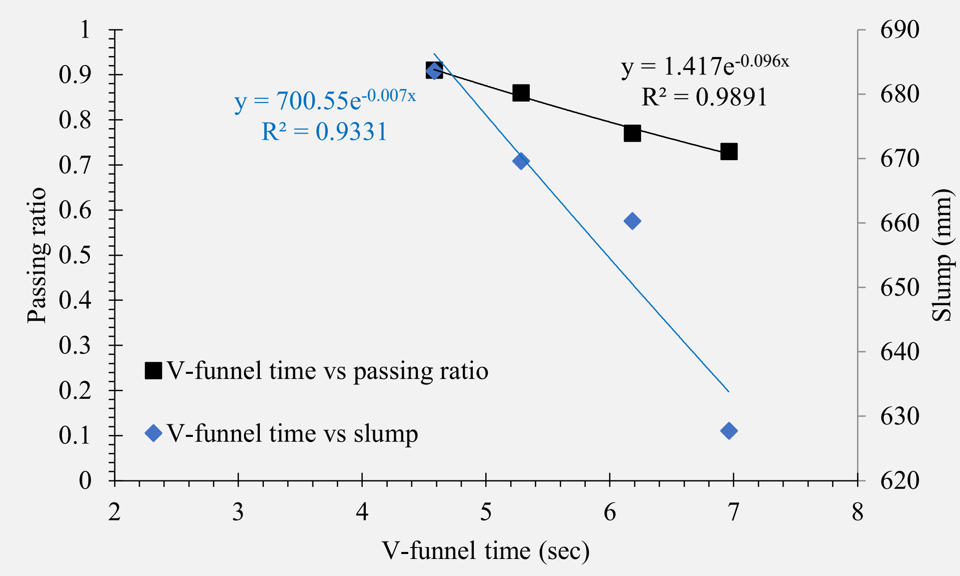


Figure 5. Correlation of V-funnel time with passing ratio and slump of SGC specimens.

3.3. Compressive strength

Findings of the compression testing of 7-day, 28-day, 90-day, and one-year-old specimens are presented in Figure 6. 20% FSA-modified specimen presented a rise in the compression strength. The reference mix accomplished 36.1 MPa of 28-days compression strength, which improved to 39.3 MPa with the inclusion of 20% FSA. Nevertheless, beyond 20%, the specimen experienced a decline in strength. 60FSA-SGC specimen presented the minimum value of resulting strength with 34.8 MPa.

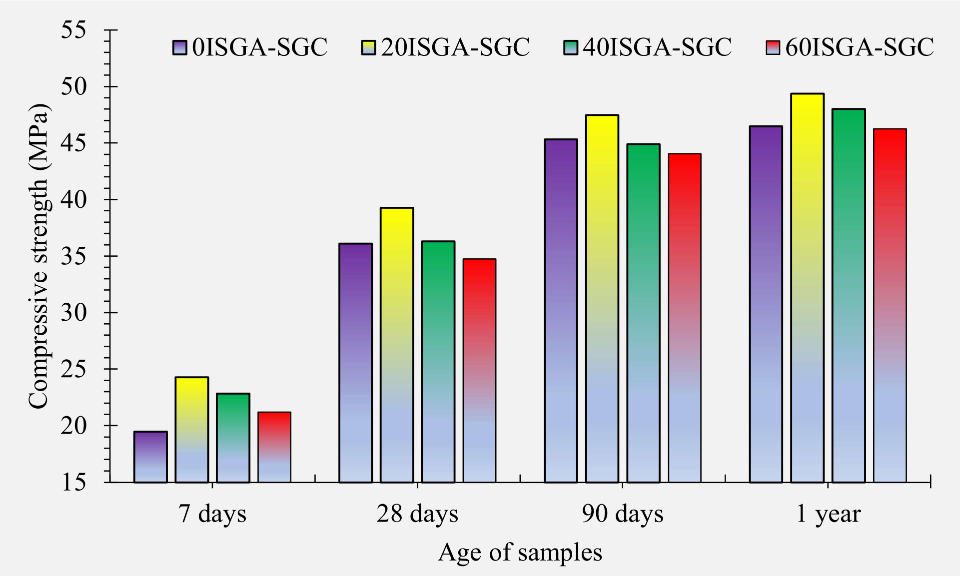


Figure 6. Compression strength of different SGC specimens

Similar to conventional concrete, the compressive strength of the SGC specimen improved with time. However, this upward trend plateaued after 90 days. In contrast to the strength range of 44 to 47.5 MPa at 90 days, the specimens showed a slight increase of 2.5% to 6.9% after one year, reaching a strength range of 46.3 to 49.4 MPa. Specimens tested for strength at 7 to 28 days showed the most significant improvement, with a 58% to 86% increase in strength. The 60FSA-SGC specimen exhibited the lowest compressive strength across all curing ages, while the 20FSA-SGC specimen showed the highest strength. Interestingly, the 60% FSA-modified specimen retained a slight increase in strength compared to the reference mix specimen. Therefore, it is clear that up to 60% replacement of sand with FSA had no adverse impact on the compressive strength of the concrete.

In general, the above findings were in close agreement with previous research. For instance, FSA-modified FA sourced GPC specimens experienced a rise in compression strength [7]. At 100% replacement level of FSA, the specimen cured under an ambient environment presented a compression strength of 40.7 MPa. Nevertheless, the largest compression strength was reported at 60% of the replacement level. In addition, with increasing the FSA level, the GPC specimen presented a corresponding increase in strength, while the minimum strength value of 30.1 MPa was found in the reference mix. The discrepancy in study findings may be associated with deviation in interacting ingredients within the GPC mix. Because the test environments were different in the compared works, therefore resulting interaction varied with constituents, percentages, and humidity environment with lacked standardized GPC guidelines [20].

4. CONCLUSIONS

The investigation into the use of fayalite slag aggregates (FSA) as a partial substitute for sand in self-compacting geopolymer concrete (SGC) revealed several important findings. Firstly, incorporating 20% FSA resulted in the highest compressive strength, reaching 49.38 MPa after one year. This enhancement was attributed to the densified microstructure of the mixture and the additional formation of calcium products with the inclusion of ultrafine slag (UFS) and FSA. However, higher proportions of FSA led to excessive water release, which weakened the microstructure and compromised its properties.

Secondly, increasing the amount of FSA improved the workability of SGC specimens, with the 60FSA-SGC specimen showing the highest slump value of 683.5 mm. The combined effect of UFS and FSA enhanced the flowability of SGC specimens, making it easier to compact the mixture.

Finally, significant differences in mechanical strength and durability were observed when incorporating fly ash, ultrafine slag, and fayalite slag aggregates. The study suggests that using FSA is advantageous for SGC, as it does not significantly affect its mechanical properties and promotes environmentally sustainable construction practices. In summary, the study highlights the potential of FSA to partially replace sand in SGC, with UFS and FA acting as binding agents. The resulting SGC meets the required criteria and is recommended for use in on-site construction projects.

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