A Comparative Study on the Durability of Geopolymer Mortars Produced with Ground Glass Fiber, Fly Ash, and Glass-Powder in Sodium Sulfate Solution

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A comparative study on the durability of geopolymer mortars produced with ground glass fiber, fly ash, and glass-powder in sodium sulfate solution

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Abstract:

An experimental investigation was conducted to investigate the performance of geopolymers made with three different precursors consisting of fly ash, Ground Glass Fiber (GGF), and Glass-Powder (GLP) exposed to sodium sulfate solution. Precursors were activated using either sodium hydroxide solution or combinations of sodium hydroxide and sodium silicate solution with varying levels of sodium and silica content. Among the mixtures with each of the three precursors, mortar mixtures with the highest compressive strength were selected to test their resistance against exposure to a 5% sodium sulfate solution. Changes in the weight and compressive strength of the specimens were monitored up to 120 days of exposure. In addition, change in the microstructure of geopolymer samples and mineral phases was investigated using SEM-EDX and XRD analyses, respectively. Further, techniques such as mercury intrusion porosimetry (MIP) spectrometry and inductively coupled plasma mass spectrometry (ICP-MS) were used to study the pore structure and the leachability of elements from geopolymers, respectively. Results of this study revealed that the GGF and fly ash-based geopolymers performed significantly better in comparison to the GLP-based geopolymer, when exposed to the sodium sulfate solution. The durability of GGF and Fly ash based geopolymer samples could be related to their stable alumino-silicate gel that develops upon geopolymerisation as well as the low amount of calcium oxide in the geopolymer systems. On the other hand, the poor performance of the GLP-based geopolymer could be related to the less stable geopolymerisation products which result in increased porosity, and the high amount of available alkalis present in the raw GLP.

Keywords: Geopolymer; Ground glass fiber; fly ash; strength; Alkali activator; Curing temperature
1. Introduction:

Sulfate attack is known as one of the major durability problems affecting the performance of portland cement concrete (1). This chemical attack is mainly associated with the formation of non-cohesive and expansive by-products such as gypsum and ettringite; which lead to cracking and softening of the paste matrix resulting in mass loss and reduction in the mechanical properties of the portland cement concrete (2). In order to mitigate durability issues associated with sulfate attack, use of adequate amounts of supplementary cementitious materials (SCMs) such as slag is practiced (3). According to Neville (4), the use of SCMs as cement replacement material can help the mitigation of sulfate attack by reducing the amount calcium aluminate (C$_3$A) and calcium Hydroxide (CH), which prevents the formation of deleterious compounds such as gypsum and ettringite. Considering the deterioration of concrete in the high sulfate environment, evaluation of the performance of any cementitious materials against a sulfate-rich environment is critical.

Geopolymer-based concretes have recently attracted attention as a potential replacement for portland-cement based concrete, particularly in applications where aggressive chemical environments are encountered. Typically, geopolymers are produced by the alkali activation of silica and alumina-rich materials using alkaline activators such as sodium hydroxide or sodium silicate solutions. This results in the production of an amorphous three-dimensional alumino-silicate network, known as the geopolymer (5). Efforts to study the durability performance of geopolymer concrete and mortar against aggressive environments have been conducted by exposing test specimens to different sulfate-rich solutions such as sodium sulfate and magnesium sulfate solutions (6-12). However, thus far most of the studies were conducted on fly ash or meta-kaolin based geopolymers; and no such durability studies have been conducted on
geopolymers produced with glass-based precursor materials such as ground glass fibers (GGF) and ground soda-lime glass powder (GLP). The purpose of this investigation is to evaluate the performance of geopolymers produced using GGF and GLP precursors when exposed to sulfate rich environment. In this study a 5% sodium sulfate solution was used to simulate a sulfate-rich environment.

1.1. Background

Geopolymer-based concrete is increasingly being used as an alternative to portland cement concrete in specific applications such as precast concrete products, including sewer pipes, culverts, railway sleepers, pre-fabricated units for housing market, etc. (13-17), repair or a retrofitting material for existing portland-cement-concrete elements or structures (18-20), and as a repair coating or a construction material in marine sites (21-24).

Based on literature review, precursor materials such as fly-ash, slag, meta-kaolin and their combinations are the most widely used materials to manufacture geopolymer concrete (25-31). In addition, several other waste or industrial by-products such as: waste paper sludge ash (32), spent fluid catalytic cracking catalyst (33) waste glass-powder (34), palm oil fuel Ash (35), kaolinitic clay (36), a combination of natural pozzolan and slag (37), blends of clay and fly ash (38), and vitreous calcium alumino-silicate (39) have been studied by other authors to produce geopolymer concrete. In addition to these materials, recent studies have shown that ground glass fiber (GGF) can be effectively activated by an alkali activator to produce a geopolymer mortar (40).

Each year, a large amount of glass fiber is produced around the world for use in various applications. The production process of high-quality glass-fiber is often associated with
generation of hundreds of thousands of tons of waste glass fiber that is deemed off-specification, due to strict technical requirements. The waste glass fiber is typically disposed off in landfills. It has been reported that, in the United States alone around 250,000 tons to 500,000 tons of waste glass fiber ends-up in landfills each year (41). Considering the chemical composition of this material, which is rich in silica, alumina, and calcium, it could be potentially used as a supplementary cementitious material (SCM) or as a precursor for the production of geopolymer (42, 43). Recent studies have shown that activation of GGF using a sodium hydroxide solution, without the need for a sodium silicate solution, can produce a geopolymer mortar mixture with high early strength as high as 80 MPa after only 3 days (40).

Unlike portland cement paste in which calcium silicate hydrate (CSH) is the main constituent of the hydration product, geopolymers are made of an amorphous alumino-silicate matrix (44, 45). Therefore, the durability of geopolymers in aggressive environments can be expected to be different from that of portland cement-based materials. Several studies have reported findings on different durability aspects of geopolymer concrete. Studies on the durability properties such as resistance against alkali-silica reaction (ASR) of aggregates (46-48), resistance against acid attack (8, 49-52), sulfate-rich solutions (6-12), freeze and thaw (10, 53), etc. have shown superior performance of geopolymers produced from precursors such as fly ash, bottom ash, meta-kaolin, slag etc., compared to portland cement concrete.

Considering the differences between the chemical nature of the matrix in portland cement and geopolymer concretes, particularly due to the lower amount of calcium in geopolymers, the behaviors of these materials (portland cement and geopolymers) are found to be different when exposed to a sulfate rich media (54). Monitoring the changes in material properties such as compressive strength (6, 11, 12, 35, 55, 56), length of specimens (i.e. expansion) (51, 56, 57),
porosity and microstructure (57) have been used to study the behavior of geopolymers when exposed to a sulfate solution such as sodium sulfate or magnesium sulfate. In most of these studies, it was observed that geopolymers had a better performance when compared to portland cement concrete, i.e. lower expansion, lesser degree of loss in compressive strength, and minimal change in the microstructure of the matrix. The better performance of geopolymer samples has been attributed to factors such as: lower amount of calcium oxides in the structure of geopolymers (7, 35, 36, 55, 56), further geopolymerisation while exposed to the sulfate solution (6, 10), formation of new crystals in the structure of the exposed samples (8), and the cross-linked structure of the alumino-silicate gel of geopolymers (35, 54).

Despite its better performance in comparison to portland cement mixtures, in some cases, reduction (or fluctuation) in the mechanical properties has been reported for the geopolymer samples which were subjected to sulfate solutions (7, 8, 11, 12). In these studies, such behavior was mainly attributed to the leaching of alkalis from the geopolymer into the sulfate solution, which alters the structure of geopolymer and negatively affects the mechanical properties. Other observations have also reported the formation of ettringite and gypsum in the matrix of geopolymer exposed to sulfate solution, which leads to expansion and consequent mechanical degradation of the geopolymer (9, 12, 56, 57). However, the formation of these products was mostly observed when samples were exposed to the magnesium sulfate solution (9, 12, 54), while it was not the case for the samples exposed to the sodium sulfate solution; as no or very small traces of gypsum and ettringite were seen in these samples (6, 9, 10, 35, 54).

Effect of sulfate solution on the geopolymers has been reported to depend on the cations accompanying the sulfate in the solution (i.e. Na or Mg) (9, 11). Some studies (9, 54, 56) reported magnesium sulfate solutions to be more aggressive towards geopolymer samples in
comparison to sodium sulfate solution, while other studies (11), reported more damaging effect of sodium sulfate solution on geopolymer samples compared to magnesium sulfate solutions. Considering the dissimilar effects of these two different solutions and the associated mechanism of damages from these solutions, present study will focus only on the effect of a 5% sodium sulfate solution on a GGF and GLP-based geopolymer. In addition, results from glass-based geopolymers were compared with a fly ash-based geopolymer to investigate how different precursors affect the properties of geopolymers exposed to a sodium sulfate solution. Although, parallel studies on the effects of magnesium sulfate solutions on geopolymers were conducted, the findings from those studies are not presented here and will be presented in future.

1.2. Significance of the research

Earlier studies have revealed the superior performance of geopolymers in comparison to portland cement concrete when exposed to sulfate-rich environment. However, most of these studies have been conducted on fly ash, meta-kaolin, or slag-based geopolymers; and very limited studies have been conducted on other alternative precursors. Two of such precursors are GGF and GLP, which can be activated by alkali solutions to form geopolymers. In order to evaluate the durability of these novel types of geopolymers when exposed to a sulfate-rich media, in this study the performance of GGF and GLP-based geopolymers exposed to sodium sulfate solution was evaluated and the results were compared to the performance of a geopolymer produced from fly ash. To study the deterioration mechanism, parameters such as the change in the pH of the sulfate solution, change in the weight and compressive strength of geopolymer specimens, dissolution of geopolymer pastes in the sulfate solution were monitored during the test period. In addition, Scanning Electron Microscope (SEM) and Energy X-Ray Dispersive analysis (EDX),
XRD and Thermogravimetric Analysis (TGA), were conducted to investigate the microstructure of the mortar samples.

2. Materials:

In this study, ground glass fiber (GGF) from a Type E glass fiber, a class F fly ash, and glass-powder (GLP) produced from crushing soda-lime glass bottles were used as the precursor source materials of alumino-silicate materials. GGF was obtained from a commercial source, where it is produced by grinding off-specification Type E glass fibers into particles with an average size of 4 microns. The class F fly ash was obtained from a local source. The GLP was obtained from a commercial source that produces the material by grinding waste glass container into a fine powder with an average particle size of 17 microns. The chemical composition and physical properties of the materials are presented in Table 1 and Table 2 respectively. Moreover, the XRD pattern of raw GGF, Fly ash, and GLP, are presented in Figure 1.

<table>
<thead>
<tr>
<th>Cementitious material</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>CaO</th>
<th>MgO</th>
<th>Na₂O</th>
<th>K₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>GGF (%)</td>
<td>47.72</td>
<td>10.36</td>
<td>0.34</td>
<td>19.62</td>
<td>2.27</td>
<td>0.67</td>
<td>0.10</td>
</tr>
<tr>
<td>Fly ash (%)</td>
<td>50.70</td>
<td>25.10</td>
<td>12.50</td>
<td>3.30</td>
<td>1.10</td>
<td>0.51</td>
<td>2.27</td>
</tr>
<tr>
<td>GLP (%)</td>
<td>69.60</td>
<td>2.20</td>
<td>0.90</td>
<td>11.60</td>
<td>0.40</td>
<td>12.03</td>
<td>0.40</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Specific Gravity</th>
<th>Amount Passing #325 Sieve</th>
<th>Loss On Ignition</th>
<th>Blaine's fineness (cm²/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GGF</td>
<td>2.60</td>
<td>96%</td>
<td>1.0%</td>
<td>10200</td>
</tr>
<tr>
<td>Fly ash</td>
<td>2.25</td>
<td>76%</td>
<td>2.3%</td>
<td>6040</td>
</tr>
<tr>
<td>GLP</td>
<td>2.40</td>
<td>83%</td>
<td>1.5%</td>
<td>5920</td>
</tr>
</tbody>
</table>

Two activators, including a combination of sodium-silicate and sodium hydroxide solution, and sodium-hydroxide solution were used in the present study. The sodium-silicate solution, with the
solids-to-water ratio of 40% and SiO$_2$:Na$_2$O ratio of 3 (by weight), and the sodium hydroxide pellets, with 98% purity, were used to produce the activator solutions with different concentrations. For preparation of the sulfate exposure solution, ASC (American Society of Chemicals) grade anhydrous sodium sulfate (Na$_2$SO$_4$) powder was dissolved in deionized water to produce a 5% sodium sulfate solution (by weight).
2.1. Preparation and selection of mixture designs:
To prepare the geopolymer mixtures, each of the precursors was activated with an alkali activator solution with the Na₂O-to-precursor mass ratio of 10% (based on the preliminary test results), while the SiO₂-to-Na₂O ratio was studied at three levels, i.e. 0, 0.5 and 1.0. In all the mixtures, the sand content was selected to fill 55% of the total volume, and the water-to-binder ratio was maintained between 0.30 and 0.35. For this calculation, only water that is present in the solution was used. This range was chosen to get the highest possible strength while the mixtures were workable without the need for any water reducers.

Preliminary tests were conducted to select the mix design for each precursor. Compressive strength test was performed on at least three mortar cube samples at 3, 7 and 28 days age, and the mixture resulting in the highest compressive strength after 28 days was selected for the durability test. The mix designs of the geopolymer paste and results of compressive strength test are presented in Table 3. Based on the compressive strength tests results, GGF-0-10, F-1-10, and GLP-1-10 mixtures, which showed the highest compressive strengths were selected to be the mixtures to be exposed to the sodium sulfate solution.

To prepare the activator solutions, required amounts of sodium hydroxide pellets and sodium-silicate solution were dissolved in water to achieve the desired concentrations. After the dissolution of sodium hydroxide pellets, the precursor was added to the solution and mixed until a homogenous paste was achieved. Finally, the required amount of fine aggregate was added to the paste, and the mixture was further mixed for an additional 5 minutes. After completing the mixing process, the mixture was placed into 50 mm x 50 mm x 50 mm cube molds in two layers. Each layer was tamped and vibrated for 30 seconds using a vibration table. The molds were then placed in sealed boxes and moved into a 60°C chamber for 24 h. After 24 hours, specimens were...
removed from their molds and kept in the ambient temperature for 48 h, before being introduced into the 5% sodium sulfate solution bath for exposure.

Table 3. Mix ID and the proportion of geopolymers

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Precursor</th>
<th>Water/Binder</th>
<th>Na₂O/Binder (%)</th>
<th>SiO₂/Na₂O</th>
<th>Compressive strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3 days</td>
</tr>
<tr>
<td>GGF-0-10</td>
<td>GGF</td>
<td>0.33</td>
<td>10</td>
<td>0</td>
<td>79</td>
</tr>
<tr>
<td>GGF-0.5-10</td>
<td>GGF</td>
<td>0.33</td>
<td>10</td>
<td>0.5</td>
<td>67</td>
</tr>
<tr>
<td>GGF-1-10</td>
<td>GGF</td>
<td>0.33</td>
<td>10</td>
<td>1</td>
<td>69</td>
</tr>
<tr>
<td>F-0-10</td>
<td>Fly ash</td>
<td>0.30</td>
<td>10</td>
<td>0</td>
<td>14</td>
</tr>
<tr>
<td>F-0.5-10</td>
<td>Fly ash</td>
<td>0.30</td>
<td>10</td>
<td>0.5</td>
<td>35</td>
</tr>
<tr>
<td>F-1-10</td>
<td>Fly ash</td>
<td>0.30</td>
<td>10</td>
<td>1</td>
<td>58</td>
</tr>
<tr>
<td>GLP-0-10</td>
<td>GLP</td>
<td>0.35</td>
<td>10</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>GLP-0.5-10</td>
<td>GLP</td>
<td>0.35</td>
<td>10</td>
<td>0.5</td>
<td>19</td>
</tr>
<tr>
<td>GLP-1-10</td>
<td>GLP</td>
<td>0.35</td>
<td>10</td>
<td>1</td>
<td>37</td>
</tr>
</tbody>
</table>

2.2. Test procedure:

Three days after casting, mortar cube specimens were immersed in a 5% sodium-sulfate solution at ambient temperature. The weight change and the residual compressive strength of the specimens were measured at 7, 28, 56 and 120 days after submerging in the sulfate solution. The sulfate soak solutions were periodically replaced by a fresh sulfate solution at 7, 14, 21, 28 and 56 days. To measure the weight change, mortar cube specimens were weighed before exposing to the sodium-sulfate solution (initial weight), and then were weighed in the saturated surface dry condition at the above-mentioned time periods. After measuring their weights, the specimens were tested for their compressive strength.

To study the dissolution behavior of the geopolymers in the sodium sulfate solution, geopolymer paste samples from each source material (i.e. GGF, fly ash and GLP-based geopolymer) were
used. In this test, representative paste samples prepared with each of the precursor materials were mechanically crushed using a hammer into a fine powder, and the portions passing #100 sieve (150 microns) and retained on #200 sieve (75 microns) were collected. Five grams of the sieved material was then introduced into 100 ml of the 5% sodium sulfate solution and stored in a sealed bottle. For each of the geopolymer specimens, six samples were prepared by the above-mentioned method. Each bottle was vigorously shaken for 1 minute and then left to rest at the ambient temperature until the test date (i.e. 3, 7, 14, 28 and 56 days).

On the test day, each solution was again vigorously shaken and then filtered using a micro-fiber filter (Whatman Grade 934-AH Micro Filter). The filtered solution was collected for pH measurement and elemental analysis using inductively coupled plasma mass spectrometry (ICP-MS) test to measure the amount of selected elements (i.e. Si, Al, Ca) that leached into the solution. Titration method was adopted to measure the pH of solutions. For this process, phenolphthalein was used as the indicator, while the solution was titrated with 0.01N HCl solution. The filtrate part of each paste sample was also collected, washed with 100 ml of deionized water and was allowed to dry at 23°C and 50% relative humidity. After drying, the samples were sealed. Selected samples were then evaluated using XRD to examine any changes in mineralogy such as formation of gypsum and Ettringite.

To determine the amount of calcium hydroxide (CH) in the specimens, Thermogravimetric analysis (TGA) was performed on representative paste samples using TA Instrument (2950 model), employing a platinum pan with nitrogen purge gas was used for this purpose. The temperature was raised from ambient to 600 degrees Celsius at a temperature ramp of 10 degrees per minute. Representative crushed geopolymer paste samples passing #200 sieve were used for this test. The crushed geopolymer samples were gradually heated, and the change in their mass
was recorded. Decomposition of CH occurs within the temperature range between 440 to 520°C and causes a mass loss in the sample (37). The mass loss in this range can be used to calculate the amount of calcium hydroxide in the sample.

Mercury Intrusion Porosimetry (MIP) was used to monitor the change in the porosity of samples exposed to the sodium sulfate solution. Three days after casting, geopolymer samples were cut into sections of 10 x 10 x 10 mm cubes and were placed in a 5% sodium-sulfate solution. On the test date (i.e. 7, 28, and 56 days), specimens were removed from the solution and were washed in deionized water. Specimens were then dried in an 110°C oven for 2 h and were tested using MIP to determine the porosity and pore characteristics. MIP test was conducted using a Quantachrome Poremaster 60 with mercury having a contact angle of 140°. Finally, to study the microstructure of the samples, scanning electron microscopy images was a Hitachi TM 3000 unit, equipped with a Swift EDX (energy-dispersive X-ray spectral analysis) was used in the back-scatter mode.

3. Results and Discussion

3.1. Change in the weight

Weight change in the geopolymer mortar samples that were immersed in a 5% sodium-sulfate solution was monitored up to 120 days (Table 4). As it can be seen in Table 4, GGF-based geopolymer samples showed no significant change in weight, with only 0.4% weight gain after 120 days of exposure to the sodium sulfate solution, while fly ash-based geopolymer gained a weight of 2.2%, after 120 days of exposure to the sodium sulfate solution. On the other hand, GLP-based geopolymer showed a steady weight loss during the test period, and lost 2% of its initial weight after 120 days of exposure to the sodium sulfate solution.
Table 4. Change in the weight of geopolymer mortar specimens due to soaking in the 5% sodium sulfate solution

<table>
<thead>
<tr>
<th>Submersion time (Day)</th>
<th>Weight change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GGF-0-10</td>
</tr>
<tr>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>0.2</td>
</tr>
<tr>
<td>28</td>
<td>0.3</td>
</tr>
<tr>
<td>56</td>
<td>0.3</td>
</tr>
<tr>
<td>120</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Since all geopolymer specimens were cured at 60°C temperature, it is thought that the voids and porosity in the specimens should have been almost free of water at the beginning of the test. Therefore, the weight gain of the fly ash and GGF-based geopolymer mortar samples can be related to the saturation of the empty or partially filled voids and pores. However, the smaller amount of weight gain in the GGF-0-10 specimens in comparison to the F-1-10 specimens can be related to the lower amount of porosity of the GGF-0-10 specimens (Section 3.5).

The visual appearance of F-1-10 and GGF-0-10 specimens after being soaked in the 5% sodium sulfate solution for 120 days are shown in Figure 2a, and 2b respectively. As it can be seen in these figures, neither F-1-10 nor GGF-0-10 sample showed any visible sign of cracking, leaching, and deterioration. Therefore, in the absence of any visible damage the weight gain seen in the fly ash and GGF-based specimens can be related to the penetration of the solution into the voids and pores of these specimens.
The weight loss observed in the GLP-based specimens is likely to be due to the leaching and dissolution of the paste matrix into the soak solution, as presented in Figure 3. Figure 3a shows GLP-1-10 mortar cube after being removed from the sulfate solution and dried. Figure 3b shows the SEM and EDX analysis of the white deposit shown in Figure 3a. As it can be observed from the EDX results, there is a considerable amount of Si in the deposit; which has been released from the geopolymer sample. The high amounts of Na and S measured in the deposit can be attributed the precipitation of these ions from the sodium sulfate solution on to the surface of the specimen.
Average weight Percentage of Elements

<table>
<thead>
<tr>
<th></th>
<th>Na</th>
<th>Mg</th>
<th>Al</th>
<th>Si</th>
<th>S</th>
<th>K</th>
<th>Ca</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average (W%)</td>
<td>32.19</td>
<td>1.02</td>
<td>3.25</td>
<td>28.87</td>
<td>24.39</td>
<td>2.52</td>
<td>7.81</td>
</tr>
</tbody>
</table>

Figure 3. a) Formation of a white deposit on the surface of GLP-1-10 sample. b) EDX results of the white deposit

3.2. Change in the compressive strength

The compressive strength of geopolymer mortar cubes that were immersed in the 5% sodium sulfate solution are presented in Table 5. It can be observed that the compressive strength of the fly ash and GGF-based specimens decreased in the early ages (7 to 28 days), and subsequently increased at the later ages (56 to 120 days). In the case of F-1-10 specimens, the lowest compressive strength (44 MPa) was seen after 7 days of exposure in the solution. Nevertheless, the specimens regained the compressive strength at later ages and reached 58 MPa after 120 days of exposure. In the case of GGF-0-10 specimens, the loss in compressive strength was not as rapid as observed in F-1-10 specimens, and the lowest compressive strength was seen after 28 days (61 MPa). However, similar to the F-1-10 mixture, the GGF-0-10 specimens regained their compressive strength and reached 70 MPa after 120 days of the exposure.
On the other hand, in the case of GLP-1-10 specimens, a significant strength loss was seen up to 56 days. The strength gain of the GLP-1-10 specimens was not considerable at the later age (from 56 days to 120 days). These specimens lost more than 50% of their initial compressive strength after 120 days of immersion in the 5% sodium sulfate solution.

Table 5. Change in the compressive strength of geopolymer mortar samples due to the sulfate attack

<table>
<thead>
<tr>
<th>Submersion time (Day)</th>
<th>Compressive strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GGF-0-10</td>
</tr>
<tr>
<td>0</td>
<td>79</td>
</tr>
<tr>
<td>7</td>
<td>67</td>
</tr>
<tr>
<td>28</td>
<td>61</td>
</tr>
<tr>
<td>56</td>
<td>76</td>
</tr>
<tr>
<td>120</td>
<td>70</td>
</tr>
</tbody>
</table>

From the previous studies that attempted to study the behavior of geopolymers exposed to sulfate-rich solutions, conflicting trends in compressive strength results were reported. While strength gain was reported in some studies (6, 35, 56, 59), strength loss was reported in other studies (6, 11, 12, 54, 60), and fluctuation in the mechanical properties has been reported by others (6-8, 11). In these studies, the principal reason for the strength gain was reported to be due to the further geopolymerisation process, formation of a new zeolite phase (faujasite), which reduces the porosity; while the main causes of the strength loss were attributed to the dissolution of alkali from the geopolymer matrix into the sulfate solution, leaching of Si in to the sulfate solution, and the formation of gypsum in geopolymer matrix.

In order to better understand the changes in the mechanical properties in geopolymer samples exposed to sodium sulfate solutions, a comprehensive experimental program was conducted to evaluate the effect of each of the above mentioned mechanisms on the compressive strength of the geopolymer mixtures. Different parameters, including leaching of alkalis from the geopolymer paste, changes in the pH of the sodium sulfate solution and dissolution of
geopolymer paste in the sodium sulfate solution were measured. In addition, other tests such as MIP, XRD, SEM-EDX and TGA analysis, were conducted on the geopolymer specimens to better understand changes in the porosity, mineralogy and microstructure. The results of these experiments are presented and discussed in the following sections.

3.3. Leaching of the alkalis from geopolymers into the soak solution

The main mechanism for the deterioration of the geopolymer samples in a sulfate-rich media has been suggested to be due to dissolution of the alkalis from the geopolymer into the sodium-sulfate soak solution (8, 11) resulting in the increase in the porosity (8) or possibly causing the formation of micro-cracks (11), which decreases the mechanical properties. In the present study, dissolution of alkalis (Na and K cations) from the geopolymer samples was evaluated by measuring the changes in the alkali content of the paste portion of the geopolymers, as well as change in the pH of the filtered sodium sulfate solution. The procedure for obtaining the filtered solution is presented in section 2.2.

3.3.1. Change in the alkali content of the geopolymers’ paste

Table 6 presents the alkali content of the paste portion of geopolymer samples before exposure to sodium sulfate solution, after 28 days, and after 120 days of immersion into the sodium sulfate solution. These values are based on the averaged EDX results from at-least three locations, at a distance of 1000 microns from the surface of specimens in the paste portion of the geopolymer samples. As this table shows, in all the geopolymer mixtures, the EDX results confirmed the dissolution of alkali into the sodium sulfate soak solution, as sodium content in the geopolymer matrix changed significantly before and after the exposure. In GGF-1-10 sample, a considerable
reduction in the sodium content was seen at 28 days; however, after 28 days the sodium content remained fairly stable between 28 and 120 days.

In the case of F-1-10, a rapid decrease in sodium and potassium contents was observed from the beginning of the test up to 28 days. Sodium content decreased from 11.70% to 8.26% and potassium content decreased from 3.21% to 2%. However, the alkali reduction mechanism seems to stop at later ages as the sodium and potassium content values at 120 days are close to the 28-day values. Similar trend was also seen in the case of GLP-1-10 sample. This material showed a rapid decrease in both sodium and potassium content up to 28 days, and further reduction in the alkali content occurred at a much slower pace until 120 days. The significant reduction of alkali content in the GLP-1-10 mixture, suggests the weaker bonds of alkalis (or higher amount of un-fixed alkalis) in this material in comparison to other tested geopolymer mixtures (i.e. GGF and fly ash-based geopolymers). In addition, the dramatic strength loss of this material could be also related to the dissolution of the paste portion of GLP-1-10 geopolymer.

Table 6. Change in the sodium and potassium content of the geopolymer samples due to sulfate attack

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Sodium</th>
<th>Potassium</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GGF-0-1</td>
<td>F-1-10</td>
</tr>
<tr>
<td>Before immersion</td>
<td>13.39</td>
<td>11.70</td>
</tr>
<tr>
<td>After 28 days</td>
<td>8.66</td>
<td>10.41</td>
</tr>
<tr>
<td>After 120 days</td>
<td>9.34</td>
<td>7.94</td>
</tr>
</tbody>
</table>

3.3.2. Change in the pH of the sodium sulfate solution

Considering that the pH of the 5% sodium sulfate solution is 7, change in the pH value of sodium sulfate solutions upon introduction of the geopolymer samples into the soak solution bath was tracked with age and these results are presented in Figure 4. With all the geopolymer
samples, a significant change in the pH value of the sodium sulfate soak solution was observed within the first few days. This can be related to the dissolution of alkalis from the geopolymer matrix into the solution. However, the pH value of the soak solution remained almost constant after 7 days and did not show a considerable change up to 56 days.

Among the different samples tested, the largest change in the pH value of the sodium sulfate soak solution was seen with the GLP-1-10 sample, wherein the pH of the soak solution changed from 7 to almost 13 within the first seven days of exposure. On the other hand, solutions containing GGF-0-10 and F-1-10 samples showed an increase in pH from 7 to 12.45 and 12.41, respectively, within the first 7 days and thereafter showed almost the same pH. The higher initial pH in the case of GLP-1-10 samples is thought to be related to the large amount of available alkalis, as well as the low amount of Al in the GLP composition (Table 1). In the geopolymer systems, alkali ions are balanced with the negative charge of aluminum in a tetrahedral coordination (25, 61). Therefore, it is thought that the low amount of Al in the GLP structure results in a high amount of unfixed alkalis in the geopolymer matrix, which can freely leach into the sodium-sulfate solution and increase the pH value.
In the case of fly ash and GGF-based geopolymer samples, pH values increased up to 14 days of exposure, and reached 12.43 and 12.50 respectively. The values remained the same until 28 days, and then declined to 12.36 and 12.45 respectively after 56 days of exposure. While the initial increase in the pH values has been related to the leaching of alkali ions from the pore solution and the dissolution of unfixed alkali ions (6, 8, 11), the later reduction in the pH contents thought to be related to the further geopolymerisation of the exposed samples. Further polymerisation of geopolymer samples in the sodium-sulfate solution was also suggested by Ismail et al. and Slaty et al. (9, 35). Moreover, a few studies have shown that sodium-sulfate solution can be used as an activator in activation of slag-based geopolymer systems (62, 63). It should be mentioned that the leaching of alkalis from the geopolymer samples in itself cannot be considered as the main deterioration mechanism of the geopolymer samples when exposed to a sulfate-rich solution such as sodium sulfate solution. Results from other studies have shown that leaching of alkalis (increase in the pH value of the exposed liquid) was observed for cases in which geopolymer samples had been kept in the deionized water or sea water (36, 49). Other studies have also shown a decrease or fluctuation in the mechanical properties of geopolymer samples kept in deionized water (7, 8, 36, 49, 64). Furthermore, results of our ongoing experiments showed an increase in the pH value of a deionized water sample that was in contact with geopolymer samples in comparison to a 5% sodium sulfate solution that had been kept in a same condition.

3.4. Dissolution of geopolymers in sodium sulfate-solution:

Dissolution of key elements, including Ca, Si and Al from geopolymer samples into the sodium sulfate solution is presented in Table 7. These results can partially explain the reduction of mass and compressive strength of the GLP-1-10 samples, since a significant amount of Si was dissolved from this sample. Due to the high amount of already available Na (from the sodium-
sulfate solution), it was not practical to trace the change in the concentration of this element; however, the measured high pH values in all the tested samples suggest the dissolution of Na from the paste into the solution.

Table 7. Concentration of ions leached from each geopolymer sample into the sodium sulfate solution (dissolution test)

<table>
<thead>
<tr>
<th>Age (day)</th>
<th>Ions leached from GGF-1-10 (ppm)</th>
<th>Ions leached from F-1-10 (ppm)</th>
<th>Ions leached from GLP-1-10 (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ca</td>
<td>Al</td>
<td>Si</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td>2</td>
<td>59</td>
</tr>
<tr>
<td>7</td>
<td>12</td>
<td>2</td>
<td>113</td>
</tr>
<tr>
<td>28</td>
<td>8</td>
<td>1</td>
<td>112</td>
</tr>
<tr>
<td>56</td>
<td>14</td>
<td>1</td>
<td>113</td>
</tr>
</tbody>
</table>

As it can be seen in Table 7, for the case GGF and fly ash-based geopolymers, low amounts of Si and negligible amount of Al and Ca were dissolved into the sodium-sulfate solution. The low amount of dissolution of Si and Al, which are known to form the main structural units of geopolymer paste, suggests that the main structure of geopolymers remains almost intact when GGF-0-10 and F-1-10 samples are immersed into the sodium-sulfate solution.

The high amount of Si dissolved into the sodium sulfate soak solution in the case of GLP-1-10 suggests that the Si in the GLP-based sample is not strongly bound. This is thought to be due to the formation of an ASR-like gel material in the GLP matrix, which was seen all over the paste matrix of GLP-1-10 sample. The chemical composition of the gel consisted of a low amount of Ca along with the high amount of Si and Na (Figure 5). It has been proposed in earlier studies that in the absence of Ca, ASR gel has a low viscosity (65, 66), and would easily dissolve in the alkali solution. Therefore, the high amount of Si and Na in the exposed solution could be explained by the dissolution of the low-viscosity ASR gel into the sodium-sulfate solution.
3.5. Mercury Intrusion Porosimetry (MIP)

Pore size distribution of unexposed samples and change in the total porosity of exposed mortar samples are presented in Figure 6a and Figure 6b respectively. According to the results presented in Figure 6a, G-0-10 sample has the lowest total porosity (0.03 cc/g), which is followed by GLP-1-10 sample (0.07 cc/g), and F-1-10 sample (0.10 cc/g). In the case of GLP-1-10, GGF-0-10, and F-1-10 samples, most of the pore sizes were between the 1 to 100 µm, 1 to 20 µm, and 0.01 to 1 µm, respectively. In GGF and GLP-based samples, pores with the sizes larger than 1 µm accounted for 91% and 84% of the total intruded volume, respectively. On the other hand, in the case fly ash-based geopolymer sample most of the intruded volume occurred at smaller pore sizes. In this sample (F-1-10), 83% of the total intruded volume was shown to occur at pore sizes smaller than 1 µm. However, considering the spherical shape of the fly ash particles and particularly the cenospheres (i.e. hollow fly ash particles) (Figure 7), the rapid rise in the intruded volume at the smaller pores size seems to result from the small size of pore entrances.
rather than the actual pore diameter itself. It should be pointed out that the MIP test identifies the size of the entrance paths to the pores not the actual pore diameters themselves. This phenomenon will cause a significant increase in the intruded volume to be registered at small pore sizes.

Figure 6. MIP test results. a) Pore size vs volume intruded for non-exposed samples, b) change in the porosity of exposed samples by time.
Figure 6b shows the variation of the total porosity of geopolymer samples exposed in 5% sodium-sulfate solution with age. In this study, change in the total amount of intruded volume of the samples exposed to the sodium-sulfate solution is thought to occur because of the following reasons: 1) further geopolymerisation/hydration of the unreacted precursors, 2) dissolution of the paste components (Si, Al and Ca) in the solution, and 3) precipitation of the sodium sulfate into the voids.

![Figure 7. Hollow fly ash particles in F-1-10 sample](image)

As it is obvious from the results, the total amount of porosity in the case GGF and fly ash-based geopolymer samples did not change significantly. The slight reduction in the porosity of the GGF and fly ash based samples is thought to be as a result of further geopolymerisation of the unreacted GGF and fly ash particles, which could refine the paste matrix of the samples and reduce the porosity. Preliminary results from an investigation on the alkali activation of GGF at
ambient temperature using the same activator as used in this study showed a gradual strength gain in the geopolymer mortar samples up to 28 days. In addition, SEM-EDX as well as XRD analysis that was performed on the exposed samples did not confirm the presence of any noticeable amount of sodium sulfate crystals. Therefore, considering the dissolution results (presented in section 3.4), in which no considerable amount of Si, Ca and Al, had leached from the GGF and fly ash-based geopolymer pastes (Table 7), it could be concluded that the dissolution of pastes into the sodium sulfate solution could not cause a possible increase in the pore volume. As a result the slight reduction seen in porosity of the exposed GGF and fly ash-based samples could be mainly attributed to the further geopolymerisation. The further geopolymerisation of fly ash-based geopolymer samples immersed in sodium sulfate solutions have been also suggested by other studies (6, 9).

In the case of GLP-1-10 specimens, an increase in the total porosity is thought to be as a result of significant dissolution of the paste, with an ASR gel-like composition, in the sodium sulfate solution. As it is presented in Table 7, high amount of Si and Ca had leached out from the GLP-based geopolymer paste. Considering the high amount of available alkalis in the GLP-1-10 geopolymer paste, both from the GLP precursors (Table 1) and the activator solution, the pH of the pore solution would be very high causing leaching of Si from the GLP-1-10 paste into the solution. As presented in Figure 6b, the total amount of porosity showed an almost 50% increase after 56 days of exposure to the sodium sulfate solution, which could significantly affect the mechanical properties of the GLP-based geopolymer.

3.4. X-Ray Diffraction (XRD)

XRD patterns of 28-days exposed geopolymer pastes as well as unexposed ones are presented in Figure 8 through Figure 10. As it can be seen in Figure 8a, peaks in the unexposed F-1-10
sample are mostly associated with the presence of Quartz, Mullite and Hematite. These peaks were also seen in the XRD pattern of the raw fly ash (Figure 1), indicating that the abovementioned crystalline phases do not readily contribute in the geopolymerisation reactions. The XRD results from the exposed sample showed the formation of a few new phases such as natrite (Na$_2$CO$_3$), as well as the small amount of calcite, and feldspar. Presence of the two later phases has been also reported in the previous works (6, 7).

Comparison between the XRD pattern of the raw fly ash and F-1-10 geopolymer paste showed a shift in the center of the hump for amorphous or vitreous phases of the original fly ash after the activation (see the hump between 18°-38° 2θ at Figure 1b and Figure 8a). Moreover, comparison of XRD pattern of the exposed and the unexposed F-1-10 samples (Figure 8a and Figure 8b) did not reveal any notable shift in the hump of the XRD pattern; however, peaks of some crystalline phases such as quartz, mullite, and hematite showed a lower intensity.
In the case of GGF-0-10 sample, crystalline phases such as quartz, calcite, and tobermorite were seen in the unexposed sample (Figure 9a). Formation of these phases has been also reported in an alkali activated VCAS by Tahsima et al. (39). The XRD pattern of the exposed GGF-0-10 sample (Figure 9b) indicated an amorphous phase with no major crystalline phases. In addition, no change was seen in the amorphous hump, suggesting that the major geopolymer phases did not go through any significant deterioration in the exposed solution. These results are in agreement with the results from the dissolution test (Table 7); in which no considerable amount
of Al was found in the filtered sodium sulfate solution that was in contact with the GGF-based geopolymer paste, even though there was an elevated level of Si in the solution. It should be mentioned that if geopolymer gel were to deteriorate in the sodium sulfate solution, Al ions should have been detected in the solution along with the Si ions. It is therefore suggested that the presence of the Si ions in the solution could be related to the dissolution of microcrystalline quartz grains (which are less stable than well-formed larger quartz grains) into the soak solution. Absence of the peaks associated with quartz in the exposed samples compared to the unexposed samples reinforces this hypothesis.
Figure 9. XRD pattern of the unexposed and exposed GGF-based geopolymer samples. (Q: Quartz, C: Calcite, T: Tobermorite, N: Natrite)

Figure 10a and 10b present the XRD pattern of unexposed and exposed GLP-1-10 geopolymers, respectively. As shown in these figures, both exposed and unexposed samples have an amorphous structure with a few recognizable peaks. In the case of the unexposed sample, quartz was the main crystalline phase; which was also seen in the raw GLP precursors. On the other hand, peaks associated with quartz (with a lower intensity), and calcite were observed in the exposed GLP1-10 sample. While the comparison between the XRD patterns of the unexposed GLP-base sample and the raw GLP precursor revealed a clear shift in the amorphous hump,
A comparison of the exposed and the unexposed XRD patterns of the GLP samples showed a reduction in the height of the amorphous hump. This suggests that the GLP-based geopolymer is not stable in contact with the sodium sulfate solution and would dissolve into the solution. The high amount of dissolved Si ions in the solubility test can therefore be explained by the dissolution of the reaction product of the GLP-based geopolymer in the exposure solution.

Figure 10. XRD pattern of the unexposed and exposed GLP-based geopolymer samples. (Q: Quartz, C: Calcite,)
While formations of gypsum and ettringite are known to be the main cause of deterioration in the portland cement based specimens that are exposed to a sodium sulfate solution, no clear sign of gypsum or ettringite was seen in XRD patterns of all the exposed samples. These results are in agreement with the previous studies (6, 9, 35, 54) in which formation of gypsum and ettringite was not confirmed in geopolymer samples exposed to sodium sulfate solutions. In GGF and Fly ash-based samples, the amorphous humps stayed unchanged between the unexposed and the exposed samples; indicating that the geopolymer products stayed stable in the exposed solution. On the other hand, the amorphous hump of the GLP-based geopolymer sample exposed to the sodium sulfate solution showed a reduction in the height of the hump indicating the instability of the geopolymerized product when exposed to sodium sulfate solution. Finally, it should be added that the reduction in the intensity of the few crystalline phases of GLP-1-10 samples suggests the partial dissolution of the unreacted precursors’ particles due to the high pH of the exposure solution (after being in contact with the geopolymer samples).

3.7. SEM analyses

In this study, Scanning Electron Microscopy (SEM) and the Energy-Dispersive X-ray Spectral Analysis (EDX) were used to study the microstructure and the chemical compositions of the geopolymer mortars. The SEM images at a lower magnification showing the condition of the exposed samples after 28 and 120 days are presented in Figure 11. Figure 12 shows the microstructures of the 120-day exposed specimens at a greater magnification. SEM observation of GGF and fly ash-based mortar specimens did not show any significant signs of cracking or paste dissolution after 28 and 120-day exposure to the sodium sulfate solution. On the other hand, a clear sign of damage in the form of deep cracks was seen in the paste portion of the GLP-based specimens after 28 days. Further exposure of the GLP-based specimens, up to 120 days,
led to the dissolution of the paste in the solution (Figure 12). As it can be observed in this figure, as a result of the paste dissolution, the paste has been dissolved away from the aggregate boundaries and in some cases, aggregate particles have been removed from their places. A magnified image of the geopolymer paste portion of each of the geopolymer mortar samples is presented in Figure 12. As it could be seen in the Figure 12a and 12b, the paste portion of the GGF and fly ash-based geopolymer remained intact after 120-day exposure to the sulfate attack. However, for the case of GLP-based sample geopolymer, paste was readily dissolved in sodium sulfate solution (Figure 12c).

![Figure 11. SEM images of the geopolymer specimen exposed to the 5% sodium sulfate solution](image)

After 28 days of exposure: (a). GGF-0-10, (b). F-1-10, (c). GLP-1-10

After 120 days of exposure: (d). GGF-0-10, (e). F-1-10, (f). GLP-1-10

It should be noted that the SEM observations are in agreement with the findings from the dissolution test. Furthermore, the low amount of Si and Al leached from the GGF and fly ash-
based samples, as well as the high amount of Si and Al leached from the GLP-based geopolymers in the dissolution tests, confirm the resistance of GGF and fly ash-based geopolymer and the susceptibility of the GLP-based geopolymer to sodium sulfate solution.

3.6. EDX and TGA analysis:

To investigate the penetration of sulfate ions into geopolymers, the EDX analysis was performed on the exposed and unexposed samples. This analysis was performed to evaluate the potential risk of formation of gypsum and ettringite in the exposed samples. As it is known, presence of sulfate ions is required for this process, and therefore, the penetration of sulfate ions could be harmful for the structure of geopolymers. Table 8 shows the weight percent of sulfur in the paste portion of all tested geopolymers before and after exposure to the sodium sulfate as determined in the EDX analysis. As it can be seen, the concentration of sulfur in the geopolymer samples slightly rises after being in contact with the sodium sulfate solution. However, the measured amounts are still very low and it is unlikely that this amount of sulfur could lead to the formation of compounds such as ettringite and gypsum.
Table 8. Sulfur content of geopolymers by EDX. (*The elements considered for the EDX analysis are: Si, Al, Ca, Na, K, Fe, and S)

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Before exposure</th>
<th>After 120 days exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>GGF-0-10</td>
<td>0.01</td>
<td>0.34</td>
</tr>
<tr>
<td>F-1-10</td>
<td>0.52</td>
<td>0.84</td>
</tr>
<tr>
<td>GLP-1-10</td>
<td>0.06</td>
<td>1.29</td>
</tr>
</tbody>
</table>

Some of the earlier studies have attributed the good resistance of geopolymers against sulfate-rich solutions to their low amount of calcium oxides (7, 35, 36, 55, 56). These studies were mainly performed on fly ash, or meta-kaolin-based geopolymers in which the amount of available calcium in the precursors was limited. In the present study, however, a considerable amount of calcium was seen in the chemical compositions GGF and GLP (Table 1). Therefore, one could consider the formation of gypsum, and ettringite could take place in the GGF and GLP-based geopolymers, once the sufficient amount of sulfur is available. According to the sulfate attack studies conducted on the portland cement systems, calcium hydroxide (CH) acts as the main source of calcium supply for the formation of gypsum (1, 67). Therefore, to measure the amount of CH in the geopolymers, TGA analysis was performed on the paste samples. The TGA and differential thermal gravimetric analysis (DTGA) results, presented in Figure 13, showed a very low level of CH in both GGF-based (1.1% of the total weight), and GLP based geopolymer (1.4% of the total weight) paste samples. This suggests that despite the relatively high amount of Ca in the composition of raw GGF and GLP, calcium is mainly fixed into the other reaction products and only a small portion of it has been consumed to form CH in the geopolymer systems.
Figure 13. TGA and DTGA results of unexposed geopolymer pastes. (a). GGF-0-10, and (b). GLP-1-10.

4. Conclusion:

In this study the resistance of GGF, fly ash and GLP-based geopolymer mortar specimens exposed to a 5% sodium sulfate solutions were evaluated and compared with each other. For this purpose, parameters such as change in the visual appearance, weight and the compressive strength of geopolymer mortar samples were studied. In addition, techniques such as MIP, XRD, SEM-EDX and TGA were employed to investigate changes in porosity, mineralogy,
microstructure and formation of any new phases in the samples. Based on the results obtained from this study the most notable findings could be summarized as follow:

1. GGF and fly ash-based geopolymer samples did not show any visual signs of deterioration when exposed to sodium sulfate solution, however, the GLP-based specimens showed signs of severe deterioration, which was revealed in the forms of cracking and leaching.

2. After 120 days of exposure to sodium sulfate solution, GGF and fly-ash based geopolymers showed a slight increase in the weight, while GLP samples showed weight loss indicating the instability of GLP based geopolymers in the sodium sulfate solution.

3. Monitoring the compressive strength of the geopolymer samples exposed to the 5% sodium sulfate solution showed a decrease in the compressive strength of the GGF and fly ash-based specimens during the early ages (i.e. 7 to 28 days), which was followed by strength gain at the later ages (i.e. 56 days to 120 days). The GLP-based specimens showed a rapid reduction in their compressive strength until 28 days of exposure. After this period, the compressive strength of these samples remained almost constant, and no considerable change was seen in recorded values.

4. Based on the MIP results, no significant changes were occurred in the porosity of the exposed GGF and fly ash-based geopolymer. These results showed a slight reduction in the porosity of the exposed GGF and fly ash-based geopolymer samples after 56 days of exposure; which was attributed to the further geopolymerisation of these specimens. On the other hand, as the result of dissolution of the geopolymer paste in the soak solution, a substantial increase (almost 50%) in the porosity was seen in the exposed GLP-based geopolymer mortar specimen.
Based on the XRD results, no notable changes were seen in the XRD pattern of the exposed and unexposed GGF and fly ash-based geopolymers. However, some changes were seen in the case of exposed GLP-based specimens. This suggests the instability of the GLP-based specimens in the sodium sulfate solution, in comparison to the GGF and fly ash-based specimens.

In summary, based on the results obtained from this study, it can be concluded that the effect of sodium sulfate solution on the geopolymer samples is very much different than its effect on the portland cement-based material. As it is known, in the case sulfate attack on the portland cement-based specimens, sulfate plays its role by participating in deleterious chemical reactions leading to the formation of gypsum and ettringite. However, in this study, presence of sulfate seems to have no or a very limited effect on the mechanical properties of the GGF and fly-ash based geopolymer samples. It should be added that, in the case of GLP-based specimens, the main deterioration mechanism is thought to be because of the dissolution of the geopolymerised paste into the solution. Therefore, it is suggested that the term of “sulfate attack” might not be the best term, to describe the changes or fluctuations that might be seen in the mechanical properties of the geopolymer specimens produced from the tested precursors.
References:


