Optimization of Dune Sand-Slag Blended Geopolymer Mortar Using Taguchi Method

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Abstract. Achieving optimum performance of geopolymer mortar intended for structural and repair applications is a complex task with various factors being considered prior to production. This study explores the influence of mix design parameters on the fresh and hardened properties of geopolymer mortar made with treated dune sand (TDS) and granulated blast furnace slag (BFS). A total of nine geopolymer mortar mixtures were designed following the Taguchi method for four factors, each with three levels. These factors included BFS replacement rate by TDS, alkali-activator solution to binder ratio (AAS/B), sodium silicate-to-sodium hydroxide ratio (SS/SH), and sodium hydroxide (SH) molarity. The investigated performance quality criteria were flowability, compressive strength, water permeability, and carbon dioxide footprint. The effect of various factors on the responses was assessed through ANOVA while determining the signal-to-noise (S/N) ratios to seek the optimum proportions of mixtures. Results revealed that a mix made with TDS replacement, AAS/B, SS/SH, and SH molarity of 25%, 0.5, 1.5, and 14 M yielded superior performance.

1 Introduction

The utilization of by-products derived from industrial waste noticeably increased in concrete intended for construction applications [1, 2, 3, 4]. The incorporation of precursor binders such as granulated blast furnace slag (BFS), fly ash, and silica fume in the production of geopolymer concrete led to superior strength and durability responses compared to traditional concrete [5, 6, 7]. Such practice evoked higher interest to assess their suitability as precursor binders, thus promoting their application while mitigating the negative carbon footprint of conventional cement-based binders. Currently, it is well established that the addition of fillers such as limestone and quartz powders in concrete improved the strength and durability responses [8, 9]. This can be attributed to their filling/packing effect that helps promote the refinement of concrete microstructure [9].

Dune sand sourced from the desert can be treated into various fractions of sizes intended for different applications [9, 10]. This results in fine and ultra-fine particles characterized by superior fineness that could serve as a microfiller when incorporated in cement-based materials [11]. Treated dune sand (TDS) processed by the desert dune sand can be successfully employed by the construction industry [10, 11]. Rashad [9] reviewed the possibility of using fine quartz-powder derived from the grinding process of as-received quartz-sand as filler for concrete production. The authors reported that the incorporation of quartz powder enhanced the fresh and hardened properties of produced concrete. Such fine powder enhanced the distribution of pore shapes and sizes in the concrete microstructure. Guettala and Mezhiche proposed substituting up to 20% of the clinker in Portland cement with dune sand powder during the production of cement paste [12]. The examination of samples using X-ray diffraction revealed a partial pozzolanic activity, in which the main reaction is the fixation of the lime produced from cement hydration in the presence of the dune sand powder (pozzolanic reaction) to form semi-crystallized calcium silicate hydrate. Macht et al. reported similar findings on using finely ground sand, reflecting its pozzolanic reactivity despite its crystalline nature [13].

Although several investigations reported promising results on the incorporation of fine quartz-powder or TDS in geopolymer composite [14, 15], the optimization of mix proportions of geopolymer mortar received little attention. Indeed, the integration of multiple factors in the design of mixtures would lead to extensive experimental trials to understand the influence of factors on different responses. Conversely, advanced systematic methods, such as the Taguchi approach have been successfully employed to optimize the levels of factors in cement-based materials [16, 17]. Xu et al. investigated the applicability of the Taguchi method in optimizing the compressive strength of glass fiber-reinforced flowable mortar [18]. Likewise, Najm et al. found the optimum mix proportions of ladle slag-based geopolymer using the Taguchi method [19]. However, there are no studies that consider the optimization of mixtures proportions of

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TDS-BFS blended geopolymer mortars using the Taguchi method for superior overall performance.

This paper aims to valorize TDS in BFS-based geopolymer mortar for construction applications. The Taguchi approach was adopted to optimize the mixture proportions while considering the effect of various factors on the carbon footprint and properties of geopolymer mortar, including flowability, compressive strength, and water permeability. Such data can be of particular interest to scientists and engineers that seek to promote the use of sustainable construction materials.

2 Experimental work

2.1 Materials

Commercially available granulated blast furnace slag (BFS) and treated dune sand (TDS) were used as the precursor binders. The as-received BFS was provided by Emirates cement. Its physical and chemical characteristics are reported elsewhere [20]. Further, TDS was derived from desert dune sand that was sieved to obtain a powder finer than 75 µm. In turn, as-received dune sand was used as fine aggregates. Its particle size distribution can be found in other work [20], while its fineness modulus, and specific surface area were 1.44, and 116.8 cm²/g, respectively. Additionally, sodium silicate (SS) and sodium hydroxide (SH) were combined to form the alkaline activator solution (AAS). The SS solution is composed of 26.3% SiO₂, 10.3% Na₂O, and 63.4% H₂O. The SH solution was formulated by dissolving SH flakes in water to obtain different molarities of 6, 10, and 14 M. A polycarboxylate ether-based superplasticizer was adopted at a constant dosage of 2% of the total binder mass.

2.2 Development of mortar mixes

A series of preliminary tests were conducted on mortar mixes made with various fractions of TDS (i.e., 150-300, 75-150, 0-75, and 0-20 microns). Results showed that mortar mixtures containing 0-75 microns of TDS achieved the ultimate strength response. Accordingly, such fraction was used in the development of geopolymer mortar mixes. The Taguchi method was adopted to find the optimum mixture proportions while limiting the extensive number of experimental runs. In this study, four factors having three levels each, were evaluated as summarized in Table 1. The factors were TDS replacement percentage, AAS/binder ratio (AAS/B), SS/SH, and SH solution molarity. As a result, nine geopolymer mortar mixes were generated by adopting the factors and levels into the orthogonal array, as shown in Table 2. The corresponding levels were based on typical values used in alkali-activated mortars [21, 22] and trial mixes conducted in the early stages of this work. The orthogonal array considered in the Taguchi optimization method is converted into a signal-to-noise (S/N) ratio to calculate the difference between experimental values and targeted ones. In this method, two responses are considered, namely, the Larger-the-better and the Smaller-the-better, as shown in Equations (1) and (2), respectively. The former is employed to maximize the required response, while the latter is selected if minimizing the response is needed.

\[
S/N = -10 \times \log \left( \frac{1}{n} \sum_{i=1}^{n} y_i^2 \right)
\]

Where n is the number of a given experiment and y is the recorded experimental response to be considered.

Table 1. Factors and levels of geopolymer mortar mixtures.

<table>
<thead>
<tr>
<th>Levels</th>
<th>TDS replacement</th>
<th>AAS/B</th>
<th>SS/SH</th>
<th>SH Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25</td>
<td>0.5</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>0.55</td>
<td>1.5</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>75</td>
<td>0.6</td>
<td>2</td>
<td>14</td>
</tr>
</tbody>
</table>

Table 2. Mixture proportions of geopolymer mortar mixtures.

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>TDS replacement</th>
<th>AAS/B</th>
<th>SS/SH</th>
<th>SH solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>25</td>
<td>0.5</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>D2</td>
<td>25</td>
<td>0.55</td>
<td>1.5</td>
<td>10</td>
</tr>
<tr>
<td>D3</td>
<td>25</td>
<td>0.6</td>
<td>2</td>
<td>14</td>
</tr>
<tr>
<td>D4</td>
<td>50</td>
<td>0.5</td>
<td>1.5</td>
<td>14</td>
</tr>
<tr>
<td>D5</td>
<td>50</td>
<td>0.55</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>D6</td>
<td>50</td>
<td>0.6</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>D7</td>
<td>75</td>
<td>0.5</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>D8</td>
<td>75</td>
<td>0.55</td>
<td>1.5</td>
<td>14</td>
</tr>
<tr>
<td>D9</td>
<td>75</td>
<td>0.6</td>
<td>1.5</td>
<td>6</td>
</tr>
</tbody>
</table>

2.3 Sampling and testing procedures

For mixing, the dry materials (i.e., TDS, BFS, and dune sand) were first homogenized in a pan for 5 minutes, and then, the AAS and superplasticizer were gradually introduced to the dry components and mixed for additional 3 minutes. The flowability of fresh mortar mixes was conducted as per ASTM C230 [23]. The fresh mixtures were cast in cubic (50 mm³) and cylindrical (100 mm × 200 mm) steel moulds for the assessment of hardened properties. The specimens were demolded after 24 hours and then cured in ambient air conditions. The compressive strength and sorptivity were determined as per ASTM C109, and ASTM C1585 test methods, respectively [24, 25]. The temperature and relative humidity during mixing and sampling were maintained at 25±2°C and 50±5%, respectively.
3 Results

3.1. Fresh properties

Figure 1 shows the flowability responses of investigated mixtures. It can be noticed that mixtures D1, D2, and D3, containing 25% TDS exhibited the highest flowability responses of 213, 206, and 210 mm. Regardless of the impact of AAS/B, SS/SH, and SH molarity on the flowability of investigated mortar mixtures, it can be noticed that the use of higher concentrations of TDS was coupled with lower flowability responses, which can naturally be related to the increased mixture cohesiveness [19]. For instance, the flowability decreased from, on average, 213 mm to 179 and 159 mm for mixtures prepared with 25, 50, and 75% TDS, respectively. It is worth noting that the increase in AAS/B contributed to a slight reduction in flowability results, which can be linked to the similar behavior of the water-to-binder ratio in traditional cement-based composites [24].

Conversely, the AAS/B, SS/SH, and SH solution molarity were the least contributing factors, yielding contributions of less than 2%. Such results corroborated with experimental ones, reflecting the controlling effect of TDS on the flowability and compressive strength responses.

![Fig. 1. Flowability responses of investigated mixtures.](image1)

3.2. Hardened properties

Figure 2 plots the compressive strength and rate of water absorption or sorptivity of investigated geopolymer mortar mixtures. Clearly, the strength response followed a decreasing trend with TDS additions. For instance, the compressive strength decreased from, on average, 33.6 MPa to 15.6 and 5 MPa for geopolymer mortar mixtures containing 25, 50, and 75% TDS, respectively. The corresponding water absorption responses varied from 0.97 to 2.8, and 5.8 mm/hr⁰.⁵, respectively. Such results are in line with other studies that demonstrated the dilution effect of dune sand, especially at higher concentrations [9, 14]. It is to be noted that accurate relationship with correlation coefficient (R²) of 0.93 exists between the compressive strength and permeability responses for all tested geopolymer mortar (Figure 2). The proposed model for sorptivity is presented in Equation (3):

\[ \text{Sorptivity} = 4.53 f'c^{0.496} \]  

(3)

The analysis of variance (ANOVA) was carried out to determine the contribution of each factor to the targeted performance criteria. As summarized in Table 3, the TDS replacement was the controlling factor, exhibiting the highest percentage of more than 96% among others.

![Fig. 2. Compressive strength and sorptivity responses of investigated mixtures.](image2)

![Fig. 3. Relationship between \( f'c \) and sorptivity of investigated mixtures.](image3)

<table>
<thead>
<tr>
<th>Factor</th>
<th>Flow</th>
<th>( f'c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDS replacement</td>
<td>99.0%</td>
<td>96.8%</td>
</tr>
<tr>
<td>AAS/B</td>
<td>0.1%</td>
<td>1.0%</td>
</tr>
<tr>
<td>SS/SH</td>
<td>0.8%</td>
<td>1.2%</td>
</tr>
<tr>
<td>SH</td>
<td>0.1%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Total</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

3.3. Carbon footprint

The environmental impact of investigated mixtures was determined by totalling the CO₂ footprint of each ingredient. The CO₂ footprint of material components was collected from a previous study [27]. It can be noticed that the CO₂ footprint responses associated with the production of 1 m³ of mortar hovered around 322 ± 65 kg/m³, which shows a slight dependency on the TDS addition rate (Figure 4). The positive impact of TDS was
overshadowed by other components, including AAS/B and SH molarity. This can be attributed to the low CO₂ footprint of TDS compared to AAS [28, 29], leading to a marginal impact on the total CO₂ footprint of the geopolymer mix.

![Graph of CO₂ footprint responses of investigated mixtures.](image)

**Fig. 4.** CO₂ footprint responses of investigated mixtures.

### 3.4. Performance optimization

Referring to Equations (1) and (2), two different models were established to optimize the flowability and compressive strength of geopolymer mortar. Thus, the S/N ratios were computed for each factor to secure superior performance of the targeted criteria. It is worth noting that the sorptivity of mixtures was not considered in this progression since high correlation values exist between strength and sorptivity responses, as reported in the previous section. As shown in Figure 5, the maximum flowability response was characterized by TDS replacement, AAS/B, SS/SH, and SH solution of 25%, 0.6, 1.0, and 8 M, respectively. Conversely, the maximum compressive strength per the same optimization process corresponded to 25% of TDS replacement, 0.50 of AAS/B, 1.5 of SS/SH, and 14 M of SH solution.

![Graph of S/N ratios for flowability and f’c.](image)

**Fig. 5.** S/N ratios of (a) TDS replacement, (b) AAS/B, (c) SS/SH, and (d) SH solution for flowability and f’c.

### 4 Conclusions

The optimization of mixture proportions of TDS-BFS blended geopolymer mortar was successfully carried out using Taguchi’s approach. An L9 orthogonal array was developed by considering four factors having three levels each. These factors included the TDS replacement, AAS/B, SS/SH, and SH solution molarity. The ANOVA results revealed that the BFS replacement percentage by TDS is the most contributing factor towards the fresh and hardened properties while the AAS/B, SS/SH, and SH solution molarity were the least influential. Geopolymer mortar composed of 25% TDS and 75% BFS achieved superior flowability and strength responses among all tested mixtures.

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References