

Article

Analysis of Rheological Characteristic Studies of Fly-Ash-Based Geopolymer Concrete

Kiran Kumar Poloju ¹, Shalini Annadurai ², Ram Kishore Manchiryal ¹, Mallikarjuna Rao Goriparthi ³, Prabu Baskar ², Mayakrishnan Prabakaran ^{4,*} and Jongpil Kim ^{4,*}

¹ Department of Civil Engineering, Middle East College, Muscat 124, Oman

² Department of Civil Engineering, Sona College of Technology, Salem 636005, India

³ Department of Civil Engineering, Vardhaman College of Engineering, Hyderabad 501218, India

⁴ Department of Chemistry, Dongguk University, Seoul 04620, Republic of Korea

* Correspondence: prabakarannitt@gmail.com or prabakaran@dongguk.edu (M.P.); jpkim153@dongguk.edu (J.K.)

Abstract: Concrete is a versatile construction material used along with a reinforcement. Concrete is made up of binder materials and aggregates. Cement is a primary binder material used to produce conventional concrete. Carbon dioxide emissions in the atmosphere are a symptom of the issue related to Portland cement manufacture. It is estimated that one ton of cement produced releases an equal amount CO₂ into atmosphere. On other hand, many industrial wastes are dumped in open spaces, leading to land pollution. Researchers have developed a construction material known as geopolymer concrete that uses industrial waste materials as a binder material to address these two issues. Excellent mechanical and durability characteristics are displayed by geopolymer concrete. For the creation of geopolymer concrete, fly ash is employed as a binder material. The drawback of utilizing fly ash is the curing method. Due to increased setting time, concrete samples require either heat curing or oven-curing. Geopolymer paste preparation is based on the type of binder materials used. In this study, GGBS is partially added with fly ash to cure specimens in ambient temperature due to presence of a higher amount calcium in GGBS. The present study investigates the consistency of geopolymer pastes, their workability, and the compressive strength of cement mortars by varying the amount of binder content (360 kg/m³ & 400 kg/m³). The molarity of NaOH was varied from 8 to 12. The ratio between binder material and alkaline to binder ratio were 0.45 and 0.50, respectively. The specimens were cured in both ambient and oven temperatures to study their strength development caused by temperature. A total of 396 specimens were cast to study the behavior of geopolymer concrete made with fly ash and GGBS (FAG). The test results revealed that the substitution of 50% GGBS with fly ash exhibited better strength properties during curing. Additionally, by increasing the binder content to 400 kg/m³, the results of 80% GGBS and 20% fly ash revealed excellent consistency among all other mixes. The oven-cured specimens showed more strength compared to specimens cured in ambient temperature, but the ambient cured specimens (ACS) attained the required strength. It was also not practically possible to cure the structural members by oven-curing in the field. The mix with 80% of GGBS and 20% fly ash can be used for construction. The required strength can also be achieved by increasing the molarity ratio.

Keywords: normal consistency; geopolymer mortar; geopolymer concrete; fly ash; GGBS; scanning electron microscope; X-ray diffraction



Citation: Poloju, K.K.; Annadurai, S.; Manchiryal, R.K.; Goriparthi, M.R.; Baskar, P.; Prabakaran, M.; Kim, J. Analysis of Rheological Characteristic Studies of Fly-Ash-Based Geopolymer Concrete. *Buildings* **2023**, *13*, 811. <https://doi.org/10.3390/buildings13030811>

Academic Editor: Jianguang Fang

Received: 15 February 2023

Revised: 16 March 2023

Accepted: 18 March 2023

Published: 20 March 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Conventional concrete comprises binding material, water, and fine and coarse aggregates [1]. Moreover, cement emits carbon dioxide, which accounts for 8% of worldwide emissions of greenhouse gases. It is known that more cement will be required for construction. Presently, 3% of the required cement is produced each year. New technology can

mitigate the adverse effects of the cement trade [2–4]. In a search for new technologies, ceramic powder made from calcium-rich ceramic tiles has more enhanced properties than conventional concrete [5], but concrete that has been stretched is weaker than concrete that has been compressed. Therefore, fibers should be added to strengthen concrete [6]. Measuring fire resistance at various temperatures is crucial in determining the resistance of concrete [7]. Ensuring the longevity of concrete and keeping it eco-friendly is essential when searching for an alternative that can replace cement. Using raw materials such as GGBS and FA as sources, geopolymer concrete is constructed entirely of cement replacement. Materials are brought to life and bound by an activator solution [8]. In many countries, geopolymer concrete has replaced conventional concrete as it is more environmentally friendly than OPC.

In 1970, Joseph Davidovits developed geopolymer to detect silica and alumina waste chemicals using alkaline water. By substituting FAG for cement in GPC, CO₂ emissions were reduced, and so it contributes to environmental protection [9,10]. Loose particles make up GPC, which, when combined with geopolymer, creates a strong, acid-resistant substance. GGBS is obtained from the steel industry and contains calcium, magnesium, aluminum, and silicon oxides [11]. At the same time, fly ash from power plants contains silicon, calcium, aluminum, and iron. Despite the fact that there are two different types of fly ash. Class F fly ash, which has less calcium, is used in this investigation. The hydration process of GPC is similar to that of OPC [12]. However, water does not activate the silica and alumina binders in geopolymer concrete. Therefore, as an alternative to water, an alkaline solution is used to activate GGBS and fly ash to form a paste that quickly sets and becomes complex, similar to cement paste. NaOH is combined with Na₂SiO₃ to manufacture an alkaline activator solution. The solution is used in accordance with the sodium hydroxide (NaOH) content and its molarity (M), which ranges from 6 to 18 [13].

Na₂SiO₃/NaOH ratio, curing period and molarity influence geopolymer concrete's properties [14–16]. Geopolymer is a concrete binder that is strong, long-lasting, inexpensive, and environmentally friendly. Fly ash contains silicon and aluminum, which dissolve faster and add weight. Fly ash can be replaced by GGBS to increase both strength and the rate of polymerization [17]. To begin with, it is necessary to understand the term “geopolymers”, coined in 1978 by a Frenchman to describe mineral-based binders. GPC power gel contains silicon dioxide and alumina that have been alkali-solved. Fly ash, metakaoline, and GGBS are used in geopolymer concrete constructed of high Ca and low-calcium fly ash, along with slag that has been alkaline-activated [18–20]. The sodium silicate is added (0, 1, 1.5, 2, and 2.5) for 24 h in a sodium hydroxide solution to form the alkaline activator. Due to their homogeneity, the less porous matrix has a higher compressive strength due to having a ratio between sodium and silicate of 1 [21]. FAG alters alkaline activator mixtures [22]. Curing temperature, silicate modulus (0, 1, and 1.5), and the Na₂O concentration (6 and 8%) all affect the strength of geopolymer mortar cubes. GGBS has a higher Na₂O content than fly ash. Similar to this, geopolymer concrete's strength qualities are improved by nano-silica [23,24]. As concrete glue, geopolymer can be used in place of cement. Si and Al were excellent forerunners [25]. In their research, fly ash was an excellent base material for GPC but required 24 h at 60 °C to harden, making it difficult to use on construction sites. Hence, the development of geopolymers with different mineral binders with similar chemical properties [26]. The Si and Al in geopolymer gel are strengthened by alkaline solutions. Fly ash-based GPCs are cured for 24 to 48 h at 40 to 70 °C for early polymerization [27]. Geopolymer concrete possess excellent properties against acid resistance [28]. At heat changes from 30 °C to 60 °C and also 90 °C, normal consistency and setting times from 8 to 16M and strength proportions of 1, 2, 3, and 4 revealed good workability properties [29]. When the sodium hydroxide (NaOH) concentration was raised, setting time was reduced. This showed the temperature affected the initial as well as final setting property. However, higher temperatures accelerated the setting process.

Geopolymer concrete made with 8M, 12M, and 16M for 1440 min at room temperature and at 60 °C in oven-curing showed that GGBS shortened the time required for setting

due to oven-curing [30]. However, ambient curing can also help with strength improvement. Geopolymer concrete cured between 40 °C and 70 °C temperature showed excellent strength properties [31]. Therefore, after evaluating various studies, this study looks into the peculiarities of geopolymer mortar and demonstrates how collecting and utilizing carbon emissions in novel ways can produce astounding results. The literature reveals that fly ash may work well as a GPC base material. Processing fly ash reduces greenhouse gas emissions by 80% to 90%, and it is also both cost-effective and environmentally friendly as it treats waste and emits few greenhouse gases [32,33]. Researchers investigated geopolymer concrete with various molarities and GGBS substitutions and found that increased GGBS improved the mechanical properties of GPC, but studies on 100% replacement are scarce. It becomes difficult to use when the alkaline-to-binder ratio decreases. The implications of this research effort are examined in this paper. Additional research is needed to treat GGBS conditions. Three molarities were tested (8M, 10M, and 12M), with a Na_2SiO_3 : NaOH ratio of 1.0, and five GPC mixes. Five combinations replaced the slag percentage from fly ash (0%, 30%, 60%, 90%, and 100%). The strongest concentration was 12M sodium hydroxide, as a higher amount quickened the polymerization process by dissolving FAG particles [34,35]. This was why geopolymer concrete was weaker at low molarity and stronger at high molarity. Compressive strength was tried with various GPC grades in ambient curing as heat curing caused practical issues [36]. In contrast to most studies, they used fly ash with cement-like properties. Each grade tested four different molarity combinations to see how the grades were affected. Compressive strength increases with increasing NaOH molar content.

Curing temperature influences geopolymer strength. It is an excellent concrete binder as it is strong and long-lasting and can be used in various molarities, curing conditions, and GGBS concentrations without changing. As alkaline activator sources are cheap and easy to find, they are perfect for making geopolymer concrete. GGBS has a higher pozzalonic content than fly ash. A few studies on thermo gravimetric analysis (TGA) results were attained and described how geopolymer materials lose mass when heated up to 1000 °C higher [37]. Due to free water evaporating, a sharp decrease in mass was noticed before 200 °C. Mass loss at temperatures above 200 °C was attributed to the dehydroxylation of chemically bonded water. Fly-ash-cement-based GC's DTA curve did not exhibit proper thermal resistance for temperatures above 600 °C, according to the TGA/DTA research. The DTA curve showed a mass loss of 15–18% for blends that were ambient-cured. Likewise, weight loss in oven-cured fly ash-cement-based GC specimens was 12–13%. There are various studies performed on geopolymer concrete prepared with fly ash. However, only a small number of experiments were conducted to examine how well geopolymer concrete performed in addition to GGBS with fly ash under various curing conditions by altering the binder concentration. The present research aims to investigate the performance of geopolymer concrete in ambient- and heat-curing conditions. This study used sodium hydroxide in different concentrations (molarities) other than 8, 10, and 12. The workability, consistency, and strength properties were studied by varying the binder content with respect to different percentages of FAG.

2. Experimental Study

2.1. Materials

GGBS and fly ash (FA) procured locally were used as binder materials. The calcined materials had specific gravity values of 2.9 and 2.2. The exact chemical proportions, on the other hand, are listed in Table 1, which shows that fly ash is rich in Al_2O_3 and SiO_2 content, but GGBS has a higher amount of calcium content which enhances the setting and strength properties.

To enhance the strength, structure, and performance of GPC, a fine powdered substance called fly ash was used as a required ingredient. The workability was increased by using a super plasticizer based on sulfated naphthalene formaldehyde [38]. This chemical was produced during the burning of pulverized coal at electricity generating plants. As a result, as coal burns, mineral impurities such as shale, quartz, and clay float out of the

burning chamber with the exhaust fumes. When pulverized coal is burned, a finely divided residue known as fly ash is created, which exhaust gases carry out of the combustion chamber. Given its cementitious qualities, GGBS is utilized in concrete. The micro characterization of FAG was analyzed using SEM, as shown in Figures 1 and 2. The SEM pictures provide for a general estimation of fly ash's form, angularity, size, and surface roughness. Straight, elongated and flaky, with sharp edges, rough surfaces, and a range of sizes, GGBS particles are also elongated and flaky. The tiniest FA particles, which are one to ten microns in size and correspond to a tenth of the largest FA particle, are available.

Table 1. GGBS and FA: Chemical Composition.

| Chemical Composition | GGBS | Fly Ash |
|--------------------------------|-------|---------|
| Fe ₂ O ₃ | 0.82 | 4.31 |
| Al ₂ O ₃ | 20.23 | 26.49 |
| SiO ₂ | 33.90 | 59.90 |
| SO ₃ | 0.89 | 0.37 |
| Na ₂ O | Nil | 0.24 |
| MgO | 7.91 | 1.26 |
| CaO | 32.36 | 4.13 |

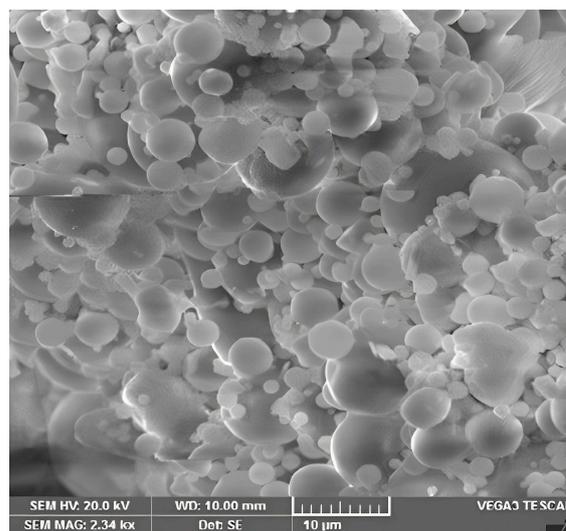


Figure 1. Picture shows fly ash SEM image.

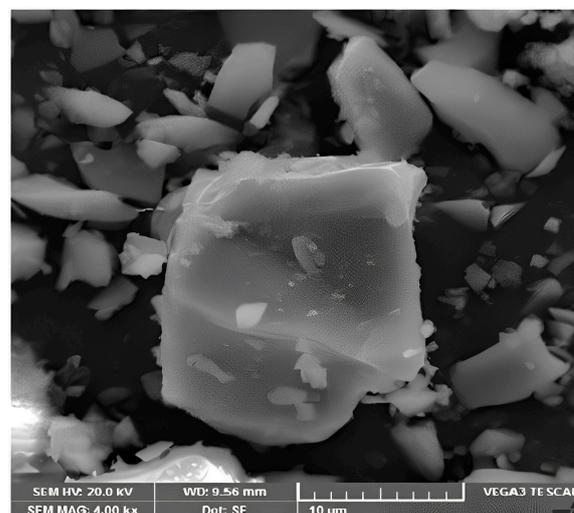


Figure 2. Picture shows GGBS SEM image.

The mineralogy of materials was investigated by the authors using the X-ray diffraction (XRD) technology to explain their properties [39]. Powder diffractometers with Bragg–Brentano geometry and the previously mentioned radiation parameters of 30 mA, 40 KV, and CuK were used to collect the XRD data. The XRD scans were from 10 to 90 degrees in stages of 0.05 degrees at a rate of one degree per minute. The XRD had a wavelength of 0.154 nanometers. Figures 3 and 4 show the fly ash XRD patterns and GGBS, respectively. To make it easier to understand, the XRD pattern of unprocessed fly ash is shown in observations with just one letter. The mullite and quartz (SiO_2) crystalline phases were visible in the diffractogram. There are ring lines with 26-degree peaks in the crystalline fly ash. GGBS is composed of crystalline silica and alumina and has a more amorphous XRD pattern than the crystalline phases of fly ash. Its temperature range is between 20 and 40 degrees, and it has a diffuse band with a broad spectrum and a reactivity of 2.

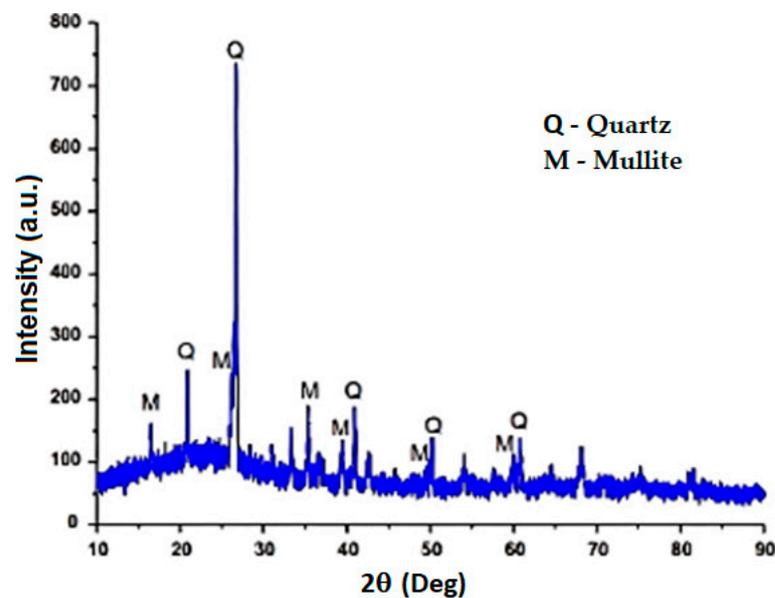


Figure 3. Fly ash XRD pattern.

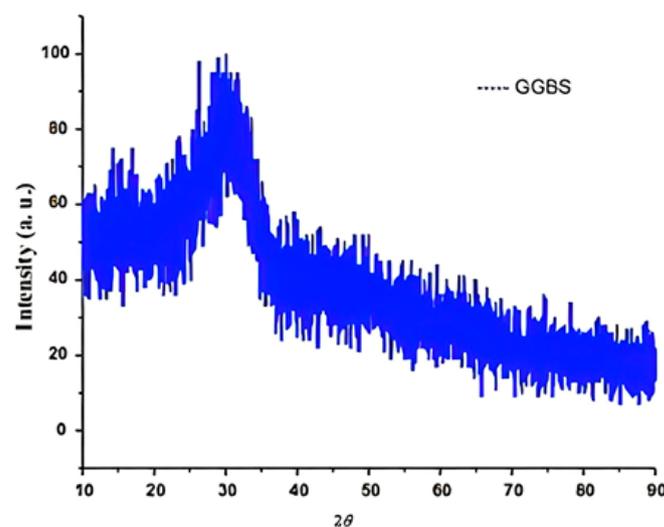


Figure 4. GGBS XRD pattern.

Fine aggregate that met Zone-2 requirements according to BIS 383-1970 was used. Locally supplied fine aggregate was used. The necessary quantities of each size fraction were combined to produce Zone-2 sand, as presented in Table 2, and physical properties,

as presented in Table 3. The fineness modulus of FA from Table 3 reveals that particle sizes fall under the category of fine sand.

Table 2. Ratios of various sand fraction sizes conforming Zone II.

| Sieve Size (mm) | % Passing Recommended by IS 383 | Adopted Grading | % Weight Retained | Cumulative % Weight Retained | Weight Retained in Grams |
|-----------------|---------------------------------|-----------------|-------------------|------------------------------|--------------------------|
| 10–4.75 | 100 | 100 | - | - | - |
| 4.75–2.36 | 90–100 | 100 | - | - | - |
| 2.36–1.18 | 75–100 | 90 | 10 | 10 | 100 |
| 1.18–0.60 | 55–90 | 65 | 25 | 35 | 250 |
| 0.60–0.30 | 35–59 | 40 | 25 | 60 | 250 |
| 0.30–0.15 | 8–30 | 10 | 30 | 90 | 300 |
| 0.15 | 0–10 | 0 | 10 | 100 | 100 |

Table 3. Fine aggregate physical properties.

| Property | Value |
|------------------|------------|
| Fineness modulus | 2.59 |
| Bulk density | 1.45 gm/cc |
| Specific gravity | 2.65 |

Crushed stone with an average size of 20 mm from a nearby crushing plant was used as the coarse aggregate. In this experiment, 20 mm well-graded aggregate following IS 383 was used. The proportions of each size fraction that must be blended were determined by the dimensions of the sieve set used to remove the coarser aggregate from the mines, as illustrated in Table 4. Table 5 displays the physical characteristics of coarse aggregate. Although the CA, fineness modulus was 6.9, it fell within the acceptable range (6.0–6.9) for aggregates with a 20 mm size.

Table 4. Proportions of different size fractions of CA.

| Size of Sieve (mm) | Retained Weight (%) | Weight Retained Cumulative % | Passing Weight (%) | Graded Aggregate % Weight Passing (IS 383) |
|--------------------|---------------------|------------------------------|--------------------|--|
| 80 | 0 | 0 | 100 | - |
| 40 | 0 | 0 | 100 | 100 |
| 20 | 0 | 0 | 100 | 95–100 |
| 10 | 70 | 70 | 30 | 25–55 |
| 4.75 | 30 | 100 | 0 | 0–10 |

Table 5. Coarse aggregate physical properties.

| Property | Bulk Density | Fineness Modulus | Specific Gravity |
|----------|--------------|------------------|------------------|
| Value | 1.5 gm/cc | 6.9 | 2.80 |

2.2. Alkaline Activator Solution (AAS) and Geopolymer Paste Preparation

The potency of the GPC solution was governed by the NaOH content. The nominal molarity range for GGBS and fly ash combinations is 2 to 10 M. A larger concentration of sodium hydroxide is produced by high strength. Geopolymer samples were produced for 8 to 12 M of NaOH. The material properties were studied using geopolymer concrete and 8M sodium hydroxide. One liter of potable water contains 0.320 kg of sodium hydroxide pellets dissolved. Before casting, for 1 day the Na_2SiO_3 was mixed 2.5 times with sodium hydroxide and stored at temperature (room condition) (26 ± 2 °C) with 65% relative humidity (RH). Sodium silicate solution was combined with 2.5 times the weight of the NaOH solution. Figure 5 shows the mix of normal consistency.



Figure 5. Geopolymer paste preparation for normal consistency test.

Dry resources, such as FAG ash, were blended in pan mixers in different amounts. The mixture was mixed with the alkaline solution for 3 minutes to achieve homogeneity. Next, various geopolymer pastes with variable quantities of alkaline activators were prepared using different percentages of source material (sodium hydroxide).

2.3. Preparing and Curing Specimens

The ingredients were measured in a weighing machine and combined in a 100 kg revolving drum pan mixer. After thoroughly blending the dry components, the alkaline activator solution and super plasticizer were added. Continuous mixing, on the other hand, provided uniform mixing for 5 to 7 min for the GPC to be workable. The table vibration procedure was employed for 45 s when the newly mixed concrete was placed in concrete molds of 150 mm cubic dimension followed by one-day settling. The specimens were demolded and completely cured. The cured samples were left out in the open (room temperature of 25 ± 2 °C and relative humidity of 65%). During the hot air micro oven-curing procedure, the demolded samples were maintained at 60 °C for 1 day. Samples were taken out from the oven the following day and allowed to cool for the required amount of time (7 or 28 days).

To establish the normal consistency of the source material, 99 samples were made with 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100% substitution of GGBS in fly ash for 8M, 10M, and 12M. Another 99 samples were made with 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100% substitution of GGBS in fly ash for 8M, 10M, and 12M, to examine the setting property. In total, 198 samples were made with 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100% replacement of GGBS in FA for 8M, 10M, and 12M under both oven- and room-curing and were cast to measure the strength (compressive) of mortar. Table 6 presents the mix quantity details of geopolymer concrete.

Table 6. Detailed mix proportion to cast specimens in kg/m³.

| Mix | Mix 1 100:0 | Mix 2 90:10 | Mix 3 80:20 | Mix 4 70:30 | Mix 5 60:40 | Mix 6 50:50 | Mix 7 40:60 | Mix 8 30:70 | Mix 9 20:80 | Mix 10 10:90 | Mix 11 0:100 |
|----------------------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|-----------------|-----------------|
| Fly ash | 880 | 792 | 704 | 616 | 528 | 440 | 352 | 264 | 176 | 88 | 0 |
| GGBS | 0 | 88 | 176 | 264 | 352 | 440 | 528 | 616 | 704 | 792 | 880 |
| Fine agg. | | | | | | 880 | | | | | |
| NaOH | | | | | | 125.71 | | | | | |
| Na ₂ SiO ₃ | | | | | | 314.29 | | | | | |
| Alkaline liquid | | | | | | 440 | | | | | |
| SS/SH ratio * | | | | | | 2.5 | | | | | |

* SS/SH—sodium silicate/sodium hydroxide.

3. The Findings and Discussion

3.1. Geopolymer Paste Consistency

Table 7 presents the consistency for various amounts of replacement of the original content. According to the findings, there was an increase in average consistency values for a few mixes with an increase in GGBS concentration. Fly ash-containing geopolymer paste needed less alkaline content than the GGBS-containing paste to achieve better consistency. The addition of GGBS to intermediate mixes improved standard uniformity. As fly ash had less internal friction due to its spherical form, Vicat's plunger operated at a lower alkaline activator level. As the surfaces of GGBS particles were elongated, straight, flaky, and sharp, they had more internal friction than fly ash particles, which required a large volume of solution to attain uniformity. When mixed with fly ash at 80%, GGBS had a consistency of 37%.

Table 7. Results of normal consistency.

| Binder Material | | Normal Consistency (%) | | | |
|-----------------|------|------------------------|-----|-----|--|
| Fly Ash | GGBS | 8M | 10M | 12M | |
| 100 | 0 | 28 | 28 | 27 | |
| 90 | 10 | 27 | 27 | 28 | |
| 80 | 20 | 31 | 30 | 31 | |
| 70 | 30 | 33 | 31 | 32 | |
| 60 | 40 | 33 | 33 | 32 | |
| 50 | 50 | 33 | 33 | 33 | |
| 40 | 60 | 33 | 33 | 35 | |
| 30 | 70 | 33 | 35 | 38 | |
| 20 | 80 | 37 | 37 | 39 | |
| 10 | 90 | 37 | 37 | 39 | |
| 0 | 100 | 37 | 37 | 39 | |

The most substantial concentration was 12M sodium hydroxide as the higher amount of sodium hydroxide quickened the polymerization process by dissolving the FAG particles. This might be one of the reasons for the changing consistency values. Moreover, GGBS particles had a sharp and elongated flaky morphology, resulting in substantially more internal friction than that of the fly ash particles. As a result, a strongly alkaline solution was required to attain the requisite normal consistency. Similarly, 100% fly ash needed minimum alkaline activator solution to obtain the same 28 percent consistency as that manufactured with 100 percent GGBS because fly ash particles needed less solution. Further, the normal consistency increased when the GGBS level increased [40]. Typical viscosity rose from 28 to 33 percent when 70 percent fly ash and 30 percent GGBS were used (cement usually has a consistency between 28 and 32 percent). The viscous nature of the alkaline activator solution was substantially more than that of water, distinguishing it from cement paste. Therefore, geopolymer concrete cannot be utilized in its green condition unless mixed with an alkaline solution. Furthermore, enhancing the level of NaOH does not affect consistency. As a result, increasing GGBS leads to higher than normal consistency.

3.2. Final Setting Time

Figure 6 shows how variations in sodium hydroxide concentration (8M, 10M, and 12M) and GGBS proportions in fly ash were utilized to evaluate the setting behavior of geopolymer. Use of a sodium concentration of 12M quickens polymerization due to dissolving both FAG particles. These findings pertain to the ultimate setting times of geopolymer pastes composed of different GGBS and fly ash. The mix's maximum setting time changed as sodium hydroxide's molarity varied with FAG [41]. The alumina content had an extensive influence of geopolymer concrete's setting time. Earlier studies mentioned that the setting property of the mix was lower when the alumina concentration increased. As a result, GGBS mixed with FA might be suggested to achieve the setting time required. The standard consistency of 28% with 100% fly ash led to an estimated setting time of 0.85P

($0.85 \times 28 = 23.8\%$). Similarly, the AA used to compute the setting time behavior of 100% GGBS-based paste was 0.85P ($0.85 \times 37 = 31.45\%$). The reactive process of FA was lower than that of GGBS, indicating more reactive molecules. Fly ash was slow to develop and gain strength due to its poor reactivity. Fly ash frequently does not dissolve entirely before hardening [40]. Mullite in fly ash did not react after alkali activation of ash/slag blends, although calcium appeared to be active. Fly ash took longer to set than GGBS when used with a solution. From the findings, GGBS was a better raw material source for geopolymer materials with high early strength than fly ash.

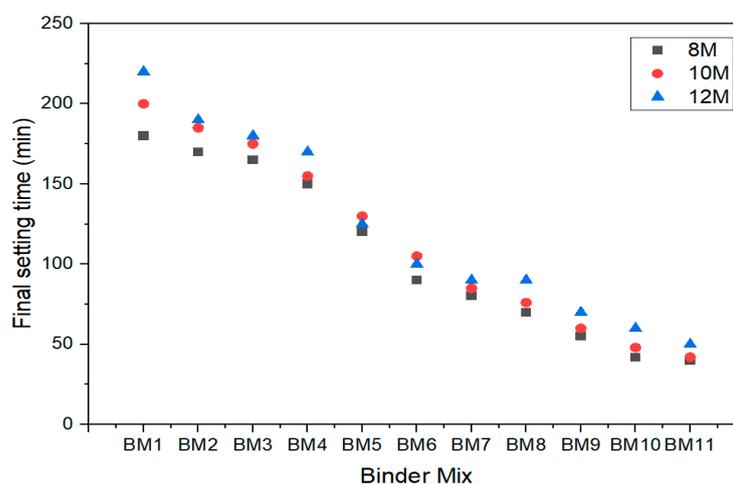


Figure 6. Final setting time of paste.

When GGBS was substituted by 20%, the setup time dropped from 200 to 125 min (for 8M sodium hydroxide). According to their test results, final setting time of GGBS with 8M mix was significantly shortened than the value of 100 percentage fly ash. Geopolymers cannot be employed in traditional buildings due to their rapid setting time. As a result, GGBS and fly ash are an appropriate combination for improved setup behavior.

3.3. Compression Strength of Mortar

The 1:1 ratio of alkali binder to compressive strength are for fly ash + GGBS. Figures 7 and 8 show the mortar findings at various sodium hydroxide concentrations. Geopolymer mortar had a strength range of 39 to 75 N/mm². Compressive strengths changed from 39 to 70 N/mm² when the molarity of the NaOH changed, especially for the outside cured materials. Mortar strength was enhanced by adding more NaOH, which could be due to the alkaline activator's increased sodium hydroxide level. 8M, for example, comprises 320 g of NaOH, whereas 12M contains 480 g. The increase in the percentage of FA substitution in ambient curing specimens with GGBS increased mortar compressive strength. Studies have shown that oven-curing makes specimens stronger than ambient curing due to early polymerization. Our research concentrated on how GGBS and ambient curing affected the specimen's strength because heat curing was not a possibility on site. The findings also showed that GGBS activity was essential to achieve oven-curing strength. The homogeneity of the geopolymer paste and aggregates were strongly correlated by FAG, indicating that the stronger material may have come about as a result of a chemical reaction that took place during polymerization. There was a small change in strength between outdoor and oven-curing as the GGBS concentration increased indicating the use of low molarity salt.

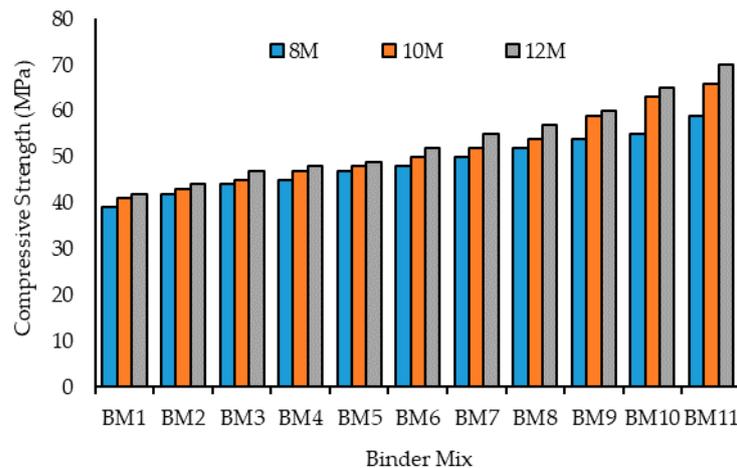


Figure 7. GP mortar compressive strength under ambient curing.

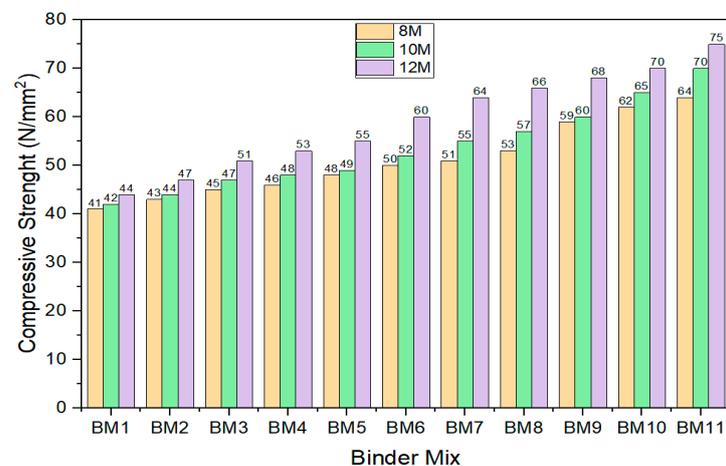


Figure 8. GP mortar compressive strength under oven-curing.

Compressive strengths for geopolymer mortars ranged from 39 to 75 MPa. Comprehensive strength increased by adding additional amounts of NaOH to the mortar. This might be caused by the alkaline activator's increased sodium hydroxide level. For instance, 8M contained 320 g of NaOH, while 12M had 480 g. The degree of FA and GGBS enhanced the mortar strength in ambient curing. Premature polymerization, according to a previous study, made oven-cured specimens more durable than ambient-cured specimens. We concentrated on how GGBS and ambient curing affected specimen strength as heat curing is not an option on the site. Finally, the findings showed that GGBS activity was essential to achieve oven-curing strength [42]. Strength was approximately 48 MPa when GGBS and FA were mixed in equal parts. Similarly, the compression strength of 10M and 12M under outdoor and over-curing conditions was 66 percent, 70 percent, and 70–75 percent, respectively. When GGBS concentration was raised from 0% to 50%, strength improved by approximately 7 MPa. Geopolymer mortar had compressive strengths of about 75 and 70 MPa for 100% GGBS content after oven- and outdoor curing. When GGBS and FA were used as the primary materials for geopolymers, they were as strong as concrete. The increased calcium concentration of GGBS might account for its higher compressive strength (32.6 percent). Geopolymer mortar based on fly ash surpassed the outdoor sample. Thermal curing allowed for faster production of geopolymers. Heat curing accelerated polymerization resulting in faster enhanced strength. When GGBS and FA were used as the primary materials for geopolymers, they were as strong as concrete. Improved compressive strength was due to increased calcium content in GGBS.

3.4. Workability of FA-Based Geopolymer Concrete

Geopolymer concrete initially required a lot of effort to compact it due to its hard consistency. Only water-reducing high-range admixtures, especially naphthalene-based superplasticizers, could make geopolymer concrete practical. A binder dosage limit of 4% by mass was required to complete this trial. The slump test results of workability are shown in Figure 9. Based on slump values, the fall was visible at higher percentage of alkaline/binder ratios, binder concentrations, and fly ash levels. The alkaline/binder ratio increased and decreased slump values with the same binder content. Due to the lower alkaline concentration, an additional superplasticizer was necessary to achieve optimum workability as GGBS particles were angular and reacted quickly. Substituting GGBS for fly ash reduced slump values.

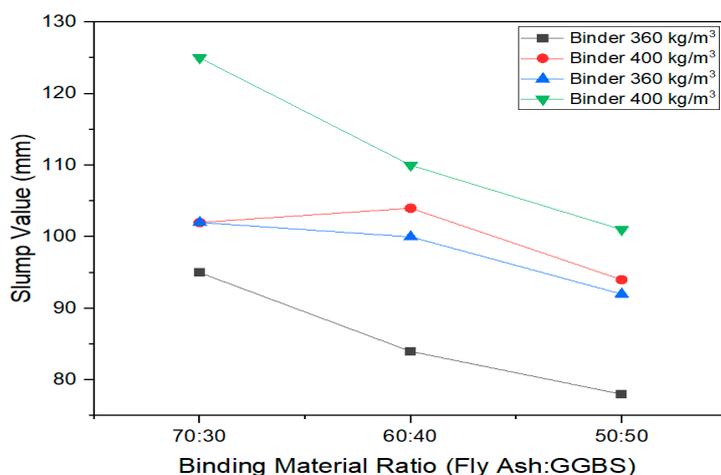
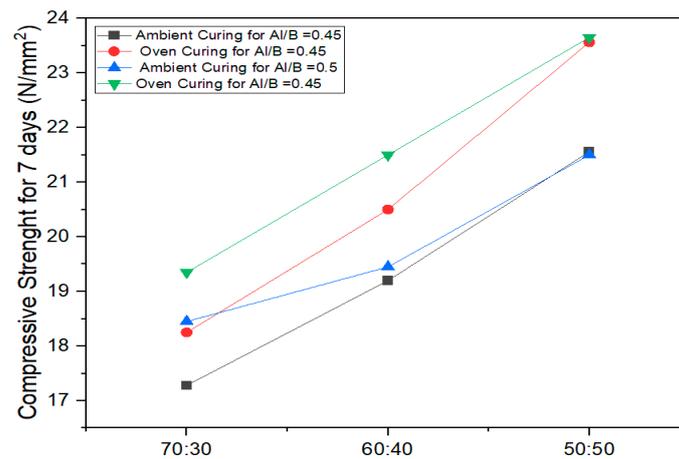


Figure 9. Workability of GPC.

3.5. Compression Strength Development of GPC

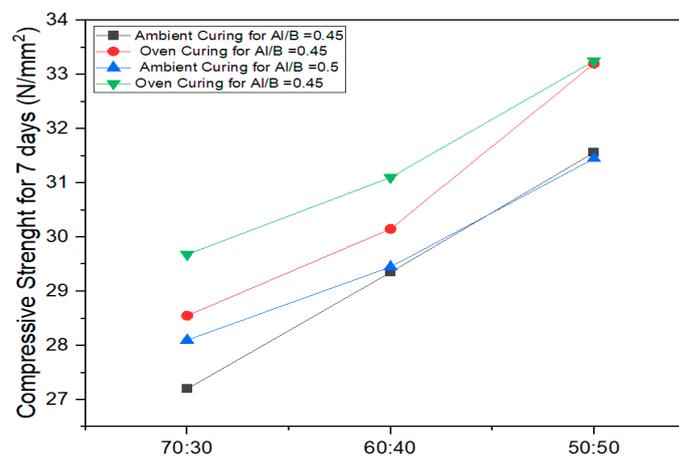
Compression strength was determined and is given in Figures 10–13. In addition, different GGBS to fly ash alternatives, ratios between alkaline and the binder, and ambient curing schedules were selected from the aforementioned mix, and a thorough analysis of the impact of healing and aging was provided. Though concrete strengthens after 28 days, it was frequently referred to as 28-day concrete strength. GPC's 7-day and 28-day strengths have significant correlations. The strength properties after 7 and 28 days is being studied. The molarity of NaOH in geopolymer concrete is proportional to the binder concentration and curing regime. When compared to when one is aged, strength increases more quickly in early stage development. Strength was clearly improved for GPCs that were oven-cured compared to GPCs that were cured outdoors for both forms of curing. The oven-cured sample (OCS) outperformed the outdoor-cured sample in strength after curing of 7 days. Although the early rate of strength growth was notable, it did not endure as long as with traditional concrete. This was shown by the ratio of the compressive strength after 28 days to 7 days. The strength test findings reflect that, for all binder formulations, increasing the amount of GGBS improved compressive strength. As a rich calcium silicate hydrate gel was produced when GGBS was substituted for fly ash, there was an increase in strength.

FA was gradually replaced with GGBS, increasing strength and speeding up the setting process. Strength was the greatest when the alkaline/binder (A/B) ratio was 0.5. The same findings were obtained when oven-cured specimens were used. The results demonstrated that when fly ash was substituted at a lower amount by 30%, the OCS showed higher compressive strength. As the replacement level rises (40% and 50%), the values for the strength of OCS and ambient cured specimens are practically identical. This means it is possible to increase the applicability of GPC in field circumstances by substituting GGBS at the proper percentages for fly ash.



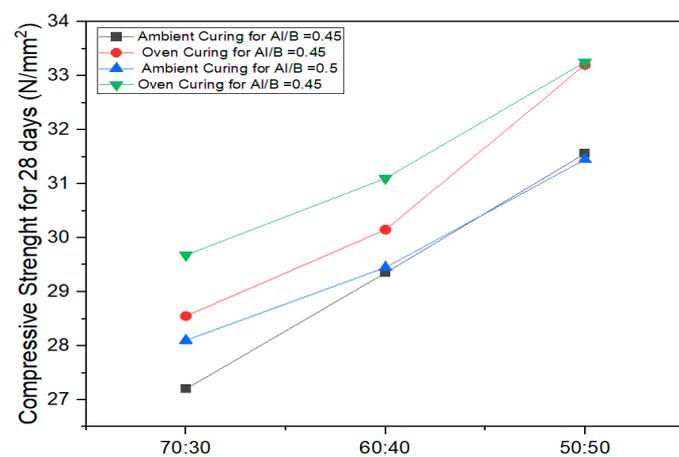
Binding Material Ratio (Fly Ash:GGBS) for binder content 360 kg/m³

Figure 10. Compressive strength of GPC of 360 kg/m³ for 7 days.



Binding Material Ratio (Fly Ash:GGBS) for binder content 400 kg/m³

Figure 11. Compressive strength of GPC of 400 kg/m³ for 7 days.



Binding Material Ratio (Fly Ash:GGBS) for binder content 360 kg/m³)

Figure 12. Strength of GPC of 360 kg/m³ for 28 days.

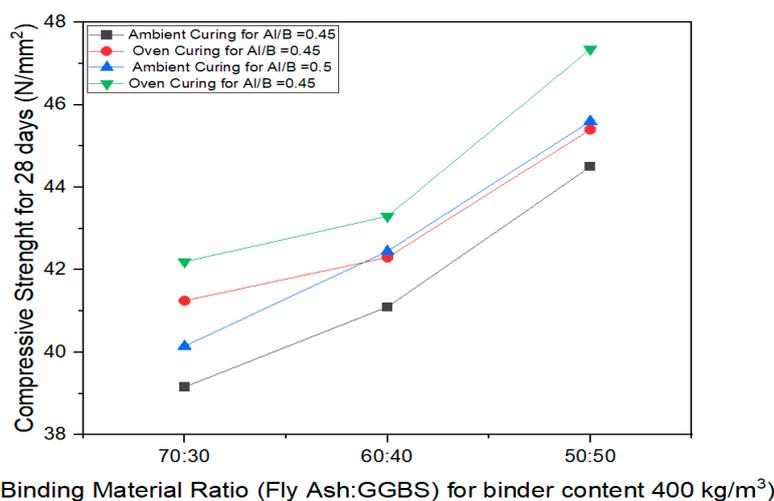


Figure 13. Strength of GPC of 400 kg/m³ for 28 days.

Using the obtained results, compressive strength and slump values for intermediate binder contents at different curing temperatures, curing periods, and NaOH concentrations can be estimated by varying aggregate/binder, proportion of FA & GGBS, alkaline/binder, slump value, and compressive strength. It is critical to investigate how the mix's components affect the geopolymer concrete's durability over time. A mix design is a specified combination of fundamental components required to produce concrete with the desired target strength. As a result, concrete's composition is crucial to achieve strength at 28 days. It is common knowledge that strengthening concrete involves raising its alkaline content. Furthermore, the quantity of both the aggregates in the mix and the binder concentration impact the concrete's strength. A combined design strategy for FAG-based GPC is provided based on expected compressive strength estimations. Design engineers may be able to build GPC with any required compressive strength using this approach. Correlations between the alkaline/binder and aggregate/binder were developed using data from the mixed proportions and compressive strength. These links aided in the creation of mixed design strategies for GPC under a range of curing circumstances.

3.6. Impact of Curing on Strength of GPC

In comparison to the outside, geopolymer had a higher strength in the range. At temperatures greater than the ambient temperature, polymerization proceeded expeditiously resulting in increased strength. As a result, in many real-world situations, concrete should be allowed to cure at ambient temperature. The maximum strength of the GPC specimens was achieved to be 8M (NaOH) at around 45 MPa for 400 kg/m³ as opposed to 47 MPa when curing was undertaken indoors. Ambient curing of FAG-based GPC was possible even with a low NaOH molarity. Field oven-curing was thus difficult. Hence without the need of an oven, GPC manufactured from GGBS, which substitutes for fly ash, can be produced. When the level of GGBS in the mixture was altered with rising alkaline content after 7 days it could be continued for 28 days. In terms of performance, geopolymer concrete based on GGBS outperformed combinations based on 50% GGBS after 28 days. The mixture's strength was boosted due to GGBS's higher calcium content. Soluble calcium when added increased compressive strength and speeded up the hardening process [43].

4. Conclusions

The research results indicated that GPC can be made with FAG to reach the necessary strength through ambient curing. The molarity of NaOH influenced the consistency of the geopolymer paste, which was crucial in polymerization. Owing to fly ash's particle structure, it required less alkaline activator owing to decreased friction inside the substance. Geopolymer made with 80% GGBS and 20% fly ash showed the excellent consistency

and strength properties due to higher amounts of GGBS. The quantity of binder content influenced the strength properties of GPC as also polymerization. Compared to ACS, the heat cured specimen's showed good results but the desired strength was achieved in ambient curing only. SEM images showed the morphology and shape of FAG. By ensuring 400 kg/m³ of binder content in outdoor curing circumstances, combining FAG could be a viable solution to manufacture geopolymer concrete. Studies in the future can be extended by varying binder materials and the types of alkaline activator solutions.

Author Contributions: K.K.P. and S.A.: Software, Investigation, Formal Analysis, Resources, Writing—Original Draft, Visualization. R.K.M., M.R.G. and P.B.: Software, Methodology, Resources, Data Curation. M.P. and J.K.: Investigation, Resources, Data Curation, Writing—Original Draft, Writing—Review & Editing, Supervision, Project Administration, Funding Acquisition. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF), funded by the Ministry of Education (NRF-2022R1A6A1A03053343).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

- Ramadhansyah, P.J.; Abu Bakar, B.H.; Megat Azmi, M.J.; Wan Ibrahim, M.H. Engineering Properties of Normal Concrete Grade 40 Containing Rice Husk Ash at Different Grinding Times. *Int. J. Technol.* **2011**, *1*, 10–19.
- Hashmi, D.A.F.; Khan, M.S.; Bilal, M.; Shariq, M.; Baqi, A. Green Concrete: An Eco-Friendly Alternative to the OPC Concrete. *Construction* **2022**, *2*, 93–103. [[CrossRef](#)]
- Karttunen, E.; Tsytsyna, E.; Lintukangas, K.; Rintala, A.; Abdulkareem, M.; Havukainen, J.; Nuortila-Jokinen, J. Toward Environmental Innovation in the Cement Industry: A Multiple-Case Study of Incumbents and New Entrants. *J. Clean. Prod.* **2021**, *314*, 127981. [[CrossRef](#)]
- Watari, T.; Cao, Z.; Hata, S.; Nansai, K. Efficient Use of Cement and Concrete to Reduce Reliance on Supply-Side Technologies for Net-Zero Emissions. *Nat. Commun.* **2022**, *13*, 4158. [[CrossRef](#)] [[PubMed](#)]
- Zhang, G.; Ahn, Y.; Lin, R. Effect of Waste Ceramic Powder on Properties of Alkali-Activated Blast Furnace Slag Paste and Mortar. *Polymers* **2021**, *13*, 2817. [[CrossRef](#)]
- Wang, W.; Shen, A.; Lyu, Z.; He, Z.; Nguyen, K.T.Q. Fresh and Rheological Characteristics of Fiber Reinforced Concrete—A Review. *Constr. Build. Mater.* **2021**, *296*, 123734. [[CrossRef](#)]
- Radzi, N.A.M.; Hamid, R.; Mutalib, A.A.; Kaish, A.B.M.A. A Review of the Structural Fire Performance Testing Methods for Beam-to-Column Connections. *Adv. Civ. Eng.* **2021**, *2021*, 5432746. [[CrossRef](#)]
- Xie, J.; Wang, J.; Rao, R.; Wang, C.; Fang, C. Effects of Combined Usage of GGBS and Fly Ash on Workability and Mechanical Properties of Alkali Activated Geopolymer Concrete with Recycled Aggregate. *Compos. Part B Eng.* **2019**, *164*, 179–190. [[CrossRef](#)]
- Hanifa, M.; Agarwal, R.; Sharma, U.; Thapliyal, P.C.; Singh, L.P. A Review on CO₂ capture and Sequestration in the Construction Industry: Emerging Approaches and Commercialised Technologies. *J. CO₂ Util.* **2023**, *67*, 102292. [[CrossRef](#)]
- Salman, N.M.; Ma, G.; Ijaz, N.; Wang, L. Importance and potential of cellulosic materials and derivatives in extrusion-based 3D concrete printing (3DCP): Prospects and challenges. *Constr. Build. Mater.* **2021**, *291*, 123281.
- Desta, E.; Jun, Z. A Review on Ground Granulated Blast Slag GGBS in Concrete. In Proceedings of the Eighth International Conference on Advances in Civil and Structural Engineering, Kuala Lumpur, Malaysia, 3–4 February 2018; pp. 5–10. [[CrossRef](#)]
- Saha, A.K. Effect of class F fly ash on the durability properties of concrete. *Sustain. Environ. Res.* **2018**, *28*, 25–31. [[CrossRef](#)]
- Palomo, A.; Fernández-Jiménez, A. Alkaline Activation, Procedure for Transforming Fly Ash into New Materials. Part I: Applications. In Proceedings of the World of Coal Ash (WOCA) Conference, Denver, CO, USA, 9–12 May 2011; pp. 1–14.
- Hardjito, D.; Cheak, C.C.; Ho, C.L.I. Strength and Setting Times of Low Calcium Fly Ash-based Geopolymer Mortar. *Mod. Appl. Sci.* **2008**, *2*, 1–9. [[CrossRef](#)]
- Kumar, P.K.; Srinivasu, K. Impact of GGBS and strength ratio on mechanical properties of geopolymer concrete under ambient curing and oven curing. *Mater. Today Proc.* **2021**, *42*, 962–968.
- Joseph, B.; Mathew, G. Influence of Aggregate Content on the Behavior of Fly Ash Based Geopolymer Concrete. *Sci. Iran.* **2012**, *19*, 1188–1194. [[CrossRef](#)]
- Balakrishnan, D.; John, T.; Thomas, J. Properties of Fly Ash Based Geo-Polymer Concrete. *Am. J. Eng. Res.* **2013**, *4*, 21–25.
- Nuaklong, P.; Wongsu, A.; Sata, V.; Boonserm, K.; Sanjayan, J.; Chindaprasirt, P. Properties of High-Calcium and Low-Calcium Fly Ash Combination Geopolymer Mortar Containing Recycled Aggregate. *Heliyon* **2019**, *5*, e02513. [[CrossRef](#)]

19. Purdon, A.O. The action of alkalis on blast-furnace slag. *J. Soc. Chem. Ind.* **1940**, *59*, 191–202.
20. Al-mashhadani, M.M.; Canpolat, O.; Aygörmez, Y.; Uysal, M.; Erdem, S. Mechanical and Microstructural Characterization of Fiber Reinforced Fly Ash Based Geopolymer Composites. *Constr. Build. Mater.* **2018**, *167*, 505–513. [[CrossRef](#)]
21. Morsy, M.S.; Alsayed, S.H.; Al-Salloum, Y.; Almusallam, T. Effect of sodium silicate to sodium hydroxide ratios on strength and microstructure of fly ash geopolymer binder. *Arab. J. Sci. Eng.* **2014**, *39*, 4333–4339. [[CrossRef](#)]
22. Deb, P.S.; Nath, P.; Sarker, P.K. The Effects of Ground Granulated Blast-Furnace Slag blending with Fly ash and activator content on the workability and strength properties of geopolymer concrete cured at ambient temperature. *Mater. Des.* **2014**, *62*, 32–39. [[CrossRef](#)]
23. Mohammed, B.S.; Liew, M.S.; Alaloul, W.S.; Khed, V.C.; Hoong, C.Y.; Adamu, M. Properties of Nano-Silica Modified Pervious Concrete. *Case Stud. Constr. Mater.* **2018**, *8*, 409–422. [[CrossRef](#)]
24. Sharif, H.H. Fresh and Mechanical Characteristics of Eco-Efficient Geopolymer Concrete Incorporating Nano-Silica: An Overview. *Kurd. J. Appl. Res.* **2021**, *6*, 64–74. [[CrossRef](#)]
25. Akgaoglu, T.; Qubukguoglu, B.; Awad, A. A Critical Review of Slag and Fly-Ash Based Geopolymer Concrete. *Comput. Concr.* **2019**, *24*, 453–458. [[CrossRef](#)]
26. Okoye, F.N.; Prakash, S.; Singh, N.B. Durability of Fly Ash Based Geopolymer Concrete in the Presence of Silica Fume. *J. Clean. Prod.* **2017**, *149*, 1062–1067. [[CrossRef](#)]
27. Ranjith, R.; Easwaran, P.; Kalaivani, M.; Ramesh, S. Strength and Structural Properties of Geopolymer Concrete with Natural Fibers—A Review. *Int. Res. J. Multidiscip. Technovation* **2019**, *1*, 432–438.
28. Kumaravel, S.; Girija, K. Acid and Salt Resistance of Geopolymer Concrete with varying concentration of NaOH Address for Correspondence. *J. Emerg. Technol. Innov. Res.* **2013**, *4*, 1–3.
29. Rao, G.M.; Rao, T.G. Final setting time and compressive strength of FAG-based geopolymer paste and mortar. *Arab. J. Sci. Eng.* **2016**, *40*, 3067–3074. [[CrossRef](#)]
30. Rao, G.M.; Satheesh Kumar, K.; Poloju, K.K.; Srinivasu, K. An Emphasis of Geopolymer Concrete with Single Activator and conventional concrete with recycled aggregate and data Analyzing using Artificial Neural Network. In Proceedings of the 3rd International Congress on Advances in Mechanical Sciences, Hyderabad, India, 27–28 August 2020. [[CrossRef](#)]
31. Duxson, P.; Fernández-Jiménez, A.; Provis, J.L.; Lukey, G.C.; Palomo, A.; Van Deventer, J.S.J. Geopolymer Technology: The Current State of the Art. *J. Mater. Sci.* **2007**, *42*, 2917–2933. [[CrossRef](#)]
32. Naik, T.R.; Dhir, R.K.; Dyer, T.D.; Newlands, M.D. Sustainability of Cement and Concrete Industries. In *Achieving Sustainability in Construction*; Ice Publishing Team: London, UK, 2015. [[CrossRef](#)]
33. Duxson, P.; Provis, J.L.; Lukey, G.C.; van Deventer, J.S.J. The role of inorganic polymer technology in developing green concrete. *Cem. Concr. Res.* **2007**, *37*, 1590–1597. [[CrossRef](#)]
34. Oyeibisi, S.; Ede, A.; Ofuyatan, O.; Alayande, T.; Mark, G.; Jolayemi, J.; Ayegbo, S. Effects of 12 Molar Concentration of Sodium Hydroxide on the Compressive Strength of Geopolymer Concrete. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *413*, 012066. [[CrossRef](#)]
35. Jawahar, J.G.; Mounica, G. Strength Properties of FAG-Based Geopolymer Concrete. *Asian J. Civ. Eng.* **2016**, *17*, 127–135.
36. Mohankumar, G.; Manickavasagam, R. Study on the Development of Class C Flyash Based GPC by Ambient Curing. *Int. J. Appl. Eng. Res.* **2017**, *12*, 1227–1231.
37. Bellum, R.R.; Muniraj, K.; Madduru, S.R.C. Influence of Activator Solution on Microstructural and Mechanical Properties of Geopolymer Concrete. *Materialia* **2020**, *10*, 100659. [[CrossRef](#)]
38. Nagajothi, S.; Elavenil, S. Effect of GGBS Addition on Reactivity and Microstructure Properties of Ambient Cured Fly Ash Based Geopolymer Concrete. *Silicon* **2021**, *13*, 507–516. [[CrossRef](#)]
39. Quinn, P.S.; Benzonelli, A. XRD and Materials Analysis. *Encycl. Archaeol. Sci.* **2018**, 1–5. [[CrossRef](#)]
40. Wang, S.D.; Pu, X.C.; Scrivener, K.L.; Pratt, P.L. Alkali-activated slag cement and concrete: A review of properties and problems. *Adv. Cem. Res.* **1995**, *7*, 93–102. [[CrossRef](#)]
41. Jayarajan, G.; Arivalagan, S. An experimental study of geopolymer concrete incorporated with fly-ash & GGBS. *Mater. Today Proc.* **2021**, *45*, 6915–6920.
42. Wattimena, O.K.; Hardjito, A.D. A Review on the Effect of Fly Ash Characteristics and Their Variations on the Synthesis of Fly Ash Based Geopolymer. *AIP Conf. Proc.* **2017**, *1887*, 020041. [[CrossRef](#)]
43. Manchiryal, R.K.; Poloju, K.K.; Al Balushi, Y.A.A.; Al Banna, W.N.M. Variation of Sodium Hydroxide Concentration Impact on Rheological Properties of Geopolymer Paste. *Int. J. Adv. Appl. Sci.* **2023**, *10*, 62–68. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.