Fly Ash-Based Geopolymer Composites: A Review of the Compressive Strength and Microstructure Analysis

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Abstract: Geopolymer (GP) concrete is a novel construction material that can be used in place of traditional Portland cement (PC) concrete to reduce greenhouse gas emissions and effectively manage industrial waste. Fly ash (FA) has long been utilized as a key constituent in GPs, and GP technology provides an environmentally benign alternative to FA utilization. As a result, a thorough examination of GP concrete manufactured using FA as a precursor (FA-GP concrete) and employed as a replacement for conventional concrete has become crucial. According to the findings of current investigations, FA-GP concrete has equal or superior mechanical and physical characteristics compared to PC concrete. This article reviews the clean production, mix design, compressive strength (CS), and microstructure (Ms) analyses of the FA-GP concrete to collect and publish the most recent information and data on FA-GP concrete. In addition, this paper shall attempt to develop a comprehensive database based on the previous research study that expounds on the impact of substantial aspects such as physio-chemical characteristics of precursors, mixes, curing, additives, and chemical activation on the CS of FA-GP concrete. The purpose of this work is to give viewers a greater knowledge of the consequences and uses of using FA as a precursor to making effective GP concrete.

Keywords: geopolymer; fly ash; carbon dioxide emission; microstructure; alumino-silicates; compressive strength; mix design

1. Introduction

The most utilized construction material is concrete because of its performance, cost, ability to form different shapes, and availability of raw materials locally [1–3]. However, the increasing demand for concrete for various construction applications has led to a corresponding high consumption of raw materials utilized in the manufacture of concrete [1,4,5]. The production of PC, which is the primary binder in concrete, has also been shown to have a hugely detrimental influence on the environment. It has been estimated that approximately one ton of CO2 is emitted into the environment for every ton of PC produced [6–9]. It has been estimated that between 2017 to 2050, the manufacture of PC annually will grow by 50%. The substantial rise in the demand for PC to produce concrete...
is expected to substantially increase the amount of CO$_2$ emitted into the environment. CO$_2$ emissions estimated between 85 to 105 gigatons could be emitted into the atmosphere over the next 33 years because of the production of PC [6,10,11]. In addition to the high emission linked with PC production, about 2 to 3% of the worldwide energy demand is also consumed [6,11]. Figure 1 shows the global cement production and the amount of pollution associated with it. These high CO$_2$ emissions ensuing from PC production would hinder the world from achieving its sustainability goals and result in more detrimental impacts on the environment. Thus, this study aims to explore alternative sustainable materials such as GP concrete that can be used in place of PC concrete [2,12].

GP concrete is deemed the next generation of concrete because of its sustainability benefits as it offers an innovative way to totally eliminate PC as a binder in the manufacture of concrete, thereby resulting in a substantial reduction in CO$_2$ emissions [13–15]. Generally, in the literature, ligands with precursors based on alumina and silica are treated as GPs, while alkali-activated cement is based on precursors rich in calcium. In contrast to PC concrete, the binder phase in GP concrete is formed because of the process known as geopolymerization. Geopolymerization occurs when silicate and aluminate monomers in alumino-silicate precursors are activated with an alkali/acidic medium [16]. The alumino-silicate precursors used in GPs can be natural materials (e.g., kaolin, mining waste) or waste materials (e.g., palm oil ash, FA, rice husk ash, granulated blast slag) [17]. Figure 2 presents the common alumino-silicate precursors used in GP concrete. In addition to the sustainability benefits of GP concrete [18–20], the use of GP concrete also opens a pathway to effectively manage wastes that could have an adverse effect on health, safety, and the environment [21]. Studies have also shown that GP concrete with a similar cost to that of PC concrete can be produced while reducing CO$_2$ emission by about 22–72% [22]. In addition, GP concrete has been shown to have superior mechanical characteristics [23–26], an adjustable thermal expansion coefficient [27], high-temperature resistance [28], and acid resistance [29–32]. Figure 3 presents a schematic diagram of using GP concrete as a sustainable construction material.

![Figure 1](image-url)  
**Figure 1.** Global cement production volumes and process-related carbon dioxide emissions. Adapted from [33].
Figure 2. Precursor materials that are commonly utilized in GP composites. Adapted from [34].

Figure 3. Benefits of GP concrete in sustainable construction. Adapted from [35].
GPs are composed of the alumino-silicate precursor which is composed of amorphous silica and alumina alongside an activator that acts as the dissolving agent. Geopolymerization is the process by which zeolitic-like materials are converted into a three-dimensional (3D) alumino-silicate gel [1,36–38]. A polycondensation procedure involving silicate and aluminate in an alkaline environment develops the corresponding performance of the generated binder [27]. The common activators used in synthesizing GPs are either MOH-type caustic alkalis or \( R_2O \cdot (n)SiO_2 \)-type silicates or both. \( M \) in the MOH indicates the alkali-metal such as K, Na, and Ca in the activator, which is generally sodium hydroxide (NaOH), sodium carbonate (NaCO\(_3\)), potassium hydroxide (KOH), or sodium sulfate (Na\(_2\)SO\(_4\)) [39]. In addition to the common activators mentioned, various alternative activators such as rice husk ash and silica fume have been utilized as activator components in synthesizing GPs. Compared to the hydration reaction of PC, the water used in the synthesis of GPs only helps in producing a workable mixture and does not participate in the geopolymerization and polycondensation process [40]. Figure 4 presents a schematic diagram of GP production [41–44].

![Production of GP](image_url)

**Figure 4.** Production of GP. Adapted from [35].

This study aims to analyze and answer a lot of worries concerning the viability of FA-GP concrete as the next-generation sustainable concrete. Despite these numerous advantages, the impact of FA on the long-term characteristics of GP concrete remains a source of worry that must be fully understood before FA-GP concrete can be considered a sustainable alternative. In a summary, the purpose of this work is to give viewers a greater knowledge of the consequences and uses of using FA as a precursor to making effective GP concrete [45–47].

Depending on their local availability, use, and production cost, various types of precursors have been used to produce GPs [5,36,48]. The most common precursor used to make GP concrete is FA because of its high composition of silicate and aluminate coupled with its local availability. FA has been extensively used in PC concrete to partially replace PC as the binder [49]. Figure 5 presents many applications of FA compounds. The global FA generation is anticipated to reach over 363 million tons per year, with India leading the way, followed by China and the US [13,22]. Figure 6 presents global FA generation and usage. As the precursor, about 450 kg/m\(^3\) of FA is utilized for every ton of FA-GP concrete [22]. Because FA is the primary ingredient used for the synthesis of FA-GP concrete, it is anticipated that about 2 billion tons of FA would have been needed to substitute 100% PC [22,50]. As there is a substantial quantity of FA available worldwide,
its use in developing FA-GP concrete can be deemed a sustainable tactic [51]. This review paper focuses on the up-to-date development of FA-GP concrete. The emphasis is on identifying how the silicon/aluminum (S/A) ratio proportions, the additives, and the kind and quantity of alkali sol are employed to controllably enhance the qualities of FA-GP concrete. The critical property of concrete, namely the CS, is also discussed. A relationship between the Ms characteristics and CS of the FA-GP concrete is also established.

Figure 5. FA’s main components and applications. Adapted from [52].

Figure 6. (a) FA generation in the United States from 2008 to 2019; (b) FA application fields in the United States in 2019. Adapted from [53].
2. Significance of Study

This study aims to analyze and answer a lot of worries concerning the viability of FA-GP concrete as the next-generation sustainable concrete. Numerous investigators that presented evaluations on FA-GP concretes discovered that the strength characteristics of the FA-GP concrete might be equal, if not considerably higher, compared to those of PC concrete [54,55]. Furthermore, the application of FA-GP concrete technologies may give environmental and economic benefits. As a result, FA-GP concrete is growing in recognition in the construction sector. Despite these numerous advantages, the impact of FA on the long-term characteristics of GP concrete remains a source of worry that must be fully understood before FA-GP concrete can be considered a sustainable alternative. A small number of review articles have been published that provide a complete overview of the uses and effects of FA on the different technical features of GP concrete. Similarly, the current work intends to evaluate and compile the outcomes of numerous investigations under one tent, with a focus on the Ms characteristics of FA-GP concrete. This review study combines the clean manufacturing of FA particles and parameters influencing the properties of FA-GP concrete and addresses the Ms characteristics and CS of FA-GP concrete in depth. In summary, the purpose of this work is to give viewers a greater knowledge of the consequences and uses of using FA as a precursor to making effective GP concrete.

3. Geopolymerization

Geopolymerization is a chemical reaction between alumino-silicate precursors and an alkaline component that results in a hardened product at room temperature or occasionally at an increased temperature [56]. Alkali-activated binders or alkali-activated materials are two terms for the same thing [57]. Materials rich in silica and alumina, such as ferrous slag, non-ferrous slags, calcined clay, and natural pozzolans, can be utilized as a source of alumino-silicate in geopolymerization [58–60]. The suggested structure of GP by Davidovits [56] is presented in Equation (1).

\[
Mn[(SiO_2)Z AlO_2]n,wH_2O
\]  

(1)

In Equation (1), M is a symbol of the alkali-metal cation, n is a symbol of the gradation of polycondensation, w is a symbol of the quantity of chemically attached water molecules, and z is a symbol of the silicon to an aluminum ratio. The GP structures are classified into three varieties based on the value of z: -Si-O-Al-O- (Gel 1, S/A = 1), -Si-O-Al-O-Si-O- (Gel 2, S/A = 2), and -Si-O-Al-O-Si-O-Si-O- (Gel 3, S/A = 3) [61–63]. Figure 7 illustrates these structures.

Figure 8 presents a rough idea of how a conceptual model of [64] works in the GP reaction. Dissolution of alumina and silica happens in GP reactions because of an alkaline environment composed of sodium and potassium hydroxides and silicates; the rearrangement and swapping of dissolved species results in GP gel formation [65]. Based on the chemical composition of the precursors, gel formation in GP reactions is classified into two types. Blast furnace slag (BFS) is a high-calcium precursor that creates the (C-A-S-H)–type of gel, whereas metakaolin (MK) and FA are low calcium precursors that make the N-A-S-(H) type of gel [64,65]. Strength is developed as the GP gel hardens.

In comparison, five distinct chemical processes exist for the GP, as illustrated in Figure 8b showing the Shi, Jiménez, and Palomo conceptual model [66–68]. When activated silico-aluminous cementitious materials react with alkaline activators, GPs are generated. According to this paradigm, polymerization processes are categorized into four groups: deconstruction, gel formation, polycondensation, and crystallization.
Figure 7. GP structures according to Davidovits [56]. Adapted from [66].

Figure 8. (a) A Provis conceptual model of geopolymerization [64,69]; (b) a Glukhovsky conceptual model for geopolymerization [70].
4. FA-GP Concrete

FA is an abbreviation for “pulverized fuel ash” generated after the collection of boiler flue gas from coal power plants, as shown in Figure 9 [71,72]. The characteristics of the FA in terms of chemical and physical can be correlated to calcined condition and formation process. FA’s primary chemical compositions are SiO$_2$, Al$_2$O$_3$, and CaO [73], and the amorphous slope glass dosage has the greatest influence on activity [74–77]. The noxiousness of FA leachate exhibited negligible ecotoxicity [78]. SEM-EDS analysis indicates that FA possesses mullite and quartz phases [79] as shown in Figure 10. These phases are critical to the strength development of GPs [80–83].

![Figure 9. Clean production of FA. Adapted from [84].](image1)

![Figure 10. SEM-EDS characterization of FA mineral phase composites based on intuition. Adapted from [79].](image2)
The formation of FA-GP concrete is based on the breakdown of alumino-silicate in FA, which is accelerated by alkali, followed by polycondensation. Manufacturing is supposed to be more energy- and resource-efficient since reactions can occur at low temperatures. The actual responses that occur during the process, on the other hand, are exceedingly complicated and remain a mystery. Condensation between the resulting Si$^{4+}$ and Al$^{3+}$ molecules occurs because of FA–alkali reactions, followed by more intricate nucleation, oligomerization, and polymerization, culminating in a novel alumino-silicate-based polymer with a 3D network structure. In experiments or applications, the produced FA-GP concrete is placed in a mold and dried in an oven at a specific temperature or at room temperature for a specified period to form the structure indicated in Figure 11.

Alkali activation of FA is expected to be critical for geopolymerization formation: in an alkaline sol, the silica, alumina, or alumino-silicates in FA hydrolyze, and the -Si-O-Si- or -Si-O-Al- bonds of alumino-silicate break, releasing active Al$^{3+}$ and Si$^{4+}$ species, which combine to form nuclei and alumino-silicate oligomers composed of SiO$_4^{4-}$ and AlO$_4^{3-}$ tetrahedra. Based on the S/A ratio, the networks in alumino-silicate oligomers can be polyciliate -Al-O-Si-chain, polyciliate siloxo -Al-O-Si-Si-chain, or polyciliate disiloxo -Al-O-Si-Si-Si-. Al$^{3+}$ partly replaces Si$^{4+}$ in alumino-silicate monomers, and the resulting negative charge in the alumino-silicate bonds is neutralized by alkali cations such as K$^+$ and Na$^+$ [85,86], as illustrated in Figure 11. In this situation, the S/A ratio substantially impacts the final structure of the resulting GP composites [87]. It has been discovered, for example, that the S/A ratio in the FA reactor has a substantial influence on the pores (number and size) of crystalline products, which is one of the major characteristics governing the mechanical strength of GP compositions [88,89]. Table 1 outlines the various FA categories and mineral phases, providing details on their possible usage as GP precursors and the prospective end product.

![Figure 11](image_url)

Figure 11. The schematic diagrams illustrate the pathway from FA to FA-GP concrete. Adapted from [90].
Table 1. FA classification and applications for the production of inorganic GPs. Adapted from [91].

| FAs                        | Origin                                                                 | Characteristic                              | Mineral Phases                       | Potential of Products        | Potential for Geopolymerization                           |
|----------------------------|------------------------------------------------------------------------|---------------------------------------------|---------------------------------------|-----------------------------|----------------------------------------------------------|
| 1. Pozzolanic (sialic)     | Highly ranked fuels, bituminous with detrital quartz, kaolinite, illite, mica, k-feldspars | Maximum values of fine fraction, true density | Viscous melt (glass), minimum values of crystallization | Dense and porous GP pastes  | Good activation but with a low rate of high dissolution pH of alkaline sol |
| 2. Active low pozzolanic, calsialic, ferrisialic, ferricalsialic | Variable rank of fuel but mostly liquid with carbonates, sulfates, sulfides, detrital silicates | Maximum values of the water-soluble fraction | Oxyhydroxides, sulfates, carb, and actives silicates | Porous matrix paste       | Aam low alkaline sol and pH                                |
| 3. Ferrisialic inert (sialic), calsialic | Variable rank of fuels, bituminous and sub-bituminous | High content of original infused quartz, max true density, min of water-soluble elements | Mullite and quartz                     | Dense and less porous composites | Low dissolution rate, high pH                             |
| 4. Ferricalsialic          | Low-rank fuels, lignites, bituminous gypsum, ferrite, calcite, dolomite | Max bulk density                            | Fe, Mg, Na phases                     | Porous product paste         | High dissolution rate, poor polymerization                |
| 5. Sialic and calsialic mixed between inert and active | Lower-rank fuel, lignites and sub-bituminous with carbonate and sulfates | Maximum values of light fraction            | Oxyhydroxides sulfates, carbonates, and active Ca and Caemg silicates | Paste and mortars, porous metallic corrosion, and pores | A medium reactive low alkaline sol                        |

5. Chemical Composition of Binder Materials

Various parameters such as particle size, S/A ratio, amorphous composition, and phase composition affect the structure and characteristics of GPs [92]. Precursors such as FA have a high amount of alumina and silica, granting them the ability to act as supplementary cementitious materials. Silicon oxide and aluminum oxide are the two most common oxides found in FA. Because PC is made from limestone, it has more calcium oxide and silicon oxide but less aluminum oxide. Table 2 presents the conclusions of XRF experiments on FA industrial by-products utilized in the production of GPs that have been described in different articles. In addition, Figure 12 shows an XRD study of several raw materials, indicating the materials’ phases. Figure 13 shows SEM of FA concrete in conjunction with EDS in the compositions of different hydration products in the same picture at multiple places.

Table 2. Oxide composition for PC and FA binder materials.

| Material and Ref. | SiO₂  | Fe₂O₃ | Al₂O₃ | CaO | Pb | Na₂O | P₂O₅ | MnO | K₂O | SO₃ | MgO | SrO | TiO₂ | CuO | Cl | LOI |
|------------------|-------|-------|-------|-----|----|------|------|-----|-----|-----|-----|-----|-----|-----|----|----|
| PC [93]          | 19.0  | 3.20  | 4.68  | 66.8| 26.8| 0.09 | 0.08 | 0.19| 1.17| 3.00| 0.81| -   | -   | -   | -  | 2.48|
| FA [94]          | 48.8  | 10.20 | 27.00 | 6.20| 86.0| 0.37 | 1.20 | 0.15| 0.85| 0.22| 1.40| 0.16| 1.30| –   | –  | 1.70|
| FA [95]          | 61.8  | 4.11  | 28.05 | 0.87| 94.0| 0.40 | -    | 0.82| 1.32| 0.38| -   | -   | -   | -  | 0.49|
### Table 2. Cont.

| Material and Ref. | Composition (wt.%) |
|-------------------|---------------------|
|                   | SiO₂ | Fe₂O₃ | Al₂O₃ | CaO | Pb | Na₂O | P₂O₅ | MnO | K₂O | SO₃ | MgO | SrO | TiO₂ | CuO | Cl | LOI |
| FA [96]           | 50.7 | 8.00  | 28.00 | 1.30 | 68.3 | 1.00 | 1.00 | 0.00 | 3.00 | 2.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| FA [93]           | 64.9 | 5.69  | 26.4  | 0.33 | 97.3 | 0.49 | –    | 0.25 | 0.33 | 0.85 | –    | –    | –    | –    | 0.45 |
| FA [97]           | 17.5 | 12.43 | 36.37 | 10.5 | 66.3 | –    | –    | 1.77 | 1.39 | 3.05 | –    | 0.88 | –    | 1.19 | –    | 0.19 |
| FA [100]          | 54.7 | 5.15  | 27.28 | 5.31 | 87.1 | 0.43 | 1.12 | 0.10 | 2.00 | 1.01 | 1.10 | 0.36 | 1.82 | 0.01 | –    | 3.60 |
| FA [102]          | 27.3 | 2.01  | 50.85 | 5.41 | 80.2 | 0.04 | –    | 0.02 | 0.33 | 0.28 | –    | 2.12 | –    | 7.74 | –    | 0.45 |
| FA [103]          | 50.6 | 6.35  | 18.96 | 14.1 | 75.9 | 0.69 | –    | –    | 0.74 | 3.12 | –    | –    | –    | –    | 0.17 | –    | 0.19 |
| FA [71]           | 66.5 | 3.54  | 22.47 | 1.64 | 92.5 | 0.58 | –    | 1.75 | 0.10 | 0.65 | –    | 0.88 | –    | 1.66 | –    | –    | 3.60 |
| FA [108]          | 51.1 | 12.50 | 25.70 | 4.30 | 89.3 | 0.80 | 0.90 | 0.20 | 0.70 | 2.15 | –    | 1.30 | –    | –    | –    | 0.60 |
| FA [107]          | 47.8 | 14.09 | 28.00 | 3.81 | 89.9 | 0.41 | 1.81 | 0.21 | 0.62 | 0.27 | 0.93 | –    | 1.99 | –    | –    | 0.43 |
| FA [109]          | 54.4 | 8.14  | 27.72 | 1.29 | 90.3 | 0.67 | –    | 0.11 | –    | –    | –    | –    | –    | 4.11 | –    | –    | 0.43 |
| FA [109]          | 52.7 | 9.92  | 18.05 | 12.9 | 76.7 | 1.11 | –    | 2.09 | 1.76 | 3.86 | –    | 1.01 | –    | 1.60 | –    | –    | 0.50 |
| FA [110]          | 58.4 | 4.19  | 23.80 | 7.32 | 86.3 | 1.43 | –    | 2.02 | 0.44 | 1.11 | –    | –    | –    | –    | –    | 0.10 |
| FA [112]          | 35.8 | 17.31 | 15.05 | 17.1 | 68.2 | 1.58 | 0.30 | 3.12 | 5.94 | 2.34 | –    | –    | –    | –    | –    | –    | 0.90 |
| FA [119]          | 50.8 | 6.82  | 23.15 | 6.87 | 80.8 | 1.29 | 1.14 | 2.14 | 1.24 | 1.70 | 0.19 | 1.01 | –    | –    | 0.55 | –    | –    |

**Figure 12.** XRD of FA. Adapted from [113].
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6. Mix Design of GP Concrete

GP concrete’s CS is heavily influenced by its content and mix design. As demonstrated in Table 3, variables such as SiO$_2$/Al$_2$O$_3$, temperature curing, supplementary water, the molarity of Na$_2$O/Al$_2$O$_3$, and NaOH ratio have a critical influence on the CS of FA-GP concrete [114–116]. Pimraksa, Chindaprasirt, Rungchet, Sagoe-Crentsil, and Sato [117] observed that increasing the molarity of NaOH accelerates the geopolymerization process, leading to increased CS [118–121]. Moreover, the findings by Al Bakri, Kamarudin, Bnhussain, Nizar, Rafiza, and Zarina [122] and Songpiriyakij, Kubprasit, Jaturapitakkul, and Chindaprasirt [123] demonstrated that the Na$_2$SO$_3$/NaOH ratio has a substantial impact on GP concrete strength growth. Other studies [124–133] have also observed that temperature and curing time have a considerable impact on the mechanical characteristics of GP concrete.

The creation of a standard for GP concrete is currently in its early stages. June [134], Ferdous, Manalo, Khennane, and Kayali [135] and Anuradha, Sreevidya, Venkatasubramani, and Rangan [136] offered numerous strategies for achieving mixed GP concrete proportions. According to Lokuge, Wilson, Gunasekara, Law, and Setunge [137], in comparison to PC concrete, creating the design mix of GP concrete is complicated and challenging as a result of the involvement of various variables.

The low-calcium FA was used in all experimental trials indicated in Table 3. The Fe$_2$O$_3$ percentage is around 10 to 20% by weight, while the CaO percentage is less than 5% [95,112,138]. According to research on the particle size distribution of FA, 80% of the particles of FA were smaller than 50 μm [127].

As in PC concrete, fine and coarse aggregates can be used as aggregates in GP concrete [126,127]. The alkali activator (AA) used to produce FA-GP concrete can be a combination of NaOH sol and Na$_2$SiO$_3$ sol. Aluminum oxides and silicon contribute to over 80% of the total weight, with a silicon-to-aluminum ratio of almost 2 for low-calcium FA. The binder is the primary distinction between GP concrete and PC concrete. The GP paste is made by reacting Al$_2$O$_3$ and SiO$_2$ within FA with an alkaline activator sol, which bonds unreacted components to the GP concrete [27]. Sand and gravels, as in PC concrete, make up roughly 75 to 80% of the GP concrete mass. The technologies now available for PC concrete can compute this component of GP concrete mixes [139]. Phoo-ngernkham, Phi-

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Figure 13. SEM and EDX curve showing the chemical composition of FA spots. Adapted from [49].
angphimai, Damrongwiriyanupap, Hanjitsuwan, Thumrongvut, and Chindaprasirt [140] proposed using the multivariate adaptive regression spline (MARS) approach to formulate a GP concrete combination with a 28-day goal strength. This approach is based on contour plots generated between a variety of variables that affect GP concrete’s CS. The method illustrated in Figure 14 can be utilized to build a GP concrete mix design.

The amounts and characteristics of the basic ingredients used in the creation of GP concrete influence its workability and CS. According to Pimraksa, Chindaprasirt, Rungchet, Sagoe-Crentsil, and Sato [117], increasing the dosage of NaOH sol increased the CS of GP concrete. It was also discovered that increasing the ratio of Na₂SiO₃ sol to NaOH sol by mass results in higher CS of GP concrete and that increasing the workability of GP concrete by incorporating superplasticizer, up to 4% FA by mass, improves the workability of GP concrete; however, this may hurt the CS of GP concrete. It was also discovered that as GP concrete’s water content increases, its workability increases.

Figure 14. Mixture design method for GP concrete. Adapted from [141].
Table 3. Composition of FA-GP concrete.

| Ref. | FA (Kg/m³) | Aggregates (kg/m³) | Alkaline Activator (AA) (kg/m³) | NaOH Molarity (M) | Added Water (kg/m³) | Curing Conditions | Strength (MPa) |
|------|------------|--------------------|---------------------------------|------------------|---------------------|------------------|---------------|
|      |            | Fine   | Coarse | Na₂SiO₃ (SS) | NaOH (SH) |            | Temperature (C) | Time (h) |
| [142] | 450        | 500    | 1150   | 162         | 108       | 16     | 24             | 24        | 24        | 38.4 |
|       | 450        | 500    | 1150   | 162         | 108       | 12     | 24             | 24        | 24        | 41.4 |
|       | 450        | 500    | 1150   | 162         | 108       | 8      | 24             | 24        | 24        | 40.0 |
| [143] | 400        | 651    | 1209   | 114.3       | 45.7      | 14     | 22             | 22        | 24        | 26.7 |
|       | 349        | 620    | 1221   | 194         | 12        | 13.3   | 23             | 24        | 24        | 41.7 |
| [144] | 225        | 627    | 1164   | 112.5       | 45        | 14     | 24             | 24        | 24        | 41.1 |
|       | 400        | 548    | 1164   | 160         | 80        | 24     | 24             | 24        | 47.0      |
|       | 300        | 623    | 1323   | 108         | 72        | 24     | 24             | 24        | 39.0      |
| [147] | 400        | 554    | 1293   | 113         | 45        | 14     | 100            | 100       | 24        | 33.5 |
|       | 400        | 850    | 950    | 143         | 57.0      | 12     | 40             | 70        | 24        | 53.5 |
|       | 400        | 850    | 950    | 143         | 57.0      | 12     | 48             | 60        | 48        | 44.8 |
|       | 400        | 850    | 950    | 143         | 57.0      | 12     | 60             | 70        | 24        | 37.3 |
|       | 400        | 850    | 950    | 143         | 57.0      | 12     | 80             | 70        | 24        | 22.6 |
| [90]  | 400        | 658    | 1222   | 84          | 56.0      | 14     | 0.0            | 20–23     | 27.0      |
|       | 400        | 658    | 1222   | 100         | 40.0      | 14     | 0.0            | 20–23     | 72        | 25.0 |
| [124] | 408        | 647    | 1201   | 103         | 41.0      | 14     | 0.0            | 90        | 24        | 89.0 |
|       | 408        | 554    | 1294   | 103         | 41.0      | 14     | 21.3           | 30        | 24        | 32.0 |
|       | 476        | 554    | 1294   | 120         | 48.0      | 14     | 0.0            | 60        | 24        | 68.0 |
|       | 476        | 554    | 1294   | 120         | 48.0      | 8.0    | 0.0            | 60        | 24        | 63.0 |
|       | 408        | 647    | 1201   | 103         | 55.4      | 8.0    | 0.0            | 75        | 24        | 44.0 |
|       | 408        | 647    | 1201   | 103         | 41.0      | 10     | 7.5            | 60        | 24        | 45.0 |
|       | 408        | 554    | 1294   | 103         | 41.0      | 14     | 0.0            | 60        | 24        | 44.0 |
|       | 408        | 647    | 1201   | 103         | 41.0      | 14     | 17.6           | 60        | 24        | 43.0 |
|       | 408        | 647    | 1201   | 103         | 41.0      | 12     | 14.4           | 60        | 24        | 42.0 |
|       | 408        | 554    | 1294   | 103         | 51.5      | 14     | 16.5           | 60        | 24        | 42.0 |
|       | 408        | 554    | 1294   | 103         | 51.5      | 14     | 16.5           | 60        | 24        | 41.0 |
|       | 408        | 554    | 1294   | 103         | 51.5      | 14     | 16.5           | 60        | 24        | 41.0 |
|       | 408        | 554    | 1294   | 103         | 51.5      | 14     | 16.5           | 60        | 24        | 40.0 |
|       | 408        | 554    | 1294   | 103         | 41.0      | 14     | 26.5           | 60        | 24        | 40.0 |
|       | 408        | 554    | 1294   | 103         | 41.0      | 14     | 10.7           | 30        | 24        | 35.0 |
|       | 408        | 554    | 1294   | 103         | 41.0      | 14     | 8.0            | 20        | 60        | 18     | 29.0 |
|       | 408        | 554    | 1294   | 103         | 41.0      | 8.0    | 20             | 60        | 18        | 29.0 |
|       | 408        | 554    | 1080   | 103         | 41.0      | 8.0    | 20             | 60        | 18        | 29.0 |
Table 3. Cont.

| Ref. | FA (Kg/m³) | Aggregates (kg/m³) | Alkaline Activator (AA) (kg/m³) | NaOH Molarity (M) | Added Water (kg/m³) | Curing Conditions | Strength (MPa) |
|------|------------|-------------------|---------------------------------|-------------------|---------------------|------------------|---------------|
|      |            | Fine  | Coarse | Na₂SiO₃ (SS) | NaOH (SH) |               | Temperature (C) | Time (h) |               |
| 408  | 616        | 1232  | 103    | 41.0         | 14        | 0.0             | 60            | 24      | 66.8          |
| 408  | 616        | 1232  | 103    | 41.0         | 8.0       | 0.0             | 60            | 24      | 55.0          |
| 408  | 616        | 1232  | 103    | 41.0         | 10        | 7.5             | 60            | 24      | 52.0          |
| 408  | 616        | 1232  | 103    | 41.0         | 12        | 14.4            | 60            | 24      | 51.0          |
| 408  | 616        | 1232  | 103    | 41.0         | 16        | 26.5            | 60            | 24      | 48.0          |
| 408  | 616        | 1232  | 103    | 41.0         | 14        | 20.7            | 60            | 24      | 45.0          |
| 408  | 616        | 1232  | 103    | 41.0         | 14        | 10.6            | 60            | 24      | 35.0          |
| 408  | 616        | 1232  | 103    | 55.4         | 8.0       | 0.0             | 60            | 24      | 33.0          |
| 408  | 616        | 1232  | 103    | 41.0         | 14        | 21.3            | 60            | 24      | 32.0          |
| 408  | 616        | 1232  | 103    | 48.0         | 14        | 0.0             | 60            | 24      | 28.0          |
| [127] |          |      |        |              |            |                 |               |         |               |
| 420  | 750        | 1125  | 100.0  | 40.0         | 16        | 0.0             | 100           | 24      | 70.5          |
| 400  | 535        | 1356  | 128.6  | 51.5         | 16        | 12.7            | 100           | 24      | 52.0          |
| 380  | 540        | 1233  | 141.3  | 56.5         | 16        | 14.6            | 100           | 24      | 49.0          |
| 405  | 545        | 1235  | 132.4  | 52.9         | 16        | 28.0            | 100           | 24      | 46.0          |
| 400  | 540        | 1265  | 105.7  | 42.3         | 16        | 24.3            | 100           | 24      | 44.0          |
| 309  | 648        | 1204  | 59.0   | 27.7         | 10        | 83.7            | 100           | 24      | 42.0          |
| 254  | 694        | 1290  | 48.5   | 22.8         | 10        | 68.7            | 100           | 24      | 36.8          |
| 365  | 602        | 1118  | 73.0   | 34.3         | 10        | 103.5           | 100           | 24      | 35.3          |
| [149] |          |      |        |              |            |                 |               |         |               |
| 408  | 554        | 1294  | 103    | 41.0         | 14        | 22.5            | 60            | 24      | 36.0          |
| 350  | 645        | 1200  | 103    | 41.0         | 8.0       | 35              | 60            | 24      | 48.0          |
| [134] |          |      |        |              |            |                 |               |         |               |
| 450  | 850        | 950   | 144    | 57.0         | 12        | 48              | 60            | 24–96   | 48.5          |
| 408  | 554        | 1294  | 103    | 41.0         | 8.0       | 0.0             | 60            | 24–96   | 56.0          |
| [151] |          |      |        |              |            |                 |               |         |               |
| 428  | 623        | 1177  | 102.9  | 68.6         | 14        | 28.5            | 20–23         | 72      | 28.6          |
| [152] |          |      |        |              |            |                 |               |         |               |
| 400  | 651        | 1209  | 114.3  | 45.7         | 12        | 0.0             | 60–90         | 24–96   | 26.0          |
| 406  | 643        | 1194  | 102.0  | 41.0         | 14        | 26.8            | 70            | 12      | 37.0          |
| 424  | 623        | 1177  | 91.0   | 36.4         | 14        | 16.0            | 70            | 12      | 54.9          |
| 462  | 599        | 1153  | 132.2  | 52.9         | 14        | 21.2            | 75            | 24      | 49.6          |
| 461  | 623        | 1177  | 92.3   | 46.2         | 14        | 18.6            | 75            | 24      | 42.5          |
| 498  | 599        | 1153  | 89.7   | 59.8         | 14        | 26.5            | 60            | 24      | 39.9          |
| 444  | 623        | 1177  | 111.1  | 44.4         | 14        | 18.6            | 60            | 24      | 38.7          |
| 480  | 599        | 1153  | 112.0  | 56.0         | 14        | 23.7            | 70            | 12      | 37.1          |
| 408  | 623        | 1177  | 85.9   | 57.2         | 14        | 24.5            | 75            | 24      | 35.7          |
| 394  | 647        | 1201  | 105.1  | 52.6         | 14        | 21.5            | 60            | 24      | 29.7          |
| [153] |          |      |        |              |            |                 |               |         |               |
| 408  | 554        | 1294  | 103    | 41.0         | 16        | 22.5            | 60            | 24      | 45.0          |
| 404  | 640        | 1195  | 102    | 41.0         | 16        | 20              | 60            | 24      | 50.0          |
| [154] |          |      |        |              |            |                 |               |         |               |
| 408  | 554        | 1294  | 103    | 41.0         | 8.0       | 0.0             | 60            | 4–96    | 58.0          |
7. Compressive Strength

FA-GP concrete CS is affected by S/A ratios, alkali sols, calcium content, additives, and curing conditions.

The dosage and type of alkaline sol affect the generation of Si\(^{4+}\) and Al\(^{3+}\) from FA during geopolymerization. A dosage of alkaline sol is typically advantageous for achieving high CS \([3,142,155–165]\); however, there is an ideal limit \([166]\). For instance, by raising the NaOH content from 4.5 to 16.5 M, Somna, Jaturapitakkul, Kajitvichyanukul, and Chindaprasirt \([157]\) looked into the CS of ground FA (GFA) that had been treated at room temperature. The results showed that increasing the NaOH content from 4.5 to 9.5 M improved the CS of paste specimens. While altering the NaOH dosage levels from 9.5 to 14 M improves the CS of paste specimens, it does so to a much lesser extent. Increased alumina and silica extraction is primarily responsible for the increase in CS with increasing NaOH dosages. The CS of GFA hardened pastes begins to decline at a dosage of 16.5 M sodium hydroxide. This decrease in CS is mostly caused by excess hydroxide ions, which precipitated alumino-silicate gel at a relatively young age, resulting in the formation of weaker GPs.

To boost CS, Na\(_2\)SiO\(_3\) sol is generally combined with NaOH \([167]\). This is because of the fact that Na\(_2\)SiO\(_3\) with a high viscosity can aid in the production of GP gels, resulting in a compact final FA-GP concrete Ms. Furthermore, the activation technique affects the CS of FA-GP concrete. For instance, Rattanasak and Chindaprasirt \([168]\) first introduced NaOH sol to FA for 10 min to dissolve the Si\(^{4+}\) and Al\(^{3+}\) species, followed by Na\(_2\)SiO\(_3\) for one minute to assist in generating a homogeneous GP paste. The strength of FA-GP concrete increased as a result of the independent activation. Table 3 shows the specifics of the various alkaline sols as well as the molarity of the FA-GP concrete.

The FA-GP concrete structure is mostly determined by the S/A ratio generated by the dissolving of Al\(^{3+}\) and Si\(^{4+}\). Furthermore, the efficient S/A ratios have a substantial impact on the dissolving, hydrolysis, and condensation reactions of GPs. Condensation action in a high S/A system leads to the predominance of the silicate species itself, generating oligomeric silicates, which condense with Al(OH\(_4\))\(_4\) and create GP structures of poly(sialate-disiloxo) (Si–O–Al–O–Si–O–Si–O–) and poly(sialate-siloxo) (Si–O–Al–O–Si–O) as shown in Figure 15 \([169,170]\). As a result, a completely dense GP structural matrix has greater CS. Using a larger dosage of an alkaline activator, in contrast, can assist rapidity in the polycondensation of alumino-silicate oligomers by the transfer of Al\(^{3+}\) and Si\(^{4+}\) \([90,171–174]\).

The function of additives is to create a crucial equilibrium in oxide dosages to the required level using various add-ons \([175–178]\). Binary, ternary, and quaternary GPs have been created to achieve higher characteristics and erase any defects related to any original source \([179]\). For instance, Yang, Yao, Zhang, and Wang \([180]\) found that the high calcium dosage of GBFS in FA/GBFS GP increased the initial setting time and slowed the degree of polymerization. It has been discovered that increasing GGBFS as a partial substitute for FA considerably improves both 28-day strength and short-term strength \([143]\). Because of the presence of C-S-H gel, iron slags as a substitute for FA in FA-GP concrete demonstrated enhanced strength with increasing slag percentage \([181–183]\). Kusbiantoro, Nuruddin, Shafiq, and Qazi \([150]\) showed that samples cured in an oven had the maximum CS because of the polarization of OH ions, which tends to increase the pH of the sol and thus promotes the synthesis of -Si-O-Si- bonds in the GP gel (N-A-S-H gel) and CS \([184–187]\). While analyzing nano-structural changes in several GP composites (GBFS-based, FA-based, and mixed GBFS + FA) before and after carbonation, Bernal, Provis, Walkley, San Nicolas, Gehman, Brice, Kilcullen, Duxson, and van Deventer \([188]\) revealed that N-A-S-H gel is the main product in FA-GP concrete that is not dissolved by carbonation and instead only alkali aluminosilicate (AAS) in the pores is impacted by CO\(_2\). The use of nano-alumina and nano-silica as additives in FA-GP has been found to improve its mechanical characteristics. Phoo-ngernkham, Chindaprasirt, Sata, Hanjitsuwan, and Hatanaka \([176]\) created FA-GP pastes by adding 1% to 3% nano-silica and nano-alumina as an ingredient. The results
indicated that nanoparticle additions, independent of dose, enhanced CS. This behavior was attributed to both the increased formation of C-S-H or C-A-S-H and N-A-S-H gels in the GP paste and the micro packing effect. Table 4 illustrates the effect of various additives on the behavior of GP composites. Because the dissolution and condensation of FA comprise both alkali and alkali metals, the pH of the pore sol and the alkali-metal cations are crucial for the hydration process of FA and consequently the CS. Bhagath Singh and Subramaniam [189] and Yang and Gupta [190] found that the CS of FA-GP concrete rose as alkali dosage rose, and they ascribed this to the rapid dissolution of FA at higher pH. Because network modifiers (Ca$^{2+}$, Na$^+$, and K$^+$) are present, reacting phases including Al and Si have disorganized structures and can generate acidic -Si-OH (silanol) groups with water. The dissolution behavior of vitreous aluminum silicate-containing network modifiers is depicted in Figure 16. The presence of hydroxyl ions (OH-) in alkali sols causes the reactive alumino-silicates of FA to disintegrate. The dissolution rates of alumino-silicates are affected by their exterior and interior surface areas, as well as the degree of cross-linking in their structure [191].

Calcium has been shown to interact with silica and alumina gelation during the geopolymerization reaction, altering the Ms of FA-GP concrete and hence the CS [192,193]. The presence of C-S-H gel and N-A-S-H gel together typically increases the CS of final products. One of the explanations for this is that the crystalline C-S-H gel reduces porosity [194,195]. Figure 17a depicts the fluctuation in FA-GP concrete CS after 28 days in relation to the Na$_2$SiO$_3$/NaOH (SS/SH) ratio dosage in the FA precursor. Figure 17b depicts the change in 28-day CS of FA-GP concrete vs. CaO dosage in the FA precursor.

It is well established that typical GPs require thermal treatment to produce CSs equivalent to or greater than those of PC concrete [39,101,196–198]. Heat treatment promotes alumino-silicate gel dissolution and geopolymerization, resulting in a considerable increase in early strength [199]. Additionally, it accelerates the dissolution of silica and alumina species and the subsequent polycondensation phase. However, the thermal curing regime adopted must be suitable for promoting the proper dissolution and precipitation of dissolved silica and alumina species. Depending on the source, geopolymerization may be harmed by exceeding a specified temperature and heat treatment period, which may negatively affect the GP concrete’s mechanical properties. [156,196,200]. Noushini, Castel, Aldred, and Rawal [144] used 12 different thermal curing techniques to make FA-GP concrete with a low calcium content. Figure 18 depicts the CS of GP concrete specimens after 28 days at room temperature and after heat curing. Compressive strength initially increased faster with increasing temperature and time in cured samples, and the optimal CS was obtained at 75 $^\circ$C [144]. This could be because higher temperatures and longer curing times resulted in the formation of more reactive species; hence, with the appropriate curing temperature, more metals were incorporated into the GP matrix, and metal dosages decreased [201–203]. Table 5 illustrates the effect of various curing regimes on the performance of GP composites.

The type and fineness of the GP raw material are instrumental in developing the strength, durability, and Ms of the resulting GP matrices. Figure 19 depicts an SEM image of a polished part of an FA-GP with various FA particle types. Numerous researchers have concurred that altering the particle size distribution in the composite material has a substantial effect on the CS, physical properties, and Ms of the resulting GP paste [196,204]. In general, binder phases with a finer particle size distribution have a stronger reaction and, as a result, create GP paste with a denser Ms, better CS, and improved physical properties [200,205]. Table 6 shows how particle size distribution affects the performance of GP composites.
Si:Al=1  Poly(sialate)  (-Si-O-Al-O-)

Si:Al=2  Poly(sialate-siloxo)  (-Si-O-Al-O-Si-O-)

Si:Al=3  Poly(sialate-disiloxo)  (-Si-O-Al-O-Si-O-Si-O-)

Si:Al>3  Sialate link

**Figure 15.** Formation of different aluminum silicate chains in alumino-silicate oligomers depending on the molar S/A ratio, which then forms the GP. Adapted from [85].

**Figure 16.** The process of alumino-silicate glass dissolving during the initial stages of reactivity of a one-part GP blend. (a) H⁺ exchange for Ca²⁺ and Na⁺, (b) dissolution of Al–O–Si bonds, (c) depolymerization of the glass network, and (d) Si and Al release. Adapted from [206,207].
Figure 16. The process of alumino-silicate glass dissolving during the initial stages of reactivity of a one-part GP blend. (a) H\(^+\) exchange for Ca\(^{2+}\) and Na\(^+\), (b) dissolution of Al–O–Si bonds, (c) depolymerization of the glass network, and (d) Si and Al release. Adapted from [206,207].

Figure 17. Historical statistics on CS variations in comparison to: (a) Na\(_2\)SiO\(_3\) (SS)/NaOH (SH) [93,95,96,99,103–105,107,208] and (b) CaO content in FA-GP [123,209–221].
Figure 18. Compressive strength development of ambient and heat-cured GP concretes. Adapted from [144].

Figure 19. SEM image of a refined segment of an FA-GP concrete with several FA particle types highlighted in various colors. Yellow particles are reactive glass particles surrounded by a reaction rim [222–224]; red particles are iron-rich; pink particles are relatively unreactive glass particles with no visible reaction rim; blue particles are hollow particles whose shell was not broken during the reaction process; green particles contain visible crystalline inclusions. Adapted from [225].
Table 4. Effect of different additives on FA-GP concrete CS.

| Ref. | Main Source Material | Additives | Remarks |
|------|----------------------|-----------|---------|
| [226] | FA | CAC | Increases strength by providing an additional supply of Al and Ca. |
| [227] | FA | Water glass | Increased CS because of higher Si dosage. The recommended dose is 15 g/100 mL. |
| [228] | FA | GBFS | With an M ratio of 0.96 SiO₂/Na₂O and raw materials of 70% GGBFS and 30% FA, CSs of 48 MPa were attained. |
| [226] | FA | GBFS | Compressive strength and Ms improve when GBFS dosage increases resulting from the production of more C-S-H. |
| [229] | High-calcium FA | PC | A GP composite with a more homogeneous and dense structure than concrete was created. |
| [197] | Low-calcium FA | GGBS, POFA | The addition of 30% POFA and 70% GGBS to FA-GP concrete produced a CS of 67 MPa. POFA dosages above 33% reduce CS. |
| [230] | FA | Superplasticizer | A high superplasticizer dose increases CS. |
| [231] | FA | Chitosan biopolymer | The introduction of N-carboxymethyl chitosan substantially improved tensile strength and resulted in a minor increase in CS. |
| [180] | FA | GGBFS | Slag inclusion in the raw material can improve the CS of GP mixtures, with a slag/FA dosage ratio of 0.8, providing the maximum strength. |
| [232] | FA | Sulfate of calcium and sodium, calcium chloride, and sucrose | Sucrose substantially slows down the ultimate setting time. All admixtures help to improve CS. |
| [233] | FA | GBFS, GCS | GCS partial replacement resulted in higher CS than GBFS partial replacement. |
| [234] | FA | Red mud | After 120 days, there is a decrease in CS. Localization of heavy metals within permitted levels. |
| [150] | FA/silica fume | I: 62 °C for 24 h; II: 23 °C at room temperature. | The early strength of HCGC is influenced by higher curing temperatures. Compressive strength increases rapidly over the first 7 days and then gradually increases for the next 28 days. |
| [235] | FA | Nano-silica | The use of 6.0% nano-silica as a substitute caused improved mechanical properties. |
| [236] | FA | Aluminum-rich waste | A 2.5% admixture of dried powdered and calcined aluminum-rich waste gave early high strength of 34 MPa, but the CS dropped after that. |

CAC, calcium aluminate cement; POFA, palm oil fuel ash; GCS, ground corex slag; GGBFS, ground granulated BFS.

Table 5. Curing regime and its influence on FA-GP concrete CS from different precursors.

| Ref. | Precursor | Curing Regime | Remarks |
|------|-----------|---------------|---------|
| [237] | FA | Curing temperatures between 66 °C and 85 °C | Curing at 85 °C for 24 h resulted in much greater strength than curing at 66 °C. Over time, the rate of growth in strength dropped after 24 h. |
| [167] | Class C FA | I: 62 °C for 24 h; II: 23 °C at room temperature. | The early strength of HCGC is influenced by higher curing temperatures. Compressive strength increases rapidly over the first 7 days and then gradually increases for the next 28 days. |
| [212] | FA/silica fume | I: 96 °C (8 h); II: 96 °C (2 h) then 150 °C (6 h) dry oven; III: 96 °C (2 h) then 96 °C (6 h) steam | 50–102 MPa for I; 28–57 MPa for II. The greatest results were obtained with III: 35–77 MPa, covering with 95 °C, and steam curing. |
| [234] | FA slag | I: 26 °C (28 days); II: 26 °C (48 h) followed by 60 °C (4 h) | The second curing regime, which was longer in length and followed by high-temperature treatment, resulted in enhanced strength. |
Table 5. Cont.

| Ref. | Precursor | Curing Regime | Remarks |
|------|-----------|---------------|---------|
| [167] | FA        | 85 °C (5 h–7 days) | Strength increases when curing time is extended. Sealed curing aids in the development of strength while also preventing early carbonation. |
| [238] | FA        | 26 °C (16 h–672 h); 41 °C (72 h) to 336 h; 60 °C (16 h–120 h); and 85 °C (1 h–6 h). | 85 °C for 6 h is equivalent to 25 °C for 100 h. The strength of the K-based GP was reduced as the curing temperature increased. |
| [239] | FA        | I: 21 days at 20 °C with an initial cure at 70 °C; II: 24 h at 20 °C with an initial cure at 70 °C. | Technique II has a higher CS than method I. |
| [220] | 85% FA and 15% kaolin | 6 h, 12 h, 24 h, and 48 h for temperatures of 30 °C, 50 °C, and 70 °C. | Curing at a greater temperature for a brief time has a positive influence on strength (a couple of hours). Structure deterioration with prolonged exposure to high temperatures. |
| [240] | FA        | 24 h at 65 °C; 5 min in the microwave. After 66 °C curing for 3 h, 6 h, and 12 h, curing at room temp | The optimal curing time was 5 min in a microwave at 65 °C for 6 h. |
| [241] | FA        | 1 h of pre-curing followed by 24 h of curing at 25, 40, and 60 °C. | Curing at 60 °C is ideal (for 7- and 28-day strength) |
| [200] | FA        | 24 h, followed by 36 h in the oven (50–90 °C). | Curing in an oven at 80 °C is ideal. |
| [242] | FA        | Room temperature for 9–12 h, then salt water, normal water, and sealed curing environment. | The sealed state produced the best outcomes, followed by salt water and the least effective water cure. |

HCGC, high calcium FA-GP concrete.

Table 6. Impact of the particle size distribution of precursors on FA-GP concrete CS.

| Ref. | Precursors | Precursor Gradation | Main Constants | Compressive Strength (MPa) | Remarks |
|------|------------|---------------------|----------------|---------------------------|---------|
| [243] | FA         | 100% GFA (1.45 m²/g) 25% OFA (0.395 m²/g) + 75% GFA 50% GFA and 50% OFA 25% GFA and 75% OFA | Na₂SiO₃ with a silicate modulus of 2.5. | 6.79 | With the addition of finer binder content, the CS of 28 days is increased. |
| [244] | FA         | 365 m²/kg 440 m²/kg 612 m²/kg d₅₀ = 32.24 µm and fineness 2110 cm²/g | NaOH dosage of 13 M, Na₂SiO₃/NaOH ratio of 3, Sol/FA ratio of 0.35, curing time of 7 h at 110 °C | 21.85 | With increasing fineness, there is a substantial rise in CS after 28 days. |
| [245] | FA         | 525 m²/kg 444 m²/kg 365 m²/kg | Alkali sol with a dosage of 13 M was utilized, and the L/S ratio was 0.35 after 4 h of curing at 90 °C. | 40 | With an increase in fineness, CS and workability improve after 28 days. |
| [246] | FA         | X₁₀ = 0.12 µm, X₉₀ = 3.66 µm, X₁₀ = 0.08 µm, X₉₀ = 0.64 µm, X₁₀ = 0.04 µm, X₉₀ = 0.37 µm, | Na₂SiO₃/NaOH ratio of 0.4 and activator to FA ratio of 0.45%. | 9.5 | With an increase in fineness, there is a substantial rise in the CS of mortar after 28 days. |
| [200] | FA, RHBA   | FA 75 µm + RHBA 90 µm FA 75 µm + RHBA 7 µm FA 3 µm + RHBA 90 µm FA 3 µm + RHBA 7 µm | Curing at 80 °C for 36 h with a NaOH dosage of 12 M. | 34 | With an increase in fineness, there is a substantial rise in the 28-day CS of mortar. |
### Table 6. Cont.

| Ref.  | Precursors     | Precursor Gradation                              | Main Constants                                                                 | Compressive Strength (MPa) | Remarks                                                                 |
|-------|----------------|--------------------------------------------------|--------------------------------------------------------------------------------|----------------------------|-------------------------------------------------------------------------|
| [205] | FA, RHA        | 5.1% retained on sieve 325 of RHA
1.1% retained on sieve 325 of RHA
\( d_{50} = 15.8 \text{µm} \) and fineness 5100 cm\(^2\)/g
\( d_{50} = 24.4 \text{µm} \) and fineness 3500 cm\(^2\)/g | As-received FA, \( \text{Na}_2\text{SO}_3/\text{NaOH} \) ratio = 4, 60 °C for 48 h. | 34.5                       | Increased fineness resulted in an overall enhancement in CS after 28 days. |
| [204] | BA             | Curing at 75 °C for 48 h with a \( \text{Na}_2\text{SO}_3/\text{NaOH} \) ratio of 1.5 and a NaOH dosage of 10 M. | 64.5                       | With a rise in fineness, the CS of mortar increases in 28 days.         |
| [158] | BA             | Liquid alkaline/ash ratios of 0.429–0.709, \( \text{Na}_2\text{SiO}_3/\text{NaOH} \) ratios of 0.67–1.5, and 7.5–12.5 M NaOH. | 24–58                      | Grinding boosts reactivity and lowers porosity in BA particles, resulting in reasonably high workability and CS of 28 days. |

GFA, ground FA; OFA, oil FA; RHA, rice husk ash; RHBA, rice husk-bark ash; BA, bottom ash.

### 8. Microstructure (Ms)

#### 8.1. Scanning Electron Microscopy (SEM)

The Ms characteristics of FA-GP concrete rely on the FA characteristics, type, and dosage of activators and the curing conditions [95,96,98]. Fernández-Jiménez, Palomo, and Criado [247] presented an explanatory model of FA-GP concrete as presented in Figure 20. Before defining the alkaline activator sol, Pavithra, Srinivasa Reddy, Dinakar, Hanumantha Rao, Satpathy, and Mohanty [95] established several fixed parameters, including dosage, SS/SH ratio, curing temperature, and duration (AAS). This study discovered that as the ratio of AAS to binder increases, the strength of GP concrete decreases because of the increased amount of water in the GP mix [16]. The contact area for the reaction was obstructed by the water molecules, and this, in turn, altered the geopolymerization process between the binder and the activator, resulting in a low compressive strength of the GP concrete [248]. When AAS/binder ratios of 0.4 and 0.5 were employed, the GP concrete matrix included a negligible percentage of unreacted FA particles. Nonetheless, it has been demonstrated that the presence of unreacted FA particles in the FOC matrix aids in matrix densification and minimizes the formation of microcracks. This behavior is consistent with other studies demonstrating that the ability of unreacted FA particles to densify the Ms of GP concrete improves strength performance [96,98,249,250].

The influence of several SS to SH ratios on Ms studies has been investigated [251]. As shown in Figure 21, fully reacted FA particles were evident in GP concrete when an SS to SH ratio in the range of 0.5 to 1.0 was used. Despite the similarity in the Ms of GP concrete made with SS to SH ratios of 0.5 and 1.0, the resulting CS differs. The SS of GP concrete made with an SS to SH ratio of 1 was 65 MPa, while the GP concrete made with an SS to SH ratio of 0.5 exhibited a CS of 35 MPa for the same age. These strength findings are in agreement with a previous study where a higher dosage of silicate was found to result in better strength development as a result of the availability of additional silicates available for geopolymerization [237]. However, the Ms images presented in Figure 21 show that GP concretes made with a higher SS to SH ratio have more presence of unreacted FA particles. It is well established that an excess of AAS in the mix hampers geopolymerization by restricting the interaction of the binder and AAS [252]. When current research on this subject is compared, it is clear that most writers utilized a mass ratio of SS/SH of up to 2.5 [93,96,208,253].
Figure 20. A descriptive model of FA activation by alkali: (a) initial chemical attack, (b) bi-directional alkaline attack, (c) reaction product, (d) gel, (e) unreacted particles. Adapted from [247].

Figure 21. SEM images of FA-GP concrete generated at various Na$_2$SiO$_3$/NaOH weight proportions at 28 days: (A) 0.5, (B) 1, (C) 2, and (D) 3. Adapted from [251].
Karthik, Sudalaimani, Vijayakumar, and Saravanakumar [254] included bio-additives in GP concrete and established a correlation between the Ms density and CS. It was discovered that increasing the density of the GP concrete Ms results in increased CS. These findings corroborate previous research on including nano-silica, silica fume, nano-aluminate, and graphene oxide in FA-GP concrete [255,256]. Figure 22 shows SEM images of GP concrete nanocomposites containing 3.0 wt% nano-silica in wet and dry mix conditions. The amount of unreacted particles has been substantially reduced. Additionally, the dry mix process detects fewer microcracks than the pure GP and wet mix procedures. Further, Cai, Pan, Li, Tan, and Li [257] report that FA-GP concrete has a higher electrical resistivity than metakaolin-based GP concrete.

![SEM images of GP concrete nanocomposites](image1)

**Figure 22.** SEM images showing (a) pure GP combined with GP nanocomposites comprising 3.0 wt% nano-silica, (b) wet mix procedure, and (c) dry mix procedure. Adapted from [104].

Figure 23 shows the interfacial transition zone (ITZ) in GP concrete. According to Embong, Kusibiantoro, Shafiq, and Nuruddin [100], the enhancement of FA particle dissolution and polycondensation of aluminosilicate compounds provides a link between the aggregates and the matrix. The CS of the samples was greatly increased as a result of the development of aluminosilicate filling the ITZ.

![SEM images of GP concrete aggregates](image2)

**Figure 23.** FA-GP concrete SEM images with several types of aggregates: (a) the interface of the glass aggregate and GP; (b) the interface of the sand aggregate and GP. Adapted from [258,259].

### 8.2. Wide-Angle X-ray Properties

In reality, Lloyd, Provis, and van Deventer [260] chronicled that the boost in the quantity of silica encourages the diffusion of alkalis. Nevertheless, these phase modifications taking place during aging are absent in the XRD patterns. In addition, Abdulkareem, Mustafa Al Bakri, Kamarudin, Khairul Nizar, and Saif [97] described a broad hump ranging from 20° to 35° that indicated the presence of amorphous GP products. Previous research has revealed that FA comprises quartz and mullite mineral phases, and Table 2 also shows that iron and calcium made up more than half of the FA [261]. As a result, the reason for the presence of phases in the GP paste pattern is depicted in Figure 24. Mullite Al4.56Si1.44O9.72,
quartz SiO$_2$, magnetite Fe$_3$O$_4$, and calcium silicate Ca$_3$SiO$_5$ were recognized as crystalline phases. The inclusion of calcium silicate in the quantitative measurement of fly ash indicates slight cement contamination in Melbourne ash. The binder’s XRD phases are entirely connected to the fly ash source material, and no novel crystalline phases are generated in this binder. Furthermore, the amount of the calcium silicate phase does not decrease with time, indicating that the C$\text{S}_3$ phase in fly ash does not participate much in the reaction, and the sodium aluminosilicate hydrate (N-A-S-H) gel is still the predominant binding matrix in these specimens. As previously discussed, crystalline phases were revealed after adding an alkaline sol.

![XRD pattern of FA-GP concrete specimen at different molarities after 28 days and ages. Adapted from [258,262].](image)

**Figure 24.** XRD pattern of FA-GP concrete specimen at different (a) molarities after 28 days and (b) ages. Adapted from [258,262].
As shown in Figure 25, the intensity of most peaks on the XRD spectrum is weaker and a considerable amount of amorphous phases still exist after the dissolving testing. This is because the calcium content in the FA can produce fast precipitant (Portlandite) covering the surface of the FA, which not only prevents further dissolution of the FA but also reduces the intensity of the peaks of the crystalline phases [108].

Figure 25. XRD spectrum (a) before and (b) after the dissolution of FA. Adapted from [108].

8.3. Mercury Intrusion Porosimetry (MIP)

The study by Aligizaki [263] showed that porosity can assist in understanding the characteristics of GP concrete and PC as it is a sign of the density of the Ms, microcrack presence, and diffusion rate of pore sol. Das, Yang, Singh, Mertens, Xiao, Chawla, and Neithalath [110] examined the dimension of the pore structure of FA-GP concrete in the range of 0.0036–10 μm MIP. As shown in Figure 26, the cumulative porosity for FA-GP concrete is 32%. However, the majority of the pores measured in the GP matrix were 0.0036–1 μm in size.

Figure 26. Cumulative mercury intrusion curve for alkali-activated FA. Adapted from [110].
8.4. GP Concrete and PC Ms Comparison

As demonstrated in Figure 27, hardened GP concrete has a denser Ms than hardened PC because of the previously noted cross-linked characteristic. Because of the replacement of Al$^{3+}$ for Si$^{4+}$ in bridging locations, the C-A-S-H matrix chains in the GP system were shown to be longer than the C-S-H gel chains in the PC system [35]. Because of the stronger interlayer cohesion caused by the bonding between bridging tetrahedral conservative layers, C-A-S-H gels have a lower Ca/Si ratio and a higher Al/Si ratio than C-S-H gels [264]. The gel composition of GP concrete and PC is shown in Figure 28.

![SEM images of the binders and ITZs of (a) PCC and (b) FA-GP concrete. Adapted from [172,259,265].](image)

**Figure 27.** SEM images of the binders and ITZs of (a) PCC and (b) FA-GP concrete. Adapted from [172,259,265].

![GP and PC binder gel compositions. Adapted from [66].](image)

**Figure 28.** GP and PC binder gel compositions. Adapted from [66].
9. Challenges for Solid Wastes in Geopolymer

To accomplish the industrialization and commercialization of geopolymers, hurdles must be overcome in three areas: technology, economy, and administration. This also necessitates collaboration between the government, businesses, and the general people for co-governance, which is both an objective necessity for enhancing the quality of the ecological environment and a practical prerequisite for constructing an ecological civilization. Geopolymers derived from solid wastes are expected to become more frequently employed when nonrenewable resources are depleted. Basic research should be prioritized in order to minimize the cost and increase the workability of geopolymers. Based on fundamental research, embarking on solid wastes to explore the preparation of varied characteristics of geopolymers in order to produce high-value-added application domains should be one of the primary paths of future geopolymer research development [1,266–270].

10. Conclusions

With the main alumino-silicate precursors used in the production of GP concrete being industrial wastes, such as FA, the utilization of GP concrete in place of the conventional PCC can be used to reduce CO$_2$ emissions. The use of GP concrete would also result in an effective way to manage industrial wastes such as FA, thereby promoting the sustainable development of society. Discussions presented in this review paper showed that FA-GP concrete could be an alternative to PCC. Nevertheless, this will only happen if both an efficient raw material supply chain and a product supply chain network are in situ. From this perspective, the recent market is optimistic, but it will take time to establish GP concrete as a commercial product worldwide. Desirable performance for diverse engineering applications may be achieved with correct selection and adjustment of GP concrete composition. Regardless of the differences in the precursors’ characteristics, the production and formation and the characteristics of the FA-GP concrete products are highly influenced by the physical and chemical characteristics of FA, AAs, additives, and curing conditions. Based on the discussion in this paper, the following conclusions can be made:

1. The recommended S/A ratio for producing GPs of appropriate strength varies depending on the nature and content of the raw material. S/A ratios of 2–2.5 (class F FA) and 2.5–3.5 (class C FA) were determined to be optimal. The influence of Al and Si on setting and hardening characteristics in high-Ca FA is substantial.

2. The conventional AAs, a combination of NaOH and Na$_2$SiO$_3$, are very good and economically viable alkali activating sols. Microstructural investigations revealed that GP concrete prepared with a lower NaOH to Na$_2$SiO$_3$ ratio reacts more efficiently because of the large surface area available for reaction and binding without being clogged by excess water. However, the hydroxyl groups tend to condense when specimens are heated to high temperatures.

3. FA-ITZ GP concrete consists of gel, pores, fissures, and unreacted FA particles. N-A-S-H gel can improve the strength of the ITZ by promoting the combination of the aggregate interface and the GP matrix. As a result, FA-GP concrete has nearly no obvious weak ITZ near the aggregate.

4. The existence of C-S-H gel, as well as GP gel, improves the mechanical and Ms characteristics of precursors either having high Ca or mixed with Ca components.

5. When it comes to GP synthesis, the criticality of precursor oxide dosage cannot be overstated. In general, the Si oxide content should be between 45% and 55%, the Al dosage should be between 22% and 28%, and the FeCO$_2$ and CaO content should be between 15% and 20%.

6. The experiment using MIP analysis reveals that extending the curing duration of GP specimens is useful in minimizing pores. The increased geopolymerization limits the connection between the pores, leading to a denser pattern. Furthermore, FA particles and gel may be used to refine the pores in FA-GP concrete. As a result, FA-GP concrete gel pores and capillary pores are concentrated in the tiny pore-size region. However, it
is worth noting that the silicon content of the AA plays an essential role in the refining of the FA-GP concrete pore structure.

7. It was found that increasing the fineness leads to an increase in the reaction rate and therefore requires a minus time of heating to achieve strength, as it was found that more than 60 MPa can achieve the strength of GP concrete by increasing the fineness of the precursor material.

8. FA-GP concrete with a compact and denser structure shows high mechanical strength and good efflorescence that make it an ideal choice for the construction industry and has been effectively used in precast industries. Moreover, there is an enormous possibility of utilizing high-Ca GP as a restorative material.

11. Recommendations

Though FA-GP concrete is a relatively new, innovative, and sustainable engineered material combination with numerous advantages, some difficulties remain, and some are recommended below for further investigation:

1. Currently, the findings of relevant investigations on the Ms of FA-GP concrete are discordant in several respects. For example, the conclusions on forming a new crystalline phase prior to and during the AA reaction of FA are inconsistent. As a result, additional systematic and in-depth research is required to prove this substance’s usefulness with greater certainty. Additionally, advanced analytical techniques such as micro- or nano-analysis and nuclear magnetic resonance must be employed.

2. Suitable guidelines for the selection of aggregate contents in FA-GP concrete should be developed. It is also critical to develop design procedures for each substantial predecessor. Furthermore, the usage of dune sands, fibers, marble dust, date ash, and other materials as precursors should be investigated.

3. Detailed investigations, such as those relating to the derivation and modeling of reaction kinetics under different treatment and production circumstances of the developing class of GP raw material, such as blended GPs and biomass ash GPs, are needed.

4. GP binders need a high pH and heat curing. As a result, efforts are needed to create a room-temperature-cured one-component GP system that uses solid activators rather than alkaline sols in order to gain widespread acceptability in the field.

5. FA-GP concrete should be given more functionality instead of using it as an alternative cement only. FA-GP concrete with biomass has the potential for development as a new class of lightweight fireproof composites.

6. Lastly, more research is needed to evaluate the cost of GP concrete compared to that of standard concrete. Furthermore, contradictory findings regarding the embodied energy and carbon footprint of GPs in comparison to traditional Portland cement must be addressed.

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References

1. Ahmed, H.U.; Mohammed, A.S.; Qaidi, S.M.A.; Faraj, R.H.; Sor, N.H.; Mohammed, A.A. Compressive strength of geopolymer concrete composites: A systematic comprehensive review, analysis and modeling. *Eur. J. Environ. Civ. Eng.* **2022**, *1–46*. [CrossRef]

2. Ahmad, J.; Kontoleon, K.J.; Majdi, A.; Naqash, M.T.; Deifalla, A.F.; Ben Kahla, N.; Isleem, H.F.; Qaidi, S.M.A. A Comprehensive Review on the Ground Granulated Blast Furnace Slag (GGBS) in Concrete Production. *Sustainability* **2022**, *14*, 8783. [CrossRef]

3. Saeed, A.; Najm, H.M.; Hassan, A.; Qaidi, S.; Sabri, M.M.S.; Mashaan, N.S. A Comprehensive Study on the Effect of Regular and Staggered Openings on the Seismic Performance of Shear Buildings. *Buildings* **2022**, *12*, 1293. [CrossRef]

4. Elsheikh, A. Bistable Morphing Composites for Energy-Harvesting Applications. *Polymers* **2022**, *14*, 1893. [CrossRef] [PubMed]

5. Qaidi, S. Behaviour of Concrete Made of Recycled Waste PET and Confined with CFRP Fabrics. Master’s Thesis, University of Duhok, Duhok, Iraq, 2021.

6. Monteiro, P.J.M.; Miller, S.A.; Horvath, A. Towards sustainable concrete. *Nat. Mater.* **2017**, *16*, 698–699. [CrossRef]

7. Arshad, S.; Sharif, M.B.; Irfan-Ul-Hassan, M.; Khan, M.; Zhang, J.-L. Efficiency of Supplementary Cementitious Materials and Natural Fiber on Mechanical Performance of Concrete. *Arab. J. Sci. Eng.* **2020**, *45*, 8577–8589. [CrossRef]

8. Cao, M.; Khan, M. Effectiveness of multiscale hybrid fiber reinforced cementitious composites under single degree of freedom hydraulic shaking table. *Struct. Concr.* **2021**, *22*, 535–549. [CrossRef]

9. Cao, M.; Khan, M.; Ahmed, S. Effectiveness of Calcium Carbonate Whisker in Cementitious Composites. *Period. Polyttech. Civ. Eng.* **2020**, *64*, 265–275. [CrossRef]

10. A Miller, S.; Horvath, A.; Monteiro, P.J.M. Readily implementable techniques can cut annual CO₂ emissions from the production of concrete by over 20%. *Environ. Res. Lett.* **2016**, *11*, 074029. [CrossRef]

11. Miller, S.A.; Moore, F.C. Climate and health damages from global concrete production. *Nat. Clim. Chang.* **2020**, *10*, 439–443. [CrossRef]

12. Ahmad, J.; Aslam, F.; Martinez-Garcia, R.; De-Prado-Gil, J.; Qaidi, S.M.A.; Brahmia, A. Effects of waste glass and waste marble on mechanical and durability performance of concrete. *Sci. Rep.* **2021**, *11*, 21525. [CrossRef] [PubMed]

13. Gollakota, A.R.; Volli, V.; Shu, C.-M. Progressive utilisation prospects of coal fly ash: A review. *Sci. Total Environ.* **2019**, *672*, 951–989. [CrossRef] [PubMed]

14. Amran, Y.M.; Alyousef, R.; Alabduljabbar, H.; El-Zeadani, M. Clean production and properties of geopolymer concrete; A review. *J. Clean. Prod.* **2020**, *251*, 119679. [CrossRef]

15. Xiao, R.; Polaczyk, P.; Zhang, M.; Jiang, X.; Zhang, Y.; Huang, B.; Hu, W. Evaluation of Glass Powder-Based Geopolymer Stabilized Road Bases Containing Recycled Waste Glass Aggregate. *Transp. Res. Rec. J. Transp. Res. Board* **2020**, *2674*, 22–32. [CrossRef]

16. Ng, C.; Alengaram, U.J.; Wong, L.S.; Mo, K.H.; Jumaat, M.Z.; Ramesh, S. A review on microstructural study and compressive strength of geopolymer mortar, paste and concrete. *Constr. Build. Mater.* **2018**, *186*, 550–576. [CrossRef]

17. Albibdah, A.S. Effect of partial replacement of geopolymer binder materials on the fresh and mechanical properties: A review. *Ceram. Int.* **2021**, *47*, 14923–14943. [CrossRef]

18. Raj, M.K.A.; Muthusamy, S.; Panchal, H.; Ibrahim, A.M.M.; Alsoufi, M.S.; Elsheikh, A.H. Investigation of mechanical properties of dual-fiber reinforcement in polymer composite. *J. Mater. Res. Technol.* **2022**, *18*, 3908–3915. [CrossRef]

19. Kamal, A.; Ashmawy, M.; Shanmugan, S.; Algazzar, A.M.; Elsheikh, A.H. Fabrication techniques of polymeric nanocomposites: A comprehensive review. *Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci.* **2021**, *236*, 4843–4861. [CrossRef]

20. Elsheikh, A.H.; Panchal, H.; Shanmugan, S.; Muthuramalingam, T.; El-Kassas, A.; Ramesh, B. Recent progresses in wood-plastic composites: Pre-processing treatments, manufacturing techniques, recyclability and eco-friendy assessment. *Eur. J. Environ. Civ. Eng.* **2022**, *8*, 100450. [CrossRef]

21. Assi, L.N.; Carter, K.; Deaver, E.; Anay, R.; Ziehl, P. Sustainable concrete: Building a greener future. *J. Clean. Prod.* **2018**, *198*, 1641–1651. [CrossRef]

22. Assi, L.N.; Carter, K.; Deaver, E.; Ziehl, P. Review of availability of source materials for geopolymer/sustainable concrete. *J. Clean. Prod.* **2020**, *263*, 121477. [CrossRef]

23. Van Jaarsveld, J.G.S.; van Deventer, J.S.J.; Lukey, G.C. The characterisation of source materials in fly ash-based geopolymers. *Mater. Lett.* **2003**, *57*, 1272–1280. [CrossRef]

24. Ahmad, J.; Majdi, A.; Elhag, A.B.; Deifalla, A.F.; Soomro, M.; Isleem, H.F.; Qaidi, S. A Step towards Sustainable Concrete with Substitution of Plastic Waste in Concrete: Overview on Mechanical, Durability and Microstructure Analysis. *Crystals* **2022**, *12*, 944. [CrossRef]
25. Ahmed, H.U.; Mohammed, A.A.; Rafiq, S.; Mohammed, A.S.; Mosavi, A.; Sor, N.H.; Qaidi, S.M.A. Compressive Strength of Sustainable Geopolymer Concrete Composites: A State-of-the-Art Review. *Sustainability* 2021, 13, 13502. [CrossRef]

26. Ahmed, H.U.; Mohammed, A.S.; Faraj, R.H.; Qaidi, S.M.; Mohammed, A.A. Compressive strength of geopolymer concrete modified with nano-silica: Experimental and modeling investigations. *Case Stud. Constr. Mater.* 2022, 16, e01036. [CrossRef]

27. Davidovits, J. Geopolymers. *J. Therm. Anal.* 1991, 37, 1633–1656. [CrossRef]

28. Barbosa, V.F.; MacKenzie, K. Thermal behaviour of inorganic geopolymers and composites derived from sodium polysialate. *Mater. Res. Bull.* 2003, 38, 319–331. [CrossRef]

29. Phair, J.; Van Deventer, J. Effect of silicate activator pH on the leaching and material characteristics of waste-based inorganic polymers. *Miner. Eng.* 2001, 14, 289–304. [CrossRef]

30. Najm, H.M.; Nanayakkara, O.; Sabri, M.M.S. Destructive and Non-Destructive Evaluation of Fibre-Reinforced Concrete: A Comprehensive Study of Mechanical Properties. *Materials* 2022, 15, 4432. [CrossRef]

31. Khan, M.; Ali, M. Improvement in concrete behavior with fly ash, silica-fume and coconut fibres. *Constr. Build. Mater.* 2019, 203, 174–187. [CrossRef]

32. Khan, M.; Ali, M. Optimization of concrete stiffeners for confined brick masonry structures. *J. Build. Eng.* 2020, 32, 101689. [CrossRef]

33. Rodrigs, L. Climate change: The massive CO₂ emitter you may not know about. *BBC News* 2018, 17, 2018.

34. Farhan, K.Z.; Johari, M.A.M.; Demirboğa, R. Assessment of important parameters involved in the synthesis of geopolymer composites: A review. *Constr. Build. Mater.* 2020, 264, 120276. [CrossRef]

35. Hassan, A.; Arif, M.; Shariq, M. Use of geopolymer concrete for a cleaner and sustainable environment—A review of mechanical properties and microstructure. *J. Clean. Prod.* 2019, 223, 704–728. [CrossRef]

36. Mohamedjani, A.; Suter, D.; Jeffrey-Bailey, T.; Song, T.; Arulrajah, A.; Horpibulsuk, S.; Law, D. Recycling waste materials in geopolymer concrete. *Clean Technol. Environ. Policy* 2019, 21, 493–515. [CrossRef]

37. Ahmed, S.N.; Sor, N.H.; Ahmed, M.A.; Qaidi, S.M. Thermal conductivity and hardened behavior of eco-friendly concrete incorporating waste polypropylene as fine aggregate. *Mater. Today Proc.* 2022, 57, 818–823. [CrossRef]

38. Aslam, F.; Zaid, O.; Althoei, F.; Alyami, S.H.; Qaidi, S.M.A.; de Prado Gil, J.; Martinez-Garcia, R. Evaluating the influence of fly ash and waste glass on the characteristics of coconut fibers reinforced concrete. *Struct. Concrete*, 2022, early view. [CrossRef]

39. Ryu, G.S.; Lee, Y.B.; Koh, K.T.; Chung, Y.S. The mechanical properties of fly ash-based geopolymer concrete with alkaline activators. *Constr. Build. Mater.* 2013, 47, 409–418. [CrossRef]

40. Seeveidya, V. Investigations on the Flexural Behaviour of Ferro Geopolymer Composite Slabs; Anna University: Tamil Nadu, India, 2014. [CrossRef]

41. Emad, W.; Mohammed, A.S.; Bras, A.; Asteris, P.G.; Kurda, R.; Mohammed, Z.; Hassan, A.; Qaidi, S.M.; Sihag, P. Metamodel techniques to estimate the compressive strength of UHPFRC using various mix proportions and a high range of curing temperatures. *Constr. Build. Mater.* 2022, 349, 128737. [CrossRef]

42. Faraj, R.H.; Ahmed, H.U.; Rafiq, S.; Sor, N.H.; Ibrahim, D.F.; Qaidi, S.M. Performance of Self-Compacting mortars modified with Nanoparticles: A systematic review and modeling. *Clean. Mater.* 2022, 4, 100086. [CrossRef]

43. He, X.; Yuhua, Z.; Qaidi, S.; Isleem, H.F.; Zaid, O.; Althoei, F.; Ahmad, J. Mine tailings-based geopolymers: A comprehensive review. *Ceram. Int.* 2022, 48, 21492–21412. [CrossRef]

44. Maglad, A.M.; Zaid, O.; Arbili, M.M.; Ascensão, G.; Serbâniou, A.A.; Grădinaru, C.M.; Garcia, R.M.; Qaidi, S.M.A.; Althoei, F.; de Prado-Gil, J. A Study on the Properties of Geopolymer Concrete Modified with Nano Graphene Oxide. *Buildings* 2022, 12, 1066. [CrossRef]

45. Mansi, A.; Sor, N.H.; Hilal, N.; A Qaidi, S.M. The Impact of Nano Clay on Normal and High-Performance Concrete Characteristics: A Review. In Proceedings of the 2nd International Conference of Al-Asraa University College for Engineering Sciences (ICAUC_ES 2021), Baghdad, Iraq, 3–4 November 2021; p. 010285.

46. Martinez-Garcia, R.; Jagadesh, P.; Zaid, O.; Serbâniou, A.A.; Fraile-Fernández, F.J.; de Prado-Gil, J.; Qaidi, S.M.A.; Grădinaru, C.M. The Present State of the Use of Waste Wood Ash as an Eco-Efficient Construction Material: A Review. *Materials* 2022, 15, 5349. [CrossRef] [PubMed]

47. Qaidi, S. Ultra-high-performance fiber-reinforced concrete (UHPFRC): A mini-review of the challenges. *ScienceOpen Preprints 2022*, preprints.

48. Qaidi, S. Ultra-high-performance fiber-reinforced concrete: Applications. *Preprints* 2022. [CrossRef]

49. Hemalatha, T.; Ramaswamy, A. A review on fly ash characteristics—Towards promoting high volume utilization in developing sustainable concrete. *J. Clean. Prod.* 2017, 147, 546–559. [CrossRef]

50. Dwivedi, A.; Jain, M.K. Fly ash–waste management and overview: A Review. *Recent Res. Sci. Technol.* 2014, 6, 1.

51. Amran, M.; Debbarma, S.; Ozbakkaloglu, T. Fly ash-based eco-friendly geopolymer concrete: A critical review of the long-term durability properties. *Constr. Build. Mater.* 2021, 270, 121857. [CrossRef]

52. Ranjbar, N.; Kuenzel, C. Cenospheres: A review. *Fuel* 2017, 207, 1–12. [CrossRef]
54. Nanayakkara, O.; Najm, H.M.; Sabri, M.M.S. Effect of Using Steel Bar Reinforcement on Concrete Quality by Ultrasonic Pulse Velocity Measurements. *Materials* 2022, 15, 4565. [CrossRef] [PubMed]

55. Qaidi, S.M.A. *PET-Concrete*; University of Duhok: Duhok, Iraq, 2021.

56. Davidovits, J. Geopolymers and geopolymeric materials. *J. Therm. Anal.* 1999, 35, 429–441. [CrossRef]

57. Purdon, A. The action of alkalis on blast-furnace slag. *J. Soc. Chem. Ind.* 1940, 59, 191–202.

58. Shi, C.; Roy, D.; Krivenko, P. *Alkali-Activated Cements and Concretes*; CRC Press: Boca Raton, FL, USA, 2003.

59. Provis, J.L.; Van Deventer, J.S.J. *Alkali Activated Materials: State-of-the-Art Report*; RILEM TC 224-AAM; Springer Science & Business Media: Dordrecht, The Netherlands, 2013.

60. Liu, M.Y.J.; Alengaram, U.J.; Santhanam, M.; Jumaat, M.Z.; Mo, K.H. Microstructural investigations of palm oil fuel ash and fly ash based binders in lightweight aggregate foamed geopolymer concrete. *Constr. Build. Mater.* 2022, 322, 126340. [CrossRef]

61. Khan, M.; Cao, M.; Ali, H.; Hussain, A. Basalt Fibers in Modified Whisker Reinforced Cementitious Composites. *Ultra-High-Performance Fiber-Reinforced Concrete: Mixture Design*. Elsevier: Amsterdam, The Netherlands, 2014.

62. Khan, M.; Cao, M.; Chu, S.; Ali, M. Properties of hybrid steel-basalt fiber reinforced concrete exposed to different surrounding conditions. *Constr. Build. Mater.* 2022, 322, 126340. [CrossRef]

63. Khan, M.; Cao, M.; Xie, C.; Ali, M. Effectiveness of hybrid steel-basalt fiber reinforced concrete under compression. *Period. Polytech. Civ. Eng.* 2022, 66, 344–354. [CrossRef]

64. Provis, J.L.; van Deventer, J.S.J. Geopolymerisation kinetics. 1. In situ energy-dispersive X-ray diffractometry. *Chem. Eng. Sci.* 2007, 62, 2318–2329. [CrossRef]

65. Provis, J.L.; van Deventer, J.S.J. Geopolymerisation kinetics. 2. Reaction kinetic modelling. *Chem. Eng. Sci.* 2011, 750–763. [CrossRef]

66. Zhang, F.; Gao, Z.; Wang, J.; Guo, J.; Hu, S.; Ling, Y. Properties of fresh and hardened fly ash/slag based geopolymer concrete: A review. *J. Clean. Prod.* 2020, 270, 122389. [CrossRef]

67. Qaidi, S.M.A. *PET-Concrete Confinement with CFRP*; University of Duhok: Duhok, Iraq, 2021.

68. Qaidi, S.M.A. *Ultra-High-Performance Fiber-Reinforced Concrete: Principles and Raw Materials*; University of Duhok: Duhok, Iraq, 2022.

69. Singh, J.; Singh, S.P. Geopolymization of solid waste of non-ferrous metallurgy—A review. *J. Environ. Manag.* 2019, 251, 105971. [CrossRef] [PubMed]

70. Shin, C.; Jimenez, A.F.; Palomo, A. New cements for the 21st century: The pursuit of an alternative to Portland cement. *Chem. Eng. Sci.* 2007, 62, 2309–2317. [CrossRef]

71. Zhang, F.; Gao, Z.; Wang, J.; Guo, J.; Hu, S.; Ling, Y. Properties of fresh and hardened fly ash/slag based geopolymer concrete: A review. *J. Clean. Prod.* 2020, 270, 122389. [CrossRef]

72. Zhang, Y.; Xiao, R.; Jiang, X.; Li, W.; Zhu, X.; Huang, B. Effect of particle size and curing temperature on mechanical and microstructural properties of waste glass-slag-based and waste glass-fly ash-based geopolymers. *J. Clean. Prod.* 2020, 273, 122970. [CrossRef]

73. Gupta, V.; Pathak, D.K.; Siddique, S.; Kumar, R.; Chaudhary, S. Study on the mineral phase characteristics of various Indian biomass and coal fly ash for its use in masonry construction products. *Constr. Build. Mater.* 2022, 235, 117413. [CrossRef]

74. Hashmi, A.F.; Shariq, M.; Baqi, A.; Haq, M. Optimization of fly ash concrete mix—A solution for sustainable development. *Mater. Today Proc.* 2020, 26, 3250–3256. [CrossRef]

75. Khan, M.; Cao, M.; Hussain, A.; Chu, S. Effect of silica-fume content on performance of CaCO3 whisker and basalt fiber at matrix interface in cement-based composites. *Constr. Build. Mater.* 2021, 300, 124046. [CrossRef]

76. Khan, M.; Cao, M.; Xie, C.; Ali, M. Effectiveness of hybrid steel-basalt fiber reinforced concrete under compression. *Case Stud. Constr. Mater.* 2022, 16, e00941. [CrossRef]

77. Khan, M.; Cao, M.; Xie, C.; Ali, M. Hybrid fiber concrete with different basalt fiber length and content. *Struct. Concr.* 2021, 23, 346–364. [CrossRef]

78. Yilmaz, G. Structural characterization of glass–ceramics made from fly ash containing SiO2–Al2O3–Fe2O3–CaO and analysis by FT-IR–XRD–SEM methods. *J. Mol. Struct.* 2012, 1019, 37–42. [CrossRef]

79. Qaidi, S.M.A. *Ultra-High-Performance Fiber-Reinforced Concrete: Mixture Design*; University of Duhok: Duhok, Iraq, 2022.

80. Qaidi, S.M.A. *Ultra-High-Performance Fiber-Reinforced Concrete: Hydration and Microstructure*; University of Duhok: Duhok, Iraq, 2022.

81. Qaidi, S.M.A. *Ultra-High-Performance Fiber-Reinforced Concrete: Fresh Properties*; University of Duhok: Duhok, Iraq, 2022. [CrossRef]

82. Chou, M.I.M. *Fly Ash, Encyclopedia of Sustainability Science and Technology*; Springer New York: New York, NY, USA, 2012; pp. 3820–3843.

83. Davidovits, J. 30 years of successes and failures in geopolymer applications. Market trends and potential breakthroughs. In *Geopolymer 2002 Conference*; Geopolymer Institute: Saint-Quentin, France; Melbourne, VC, Australia, 2002; p. 29.
199. Khater, H. Effect of Calcium on Geopolymerization of Aluminosilicate Wastes. J. Mater. Civ. Eng. 2012, 24, 92–101. [CrossRef]
200. Nazari, A.; Bagheri, A.; Riahi, S. Properties of geopolymer with seeded fly ash and rice husk bark ash. Mater. Sci. Eng. A 2011, 528, 7395–7401. [CrossRef]
201. Qaidi, S. Ultra-High-Performance Geopolymer Concrete. Part 3: Environmental Parameters; University of Duhok: Duhok, Iraq, 2022.
202. Qaidi, S. Ultra-High-Performance Geopolymer Concrete. Part 4: Mix Design Methods; University of Duhok: Duhok, Iraq, 2022.
203. Qaidi, S. Ultra-High-Performance Geopolymer Concrete. Part 5: Fresh Properties; University of Duhok: Duhok, Iraq, 2022.
204. Sata, V.; Sathonsaowaphak, A.; Chindaprasirt, P. Resistance of lignite bottom ash geopolymer mortar to sulfate and sulfuric acid attack. Constr. Compos. Mater. 2012, 34, 700–708. [CrossRef]
205. Detphan, S.; Chindaprasirt, P. Preparation of fly ash and rice husk ash geopolymer. Int. J. Miner. Metall. Mater. 2009, 16, 720–726.
206. Duxson, P.; Provis, J.L. Designing Precursors for Geopolymer Cements. J. Am. Ceram. Soc. 2008, 91, 3864–3869. [CrossRef]
207. Li, Z.; Xu, G.; Shi, X. Reactivity of coal fly ash used in cementitious binder systems: A state-of-the-art overview. Fuel 2021, 301, 121031. [CrossRef]
208. Okoye, F.; Durgaprasad, J.; Singh, N. Mechanical properties of alkali activated flyash/Kaolin based geopolymer concrete. Constr. Build. Mater. 2015, 98, 685–691. [CrossRef]
209. Van Chanh, N.; Trung, B.D.; Van Tuan, D. Recent research geopolymer concrete. In Proceedings of the 3rd AFC International Conference-ACF/VCA, HCM City, Vietnam, 11–13 November 2008; pp. 235–241.
210. Rangan, B.V.; Hardjito, D.; Wallah, S.E.; Sumajouw, D.M. Studies on fly ash-based geopolymer concrete. In Proceedings of the World Congress Geopolymer, Saint Quentin, France, 28 June–1 July 2005; pp. 133–137.
211. Topark-Ngarm, P.; Chindaprasirt, P.; Sata, V. Setting Time, Strength, and Bond of High-Calcium Fly Ash Geopolymer Concrete. J. Mater. Civ. Eng. 2015, 27, 04014198. [CrossRef]
212. Hardjito, D.; Wallah, S.E.; Sumajouw, D.M.; Rangan, B.V. Fly Ash-Based Geopolymer Concrete. Aust. J. Struct. Eng. 2005, 6, 77–86. [CrossRef]
213. Sagoe-Crentsil, K.; Brown, T.; Taylor, A. Drying shrinkage and creep performance of geopolymer concrete. J. Sustain. Cem.-Based Mater. 2013, 2, 35–42. [CrossRef]
214. Atmaja, L.; Fanzuri, H.; Maharani, A. Crystalline phase reactivity in the synthesis of fly ash-based geopolymer. Indones. J. Chem. 2011, 11, 90–95. [CrossRef]
215. Kupwade-Patil, K.; Allouche, E.N. Impact of Alkali Silica Reaction on Fly Ash-Based Geopolymer Concrete. J. Mater. Civ. Eng. 2013, 25, 131–139. [CrossRef]
216. Tennakoon, C.; Shayan, A.; Sagoe-Crentsil, K.; Sanjayan, J. Importance of reactive SiO$_2$, AlO$_3$ and Na$_2$O in geopolymer formation. In Proceedings of the 9th Austroads Bridge Conference, Sydney, Australia, 22–24 October 2014.
217. Thakur, R.N.; Ghosh, S. Effect of mix composition on compressive strength and microstructure of fly ash based geopolymer composites. ARPN J. Eng. Appl. Sci. 2009, 4, 68–74.
218. Bignozzi, M.C.; Manzi, S.; Natali, M.E.; Rickard, W.D.; van Riessen, A. Room temperature alkali activation of flyash. Constr. Build. Mater. 2014, 69, 262–270. [CrossRef]
219. Lloyd, N.; Rangan, V. Geopolymer concrete with fly ash. In Proceedings of the Second International Conference on Sustainable Construction Materials and Technologies, UWM Center for By-Products Utilization, Ancona, Italy, 28 June 2010; pp. 1493–1504.
220. Van Jaarsveld, J.G.S.; van Deventer, J.S.; Lukey, G.C. The effect of composition and temperature on the properties of fly ash- and kaolinite-based geopolymers. Chem. Eng. J. 2002, 89, 63–73. [CrossRef]
221. Chotetanorm, C.; Chindaprasirt, P.; Sata, V.; Rukzon, S.; Sathonsaowaphak, A. High-Calcium Bottom Ash Geopolymer: Sorptivity, Pore Size, and Resistance to Sodium Sulfate Attack. J. Mater. Civ. Eng. 2013, 25, 105–111. [CrossRef]
222. Qaidi, S. Ultra-High-Performance Geopolymer Concrete. Part 6: Mechanical Properties; University of Duhok: Duhok, Iraq, 2022.
223. Qaidi, S. Ultra-High-Performance Geopolymer Concrete. Part 7: Mechanical Performance Correlation; University of Duhok: Duhok, Iraq, 2022.
224. Qaidi, S. Ultra-High-Performance Geopolymer Concrete. Part 8: Dynamic Behavior; University of Duhok: Duhok, Iraq, 2022.
225. Bernal, S.A.; Provis, J.L. Durability of Alkali-Activated Materials: Progress and Perspectives. J. Am. Ceram. Soc. 2014, 97, 997–1008. [CrossRef]
226. Phoo-Ngernkham, T.; Maegawa, A.; Mishima, N.; Hatanaka, S.; Chindaprasirt, P. Effects of sodium hydroxide and sodium silicate solutions on compressive and shear bond strengths of FA–GBFS geopolymer. Constr. Build. Mater. 2015, 91, 1–8. [CrossRef]
227. Torres-Carrasco, M.; Puertas, F. Waste glass in the geopolymer preparation. Mechanical and microstructural characterization. J. Clean. Prod. 2015, 90, 397–408. [CrossRef]
228. Ding, Y.-C.; Cheng, T.-W.; Dai, Y.-S. Application of geopolymer paste for concrete repair. Struct. Concr. 2017, 18, 561–570. [CrossRef]
229. Phoo-Ngernkham, T.; Sata, V.; Hanjitsuwan, S.; Rtidirud, C.; Hatanaka, S.; Chindaprasirt, P. High calcium fly ash geopolymer mortar containing Portland cement for use as repair material. Constr. Build. Mater. 2015, 98, 482–488. [CrossRef]
230. Demie, S.; Nuruddin, M.F.; Shafiq, N. Effects of micro-structure characteristics of interfacial transition zone on the compressive strength of self-compacting geopolymer concrete. Constr. Build. Mater. 2013, 41, 91–98. [CrossRef]
231. Li, Z.; Chen, R.; Zhang, L. Utilization of chitosan biopolymer to enhance fly ash-based geopolymer. J. Mater. Sci. 2013, 48, 7986–7993. [CrossRef]
232. Rattanasak, U.; Pankhet, K.; Chindaprasirt, P. Effect of chemical admixtures on properties of high-calcium fly ash geopolymer. *Int. J. Miner. Met. Mater.* 2011, 18, 364–369. [CrossRef]

233. Nath, S.; Kumar, S. Influence of iron making slags on strength and microstructure of fly ash geopolymer. *Constr. Build. Mater.* 2013, 38, 924–930. [CrossRef]

234. Zhang, M.; Zhao, M.; Zhang, G.; Mann, D.; Lumsden, K.; Tao, M. Durability of red mud-fly ash based geopolymer and leaching behavior of heavy metals in sulfuric acid solutions and deionized water. *Constr. Build. Mater.* 2016, 124, 373–382. [CrossRef]

235. Adak, D.; Sarkar, M.; Mandal, S. Effect of nano-silica on strength and durability of fly ash based geopolymer mortar. *Constr. Build. Mater.* 2014, 70, 453–459. [CrossRef]

236. Andini, S.; Cioffi, R.; Colangelo, F.; Grieco, T.; Montagnaro, F.; Santoro, L. Coal fly ash as raw material for the manufacture of geopolymer-based products. *Waste Manag.* 2008, 28, 416–423. [CrossRef]

237. Temuujin, J.; Williams, R.; van Riessen, A. Effect of mechanical activation of fly ash on the properties of geopolymer cured at ambient temperature. *J. Mater. Process. Technol.* 2009, 209, 5276–5280. [CrossRef]

238. Prabha, V.; Revathi, V. Geopolymer Mortar Incorporating High Calcium Fly Ash and Silica Fume. *J. Miner. Met. Mater.* 2012, 19, 872–878. [CrossRef]

239. Rattanasak, U.; Pankhet, K.; Chindaprasirt, P. Effect of chemical admixtures on properties of high-calcium fly ash geopolymer. *Mater. Struct.* 2012, 46, 375–381. [CrossRef]

240. Chindaprasirt, P.; Rattanasak, U.; Taebuanhuad, S. Resistance to acid and sulfate solutions of microwave-assisted high calcium fly ash geopolymer. *Mater. Struct.* 2012, 46, 375–381. [CrossRef]

241. Jamkar, S.; Ghugal, Y.; Patankar, S. Effect of fly ash fineness on workability and compressive strength of geopolymer concrete. *MATEC Web Conf.* 2017, 103, 01026. [CrossRef]

242. Giasuddin, H.M.; Sanjayan, J.G.; Ranjith, P. Strength of geopolymer cured in saline water in ambient conditions. *J. Miner. Met. Mater.* 2011, 18, 100–104. [CrossRef]

243. Villa, C.; Pecina, E.; Torres, R.; González, A. Geopolymer synthesis using alkaline activation of natural zeolite. *Ceram. Int.* 2015, 41, 583–587. [CrossRef]

244. Shinde, P.; Patankar, S.; Sayyad, A. Investigation on effects of fineness of flyash and alkaline ratio on mechanical properties of geopolymer concrete. *Res. Eng. Struct. Mater.* 2018, 4, 61–71. [CrossRef]

245. Abdulkareem, O.A.; Ramli, M. Optimization of Alkaline Activator Mixing and Curing Conditions for A fly Ash-Based Geopolymer Paste System. *Mod. Appl. Sci.* 2015, 9, 35–47. [CrossRef]

246. Alomayri, T. Experimental study of the microstructural and mechanical properties of geopolymer paste with nano material particles. *J. Build. Eng.* 2019, 100788. [CrossRef]

247. He, P.; Jia, D.; Wang, M.; Zhou, Y. Thermal evolution and crystallization kinetics of potassium-based geopolymer. *Ceram. Int.* 2011, 37, 59–63. [CrossRef]

248. Palomo, A.; Gutiérrez, M.W.; Blanco, M.T. Alkali-activated fly ashes: A cement for the future. *J. Mater. Sci.* 2009, 44, 608–619. [CrossRef]

249. Shinde, P.; Patankar, S.; Sayyad, A. Investigation on effects of fineness of flyash and alkaline ratio on mechanical properties of geopolymer concrete. *Res. Eng. Struct. Mater.* 2018, 4, 61–71. [CrossRef]

250. Mohammed, H.; Ahmed, S. Mechanical performance evaluation of concrete with waste coarse ceramic aggregate. In *Ultra-High-Performance Geopolymer Concrete. Part 9: Strain Hardening Behavior of Heavy Metals in Sulfuric Acid Solutions and Deionized Water*. *Ceram. Int.* 2015, 41, 583–587. [CrossRef]

251. Firdaus; Yunus, I.; Rosidawani, D. Contribution of Fineness Level of Fly Ash to the Compressive Strength of Geopolymer Mortar. *Environ. Eng.* 2015, 187, 56–67. [CrossRef]

252. Qaidi, S. Optimization of Alkaline Activator Mixing and Curing Conditions for A fly Ash-Based Geopolymer Paste System. *Mod. Appl. Sci.* 2015, 9, 35–47. [CrossRef]

253. Prabha, V.; Revathi, V. Geopolymer Mortar Incorporating High Calcium Fly Ash and Silica Fume. *Arch. Civ. Eng.* 2019, 65, 3–16. [CrossRef]

254. Andini, S.; Cioffi, R.; Colangelo, F.; Grieco, T.; Montagnaro, F.; Santoro, L. Coal fly ash as raw material for the manufacture of geopolymer-based products. *Waste Manag.* 2008, 28, 416–423. [CrossRef]

255. Karthik, A.; Sudalaimani, K.; Vijayakumar, C.; Saravanakumar, S. Effect of bio-additives on physico-chemical properties of fly ash geopolymer-based self-cured geopolymer mortars. *J. Hazard. Mater.* 2010, 171, 117868. [CrossRef]

256. Firdaus; Yunus, I.; Rosidawani, D. Contribution of Fineness Level of Fly Ash to the Compressive Strength of Geopolymer Mortar. *MATEC Web Conf.* 2017, 103, 01026. [CrossRef]

257. Chindaprasirt, P.; Rattanasak, U.; Vongvoradit, P.; Jenjirapanya, S. Thermal treatment and utilization of Al-rich waste in high calcium fly ash geopolymeric materials. *Int. J. Miner. Met. Mater.* 2012, 19, 872–878. [CrossRef]

258. Andini, S.; Cioffi, R.; Colangelo, F.; Grieco, T.; Montagnaro, F.; Santoro, L. Coal fly ash as raw material for the manufacture of geopolymer-based products. *Waste Manag.* 2008, 28, 416–423. [CrossRef]

259. Fu, Q.; Xu, W.; Zhao, X.; Bu, M.; Yuan, Q.; Niu, D. The microstructure and durability of fly ash-based geopolymer concrete: A review. *Ceram. Int.* 2021, 47, 29550–29566. [CrossRef]

260. Lloyd, R.R.; Provis, J.L.; van Deventer, J.S.J. Microscopy and microanalysis of inorganic polymer cements. In *Ultra-High-Performance Geopolymer Concrete. Part 9: Strain Hardening Behavior of Heavy Metals in Sulfuric Acid Solutions and Deionized Water*. *Ceram. Int.* 2015, 41, 583–587. [CrossRef]

261. Qaidi, S. Optimization of Alkaline Activator Mixing and Curing Conditions for A fly Ash-Based Geopolymer Paste System. *Mod. Appl. Sci.* 2015, 9, 35–47. [CrossRef]
262. Parveen; Singhal, D.; Junaid, M.T.; Jindal, B.B.; Mehta, A. Mechanical and microstructural properties of fly ash based geopolymer concrete incorporating alcocine at ambient curing. Constr. Build. Mater. 2018, 180, 298–307. [CrossRef]

263. Aligizaki, K.K. Pore Structure of Cement-Based Materials: Testing, Interpretation and Requirements; CRC Press: Boca Raton, FL, USA, 2005.

264. Puertas, F.; Palacios, M.; Manzano, H.; Dolado, J.S.; Rico, A.; Rodríguez, J. A model for the C-A-S-H gel formed in alkali-activated slag cements. J. Eur. Ceram. Soc. 2011, 31, 2043–2056. [CrossRef]

265. Najm, H.M.; Ahmad, S.; Khan, R.A. Mechanical and Microstructural Analysis of Waste Ceramic Optimal Concrete Reinforced by Hybrid Fibers Materials: A Comprehensive Study. J. Archit. Environ. Struct. Eng. Res. 2022, 5, 11–33. [CrossRef]

266. Najm, H.M.; Nanayakkara, O.; Ahmad, M.; Sabri Sabri, M.M. Mechanical Properties, Crack Width, and Propagation of Waste Ceramic Concrete Subjected to Elevated Temperatures: A Comprehensive Study. Materials 2022, 15, 2371. [CrossRef]

267. Najm, H.M.; Nanayakkara, O.; Ahmad, M.; Sabri Sabri, M.M. Colour Change of Sustainable Concrete Containing Waste Ceramic and Hybrid Fibre: Effect of Temperature. Materials 2022, 15, 2174. [CrossRef]

268. Najm, H.M.; Ahmad, S. Effect of elevated temperatures exposure on the mechanical properties of waste ceramic concrete reinforced with hybrid fibers materials. Sigma J. Eng. Nat. Sci. 2021; in press.

269. Najm, H.M.; Ahmad, S. The Use of Waste Ceramic Optimal Concrete for A Cleaner and Sustainable Environment—A Case Study of Mechanical Properties. Civ. Environ. Eng. Rep. 2022, 32, 85–102.

270. Najm, H.M.; Ahmad, S.; Submitter, Y. Artificial Neural Networks for Evaluation & Prediction of the Mechanical Properties of Waste Ceramic Optimal Concrete Exposed to Elevated Temperature. SSRN 2021. [CrossRef]