DEVELOPMENT OF A SELF-LEVELING FLY ASH-SLAG GEOPOLYMER MORTAR

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Exponential growth in the world population and increase in demand for concrete are pressuring researchers and scientists to find sustainable alternative materials for Portland cement and natural aggregates. Self-leveling mortar is extensively used in construction applications, such as floor leveling, repair, resurfacing, or adhesion. Yet, limited research has been carried out on enhancing this material’s sustainability. This paper aims to produce a geopolymer mortar produced with fly-ash (FA), ground granulated blast furnace slag (BFS), and desert dune sand. Geopolymer mortar samples were produced with different binder-to-sand (B:S), FA-to-slag (FA:BFS), and alkali-activator solution-to-binder (AAS/B) ratios. Alkaline solution was blended with sodium silicate and sodium hydroxide with a molarity of 8 M (ratio of 1.5). Fresh and hardened properties of the developed self-leveling mortars were assessed. Experimental results showed that the flow, initial and final setting time, and 7- and 14-day compressive strength were in respective ranges of 17.3-40.3 cm, 21-155 minutes, 42-221 minutes, 6.0-70.3 MPa, and 5.2-78.7 MPa. Furthermore, an increase in FA:BFS, B:S, and AAS/B ratios enhanced flowability and prolonged setting time but reduced compressive strength at both ages. These research findings advocate the use of a self-leveling, cement-free geopolymer mortar to be utilized in various buildings and repair applications.

Keywords: Setting time, Flow, Compressive strength, Sustainability.

1 INTRODUCTION

At the present time, despite all the negative environmental impact resulting from the production of Portland cement, it is still ranked as the predominant building material used in the world, with a global yearly production of approximately 4 Gt/year (Li et al. 2022). In 2023, the world average daily temperature reached the highest record of 17.2°C (62.9°F), with expectation that this record will be broken in the near future (Paddison 2023). Thus, there is a pressing need to find environment-friendly alternatives to Portland cement. Partial or full replacement of Portland cement with cementitious materials showed great potential in the production of construction materials with acceptable properties (Bawab et al. 2023, El-Mir et al. 2023). In specific, cement-free geopolymers are produced by mixing a sodium, potassium, or calcium-based alkaline solution with alumina silica-rich material, such as fly ash, ground granulated blast furnace slag, and metakaolin (Yousefi Oderji et al. 2019). Geopolymer materials showed great prospective to be used in different construction applications such as, strengthening of old and damaged concrete...
structures (Cao et al. 2019), screed flooring (Hwalla et al. 2023d), masonry blocks units (Hwalla et al. 2023a), and underwater building materials (Hwalla et al. 2023b).

The vast use of natural aggregates such as river sand and gravel in the production of nowadays concrete and mortar is another issue that is heavily researched. According to Branavan and Konthesingha (2019), river sand accounts for 80% of the fine aggregates utilized by small contractors in the production of concrete and mortar. The high consumption of river sand and gravel is resulting in severe environmental problems such as coastline erosion and river deltas (Collivignarelli et al. 2020). For this reason, researchers are examining alternative wastes or highly abundant aggregates as substitutions for concrete aggregates. Deserts cover around 20% of the total area of the earth, with dune sand (DS) occupying 50% of this area (Hwalla et al. 2023c). Their fine particles are primarily composed of silica ($\text{SiO}_2$) and alumina ($\text{Al}_2\text{O}_3$). Despite the low fineness modulus and poor gradation of DS (Najm et al. 2022), many studies agreed on the suitability of partial or full use of DS as fine aggregates in the production of concrete and mortar (Bawab et al. 2023, Hwalla et al. 2023d).

Self-leveling mortar is a construction material that is primarily used to achieve a level and smooth surface for uneven concrete elements and for the installation of flooring materials such as vinyl, laminate, and tile. In addition, self-leveling mortar possessing high mechanical and durability properties are used as repair materials for damaged concrete elements. Thus, self-leveling mortar is a suitable application for geopolymers and DS. This study aims to develop a self-leveling geopolymer mortar produced with fly ash (FA) and blast furnace slag (BFS) as precursors and DS as fine aggregates. The influence of the binder-to-sand ratio (B:S of 1:1, and 1:5), the FA-to-BFS ratio (FA:BFS of 60:40, and 70:30), and the alkaline activator solution-to-binder ratio (AAS/B of 0.4, 0.5, 0.6, 0.7, 0.8, and 0.9) on the initial flow, setting time and the compressive strengths were examined.

2 EXPERIMENTAL PROGRAM

2.1 Materials

Class F FA and BFS were used as precursors for the production of the geopolymers. The physical and chemical properties of binders can be found elsewhere (Hwalla et al. 2023d). DS with a density, surface area, specific gravity, and fineness modulus of 1663 kg/m$^3$, 119.7 cm$^2$/g, 2.57, and 1.3, respectively, was used as fine aggregates. For activation of the binder, a sodium-based AAS was prepared by mixing a sodium hydroxide (SH) solution having a molarity of 8 M and grade N sodium silicate (SS) solution with a SS-to-SH ratio (SS/SH) of 1.5. Such molarity and ratio were selected to achieve high flowability and acceptable setting time while maintaining adequate mechanical properties (Huseien et al. 2017).

2.2 Mix Design

Eighteen mortar mixes were produced to assess the influence of B:S, FA:BFS, and AAS/B ratios on the initial flow, the initial, and final setting times, and the compressive strength of FA-BFS blended self-leveling geopolymer mortar. The mixture proportions of different geopolymer mixes are summarized in Table 1. Mixes were designated as W-X:Y/Z, where W denotes the B:S ratio, X:Y represents the FA:BFS ratio, and Z is the AAS/B ratio. For example, 1.0-60:40/0.4 is a mix produced with B:S, FA:BFS, and AAS/B ratios of 1:1, 60:40, and 0.4, respectively. In addition, Table 1 presents the percentages of each material per mass percentages.
Table 1. Mix design ratios of self-leveling geopolymer mixes.

<table>
<thead>
<tr>
<th>Mix Number</th>
<th>Mix Designation</th>
<th>B:S</th>
<th>FA:BFS</th>
<th>AAS/B</th>
<th>FA (%)</th>
<th>BFS (%)</th>
<th>AAS (%)</th>
<th>Sand (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0-60:40-0.4</td>
<td>1:1</td>
<td>60:40</td>
<td>0.4</td>
<td>25.0</td>
<td>16.7</td>
<td>16.7</td>
<td>41.7</td>
</tr>
<tr>
<td>2</td>
<td>1.0-60:40-0.5</td>
<td>1:1</td>
<td>60:40</td>
<td>0.5</td>
<td>24.0</td>
<td>16.0</td>
<td>20.0</td>
<td>40.0</td>
</tr>
<tr>
<td>3</td>
<td>1.0-60:40-0.6</td>
<td>1:1</td>
<td>60:40</td>
<td>0.6</td>
<td>23.1</td>
<td>15.4</td>
<td>23.1</td>
<td>38.5</td>
</tr>
<tr>
<td>4</td>
<td>1.0-60:40-0.7</td>
<td>1:1</td>
<td>60:40</td>
<td>0.7</td>
<td>22.2</td>
<td>14.8</td>
<td>25.9</td>
<td>37.0</td>
</tr>
<tr>
<td>5</td>
<td>1.0-60:40-0.8</td>
<td>1:1</td>
<td>60:40</td>
<td>0.8</td>
<td>21.4</td>
<td>14.3</td>
<td>28.6</td>
<td>35.7</td>
</tr>
<tr>
<td>6</td>
<td>1.0-60:40-0.9</td>
<td>1:1</td>
<td>60:40</td>
<td>0.9</td>
<td>20.7</td>
<td>13.8</td>
<td>31.0</td>
<td>34.5</td>
</tr>
<tr>
<td>7</td>
<td>1.0-70:30-0.4</td>
<td>1:1</td>
<td>70:30</td>
<td>0.4</td>
<td>29.2</td>
<td>12.5</td>
<td>16.7</td>
<td>41.7</td>
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<tr>
<td>8</td>
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<td>1:1</td>
<td>70:30</td>
<td>0.5</td>
<td>28.0</td>
<td>12.0</td>
<td>20.0</td>
<td>40.0</td>
</tr>
<tr>
<td>9</td>
<td>1.0-70:30-0.6</td>
<td>1:1</td>
<td>70:30</td>
<td>0.6</td>
<td>26.9</td>
<td>11.5</td>
<td>23.1</td>
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<td>70:30</td>
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<td>11.1</td>
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<td>70:30</td>
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<td>10.3</td>
<td>31.0</td>
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<td>70:30</td>
<td>0.4</td>
<td>24.1</td>
<td>10.3</td>
<td>13.8</td>
<td>51.7</td>
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<td>1.5-70:30-0.5</td>
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<td>70:30</td>
<td>0.5</td>
<td>23.3</td>
<td>10.0</td>
<td>16.7</td>
<td>50.0</td>
</tr>
<tr>
<td>15</td>
<td>1.5-70:30-0.6</td>
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<td>70:30</td>
<td>0.6</td>
<td>22.6</td>
<td>9.7</td>
<td>19.3</td>
<td>48.4</td>
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<tr>
<td>16</td>
<td>1.5-70:30-0.7</td>
<td>1:1.5</td>
<td>70:30</td>
<td>0.7</td>
<td>21.9</td>
<td>9.4</td>
<td>21.9</td>
<td>46.9</td>
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<tr>
<td>17</td>
<td>1.5-70:30-0.8</td>
<td>1:1.5</td>
<td>70:30</td>
<td>0.8</td>
<td>21.2</td>
<td>9.1</td>
<td>24.2</td>
<td>45.4</td>
</tr>
<tr>
<td>18</td>
<td>1.5-70:30-0.9</td>
<td>1:1.5</td>
<td>70:30</td>
<td>0.9</td>
<td>20.6</td>
<td>8.8</td>
<td>26.5</td>
<td>44.1</td>
</tr>
</tbody>
</table>

2.3 Sample Preparation

The AAS was prepared one day before geopolymer production to ensure the full dissipation of heat. SH solution was produced by mixing 99%-pure SH pellets and tap water to achieve a molarity of 8 M. After that, SS solution was mixed with SH to produce the AAS. Meanwhile, dry materials were initially mixed for 2 to 3 minutes until homogeneity was achieved. The AAS was gradually added and mixed for another 2 to 3 minutes. The mortar was tested for fresh properties and placed into 50-mm cubic molds without any vibration. The freshly mixed mortar was covered with a plastic sheet for 1 day and demolded to cure at room temperature until testing age.

2.4 Testing Procedure

The initial flow of geopolymer mixes was assessed using the slump flow testing according to ASTM C1437. It is worth noting that the average of four readings of flow was measured while the mortar was flowing freely without any vibration. In addition, the initial and final setting times were found by using the Vicat needle apparatus following the ASTM C807.

The compressive strengths were tested after 7- and 14- days according to the ASTM C109. Preliminary testing revealed that the 28-day strength did not significantly differ from that of 14 days and, thus, was not included in the analysis. An average of three readings were taken at each age.

3 RESULTS AND DISCUSSION

3.1 Flow

Fig. 1(a) shows the initial flow values of geopolymer mixes. Overall, the flow varied between 17.9 and 40.3 cm. Indeed, it increased with an increase in the AAS/B ratio, especially between 0.4 and 0.7. However, further addition in the AAS/B ratio to 0.9 had a minor impact. For example, the flow rose from 17.9 to 35.1 cm with an increase in AAS/B from 0.4 to 0.7 in the mixes prepared with B:S and FA:BFS ratios of 1:1, and 60:40, respectively. However, it increased by only 3.2 cm with an AAS/B of 0.9. This is owed to the high viscosity of the solution, where an SH solution...
with 5.6 M was found to be 75 times more viscous than the water (Kondepudi and Subramaniam 2019).

The increase in the BFS and sand content seemed to have the same effect on the flow. Geopolymer mortars experienced a reduction in the flowability with an increase in the BFS:FA and B:S ratios. The loss of flow with the increase in BFS content is owed to the angular and coarse shape of its particles compared to those of FA. It is also due to the higher CaO content that increases the early reactivity of binding materials with the AAS. In parallel, the increase in the DS content resulted in higher internal friction between particles of sand, leading to a loss in the flow (Hwalla et al. 2023c).

![Fig. 1. (a) Initial flow values, and (b) setting time values of self-leveling geopolymer mixes.](image)

### 3.2 Initial and Final Setting Time

The initial and final setting time values are presented in Fig. 1(b). The initial and final setting times were in the respective ranges of 21-155 min and 42-221 min. The increase in the AAS content, i.e., higher AAS/B, resulted in prolonging the setting time of geopolymer mixes. For example, the initial-final setting time was prolonged by up to 3.8, 4.8, and 3.8 folds when the AAS/B increased from 0.4 to 0.9 in the mixes 1.0-60:40, 1.0-70:30, and 1.5-70:30, respectively. This is owed to the dilution of the binder matrix ions and obstruction of the activation reaction with the increase in AAS content (Ruiz-Santaquiteria et al. 2012).

Setting time values decreased with the increase in the BFS content compared to FA, i.e., higher BFS:FA. For instance, the initial setting time dropped from 55 and 155 mins to 21 and 101 mins in mixes 1.0-60:40, 1.0-70:30, and 1.5-70:30, respectively. Apparently, the increase in the CaO content accelerated the geopolymerisation reaction, leading to faster setting (Najm et al. 2022). A similar trend was noticed as more DS was added to the mix, i.e., lower B:S ratio. This is owed to the increase in the porosity of the mortar with an increase in the DS content, which allows for faster evaporation of AAS, thus faster setting (Hwalla et al. 2023d).

### 3.3 Compressive Strength

The 7- and 14- days compressive strength values were in the respective ranges of 6.0-70.6 MPa and 5.2-76.7 MPa, as presented in Fig. 2. Not only was a drop in strength noticed with an increase in the AAS content, the strength development of geopolymer mixes was also negatively impacted. Indeed, an AAS/B ratio of 0.7 caused a significant decrease in the strength development between
7 and 14 days. This may be owed to the evaporation of the excess AAS that existed in the geopolymer mortar matrix, leading to a porous structure. Nevertheless, most of the samples prepared with AAS/B less than 0.7 achieved a 14-day compressive strength exceeding 35 MPa.

On the effect of BFS and DS contents on the compressive strength of geopolymer mortar, the increase in the BFS:FA resulted in higher strength. Meanwhile, the incorporation of more DS, i.e., lower B:S ratio, led to a decrease in the compressive strength. This was owed to the creation of a denser calcium-rich gel, in the form of calcium silicate hydrate gel (C-A-S-H), from the activation of BFS (Yousefi Oderji et al. 2019). Furthermore, the drop in the strength with an increase in the DS content was due to a reduction in the paste volume, responsible for densifying the mortar matrix (Li et al. 2021).

![Compressive strengths of self-leveling geopolymer mixes at 7 and 14 days.](image)

**Fig. 2.** Compressive strengths of self-leveling geopolymer mixes at 7 and 14 days.

## 4 CONCLUSION

The flow, setting time, and 7- and 14-day compressive strength of self-leveling slag-fly ash geopolymer mortar prepared with different alkali-activator solution-to-binder, fly ash-to-slag, and binder-to-dune sand ratios were examined. According to the experimental results, the following conclusions can be drawn:

- The increase in alkali-activated solution content increased the flow values, prolonged the initial and final setting time, and reduced the compressive strengths of geopolymer mortar. Increasing the alkali-activator solution-to-binder ratio beyond 0.7 was not recommended, as it resulted in a decrease in the strength between 7 and 14 days.
- Ground granulated blast furnace slag replacement of fly ash resulted in a reduction in the flowability, a decrease in the setting time, and an increase in the strength values of geopolymer mixes at different ages.
- Increasing the dune sand content reduced the geopolymer mortar flowability, setting time, and compressive strength values at all ages.

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**References**

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