WASTE GLASS AS AN ALKALINE ACTIVATOR AND FLY ASH AS PRECURSOR IN GEOPOLYMER CONCRETE

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In this study, an alkaline activator was synthesized by dissolving waste glass in NaOH solution to explore the feasibility of using waste glass as a potential alkaline activator in the preparation of geopolymer concrete (GeoPC) with fly ash as precursor. A total of three types of glasses with different sizes were used. The exact concentration of Na$_2$O and SiO$_2$ in the activator was measured using inductively coupled plasma – optical emission spectrometry (ICP-OES). A total of 38 GeoPC mixtures were prepared using three glass types and at different Na$_2$O and SiO$_2$ concentration. The compressive strength of GeoPC was measured by testing specimens after 24 hours of heat curing (80±2°C) followed by 24 hours of ambient curing at room temperature (23±2°C). The compressive strength was found to depend on alumina and calcium content of glass type and moduli (SiO$_2$/Na$_2$O) ratio of activator. The higher liquid to solid ratio resulted in lowering of compressive strength.

Keywords: Portland cement concrete, Silica, Alumina, Compressive strength.

1 INTRODUCTION

Geopolymer concrete (GeoPC) is a novel and environmentally more sustainable construction material that can be used as an alternative to conventional Portland cement concrete (PCC). GeoPC emerge as an excellent alternative to PCC not only due to their superior properties, but also owing to their lowered air pollution and abatement in climate change (Patel and Shah 2018). GeoPC is prepared by reacting aluminosilicate-rich materials (aka precursors) with a caustic activator. Significant progress has been made on GeoPC, however, application of GeoPC is limited. One notable constraint to GeoPC adoption is the energy involved in making sodium silicate or waterglass activator. Sodium silicate, diluted with sodium hydroxide (NaOH), is considered a superior activator for GeoPC (Choi and Lee 2019). Commercial production of waterglass which requires temperatures around 1300°C is the single largest source of both greenhouse gases and cost of GeoPC (Abdulkareem et al. 2019). Using waste glass as an alkaline activator in lieu of commercial waterglass to make GeoPC has the potential to eliminate one prominent barrier of GeoPC adoption, together with using fly ash as GeoPC precursors, presents an excellent opportunity for sustainable solid waste management and sustainable construction practices. Consequently, the primary objective of this study was to explore the feasibility of using waste glass as a potential alkaline activator in the preparation of GeoPC with fly ash as precursor.
2 MATERIALS AND METHODS

2.1 Materials

In this study, class F fly ash (FA), as per ASTM C618 was used (ASTM 2022). The source of FA was Prairie State powerplant located in Minnesota and it was provided by EcoMaterial Technologies (formerly known as Boral Resources LLC). A total of five types of waste glasses were used in this study. All waste glasses were made from post-consumer bottle glass collected from material recovery facilities (MRFs). ACAS type of glass was obtained from Vitro Minerals located in Jackson, Tennessee. It is processed into a clean off-white powder with a minimum fineness of 90% passing US Sieve No. 325 (< 0.044 mm, i.e., 44 µm). Ruby 70 and DCF glasses were obtained from Ruby Lake Glass company located in Richfield Springs, New York. Ruby 70 glass (called as RG70 in this study) is coarsest glass used in this study with 99.8% passing US Sieve No. 50 (< 0.3 mm, i.e., 300 µm) and 14.5% passing US Sieve No. 200 (0.075 mm, i.e., 75 µm). DCF glass is coarser glass compared to ACAS but finer than RG70 with 99.9% passing US Sieve No. (< 0.1 mm, i.e., 100 µm) and more than 90% passing US Sieve No. 200 (0.075 mm, i.e., 75 µm). Level of contamination in these glass samples were analyzed using Loss on Ignition (LOI) technique according to ASTM D7348 (ASTM 2021b). Level of contamination were found to be less than 0.1% for all glass samples. A total of two commercially available chemicals, namely reagent grade sodium hydroxide (NaOH) from HACH Company and technical grade sodium silicate or waterglass from Science Company were obtained and used for making activators. The chemical composition of FA, ACAS, DCF and RG70 glasses are presented in Table 1.

Table 1. Chemical composition of fly ash and various glass types.

<table>
<thead>
<tr>
<th>Chemical</th>
<th>FA (%)</th>
<th>ACAS (%)</th>
<th>DCF (%)</th>
<th>RG70 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>45.20</td>
<td>62.66</td>
<td>48.08</td>
<td>48.55</td>
</tr>
<tr>
<td>CaO</td>
<td>12.20</td>
<td>20.74</td>
<td>2.04</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Al&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;</td>
<td>15.16</td>
<td>1.94</td>
<td>1.43</td>
<td>1.55</td>
</tr>
<tr>
<td>Na&lt;sub&gt;2&lt;/sub&gt;O</td>
<td>&lt;0.1</td>
<td>11.80</td>
<td>7.10</td>
<td>6.84</td>
</tr>
<tr>
<td>K&lt;sub&gt;2&lt;/sub&gt;O</td>
<td>4.6</td>
<td>0.97</td>
<td>11.45</td>
<td>11.78</td>
</tr>
<tr>
<td>FeO&lt;sub&gt;3&lt;/sub&gt;</td>
<td>17.67</td>
<td>0.66</td>
<td>0.20</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>MgO</td>
<td>0.63</td>
<td>0.53</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>SO&lt;sub&gt;3&lt;/sub&gt;</td>
<td>1.95</td>
<td>0.12</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>TiO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>1.30</td>
<td>0.17</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>SrO</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>16.45</td>
<td>16.86</td>
</tr>
<tr>
<td>BaO</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>8.05</td>
<td>9.00</td>
</tr>
<tr>
<td>ZrO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>2.18</td>
<td>2.21</td>
</tr>
<tr>
<td>PbO</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>0.90</td>
<td>1.16</td>
</tr>
<tr>
<td>LOI</td>
<td>0.50</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
</tbody>
</table>

2.2 Waste Glass-based Activator

Waste glass-based activator was prepared by dissolving waste glass in concentrated sodium hydroxide (NaOH) solution. Dissolution of waste glass reactions was carried out for 21 days in 1L-flasks containing 500 ml of NaOH solution and 50 grams of waste glass. Flasks were placed in a hot water bath regulated by a temperature controller at 80°C +/- 0.5°C while continuously mixed through magnetic stirring. 1-ml samples were taken every 48 hours and micro-centrifuged at 10,000×g for 10 minutes followed by filtration using a 0.45 µm hydrophilic filter. Na<sub>2</sub>O% and SiO<sub>2</sub>% concentration in filtered samples were determined by inductively coupled plasma – optical emission spectrometry (ICP-OES) at two Si-specific and two Na-specific wavelengths. To make specific activator, waste glass-based activators with the highest SiO<sub>2</sub> was diluted with NaOH.
solutions at various dilution ratios to produce activators with various content of SiO$_2$. Exact dilution ratio was determined based on the actual SiO$_2$% in waste glass-based activator. Final concentrations of Na$_2$O and SiO$_2$ in activators following dilution with NaOH were analyzed and confirmed by ICP-OES analysis.

2.3 GeoPC Specimen Preparation and Testing

A total of 38 GeoPC mixtures containing different percentage of silica (SiO$_2$%) in alkali activated waste glass powder activator with different concentrations of alkali (Na$_2$O%) and fly ash as precursor were prepared in this study as shown in Table 2. Specifically, 16 GeoPC mixtures (Mix#3 – 18) were prepared using ACAS glass. Out of 16 ACAS glass GeoPC mixtures, 8 mixtures were prepared at liquid (i.e., activator) to solid (i.e., fly ash) ratio of 0.3 and remaining 8 mixtures were prepared at liquid to solid ratio of 0.4. A total of 11 GeoPC mixtures (Mix#19 – 29) and 9 GeoPC mixtures (Mix#30 – 38) were prepared using DCF and RG70 glass, respectively. All GeoPC mixtures prepared using DCF and RG70 glass types were prepared at liquid to solid ratio of 0.3. To prepare GeoPC specimens, a set of six cubes of 25 mm x 25 mm x 25 mm (1 in. x 1 in. x 1 in.) were molded for all the GeoPC mixtures using silicone casting molds. After molding, specimens were cured at 80±2°C for 24 hours followed by ambient curing in the laboratory at a controlled temperature of 23.0±2°C for 24 hours. Then, specimens were tested for compressive strength in accordance with ASTM C109 (ASTM 2021a) test method.

Table 2. A summary of design of GeoPC mixtures and testing results.

<table>
<thead>
<tr>
<th>Mix #</th>
<th>Glass Type</th>
<th>Liquid activator makeup</th>
<th>Na$_2$O % in activator</th>
<th>SiO$_2$% in activator</th>
<th>Compressive strengthpsi</th>
<th>Liquid to Solid ratio (L/S)</th>
<th>Activator</th>
<th>Na$_2$O % in activator</th>
<th>SiO$_2$% in activator</th>
<th>Compressive strengthpsi</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>None (Control)</td>
<td>10M NaOH</td>
<td>24%</td>
<td>NA</td>
<td>2485</td>
<td>0.3</td>
<td>20</td>
<td>9.2M NaOH + 3.9%</td>
<td>22%</td>
<td>3.0%</td>
</tr>
<tr>
<td>2</td>
<td>10M NaOH + 10%</td>
<td>NA</td>
<td>24%</td>
<td>NA</td>
<td>3379</td>
<td>22.0</td>
<td>0.3</td>
<td>9.2M NaOH + 3.9%</td>
<td>22%</td>
<td>3.0%</td>
</tr>
<tr>
<td>3</td>
<td>10M NaOH + 1%SiO$_2$</td>
<td>NA</td>
<td>24%</td>
<td>0.8%</td>
<td>2812</td>
<td>19.4</td>
<td>0.4</td>
<td>10M NaOH + 3.9%</td>
<td>22%</td>
<td>3.0%</td>
</tr>
<tr>
<td>4</td>
<td>10M NaOH + 1%SiO$_2$</td>
<td>NA</td>
<td>24%</td>
<td>0.8%</td>
<td>2806</td>
<td>20.3</td>
<td>0.3</td>
<td>10M NaOH + 3.9%</td>
<td>22%</td>
<td>3.0%</td>
</tr>
<tr>
<td>5</td>
<td>10M NaOH + 1.5%SiO$_2$</td>
<td>NA</td>
<td>24%</td>
<td>1.2%</td>
<td>2524</td>
<td>18.1</td>
<td>0.4</td>
<td>10M NaOH + 3.9%</td>
<td>22%</td>
<td>3.0%</td>
</tr>
<tr>
<td>6</td>
<td>10M NaOH + 1.5%SiO$_2$</td>
<td>NA</td>
<td>24%</td>
<td>1.2%</td>
<td>2524</td>
<td>18.1</td>
<td>0.4</td>
<td>10M NaOH + 3.9%</td>
<td>22%</td>
<td>3.0%</td>
</tr>
<tr>
<td>7</td>
<td>10M NaOH + 2%SiO$_2$</td>
<td>NA</td>
<td>24%</td>
<td>1.5%</td>
<td>2843</td>
<td>19.3</td>
<td>0.3</td>
<td>10M NaOH + 3.9%</td>
<td>22%</td>
<td>3.0%</td>
</tr>
<tr>
<td>8</td>
<td>10M NaOH + 2%SiO$_2$</td>
<td>NA</td>
<td>24%</td>
<td>1.5%</td>
<td>2843</td>
<td>19.3</td>
<td>0.3</td>
<td>10M NaOH + 3.9%</td>
<td>22%</td>
<td>3.0%</td>
</tr>
<tr>
<td>9</td>
<td>10M NaOH + 2.5%SiO$_2$</td>
<td>NA</td>
<td>24%</td>
<td>1.9%</td>
<td>2812</td>
<td>19.4</td>
<td>0.4</td>
<td>10M NaOH + 3.9%</td>
<td>22%</td>
<td>3.0%</td>
</tr>
<tr>
<td>10</td>
<td>10M NaOH + 2.5%SiO$_2$</td>
<td>NA</td>
<td>24%</td>
<td>1.9%</td>
<td>2812</td>
<td>19.4</td>
<td>0.4</td>
<td>10M NaOH + 3.9%</td>
<td>22%</td>
<td>3.0%</td>
</tr>
<tr>
<td>11</td>
<td>ACAS</td>
<td>10M NaOH + 3.5%SiO$_2$</td>
<td>24%</td>
<td>2.7%</td>
<td>1133</td>
<td>21.4</td>
<td>0.4</td>
<td>10M NaOH + 2.5%SiO$_2$</td>
<td>24%</td>
<td>1.9%</td>
</tr>
<tr>
<td>12</td>
<td>ACAS</td>
<td>10M NaOH + 3.5%SiO$_2$</td>
<td>24%</td>
<td>2.7%</td>
<td>1133</td>
<td>21.4</td>
<td>0.4</td>
<td>10M NaOH + 3.9%</td>
<td>22%</td>
<td>3.0%</td>
</tr>
<tr>
<td>13</td>
<td>ACAS</td>
<td>10M NaOH + 4%SiO$_2$</td>
<td>24%</td>
<td>3.1%</td>
<td>1133</td>
<td>21.4</td>
<td>0.4</td>
<td>10M NaOH + 3.9%</td>
<td>22%</td>
<td>3.0%</td>
</tr>
<tr>
<td>14</td>
<td>ACAS</td>
<td>10M NaOH + 4%SiO$_2$</td>
<td>24%</td>
<td>3.1%</td>
<td>1133</td>
<td>21.4</td>
<td>0.4</td>
<td>10M NaOH + 3.9%</td>
<td>22%</td>
<td>3.0%</td>
</tr>
<tr>
<td>15</td>
<td>ACAS</td>
<td>10M NaOH + 6%SiO$_2$</td>
<td>24%</td>
<td>4.6%</td>
<td>1536</td>
<td>21.4</td>
<td>0.4</td>
<td>10M NaOH + 3.9%</td>
<td>22%</td>
<td>3.0%</td>
</tr>
<tr>
<td>16</td>
<td>ACAS</td>
<td>10M NaOH + 6%SiO$_2$</td>
<td>24%</td>
<td>4.6%</td>
<td>1536</td>
<td>21.4</td>
<td>0.4</td>
<td>10M NaOH + 3.9%</td>
<td>22%</td>
<td>3.0%</td>
</tr>
<tr>
<td>17</td>
<td>ACAS</td>
<td>10M NaOH + 8%SiO$_2$</td>
<td>24%</td>
<td>6.1%</td>
<td>1536</td>
<td>21.4</td>
<td>0.4</td>
<td>10M NaOH + 3.9%</td>
<td>22%</td>
<td>3.0%</td>
</tr>
<tr>
<td>18</td>
<td>ACAS</td>
<td>8M NaOH + 8%SiO$_2$</td>
<td>24%</td>
<td>6.1%</td>
<td>1536</td>
<td>21.4</td>
<td>0.4</td>
<td>10M NaOH + 3.9%</td>
<td>22%</td>
<td>3.0%</td>
</tr>
<tr>
<td>19</td>
<td>DCF</td>
<td>8.2M NaOH + 3.9%</td>
<td>20%</td>
<td>3.0%</td>
<td>1536</td>
<td>21.4</td>
<td>0.4</td>
<td>10M NaOH + 3.9%</td>
<td>22%</td>
<td>3.0%</td>
</tr>
</tbody>
</table>

3 RESULTS

A summary of results is presented in Table 2. Literature review shows that the most important factors affecting the properties of geopolymer pastes are glass type, Na$_2$O%, SiO$_2$%, SiO$_2$/Na$_2$O
ratio, and liquid to solid ratio (Singh et al. 2015). Further results are discussed in subsequent sections.

3.1 Effect of Glass Type in Activator on Strength

It is evident from Table 2 that mixtures containing waste-glass based activator provided strength comparable to control mixtures (Mix#1 and #2). Further, the effect of glass type can be understood by comparing results of GeoPC mixtures containing same amount of Na$_2$O% and SiO$_2$%. Overall, at similar Na$_2$O% and SiO$_2$%, mixtures prepared using ACAS glass provided highest strength followed by RG70 and DCF glasses. For instance, Mix#8, #23 and #30 were prepared using ACAS, DCF and RG70 type of glasses, respectively, and contained 24% Na$_2$O and 1.5% SiO$_2$. Among all these three mixtures, Mix#8 prepared by using ACAS provided highest compressive strength of 3040 psi followed by Mix#30 prepared by using RG70 (17.2 MPa, i.e., 2496 psi) and Mix#23 prepared by using DCF (16.9 MPa, i.e., 2448 psi). Similar behavior was observed with Mix#14 (prepared using ACAS) and Mix#21 (prepared using DCF). Specifically, both GeoPC mixtures contained 24% Na$_2$O and 3.0% SiO$_2$ but Mix#14 resulted in higher strength of 24.3 MPa (3526 psi) compared to 21.7 MPa (3148 psi) strength of Mix#21. Another example is Mix#27 prepared using DCF and Mix#34 prepared using RG70. Both mixtures contained 17% Na$_2$O and approximately 7% SiO$_2$ content but RG70 glass provided higher strength of 6.1 MPa (892 psi) compared to 4.7 MPa (679 psi) strength provided by DCF glass. This behavior could be attributed to higher alumina (Al$_2$O$_3$) content in ACAS glass (1.94%) followed by RG70 (1.55%) and DCF (1.43%) (see Table 1). Literature review shows that up to a certain limit, Al$_2$O$_3$ content was found to be responsible for observed high-strength gains in geopolymers (De Silva et al. 2007, De Vargas et al. 2011). Furthermore, high calcium content was reported to increase the geopolymerization process and thus improved compressive strength of GeoPC (Ibraheem et al. 2021). Among all three glasses used in this study, calcium oxide content in ACAS glass type is the highest (20.74%).

3.2 Effect of Na$_2$O% and SiO$_2$% of Activator on Strength

Figure 1 shows variation of compressive strength of GeoPC mixtures with Na$_2$O% of activator. It is evident from Figure 1 (a) that at fixed SiO$_2$% and glass type, compressive strength increases with Na$_2$O% up to a certain content beyond which decrease in strength was noticed. For instance, GeoPC mixtures prepared using DCF at SiO$_2$% of 3%, Na$_2$O% of 24% provided maximum strength of 21.7 MPa (3148 psi).

![Figure 1. Variation of compressive strength of GeoPC mixtures with (a) Na$_2$O% and (b) SiO$_2$% of activator.](image-url)
It was also noticed from Figure 1 (a) that for a particular glass type, strength decreased with increase in SiO$_2$%. To further understand influence of SiO$_2$% on strength, Figure 1 (b) was plotted. It is evident from Figure 1 (b) that at Na$_2$O% of 24%, both ACAS and DCF glass containing GeoPC mixtures attained peak strength at SiO$_2$% of 3.0%. No GeoPC mixture was tested for DCF at Na$_2$O% of 24% and SiO$_2$ of 3.0%. Several research studies concluded that an amorphous structure of geopolymers is preferable in order to achieve better mechanical strength (Xu and Van Deventer 2002, De Silva et al. 2007, Zhang et al. 2009, De Vargas et al. 2011). An increase in Na$_2$O content or decrease in SiO$_2$ content increases the compressive strength of geopolymers due to the formation of aluminosilicate network structures (Xu and Van Deventer 2002).

3.3 Effect of Moduli (SiO$_2$/Na$_2$O) Ratio of Activator on Strength

Some studies showed that moduli (SiO$_2$/Na$_2$O) of activator plays most important role in resistance to compression. For example, De Vargas et al. (2011) found that moduli ratio of 0.4 provided greatest compressive strength for FA based geopolymer mortars. Wang et al. (1994) reported that moduli ratio of 1.0 provided highest compressive strength for slag based geopolymer mortars cured at 20ºC. Figure 2 (a) shows variation of compressive strength of GeoPC mixtures with moduli ratio. It is evident from Figure 2 (a) that for ACAS, DCF and RG70 glass types, moduli ratio of 0.130, 0.052 and 0.055 provided greatest strength, similar to results reported by Torres-Carrasco and Puertas (2015).

3.4 Effect of Liquid to Solid (L/S) Ratio on Strength

Figure 2(b) shows variation of compressive strength of ACAS glass containing GeoPC mixtures with L/S ratio. It is evident from Figure 2 (b) that higher L/S ratio resulted in lowering of strength except GeoPC mixture with moduli ratio of 0.113. For instance, GeoPC mixtures at moduli ratio of 0.081 provided compressive strength of 21.7 MPa (3148 psi) and 15.6 MPa (2257 psi) with L/S ratio of 0.3 and 0.4, respectively. At higher moduli ratio of 0.193, no difference in strength with L/S ratio was noticed.

4 CONCLUSIONS

In this study, waste glass was investigated as an alkaline activator and fly ash as precursor in production of GeoPC mixtures. Following conclusions could be drawn from the study presented in this paper:
1) The compressive strength of GeoPC mixtures was found to depend on alumina and calcium content of glass type.
2) The compressive strength increased with Na₂O% up to a certain content beyond which decrease in strength was noticed.
3) Both ACAS and DCF glass containing GeoPC mixtures attained peak strength at SiO₂% of 3.0%.
4) The moduli (SiO₂/Na₂O) of activator played an important role in resistance to compression.
5) The higher liquid to solid ratio resulted in lowering of compressive strength.

Acknowledgments
This work was supported by Illinois Innovation Network grant. Also, authors would like to acknowledge undergraduate student, Lucas Roslewski, for preparing and testing specimens.

References