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Effect of Type of Sand on the Flowability and Compressive Strength of Slag-Fly Ash Blended Geopolymer Mortar

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Abstract – This paper investigates the influence of the type of fine aggregates on the properties of slag-fly ash blended geopolymer mortar. Twelve mixes were prepared with two types of sand: desert dune sand (DS) and crushed dolomitic limestone sand (CS). Different alkaline activator solution-to-binder (0.50, 0.60, and 0.65) and binder-to-sand ratios (1:2, 1:3, and 1:4) were considered to analyze their effect on the performance of the geopolymer mortar. The properties under investigation included the amount of additional water needed to maintain a flow of 150 ± 2 mm and the 7- and 14-day compressive strengths. Experimental test results showed that an increase in fine aggregates content resulted in a higher additional water demand, regardless of the type of sand used. As a result, the mortar compressive strength decreased by up to 29% compared to mixes with the lowest binder-to-sand ratios (1:2 for DS mixes and 1:3 for CS mixes). An increase in the alkaline activator solution-to-binder ratio reduced the additional water needed to satisfy the target flowability but increased the overall liquid-to-binder ratio. Meanwhile, for optimum compressive strength, DS-based mixes comprised B:S and AAS/B ratios of 1:2 and 0.60, respectively, while those of CS-based mixes were 1:3 and 0.65, respectively. Compared to mixes made with CS, those incorporating DS required the addition of more water to maintain the flowability and experienced up to 81% loss in compressive strength; still, DS-based mixes achieved 14-day compressive strengths exceeding 28 MPa. The experimental findings advocate the use of DS as fine aggregates in the production of slag-fly ash blended geopolymer mortar to be utilized in various construction applications.

***Keywords*:** fly ash; slag; geopolymer; mortar; dune sand; limestone; flow; compressive strength.

1. Introduction

The vast growth in population and the exponential rise in civil engineering construction work have dramatically increased the emission of greenhouse gases and the consumption of non-renewable natural resources. Globally, the construction industry is responsible for the emission of 40% of CO_2, the consumption of around 20 to 50% of natural resources, and the disposition of 50% of the total solid waste material [1], [2]. There is a pressing need for natural aggregates, such as limestone, in the production of Portland cement, as a typical concrete mix is formulated with 60 to 75% aggregates, by weight. As such, the construction industry is responsible for causing significant environmental damage [3], [4]. According to Branavan and Konthesingha [5], 80% of the fine aggregates used in the production of concrete and mortar by small contractors is river sand. Owing to the negative impact of concrete and its components on the environment, researchers, environmental agencies, and governments strive to find eco-friendly alternative materials for Portland cement and non-renewable natural aggregates.

Of the various solutions to efficiently reduce the consumption of Portland cement, its full or partial replacement with industrial wastes and cementitious materials, such as fly ash, slag, metakaolin, and silica fume, has shown promising results. In addition to alleviating the use of Portland cement, the mechanical and durability properties of construction products made with cementitious (partial replacement) or geopolymeric (full replacement) binders has been superior to those of counterparts made with cement only [6]–[11]. According to Alexander and Shashikala [11], fly ash-slag blended geopolymer mortar exhibited better resistance to acid, sulfate, and marine water attacks compared to a control mix prepared with Portland cement.

Fine aggregates play an essential role in altering the fresh and hardened properties of mortar [12]–[15]. According to Harini et al. [13], a higher degree of sand irregularities, higher sand-to-binder ratio, and single particle size gradation resulted in a less flowable mortar. Li et al. [14] showed that higher fineness modulus and better gradation increase the workability and strength of fly ash-based geopolymer mortar. Stefanidou [15] has found that mortar prepared with fine aggregates having irregular shapes possessed a higher strength due to the formation of a robust interfacial contact zone between binder matrix and aggregates. Moreover, deserts occupy around 20% of the total land area on Earth. Of this area, 10% is covered by desert dune sand [16]. Countries, such as the United Arab Emirates, Saudi Arabia, Oman, and Egypt, are predominantly covered by dune sand, with occupying as much as 75% of their land area [17]–[19]. Despite its abundance across the globe, researchers have found them to possess similar physical properties. Generally, their fine particles are mainly chemically composed of SiO_2 and Al_2O_3 [18]–[20].

The complete or partial replacement of natural fine aggregates with desert dune sand has been proposed as a sustainable alternative to decrease its adverse environmental impact [20]–[27]. While many studies agreed on the suitability of using dune sand as fine aggregates in concrete and mortar [22]–[24], others linked the poor performance of dune sand-based material to its low fineness modulus and poor granular gradation [20], [22]. Chuah et al. [22] reported that fly ash-based geopolymer mortar can be used as a construction material despite the creation of high volume air voids caused by the poor gradation of dune sand (DS). However, Abu Seif et al. [28] concluded that using more than 50% DS as fine aggregates cannot achieve an acceptable workability and compressive strength as those of cement-based mortar and concrete. Limited research has been carried to compare the effect of replacing conventional fine aggregates, as natural crushed dolomitic limestone, with dune sand on the fresh and hardened properties of slag-fly ash blended geopolymer mortar.

This study aims to assess the influence of replacing crushed dolomitic limestone sand (CS) with desert dune sand (DS), as fine aggregates, on the properties of slag-fly ash blended geopolymer mortar. Different binder-to-sand ratios (B:S of 1:2, 1:3, and 1:4) and alkaline activator solution-to-binder ratios (AAS/B of 0.55, 0.60, and 0.65) were examined. Additional water was incorporated into the mix to maintain a minimal flow of 15.0 ± 0.2 cm. The performance of the geopolymer mortar was characterized by the flow and 1- and 7-day compressive strengths.

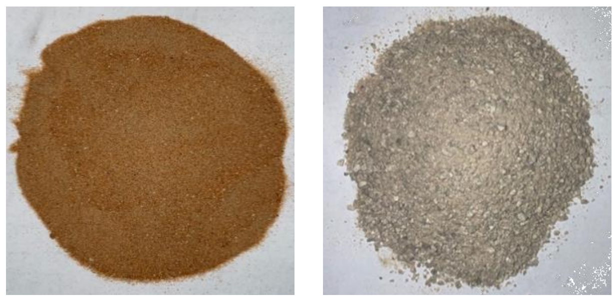
2. Experimental Program

2.1. Materials

Class F fly ash (FA) and ground granulated blast furnace slag (or simply slag) were used as aluminosilicate materials binders to produce the geopolymer mortar mixes. FA composed of 52.7, 18.6, 14.3 and 8.3% of silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), and calcium oxide (CaO) respectively, while the slag comprised 59.7, 27.0 and 7.5% of CaO, SiO_2 and Al_2O_3, respectively. Abundant local desert dune sand (DS) and natural crushed dolomitic limestone sand (CS) with a maximum size of 2.36 mm, as shown in Fig. 1, were used as fine aggregates. The specific surface area, density, specific gravity, and fineness modulus of the DS were identified as 119.7 cm^2/g, 1663 kg/m^3, 2.57 and 1.3, respectively, while the corresponding properties of CS were 81.7 cm^2/g, 2000 kg/m^3, 2.69 and 2.6. Fig. 2 presents the particle size distribution of the fine aggregates while comparing it to the upper and lower limits recommended by ASTM C33 [29]. It is worth noting that the gradation of the as-received DS did not fall between the described limits. A mix of sodium hydroxide (SH) solution, having a molarity of 8 M and grade N sodium silicate (SS) solution was used to prepare the alkaline activator solution (AAS). Tap water was used to prepare the SH solution and was added to selected geopolymer mixes to improve their flowability.

2.2. Mixture Proportioning

Twelve mortar mixes were prepared to assess the effect of the type of fine aggregates, the binder-to-sand ratio (B:S), and the AAS-to-binder ratio (AAS/B) on the flow and compressive strength of slag-fly ash blended geopolymer mortar. Table 1 summarizes the mixture proportions. Mixes were designated as X-Y-Z, where X represents the type of sand (DS or CS), Y denotes the B:S ratio, and Z is the AAS/B ratio. For example, DS-1:3-0.65 is a mix made with dune sand at a binder-to-sand ratio of 1:3 and AAS-to-binder ratio of 0.65. Six mixes were produced with DS, while the other six were made with CS. Regardless of sand type, the binder was formulated by mixing equal parts of slag and fly ash to maintain a flowable mix without the need for heat curing, based on the results of previous work [10], [30], [31]. Mortar mixes incorporating CS were made with different B:S ratios of 1:3 and 1:4. Meanwhile, mixes including DS had B:S ratios of 1:2 1:2 and 1:3; higher B:S ratios yielded non-workable mixes. Further, the AAS/B varied among 0.55, 0.60, and 0.65. The AAS AAS was prepared by mixing the SS and SH solutions at SS/SH ratio of 1.5. Such values were selected based on preliminary preliminary trial mixes and past literature [30]. Tap water was added as a function of the binder (AW/B) to achieve a minimal minimal flow of 15.0 ± 0.2 cm. The liquid-to-binder ratio (L/B) was calculated as the ratio of the sum of AW and AAS to the binder mass.



(a) (b)

Fig. 1: Fine aggregates: (a) dune sand and (b) crushed limestone sand.

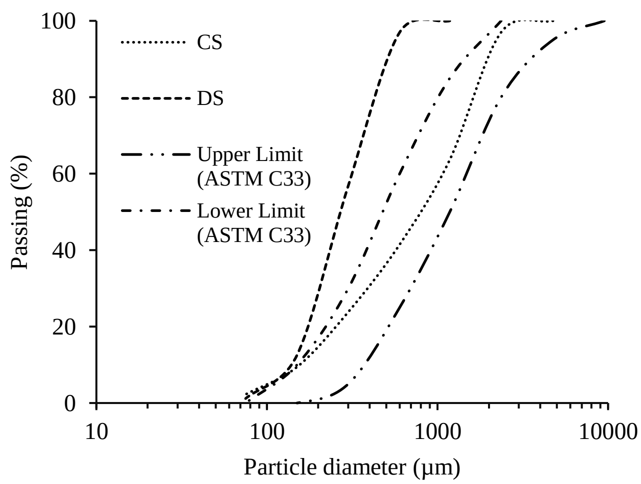


Fig. 2: Particle size distribution of the fine aggregates.

Table 1: Mixture proportions of slag-fly ash geopolymer mortar mixes.

Mix ID	FA:Slag	Type of Sand	B:S	AAS/B	SS/SH	SH Molarity (M)	L/B
DS-1:2-0.55	1:1	DS	1:2	0.55	1.5	8	0.60
DS-1:2-0.60	1:1	DS	1:2	0.60	1.5	8	0.65
DS-1:2-0.65	1:1	DS	1:2	0.65	1.5	8	0.68
DS-1:3-0.55	1:1	DS	1:3	0.55	1.5	8	0.74
DS-1:3-0.60	1:1	DS	1:3	0.60	1.5	8	0.75
DS-1:3-0.65	1:1	DS	1:3	0.65	1.5	8	0.80
CS-1:3-0.55	1:1	CS	1:3	0.55	1.5	8	0.62
CS-1:3-0.60	1:1	CS	1:3	0.60	1.5	8	0.65
CS-1:3-0.65	1:1	CS	1:3	0.65	1.5	8	0.66

CS-1:4-0.55	1:1	CS	1:4	0.55	1.5	8	0.72
CS-1:4-0.60	1:1	CS	1:4	0.60	1.5	8	0.74
CS-1:4-0.65	1:1	CS	1:4	0.65	1.5	8	0.79

2.3 Samples preparation

The AAS was prepared one day before casting the geopolymer mortar mixes. Water was added to SH flakes to achieve the needed molarity of 8 M. After the generated heat was dissipated, the SS solution was added to the SH solution to form the AAS. To initiate the formulation of the geopolymer mortar, the fine aggregates were added to slag and fly ash and mixed for 2 to 3 mins to achieve homogeneity. Then, the AAS was added gradually to the mixer and mixed for another 1 minute after which the additional water was added. Mixing continued for a total of 3 minutes. The fresh mortar was cast into 50-mm cubic moulds, covered with plastic sheets for one day, and demoulded to be cured in an ambient condition until testing age.

2.4 Test Methods

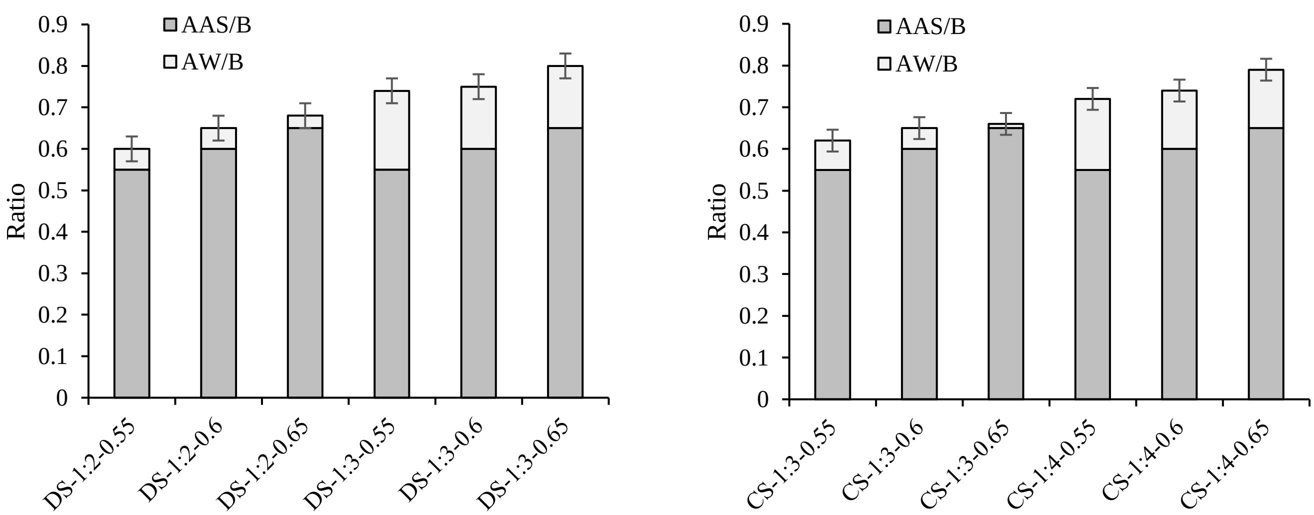
The fresh properties of geopolymer mortar mixes were assessed using the slump flow based on ASTM C230 [32]. Fresh geopolymer mortar was cast into a conical mould, placed on a flow table right after mixing, and dropped 25 times in 15 seconds. The initial flow was measured as an average of 4 diametrical readings.

The mechanical performance of geopolymer mortar was characterized by the 7- and 14-day compressive strength according to ASTM C109 [33]. Preliminary testing showed that 28-day strength was not different than that at 14 days and was therefore not included in the analysis. The average of 3 test specimens was taken to obtain an average.

3. Results and Discussion

3.1. Water Addition and Flowability

Fig. 3 shows the AAS-to-binder (AAS/B), the additional water-to-binder (AW/B), and liquid-to-binder (L/B) ratios used in each mix to achieve a flow of 15.0 ± 0.2 cm. For mixes made with DS at a B:S ratio of 1:2, increasing the AAS/B ratio from 0.55 to 0.65 was accompanied by a decrease in the AW/B ratio from 0.05 to 0.03. Meanwhile, at a higher B:S ratio of 1:3, the AW/B ranged from 0.15 to 0.19. Clearly, the higher the B:S ratio, i.e., higher sand content, the more additional water was needed to maintain the flow. Nevertheless, despite that less additional water was required at a higher AAS/B ratio, the L/B increased due higher viscosity of AAS compared to that of water [8]. This phenomenon was more apparent at a higher B:S ratio. This is owed to the creation of higher internal friction between sand particles with the increase in sand content during mortar production [34].



(a) (b)

Fig. 4: Change in the AAS/B and AW/B ratios of (a) DS-based mortar and (b) CS-based mortar to maintain a flow of 15 cm.

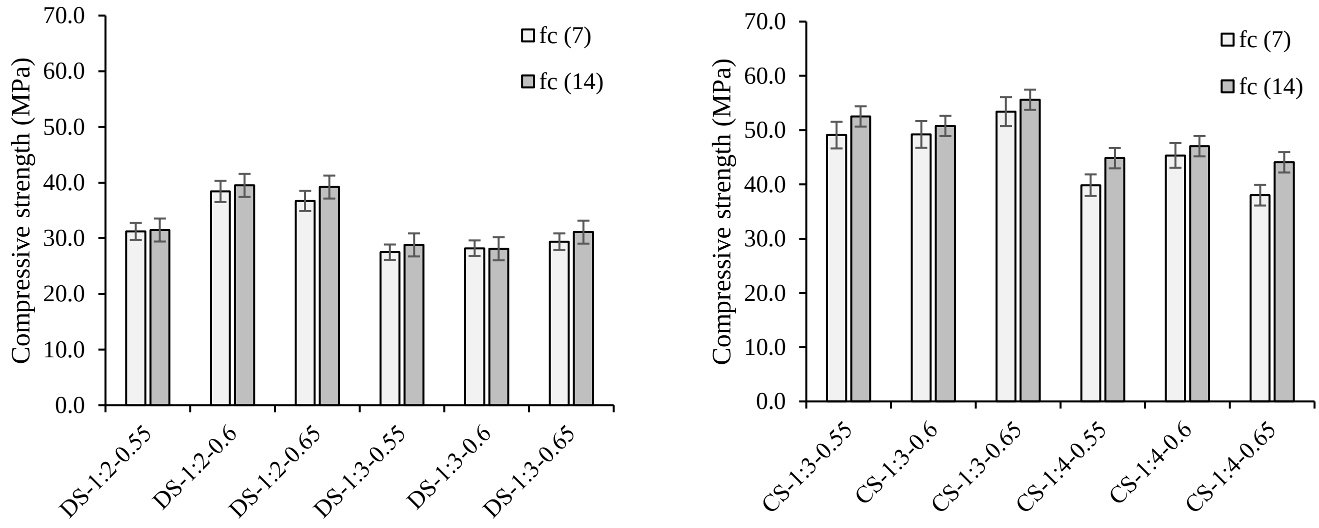
For the geopolymer mortar mixes comprising CS as the fine aggregate, increasing the AAS/B ratio from 0.55 to 0.60 0.60 resulted in a decrease in the AW/B ratio from 0.07 to 0.01. Yet, an increase in the B:S ratio from 1:3 to 1:4, i.e., higher higher sand content, was linked to higher AW/B ratios of 0.14 to 0.17. As such, the L/B ratio increased to reach 0.79. This This increase in water demand was owed to the creation of higher shear friction between sand particles, resulting in the reduction of the mortar flowability [34]. Also, similar to counterpart mixes made with DS, a higher L/B ratio was obtained when the AAS/B increased although the additional water quantity was less.

The effect of the type of sand on the initial flow was analyzed by comparing the AW/B or L/B ratios of geopolymer mortar mixes prepared with similar B:S and AAS/B ratios. It can be seen that replacing CS with DS resulted in the addition of more water to the geopolymer mortar mixes. For instance, for mortar mixes made with the same respective B:S and AAS/B ratios of 1:3 and 0.65, the mix prepared with DS needed more water (AW/B = 0.15) than that prepared with CS (AW/B = 0.01). This is primarily owed to the lower fineness modulus, poor particle size gradation, and higher specific surface area of DS compared to that of CS. Similar results were found by Li et al. [14], where the flowability of geopolymer mortar decreased with the decrease in the fineness modulus and poor gradation of river sand.

3.2. Compressive Strength

The 7- and 14-day compressive strength of slag-fly ash blended geopolymer mortar mixes are plotted in Fig. 4. Overall, the strength variation between 7 and 14 days for geopolymer mixes varied between 1 and 6%, except for CS-1:4-0.55 and CS-1:4-0.65, where the percent increase in strength reached 13%. The low strength increases of compressive strength between the 7 and 14 days is due to the fast reaction of slag with the AAS within the first few days after casting resulting in the creation of calcium aluminosilicate (C-A-S-H) and calcium silicate hydrate (C-S-H) gels. Meanwhile, the slow continuous strength development is linked to the continuous geopolymerisation of fly ash to form sodium aluminosilicate hydrate (N-A-S-H) gel [9], [10], [35], [36]. For this reason and because the 7- and 14-day test results followed similar trends, the analysis was carried out on the 14-day compressive strength only.

The effect of sand content on the compressive strength of geopolymer mortar mixes was investigated for each type of sand, i.e., DS and CS. An increase in sand content, i.e., higher B:S ratio, resulted in a decrease in strength. In fact, for DS mixes made with AAS/B of 0.55, 0.60, and 0.65, increasing the B:S ratio from 1:2 to 1:3 led to 9, 29, and 21% lower compressive strength. Similarly, geopolymer mortar mixes incorporating CS and having AAS/B of 0.55, 0.60, and 0.65 experienced reduction in the compressive strength by 15, 8, and 21%, respectively. Such loss in strength is owed to the reduction in paste volume and increase in additional water content (to maintain flowability) [14]. This detrimental effect was more intense in DS-based mixes than those made with CS, owing to the low fineness modulus, poor particle size gradation, and high specific surface area of the DS.



(a) (b)

Fig. 4: Compressive strength of (a) DS-based mortar and (b) CS-based mortar.

The influence of using different AAS/B ratios on the compressive strength of geopolymer mortar was also examined. Results show that increasing the AAS/B ratio until a specific limit improved the behavior of GP mortar under compression loading. The optimum mix prepared with DS was that with B:S and AAS/B ratios of 1:2 and 0.60, respectively, while the optimum counterpart made with CS had B:S and AAS/B ratios of 1:3 and 0.65, correspondingly. Similarly, Gugulothu and Rao [35] stated that the compressive strength of slag-based GP concrete improved with an increase in the AAS content, followed by a reduction in strength values with more AAS addition. This is owed to the creation of internal voids due to the evaporation of unreacted liquid solution in hardened mortar matrix [37].

Furthermore, the type of sand significantly impacted the compressive strength of the geopolymer mortar. By comparing the results of mixes prepared with the same B:S and AAS/B but different types of sand, CS-based mortars experienced, on average, 81% higher compressive strength than counterparts produced with DS. In fact, the 14-day strength increased from 28.8, 28.1, and 31.1 MPa to 52.5, 50.8, and 55.3 MPa upon replacing DS with CS in mixes having AAS/B of 0.55, 0.60, and 0.65, respectively. Such reduction in performance is related to the surface texture and particle gradation of DS, increase in water demand, higher volume of entrapped air voids, and reduction in the paste volume in DS-based mixes [19], [38].

4. Conclusions

The flow and 14-day compressive strength of slag-fly ash blended geopolymer mortar prepared with two types of fine aggregates, i.e., dune sand and crushed limestone sand, were examined. Different binder-to-sand and AAS-to-binder ratios were utilized in this study. Based on the experimental results, the following conclusions can be furnished:

- The increase in sand content demanded more water addition to achieve the needed flowability. The AW/B and L/B ratios gradually increased to achieve the targeted flow of 15 ± 0.2 cm. The compressive strength of DS- and CS-based geopolymer mixes decreased by 29% and 21%, respectively, with higher sand content due to the increase in the amount of additional water and reduction in paste volume.
- Increasing the AAS/B ratio from 0.55 to 0.65 resulted in less additional water (i.e., lower AW/B) being incorporated into the mix design but a liquid-to-binder (L/B) ratio. Meanwhile, changing the AAS/B ratio did not have a significant impact on the mechanical performance of geopolymer mortar mixes.
- The type of sand influenced the fresh and hardened properties of the geopolymer mortar. The replacement of DS by CS resulted in a decrease in the water demand and an improvement in the compressive strength by up to 81%. This behaviour

is owed to the lower fineness modulus, poor particle size gradation, and higher specific surface area of DS compared to that of CS. Yet, DS-based geopolymer mortar mixes could attain a 14-day compressive strength exceeding 28 MPa, rendering them suitable for use in different construction applications.

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