The Use of Recycled Aggregate Sludge for the Preparation of GGBFS and Fly Ash Based Geopolymer

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Abstract: Aggregate sludge is a waste product produced from crushing, screening, and washing processes at aggregate plants. Because of the large quantity and high treatment cost of this sludge, it cannot be disposed of as landfill, and thus, has caused environmental concern over the years in Taiwan. In this preliminary study, the recycled aggregate sludge was reutilized for construction applications through the geopolymerization process. The ground granulated blast furnace slag (GGBFS) and fly ash (FA) were selected as alkaline activated materials for the fabrication of sludge geopolymer. Several process parameters that may affect the mechanical and physical properties of geopolymer were investigated. These parameters are sludge/GGBFS/FA ratios, solid/liquid (alkali solution) ratio, the molarity of NaOH, and curing time. According to the test results, the compressive strength of geopolymer specimens (70/30 sludge/GGBFS ratios) made with 4 M and 6 M NaOH can reach 39.17 MPa and 43.6 MPa after 28 days of curing. The specimen made with 60/40 sludge/GGBFS ratios has a strength of 61.3 MPa. After replacing GGBFS with 10% fly ash (70/20/10 sludge/GGBFS/FA), the strength of the specimen can also reach 43 MPa. According to the test results obtained in this study, it was found that the higher the NaOH concentration, the higher the strength of the geopolymer, and the GGBFS also can contribute more to the mechanical properties of geopolymer than fly ash. This preliminary study suggests that it is possible to reutilize aggregate sludge for construction applications and solve its environmental disposal problem.

Keywords: aggregate plant sludge; ground granulated blast furnace slag; geopolymer

1. Introduction

Over the past decades, the sludge waste produced from aggregate crushing plants can only be retained on-site and causes environmental problems. It is because the cationic PolyDADMAC (Polydiallyldimethylammonium chloride) was used to flocculate and settle fine particles followed by filter press to further dewater and form sludge cake. According to regulation, the residual of Poly DADMAC existing in the sludge restricts its recycling for landfill purposes. The treatment cost of the sludge is estimated to be between 100 to 300 USD/m³. Therefore, a low-cost way to reutilize the sludge needs to be developed for the treatment of sludge. Besides the cement solidification of the sludge, the geopolymer process is considered as another alternative to convert the sludge waste into a useful resource and also greatly alleviate its disposal problem. Several studies have investigated various building materials using sludge [1–3].

Geopolymers are considered a class of green inorganic polymers [4]. The most common geopolymer is based on fly ash (FA) and ground granulated blast furnace slag (GGBFS) as a raw material. For example, Bhogayata et al. (2020) reported that the FA, GGBFS, and expanded clay can be used as materials for the preparation of geopolymers, and the compressive strength can reach 27 MPa with 28 days of curing [5]. Kim et al. (2018) found that the optimum replacement of cement with GGBFS can be as high as 30% and the CO₂ emission can also be reduced by 30% [6]. It has been reported that geopolymer composites made with industrial wastes such as fly ash, slags, and other aluminosilicate materials can...
effectively reduce carbon dioxide emissions by 80%. This advantage makes geopolymers a greener alternative to cement [7,8]. Based upon the studies conducted by researchers over the years, it is also possible to use geopolymer technology to recycle and reutilize aggregate sludge for the fabrication of green concrete products.

Geopolymers have been proven to possess high compressive strength, fire resistance, low shrinkage, and excellent acid resistance [9–12]. For the preparation of geopolymer, aluminosilicate material is readily dissolved in the alkaline solution to form AlO$_4$ and SiO$_4$ tetrahedral units [13]. These tetrahedral frameworks are linked to yield polymeric precursors (–SiO$_4$–AlO$_4$–, or –SiO$_4$–AlO$_4$–SiO$_4$–, or –SiO$_4$–AlO$_4$–SiO$_4$–SiO$_4$–) and share oxygen atoms within two tetrahedral units, followed by the release of water molecules [14]. Upon activation by alkali solution, Criado et al. indicated that the SiO$_2$/Al$_2$O$_3$ ratio can affect the degree of geopolymeric reaction and the characteristics of geopolymer products [9]. Alkali activation of industrial aluminosilicate waste materials, such as FA or GGBFS, produces a high-strength geopolymer binder under highly alkaline conditions [14].

There are many coal-fly-ash-based geopolymer research studies conducted using sodium silicate in the activating solution to improve the geopolymerization process [15–18], as is also the case for alkali-activated slag [19,20]. Hardjito et al. (2005) indicated low-calcium FA-based geopolymer concrete has excellent mechanical properties and acid resistance [21]. According to Bakharev’s study, geopolymer cement shows much better acid resistance than ordinary Portland cement under the attack of sulfuric acid [22]. Kupwade-Patil and Allouche’s study also discovered geopolymer concrete did not exceed the ASTM expansion threshold after being exposed to 1 M NaOH for 90 days, while visual cracks were identified in OPC specimens [23]. The GGBFS has a calcium aluminosilicate framework structure. Because of quenching treatment, it contains more than 60% of the amorphous slag that can be easily activated by alkali solutions. It is mainly constituted of calcium oxide, silica, alumina, and magnesia. The Si$^{4+}$ and Al$^{3+}$ cations form the main glassy network and the Ca$^{2+}$ and Mg$^{2+}$ ions can be the modifiers after activation by the alkali solution [24].

The purpose of this study is to investigate the feasibility of using aggregate sludge (AS), fly ash (FA), and ground granulated blast furnace slag (GGBFS) to prepare cement mortar for construction applications. In comparison with the conventional cement solidification process, the geopolymer process can reduce more than 80% carbon dioxide emission when compared with OPC production [25].

In this study, AS, FA, and GGBFS mixtures at various ratios were activated by an alkali solution to produce geopolymer mortars. The influences of alkali solution molar concentration and liquid-solid ratio (L/S) on the mechanical and physical properties of mortar were investigated. The effect of AS/GGBFS, AS/FA, AS/GGBFS mixing ratios on the characteristic of geopolymer mortars were also evaluated.

### 2. Materials and Methods

#### 2.1. Materials

The fly ash (FA) and ground granulated blast furnace slag (GGBFS) used in this study were collected from a resources corporation located in central Taiwan. The aggregate sludge (AS) was obtained from the Shang-Fu aggregate plant located in northern Taiwan. The chemical compositions of AS, FA, and GGBFS were analyzed and listed in Table 1. As shown in Table 1, the major element of AS and FA is SiO$_2$, and the GGBFS is CaO. The particle sizes of raw materials were analyzed in Table 2 and Figure 1. The particle size analysis shows the d50 (mean particle size) of AS, FA, and GGBFS are 13.17 µm, 26.70 µm, and 12.50 µm, respectively. The CNS 12223 standard was followed to analyze the chemical compositions of aggregate sludge, fly ash, and GGBFS. [26]. The XRD analyses of AS, FA, and GGBFS are shown in Figure 2. SEM morphologies are shown in Figure 3.
Table 1. The XRF chemical composition analysis of AS, FA, and GGBFS.

| Elements (wt%) | SiO$_2$ | Al$_2$O$_3$ | CaO | Fe$_2$O$_3$ | Others |
|---------------|---------|-------------|-----|------------|--------|
| AS            | 60.03   | 17.11       | 2.37| 10.89      | 9.60   |
| FA            | 67.64   | 12.58       | 4.31| 7.56       | 7.91   |
| GGBFS         | 27.56   | 10.85       | 57.62| 0.57      | 3.40   |

Table 2. The analysis of particle sizes of AS, FA, and GGBFS.

| Particle Size Distribution | d$_{10}$ (µm) | d$_{50}$ (µm) | d$_{90}$ (µm) |
|----------------------------|---------------|---------------|---------------|
| AS                         | 2.38          | 13.17         | 83.23         |
| FA                         | 6.74          | 26.70         | 93.48         |
| GGBFS                      | 4.61          | 12.50         | 53.85         |

Figure 1. Cont.
Figure 1. The particle size distribution curves of (a) Aggregate Sludge, (b) Fly Ash, and (c) Ground Granulated Blast Furnace Slag.

Figure 2. The XRD spectrum of Aggregate Sludge, Fly Ash, and Ground Granulated Blast Furnace Slag.

The 1.28 SiO$_2$/Na$_2$O molar ratios of alkali solution were prepared by mixing certain portions of Na$_2$SiO$_3$ and NaOH solutions. In order to provide sufficient Al ions for the geopolymerization process, sodium aluminate was also added into the alkali solution to have a SiO$_2$/Al$_2$O$_3$ molar ratio of 50. The parameter of the alkali solutions in this study were shown in Table 3.
Figure 1. The particle size distribution curves of (a) Aggregate Sludge, (b) Fly Ash, and (c) Ground Granulated Blast Furnace Slag.

Figure 2. The XRD spectrum of Aggregate Sludge, Fly Ash, and Ground Granulated Blast Furnace Slag.

Figure 3. The SEM morphologies of (a) Aggregate Sludge, (b) Fly Ash, and (c) Ground Granulated Blast Furnace Slag.

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2.2. Preparation of Geopolymer Mortar

There are two systems in this study, aggregate sludge-based geopolymer (AG) system and aggregate sludge/fly-ash-based geopolymer (AFG) system. The system AG was prepared by adding aggregate sludge (AS) and ground granulated blast furnace slag (GGBFS) mixtures with 80/20, 70/30, and 60/40 wt.% ratio into alkali solution with various L/S ratios (0.30, 0.40, 0.45, 0.50). The molar ratio of alkali solution is 2 M, 4 M, and 6 M. The AFG specimens were fabricated by adding AS/FA/GGBFS mixture with various wt.% ratios (80/10/10, 70/20/10, 70/10/20, 70/15/15, 60/25/15) into alkali solution (L/S ratios prepared as 0.25, 0.40, 0.50). The parameters for the preparation of AG and AFG geopolymer mortar are listed in Tables 4 and 5. After thoroughly mixing all materials for 5 min, geopolymer paste will be prepared. Geopolymer paste was cast into a \( \Phi \) 50 \times 100 mm acrylic mold. The cast geopolymer mortar specimens were then demolded after curing for 3 days at an ambient temperature. The physical and mechanical properties of the geopolymer specimens tested and shown in this study are the average value of three specimens with various curing days (3, 7, 14, and 28 days) at an ambient temperature.
Table 3. Alkali solutions condition.

| Alkali solutions | SiO$_2$/Na$_2$O Molar Ratio | SiO$_2$/Al$_2$O$_3$ Molar Ratio |
|------------------|-----------------------------|-------------------------------|
|                  | 1.28                        | 50                            |

2.2. Preparation of Geopolymer Mortar

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Table 4. The preparation parameter of AG geopolymer mortar.

| AS (wt%) | GGBFS (wt%) | NaOH Molar Ratio | SiO$_2$/Na$_2$O Molar Ratio | SiO$_2$/Al$_2$O$_3$ Molar Ratio | L/S Ratio |
|----------|-------------|------------------|-----------------------------|-------------------------------|-----------|
| 60–80    | 20–40       | 2 M–4 M          | 1.28                        | 50                            | 0.30–0.50 |

Table 5. The preparation parameter of AFG geopolymer mortar.

| AS (wt%) | FA (wt%) | GGBFS (wt%) | NaOH Molar Ratio | SiO$_2$/Na$_2$O Molar Ratio | SiO$_2$/Al$_2$O$_3$ Molar Ratio | L/S Ratio |
|----------|----------|-------------|------------------|-------------------------------|-------------------------------|-----------|
| 60–80    | 10–25    | 10–20       | 4 M              | 1.28                        | 50                            | 0.25–0.50 |

2.3. Preparation of Geopolymer Mortar

The physical properties tests of geopolymer conducted in this study include bulk density, apparent specific gravity, porosity, and water adsorption. For the standards of the experiment, CNS619/R3013 “Method of Test for Apparent Porosity, Water Absorption and Specific Gravity of Refractory Bricks” [27] was adopted to measure the bulk density, apparent specific gravity, porosity, and water adsorption of geopolymers. For the physical properties of geopolymers, the compressive strength tests were measured by CNS 1232 “Method of test for compressive strength of cylindrical concrete specimens” [28]. The compressive strength of geopolymer mortar specimens was tested after being cured at room temperature for 3 to 28 days.

3. Results and Discussion

This study deals with the influence of the ratio of AS, FA, and GGBFS, as well as the concentration of alkaline solutions on the mechanical and physical properties of AG and AFG geopolymer.

3.1. Characteristics of Geopolymer Mortar Prepared with AS and GGBFS

As shown in Table 6, AG geopolymer specimens were prepared with an AS/GGBS ratio of 80/20 and liquid (alkali solution)-solid ratios of 0.30, 0.40, and 0.50. These specimens were cured in an ambient environment for 3 to 28 days. After being cured for 7 days, the
compressive strength of specimens increased from 11.5 MPa to 24.2 MPa as liquid-solid ratios increase from 0.30 to 0.50, as shown in Figure 4. These results indicate that the higher L/S ratio provides more of the alkali solution and Si ions to promote geopolymerization. It is also obvious that the compressive strength of these specimens increases up to 20.3 MPa and 27.5 MPa after 28 days of curing. It means the longer the curing time, the more complete geopolymerization was set within the matrix of the specimens.

Table 6. The parathion parameters of AG geopolymer mortar.

| Specimens          | AS (wt%) | GGBFS (wt%) | NaOH Molar Ratio | SiO$_2$/Na$_2$O Molar Ratio | SiO$_2$/Al$_2$O$_3$ Molar Ratio | Liquid/Solid Ratio |
|--------------------|----------|-------------|------------------|-----------------------------|---------------------------------|-------------------|
| A80G20-30(4)       | 80       | 20          | 4 M              | 1.28                        | 50                              | 0.30              |
| A80G20-45(4)       |          |             |                  |                             |                                 | 0.45              |
| A80G20-50(4)       |          |             |                  |                             |                                 | 0.50              |
| A70G30-30(4)       | 70       | 30          | 4 M              | 1.28                        | 50                              | 0.30              |
| A70G30-40(4)       |          |             |                  |                             |                                 | 0.40              |
| A70G30-45(4)       |          |             |                  |                             |                                 | 0.45              |
| A70G30-45(2)       |          |             |                  |                             |                                 | 2 M               |
| A70G30-45(4)       | 70       | 30          | 4 M              | 1.28                        | 50                              | 0.45              |
| A70G30-45(6)       |          |             |                  |                             |                                 | 6 M               |
| A60G40-45(4)       | 60       | 40          | 4 M              | 1.28                        | 50                              | 0.45              |

Figure 4. Influence of L/S ration on the compressive strength of A80G20-geopolymer mortar.

3.1.1. Effect of L/S Ratio on the Compressive Strength of Geopolymer Mortar

As shown in Table 6, AG geopolymer specimens were prepared with an AS/GGBS ratio of 80/20 and liquid (alkali solution)-solid ratios of 0.30, 0.40, and 0.50. These specimens were cured in an ambient environment for 3 to 28 days. After being cured for 7 days, the compressive strength of specimens increased from 11.5 MPa to 24.2 MPa as liquid-solid ratios increase from 0.30 to 0.50, as shown in Figure 4. These results indicate that the higher L/S ratio provides more of the alkali solution and Si ions to promote geopolymerization. It is also obvious that the compressive strength of these specimens increases up to 20.3 MPa and 27.5 MPa after 28 days of curing. It means the longer the curing time, the more complete geopolymerization was set within the matrix of the specimens.

A70G30 specimens were made with 70% AS and 30% GGBFS mixtures, that is, 10% more GGBFS than A80G20 was shown in Figure 4. Figure 5 shows the compressive strength
of A70G30 geopolymers prepared by using 0.30, 0.40, and 0.45 L/S ratios, and cured for 3, 7, 14, and 28 days. After 3 days of curing, the compressive strength of specimens increased from 26.3 MPa to 33.1 MPa as the L/S ratio increases from 0.30 to 0.45. These results indicate that a higher GGBFS addition can result in early strength of geopolymer when compared with the A80G20 specimen shown in Figure 6. After specimens were cured for 28 days, their strength increased to 39.1 MPa (0.30 L/S ratio) and 43.2 MPa (0.45 L/S ratio). These test results are also in accordance with the studies conducted by Provis and Van Deventer, 2009, who concluded that a higher alkali solution addition might promote the geopolymerization reaction of GGBFS [29], and thus, increase its mechanical strength.

![Figure 5. Influence of L/S ratio on the compressive strength of A70G30-geopolymer mortar.](image)

![Figure 6. Effect of NaOH concentration on the compressive strength of AG-73 geopolymer.](image)

3.1.2. Effect of NaOH Concentration on the Compressive Strength of Geopolymer Mortar

In order to evaluate the effect of the alkali solution concentration on the mechanical strength of the geopolymer made with 70% AS and 30% GGBFS (A70G30), NaOH solutions of 2 M, 4 M, and 6 M were prepared and mixed with sodium and aluminum silicates, as shown in Table 4. After 3 days of curing, the compressive strength of specimens increased
from 22.5 MPa to 36.8 MPa as the NaOH solution concentration increased from 2 M to 6 M, as shown in Figure 6. This is believed to be because a higher NaOH concentration can lead to more Si and Al ions being dissolved from GGBFS and form more of the precursors required for geopolymerization [30]. Owing to the 6M NaOH concentration being relatively high, a large amount of geopolymer precursors can be excited quickly to carry out the reaction. However, because the reactions were conducted too fast, all the gels for subsequent structural development reacted to completion, resulting in an unsustainable increase in strength. This is probably the reason why the strength of the A70G30 specimen made with a higher NaOH concentration only increased slightly after prolonged curing.

3.1.3. AS/GGBFS Ratios on Compressive Strength of Geopolymer Mortar

The compressive strengths of geopolymers prepared with various AS and GGBFS ratios were also evaluated. This is because AS geopolymers of different mechanical strengths can find various construction applications. The compressive strengths of specimens made with 80/20, 70/30, and 60/40 AS/GGBFS ratio at 0.45 L/S ratio are shown in Figure 7. The compressive strength of specimens increases from 22.4 MPa to 61.26 MPa as GGBFS increases from 20% to 40% after 28 days of curing. The SEM morphologies of AS/GGBFS specimens are shown in Figure 8. It can be seen that the specimens incorporated with GGBFS exhibit a very dense structure. These images indicate that the GGBFS has a positive influence on producing more geopolymer gel. This is because alkaline activated GGBFS can result in the greater formation of C–S–H (Calcium Silicate Hydrate) gel. Other reaction products, such as Ettringite (calcium sulfoaluminate) and Portlandite [(Ca(OH)2] can also be found according to the study conducted by S. Kim et al. [31]. It has also been identified from the XRD spectrum of mortar pastes containing GGBFS in the Limbachiya et al. study [32].
Figure 7. Influence of AS/GGBFS ratio on the compressive strength of AG geopolymer mortar.

(a) A60G40-45(4)

(b) A70G30-45(4)

(c) A80G20-45(4)

Figure 8. SEM Images of specimens with (a) 40%, (b) 30%, and (c) 20% of GGBFS.

These results demonstrate that high GGBFS content plays the most important role in the compressive strength of geopolymer. It is obvious that high GGBFS results in higher Si and Al ion concentration in the solution for geopolymerization reaction. The same trend can also be observed in specimens prepared with 80/20 and 70/20 AS/GGBFS ratios, as well as with a 0.30 L/S ratio. After 28 days of curing, the compressive strengths of A80G20...
made with 0.30 and 0.45 L/S ratios are 20.3 MPa and 22.4 MPa, respectively. However, the A70G30 specimen can reach a much higher strength at 39.2 MPa. This indicates that GGBFS has a higher contribution to the strength of the AG geopolymer than that of the L/S ratio. This is because the composition of GGBFS is mainly CaO, SiO₂, and Al₂O₃. These chemical compositions are very similar to Portland cement with hydration characteristics. The high calcium content of GGBFS can also promote the cementation process during geopolymerization and increase the Al-O-Si bonding structures [33].

The FTIR spectrum of geopolymer specimen made with 70% AS and 30% GGBFS but with different NaOH concentrations (2 M, 4 M, and 6 M) are shown in Figure 9. These three spectrums all exhibit S-O-T and Si-O/Al-O peaks but different intensities. It also shows that specimens made with higher NaOH concentrations display higher intensity due to more gel being formed in the geopolymer matrix. According to the studies conducted by P. Innocenzi et al. and C. A. Reesm et al., the band in the range of 700 cm⁻¹ to 800 cm⁻¹ might correspond to the Si-O/Al-O bonds that exist in the geopolymer structure [34,35]. D. D. B. Nergis et al. and S. A. Khan et al. and Shadab Ali Khan et al. claim that the bands between 950–1100 cm⁻¹ represent Si-O-T bonds. The bands between 1150–1250 cm⁻¹ can be associated with the specific rhythmic band along the covalent bond axis, which is known as the stretching vibration of the Si-O-Si groups [36,37]. This FTIR analysis results can verify the specimen of higher peak intensity (6 M NaOH) also have higher compressive strength than those made with lower NaOH concentration.

![Figure 9. FTIR spectrum of AG geopolymer mortar after 28 days of curing.](image-url)
3.1.4. Physical Properties of AS/GGBFS Geopolymer Mortar

The influence of NaOH solution concentration on the physical properties was also studied for the geopolymer prepared with 70% AS and 30% GGBFS. As shown in Table 7, the bulk densities of all specimens are in the ranges of 1.35 to 1.38 after being cured for 3 to 28 days. It seems the concentration of NaOH solution does not affect the bulk density of the specimens. For specimens prepared with 4 M NaOH solution, their apparent sp. gr. slightly decreases from 2.28 to 2.24 after 28 days of curing. It is more obvious that the apparent sp. gr. of 6 M specimen reduced from 2.28 to 2.20. This is probably due to the water in the geopolymer matrix escaping after prolonged curing in the ambient environment. The porosity of the AG specimens also decreases as the curing days increase from 3 to 28 days. It was also found that the specimens made with higher NaOH concentrations have lower porosity. This is believed to be due to the higher NaOH concentration producing more gel to form the geopolymer matrix and leaving fewer pores in the specimen. Referring to Figure 6, the compressive strength of AG specimens increases from 22.5 MPa to 43.6 MPa as their porosity decreases from 38% to 31%. The water absorption results are also in accordance with the porosity of the AG specimens, that is, the higher the porosity the higher the water absorption.

Table 7. The physical properties of AG geopolymers.

| Specimens  | Curing Time (Days) | Bulk Density (g/cm$^3$) | Apparent Specific Gravity | Porosity (%) | Water Absorption (%) |
|------------|-------------------|------------------------|--------------------------|--------------|---------------------|
| A70G30-45(2) | 3                 | 1.35                   | 2.30                     | 38           | 31                  |
|            | 7                 | 1.35                   | 2.29                     | 36           | 31                  |
|            | 14                | 1.38                   | 2.29                     | 36           | 29                  |
|            | 28                | 1.37                   | 2.30                     | 35           | 28                  |
| A70G30-45(4) | 3                 | 1.36                   | 2.28                     | 36           | 29                  |
|            | 7                 | 1.38                   | 2.25                     | 36           | 28                  |
|            | 14                | 1.37                   | 2.25                     | 34           | 27                  |
|            | 28                | 1.36                   | 2.24                     | 31           | 26                  |
| A70G30-45(6) | 3                 | 1.36                   | 2.28                     | 35           | 29                  |
|            | 7                 | 1.36                   | 2.22                     | 33           | 27                  |
|            | 14                | 1.35                   | 2.22                     | 32           | 27                  |
|            | 28                | 1.36                   | 2.20                     | 32           | 27                  |

3.2. Characteristics of Geopolymer Mortar Prepared with AS, GGBFS and FA

Many studies have been conducted on coal-fly-ash-based geopolymers wherein sodium silicate was utilized in the activating solution [38,39]. Hardjito et al. also indicated that low-calcium FA-based geopolymer concrete has excellent mechanical properties and acid resistance [21]. Fly ash was also used to replace part of GGBFS for the preparation of the AS geopolymer in this study. The AS/FA/GGBFS mixtures were 80/10/10, 70/10/20, 70/15/15, 70/20/10, and 60/25/15 as shown in Table 8.

Table 8. The preparation parameters of AFG geopolymer mortar.

| Specimens  | AS (wt%) | FA (wt%) | GGBFS (wt%) | SiO$_2$/Na$_2$O Molar Ratio | SiO$_2$/Al$_2$O$_3$ Molar Ratio | L/S Ratio | NaOH Molar Ratio |
|------------|----------|----------|-------------|-----------------------------|-------------------------------|-----------|------------------|
| A70F10G20  | 70       | 10       | 20          |                             | 1.28                          | 50        | 0.40             |
| A70F15G15  | 70       | 15       | 15          |                             |                               |           |                  |
| A70F20G10  | 70       | 20       | 10          |                             |                               |           |                  |
| A80F10G10  | 80       | 10       | 10          |                             |                               |           |                  |
| A70F15G15  | 70       | 15       | 15          |                             |                               |           |                  |
| A60F25G15  | 60       | 25       | 15          |                             |                               |           |                  |
3.2.1. Effect of FA/GGBFS Ratios on the Compressive Strength of Geopolymer Mortar

Figure 10 shows the compressive strength of specimens prepared with 70% AS but replacing GGBFS with fly ash at 10%, 15%, and 25%. After 3 days of curing, the compressive strength of specimens prepared decreased from 12.8 MPa to 8.7 MPa as the fly ash in the mixtures increased from 10% to 20%. With 10% fly ash replacement, the strength of the specimen can reach 41.3 MPa after 14 days of curing but only slightly increase to 43.3 MPa after 28 days curing. For specimens prepared with 15% and 20% fly ash replacement, they have very similar strengths measured as curing days increase from 3 to 28. The SEM morphologies of specimen content with 70% sludge are shown in Figure 11. It can be clearly observed that more unreacted fly ash particles are found in Figure 11a, that is, the specimen made with a 20/10 FA/GGBFS ratio. In Figure 11b,c, a more dense geopolymer matrix can be seen than that observed in Figure 11a. This is believed to be due to the increase of GGBFS in the FA/GGBFS ratio. These SEM morphologies can also support the compressive strength test results shown in Figure 10.

![Figure 10. Effects of FA/GGBF ratios on the compressive strength of AFG geopolymer mortar.](image)

![Figure 11. Cont.](image)
Figure 11. SEM Images of specimens with (a) FA20% GGBFS10%, (b) FA15% GGBFS15%, and (c) FA10% GGBFS20%.

By comparing the strengths of A70G30 shown in Figure 5, specimens with 15% and 25% fly ash replacement are about 30 MPa, which is 10 MPa lower than specimens made without fly ash replacement.

The effect of the amount of AS addition on the characteristics of specimens was evaluated as shown in Figure 12, the compressive strength of geopolymer specimens increased as the AS in the mixtures was reduced from 80% to 60% at 3 to 28 days of curing. This is because the AS in mixtures cannot be activated by the alkali solution but only presented as a filler and was solidified by the activated FA and GGBFS solution. However, all specimens have compressive strengths higher than 26 MPa after 28 days of curing. It was also observed that the compressive strength of specimens made with 60% AS content was only slightly higher than specimens made with 70% AS content with 7 to 28 days of curing. These results show that the compressive strength of a geopolymer cannot be greatly improved by increasing FA content from 15% to 25%. According to a study conducted by Walkley et al., high Si but low Al content amorphous material, such as fly ash, may not greatly increase the strength of a geopolymer. This is because insufficient Al ions cannot form enough Si-O-Al structures but a large portion of Si-O-Si structures after the Si precursors were formed [40]. After 28 days of curing, the strengths of A70F15G15 and A60F25G15 specimens were about 8 MPa higher than that of A80F10G10. This is probably
due to the hydration characteristic of the high CaO content in the GGBFS that may promote the cementation process during geopolymerization as discussed earlier.

Figure 12. Effects of AS/FA ratio on the compressive strength of AFG geopolymer mortar.

3.2.2. Physical Properties of AS/GGBFS/FA Geopolymer Mortar

Table 9 shows the physical properties of AFG specimens prepared with 70% AS but with various fly ash and GGBFS ratios as listed in Table 6. The bulk density of all specimens tested was in the range of 1.34 to 1.39 and the apparent sp. gr. was in the ranges of 2.20 to 2.24. These results indicate that the fly ash and GGBFS ratios have no obvious influence on the specimens’ bulk density and, sp. gr. For porosity measurement, a higher FA/GGBFS ratio (20/10) generally leads to a higher porosity than those made with lower FA/GGBFS ratios (15/15 and 10/20). This result can be attributed to the higher GGBFS content having a better cementation effect during the geopolymerization reaction. The lower porosity and water absorption of AFG specimens also demonstrate higher compressive strength as shown in Figure 12.

Table 9. The physical properties of AFG geopolymers.

| Specimens    | Curing Time (Days) | Bulk Density (g/cm³) | Apparent Specific Gravity | Porosity (%) | Water Absorption (%) |
|--------------|--------------------|----------------------|---------------------------|--------------|----------------------|
| A70F20G10    | 3                  | 1.36                 | 2.22                      | 38           | 31                   |
|              | 7                  | 1.36                 | 2.24                      | 36           | 31                   |
|              | 14                 | 1.39                 | 2.23                      | 36           | 29                   |
|              | 28                 | 1.36                 | 2.20                      | 35           | 28                   |
| A70F15G15    | 3                  | 1.37                 | 2.24                      | 35           | 29                   |
|              | 7                  | 1.37                 | 2.22                      | 33           | 27                   |
|              | 14                 | 1.39                 | 2.23                      | 32           | 27                   |
|              | 28                 | 1.36                 | 2.23                      | 32           | 27                   |
| A70F10G20    | 3                  | 1.37                 | 2.24                      | 34           | 29                   |
|              | 7                  | 1.34                 | 2.23                      | 32           | 28                   |
|              | 14                 | 1.39                 | 2.23                      | 31           | 27                   |
|              | 28                 | 1.35                 | 2.23                      | 31           | 26                   |
4. Conclusions

From the test results and analysis of this study, aggregate sludge can be used as raw material for the preparation of GGBFS and fly-ash-activated geopolymers. Through the geopolymer process, aggregate sludge can be recycled and the disposal problem can be solved.

The compressive strength of geopolymer specimens (70/30 AS GGBFS ratios) made with 4 M and 6 M NaOH concentrations can reach 39.17 MPa and 43.6 MPa after 28 days of curing. For (60/40 AS GGBFS ratio) geopolymers, compressive strength can reach 61.3 MPa. It was found that GGBFS has the most influential effect on the strength of geopolymers followed by the concentration of NaOH.

For specimens (70% AS) prepared with various GGBFS and fly ash ratios, the compressive strength of the specimens decreases from 42.3 MPa to 31.7 MPa as the fly ash increases from 10 to 20%, that is, 10/20 and 20/10 FA/GGBFS ratios. It was also observed that the strength of specimens cannot be further increased by increasing fly ash to 25% because of there being insufficient Al ions to form the Si-O-Al structure.

According to the test results, geopolymer can be prepared with various AS, fly ash, and GGBFS ratios and activated by 2 M, 4 M, and 6 M NaOH solutions. The geopolymers prepared have compressive strengths between 30 MPa and 60 MPa that can be used for a variety of construction applications in the future.

Author Contributions: Conceptualization, Y.-C.D. and Y.-C.C.; Methodology, W.-H.L.; Validation, Y.-C.C.; Formal analysis, Y.-C.C.; Investigation, Y.-C.C.; Writing—Review & Editing, W.-H.L.; Writing—Review & Editing, Y.-C.D.; Supervision, W.-H.L.; Resources, Y.-C.D. and W.-H.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare that they have no competing interests.

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