EVALUATION OF EARLY-AGE COMPRESSIVE STRENGTH OF GEOPOLYMER CONCRETE MASONRY UNITS

ELEN ABUOWDA, HILAL EL-HASSAN, and TAMER EL-MAADDawy

Dept of Civil and Environmental Engineering, UAE Univ, Al Ain, UAE

This paper presents the results of the experimental study on the early-age (1-day) compressive strength of geopolymer concrete masonry units (GCMU). The binder was a combination of ground granulated blast furnace slag (or simply slag) and fly ash with ratios of 3:1 and 1:1. It was activated using an alkaline solution consisting of sodium silicate and sodium hydroxide at a mass ratio of 1.5. Additional water was added to selected mixes to enhance the castability and compactability. The effect of the mix design parameters on the early-age compressive strength of GCMU was investigated. Results showed that an increase in the binder-to-aggregate ratio increased the compressive strength by up to 57%. Similarly, increasing the alkaline solution-to-binder and slag-to-fly ash ratios led to 4 and 3.5 times higher compressive strengths, respectively. Meanwhile, additional water had a negative impact on the compressive strength of GCMU, decreasing it by up to 74%. Still, it was possible to obtain a 1-day compressive strength of 36 MPa for a GCMU having a binder-to-aggregate ratio of 1:5, slag-to-fly ash ratio of 3:1, and solution-to-binder ratio of 0.4. Such results provide evidence of the ability to utilize geopolymer concrete in the field of masonry construction.

Keywords: Bearing, Mixture proportion, Experimental testing, Sustainability.

1 INTRODUCTION

The use of masonry in construction dates back to 7000 BC. The Egyptians Pyramids, Indian Taj Mahal, and Roman Colosseum were constructed using masonry (MCAA 2023). Masonry structures are developed using masonry units bonded together by mortar (NCMA 2001). The most common types of masonry units include burnt clay bricks, concrete blocks, and stabilized mud blocks (Venugopal et al. 2016). Nowadays, masonry structures are widely used in different constructions for their excellent aesthetics, versatility, and durability properties (Petrillo et al. 2016). Among the various types of masonry, concrete blocks have been commonly used due to their relatively low cost as well as availability of raw materials and skilled labours (Kishan and Radhakrishna 2013). However, the production of one ton of their primary component, cement, emits nearly one ton of carbon dioxide into the atmosphere (Venugopal and Radhakrishna 2016, Golewski 2020). In 2022, the production of Portland cement in the United States reached 92 million tons, of which 2.5 million tons were associated to the production of masonry cement (National Minerals Information Center 2023). Such excessive manufacture of cement contributes to 7% of the total greenhouse gas emissions (Govindhan and Nivedha 2019, Singh and Middendorf 2020). These trapped gases in atmosphere can lead to global warming and its associated repercussions, including storms, heatwaves, floods, and droughts (Shaftel et al. 2022).
The term geopolymer, introduced by Professor Joseph Davidovits (1994), has gained a wide popularity as it eliminates the use of cement in concrete without compromising strength and durability properties. Compared to Portland cement, geopolymers can reduce the carbon dioxide emissions by up to 80% (Sukrirpattanapong et al. 2015, Yedage et al. 2022). Geopolymers result from the combination of an alkaline activator solution and aluminosilicate material, such as fly ash and ground granulated blast furnace slag (Azad et al. 2022). Several studies showed that using geopolymers as a substitute of Portland cement resulted in superior mechanical and durability properties (Radhakrishna et al. 2015, Venugopal et al. 2015, Patil et al. 2019, Niphadkar 2020). These properties may vary depending on the types of aluminosilicate materials and alkaline solutions being used as well as the curing conditions (Rachel 2015, Zuaiter et al. 2023). Additionally, the relative proportions of ingredients play a leading role in enhancing the properties of the geopolymer concrete. Yet, studies investigating the effect of these proportions on the performance of geopolymer concrete masonry units (GCMU) are scarce.

This study aims to examine the effect of the various mix design parameters on the 1-day compressive strength of GCMU. The primary objective was to achieve a high early strength of masonry units while meeting the structural requirements for load-bearing applications, thereby accelerating the utilization of masonry units in the construction of structures. The binder-to-aggregates, slag-to-fly ash, alkaline activator solution-to-binder, and additional water-to-binder ratios were varied. The binder was a blend of ground granulated blast furnace slag (referred to hereafter as slag) and fly ash, varying between 3:1 and 1:1. Research findings serve to provide evidence of the ability to utilize geopolymer concrete in the field of masonry construction.

2 EXPERIMENTAL PROGRAM

2.1 Materials

Slag and class F fly ash (FA) served as the two aluminosilicate sources in the precursor binder. The two materials were blended to prevent shrinkage cracks associated with slag-based geopolymers and alleviate the need for heat curing of FA-based geopolymers (El-Hassan and Ismail 2018). Said binder was activated using an alkaline solution consisting of grade N sodium silicate (SS) and 8 M sodium hydroxide (SH) solution. The coarse aggregates used to produce GCMU were natural crushed dolomitic limestone sand (CS) with a nominal maximum particle size of 10 mm. The specific gravity of slag, fly ash and CS were identified as 2.7, 2.32 and 2.69, respectively. The physical characteristics and chemical components of the three materials are shown elsewhere (Hwalla et al. 2023a). Also, tap water was used to prepare SH solution and enhance the castability of the geopolymer mix.

2.2 Mixture Proportioning

Four groups of GCMU, designated as A, B, C and D, were prepared to study the effect of varying the mix design parameters on the early-age compressive strength, including the binder-to-aggregates ratio (B: Agg), slag-to-fly ash ratio (slag: FA), alkaline activator solution-to-binder ratio (AAS: B) and additional water-to-binder ratio (AW: B). Table 1 illustrates the four groups along with their mix proportions. Mixes were designated as w-x-y-z, where w, x, y, and z denote B: Agg, slag: FA, AAS: B, and AW: B ratios, respectively. For instance, 1:7-3:1-0.4-0.2 is a mix made with B: Agg ratio of 1:7, slag: FA ratio of 3:1, AAS: B ratio of 0.4, and AW: B ratio of 0.2. The variations in the mix design parameters were selected based on past literature and industrial mixes of concrete masonry units (Hwalla et al. 2023b).
2.3 Sample Preparation and Testing

To prepare the AAS, water was added to SH flakes to obtain a molarity of 8 M. Once the solution cooled down, SS solution was added to the SH solution at a SS:SH ratio of 1.5. Meanwhile, the dry ingredients, i.e., slag, fly ash, and CS, were mixed for 2-3 minutes in a pan mixer. After homogenizing the dry ingredients, AAS was incorporated into the mix, followed by additional water, as applicable. The fresh geopolymer mixes were cast in 100-mm cubic molds, vibrated by means of a vibration table, demolded after 24 hours, and cured in an ambient condition until testing. The mechanical behavior of GCMU was evaluated by the 1-day compressive strength according to ASTM C140 (2022). Three specimens per mix were used to obtain the average 1-day compressive strength.

Table 1. Mixture proportions of slag-fly ash geopolymer concrete masonry units (%).

<table>
<thead>
<tr>
<th>Group</th>
<th>Mix ID</th>
<th>Slag</th>
<th>FA</th>
<th>Agg</th>
<th>AAS</th>
<th>AW</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1:7:3:1-0.40-0.20</td>
<td>8.7</td>
<td>2.9</td>
<td>81.4</td>
<td>4.7</td>
<td>2.3</td>
<td>Effect of B:Agg</td>
</tr>
<tr>
<td></td>
<td>1:6:3:1-0.40-0.20</td>
<td>9.9</td>
<td>3.3</td>
<td>78.9</td>
<td>5.3</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1:5:3:1-0.40-0.20</td>
<td>11.4</td>
<td>3.8</td>
<td>75.8</td>
<td>6.1</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>1:7:1:0.40-0.25</td>
<td>5.8</td>
<td>5.8</td>
<td>80.9</td>
<td>4.6</td>
<td>2.9</td>
<td>Effect of Slag:FA</td>
</tr>
<tr>
<td></td>
<td>1:7:3:1-0.40-0.25</td>
<td>8.7</td>
<td>2.9</td>
<td>80.9</td>
<td>4.6</td>
<td>2.9</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>1:7:3:1-0.35-0.25</td>
<td>8.7</td>
<td>2.9</td>
<td>81.4</td>
<td>4.1</td>
<td>2.9</td>
<td>Effect of AAS:B</td>
</tr>
<tr>
<td></td>
<td>1:7:3:1-0.45-0.25</td>
<td>8.6</td>
<td>2.9</td>
<td>80.5</td>
<td>5.2</td>
<td>2.9</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>1:7:3:1-0.40-0.00</td>
<td>8.9</td>
<td>3.0</td>
<td>83.3</td>
<td>4.8</td>
<td>0.0</td>
<td>Effect of AW:B</td>
</tr>
<tr>
<td></td>
<td>1:7:3:1-0.40-0.10</td>
<td>8.8</td>
<td>2.9</td>
<td>82.4</td>
<td>4.7</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1:7:3:1-0.40-0.20</td>
<td>8.7</td>
<td>2.9</td>
<td>81.4</td>
<td>4.7</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1:7:3:1-0.40-0.30</td>
<td>8.6</td>
<td>2.9</td>
<td>80.5</td>
<td>4.6</td>
<td>3.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1:7:3:1-0.40-0.40</td>
<td>8.5</td>
<td>2.8</td>
<td>79.5</td>
<td>4.5</td>
<td>4.5</td>
<td></td>
</tr>
</tbody>
</table>

3 RESULTS AND DISCUSSION

The early-age compressive behavior of slag-fly ash blended GCMU is presented in Fig. 1. Noteworthy that geopolymer mixes made with a B:Agg ratio of 1:6 and 1:5 met the compressive strength requirements outlined in ASTM C90 (2022) for load-bearing applications. Meanwhile, for mixes having a B:Agg ratio of 1:7, only those having a slag:FA ratio of 3:1, AAS: B ratio of at least 0.40, and AW: B ratio of at most 0.25 could be classified for load-bearing applications. The remaining mixes are recommended for non-load-bearing applications, as per ASTM C129 (2017).

The effect of increasing the binder content, i.e., higher B: Agg ratio, resulted in a higher compressive strength. In fact, the 1-day compressive strengths of mixes having binder-to-aggregates ratios of 1:6 and 1:5 were 31.3 and 36.0 MPa, respectively. These values were 37 and 57% higher than those of mixes with B: Agg ratio of 1:7, respectively. Such an increase in compressive strength is owed to the increase in paste volume available in the activation reaction (Paul and Gunneswara Rao 2022).

The type of binder had a significant effect on the 1-day compressive strength. Results showed that GCMU made with slag: FA ratio of 3:1 had a 1-day compressive strength of 11 MPa, which was nearly 3.5 times higher than that of the counterpart blocks made with slag: FA ratio of 1:1. These results were consistent with the findings of Zhan et al. (2022), and are mainly attributed to the increase in CaO content, which increased the Ca\(^{2+}\) concentration in the paste, thereby improving the dissolution rate and accelerating the hydration process.
The impact of increasing the AAS: B ratio on the early age compressive strength was also investigated. Mixes prepared with AAS: B ratios of 0.35, 0.40, and 0.45 had 1-day compressive strengths of 5.6, 21.7 and 14.3 MPa, respectively. This behavior was observed in the results of Hwalla et al. (2023c) in slag-fly ash blended geopolymer mortar. Generally, blocks exhibited nearly 4 times higher compressive strength with increased solution content from 0.35 to 0.40. However, this increase was followed by a reduction of 34% in the compressive strength due to the formation of voids caused by evaporation of unreacted liquid solution.

Although additional water was necessary to improve the castability of the mixes, excessively high AW: B ratio led to a decrease in the compressive strength of GCMU. In fact, without the additional water, the GCMU mix was too dry to cast, with no strength. Upon adding water at AW: B ratio of 0.1, the strength increased to 26.5 MPa. However, further increasing the AW: B ratio to 0.3 caused a 74% reduction in 1-day compressive strength. As such, an additional water-to-binder ratio of 0.1 was found to be the optimum for strength development, allowing silicates and aluminates in the binder to dissolve more. The addition of water beyond this level had a negative effect on strength, similar to the correlation between strength and water-to-cement ratio in traditional cement blocks (Bondar et al. 2011).

Fig. 1. Effect of mix design parameters on 1-day compressive strength of GCMUs mixes: (a) B: Agg, (b) slag:FA, (c) AAS:B, (d) AW:B.
4 CONCLUSIONS

The early-age compressive strength of slag-fly ash blended geopolymer concrete masonry units was examined. Mix design parameters were varied systematically. Based on the experimental results, the following conclusions can be drawn:

- The 1-day compressive strength was improved by 57% upon increasing binder-to-aggregates ratio from 1:7 to 1:5. A higher slag-to-fly ash ratio, i.e., 3:1, enhanced the compressive behavior of GCMU nearly 4 times compared to the counterpart blocks made with a ratio of 1:1.
- Increasing AAS: B ratio from 0.35 to 0.40 increased the 1-day compressive strength by nearly 4 times. However, this strength decreased by 34% upon adding more solution to reach a ratio of 0.45.
- The addition of water at AW: B ratio of 0.1 led to the highest compressive strength of 26.5 MPa. However, further increasing the AW: B ratio beyond 0.1 had a detrimental effect, with a sharp drop in strength of up to 74%.
- GCMU mixes made with a B: Agg ratio of 1:6 and 1:5 met the compressive strength requirements for load-bearing applications. Meanwhile, for mixes having a B: Agg ratio of 1:7, only those having a slag: FA ratio of 3:1, AAS: B ratio of at least 0.40, and AW: B ratio of at most 0.25 could be classified for load-bearing applications. The remaining mixes were recommended for non-load-bearing applications.

Acknowledgments

The authors acknowledge the financial support provided by the United Arab Emirates University (UAEU) under grant number 12R171.

References

Govindhan, S., and Nivedha, V., Experimental Study of Geopolymer Concrete Blocks, 6(3), 2019.
Hwalla, J., El-Hassan, H., Assaad, J. J., ElMaaddawy, T., and Bawab, J., *Effect of Type of Sand on the Flowability and Compressive Strength of Slag-Fly Ash Blended Geopolymer Mortar*, The 8th International Conference on Civil, Structural and Transportation Engineering, Canada, 4-6, June, 2023c.


