

# High Strength Ambient Cured Red Mud Geopolymer using Automotive Glass Waste and GGBFS: Mechanical and Microstructure Properties

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## ABSTRACT

The Bayer process for refining bauxite ore produces a highly alkaline by-product called red mud (RM). The typical disposal of this product on open land creates a high impact on the environment. To mitigate these ecological issues, utilizing RM in geopolymer concrete (GPC) offers a sustainable solution. This study aims to enhance the mechanical properties of RM-based GPC cured under ambient conditions to produce higher-grade concrete. Red mud was collected from the eastern region of the Kingdom of Saudi Arabia, and microstructural investigations were conducted to characterize the binder components. Although RM contains silica and alumina, the quantities are insufficient to produce high-strength concrete. Therefore, the geopolymerization process was enhanced by incorporating alumina, silica, and calcium-rich materials such as ground granulated blast furnace slag (GGBFS) and silica-rich automotive glass waste powder (AGWP). A series of tests aimed at optimizing the molarity (M) of sodium hydroxide (SH) solution, the sodium silicate (SS) to SH ratio, the fluid-to-binder (F/B) ratio, and the binder proportions were also conducted. Experimental results indicate that under ambient temperature (27 - 31 °C), the F/B ratio of 0.5, M=10, and SS/SH = 2.5 with binder proportions of RM: AGWP: GGBFS = 50:10:40 produces a remarkable compressive strength of 64 MPa at 28 days of the curing period. Microstructural observations revealed denser gel formation and reduced porosity in ternary blends. The results demonstrate a viable pathway to high-strength, ambient-cured RM geopolymers.

## 1. Introduction

The Portland cement production releases a lot of carbon dioxide (CO<sub>2</sub>) into the air, resulting in environmental challenges such as ozone depletion and global warming. The construction industry is responsible for 8% of all greenhouse gas emissions. Geopolymer concrete (GPC) is a promising alternative to Ordinary Portland Cement (OPC) [2]. The geopolymer is the product of polymerization between an aluminosilicate source and an alkaline reagent [3]. The GPC is called “green cement” because it doesn’t release a lot of greenhouse gases during its production.

Red mud (RM) is a highly alkaline by-product of the Bayer process used to extract alumina from bauxite ore. Depending on the efficiency of the extraction process and the sources used, one metric ton of pure alumina generally generates about 1 to 1.5 metric tons of RM. Between 2023 and 2024, yearly alumina production reached approximately 142 million metric tons. Con-

sequently, an estimated 170 million tons of RM were produced [4]. With a highly alkaline pH at 10 to 13 [5], RM contains sufficient amorphous silica and alumina to serve as a precursor for geopolymer synthesis. RM is usually disposed of in open land, which poses risks of soil and groundwater contamination [6]. Harmful compounds in RM can percolate into groundwater, leading to soil contamination. Therefore, proper disposal and effective utilization of RM are critical for the alumina industry.

The properties of the source materials, as well as key parameters such as the sodium silicate (SS) to sodium hydroxide (SH) ratio, SH molarity, and fluid-to-binder ratio (F/B), significantly affect the mechanical properties of GPC [7–10]. Certain source materials, such as slag, metakaolin, and fly ash, have demonstrated significant potential in enhancing the compressive strength of GPC [3]. Geopolymerization involves the chemical reaction of source materials, either single or in combination with

an alkaline solution. The alkaline solution is typically a combination of SS or potassium silicate with KOH or SH [11].

This research investigates the novel synergistic effects within RM-based GPC through the integration of AGWP and GGBFS to produce high-strength concrete under ambient curing conditions. The RM mainly consists of crystalline compounds, and its properties can't be generalized, as it mostly depends on the mineralogical composition of the bauxite ore and the refining process [12]. To produce high-strength concrete, supplementary materials are to be incorporated, as RM contains low concentrations of alumina and silica. In this research, ground granulated blast furnace slag (GGBFS), rich in calcium and alumina, and automotive glass waste powder (AGWP), abundant in silica, were used along with RM to enhance strength and durability. To optimize the mechanical properties of GPC, concrete samples were made with different binder proportions, various trials of SH molarities, SS-to-SH ratios, and F/B ratios. The main test used for the assessment was the compressive strength, conducted on C<sub>30</sub> grade concrete cubes cured at ambient temperature (27–31°C).

### 1.1 Geopolymer

Geopolymerization is the process of turning aluminosilicate raw materials (precursors) into a covalently bonded three-dimensional network characterized by [-Si-O-Al-O-]<sub>n</sub> bonds. This process takes place when precursors react in an alkaline environment at room temperature or elevated temperature [13]. The process has three main steps: (i) dissolution of aluminosilicates; (ii) coagulation; and (iii) polymerization or crystallization [14].

An alkaline activator reacts with the aluminosilicate source during the dissolution phase. Alkali metals make electrons unstable, which causes them to move around silicon atoms. This breaks the Si-O-Si bonds in the medium. The rate of dissolution is affected by factors like temperature, particle size, precursor reactivity, and the concentration of the alkaline solution [15]. During the coagulation phase, a notable increase in concentration results in the formation of aluminosilicate oligomers, where the gel structural orientation varies based on the concentration of Si/Al species [16]. When the Si/Al ratio is about 1, crystalline materials form during the polymerization or crystallization phase. These structures are arranged in a systematic way. Studies of synthesis that used higher ratios have also shown success [17].

Xu and Van [18] examined the compressive strength of concrete generated through binary and ternary mineral systems activated by SH + SS and KOH + K<sub>2</sub>SiO<sub>3</sub> solutions. Their study found that geopolymers could be made from geological materials like kaolinite or clay or from industrial waste products like fly ash, granulated blast furnace slag, wastepaper sludge, rice husk ash, and wheat straw ash. Cost competitiveness, material availability, and the specific performance needs are

the main factors that affect the selection of precursor materials.

Ahmari et al. [19] demonstrated that the rate of reaction increases at elevated curing temperature, which in turn increases the compressive strength. The best temperature for curing is usually between 80°C and 90°C, but an extended period of curing at ambient temperature can also make the concrete achieve sufficient strength.

K. Vijai et al. [20], Hamraj et al. [21], and Manjunathan M. Katti et al. [22] have conducted significant studies on the performance of geopolymer. K. Vijai and others looked into how different types of curing affect fly ash-based GPC. Ambient curing resulted in gradual strength increases for up to 28 days, whereas hot curing resulted in rapid strength increases that leveled off after 7 days. Hamraj et al. found that concrete made with fly ash was 90% stronger after 7 days, while concrete made with cement was only 70% stronger. However, the difference got smaller after 28 days. Manjunathan M. Katti et al. showed that incorporating the GGBFS to fly ash-based geopolymers made them stronger, with 8M alkaline solutions working better than 6M solutions. In their study, they completely replaced OPC with catalytic liquids, GGBFS, and ASTM Class F fly ash. The compressive strength was evaluated by changing the molar concentration and the binder material proportions.

### 1.2 Binder Materials

#### 1.2.1 Red Mud (RM)

Bauxite is the main mineral used in the aluminum industry. When it is processed, it makes a by-product called red mud [23]. The higher pH level of this by-product pollutes the environment [24]. Every year, more than 170 million tons of red mud are generated around the world, which has a big impact on the environment.

The color of RM can be grey, white, or red, depending on how much iron oxide is in it. It melts between 1100 and 1500 °C, has a density of 2700 to 2950 kg/m<sup>3</sup>, and a bulk density of 750 to 1000 kg/m<sup>3</sup> [25]. The pH of RM is between 10 and 12.5, which means it is very alkaline. The liquid index for RM is 1.32, and the plasticity index is between 17.2 and 30.5 [26].

Because RM consists of alumina (Al<sub>2</sub>O<sub>3</sub>), haematite (Fe<sub>2</sub>O<sub>3</sub>), silicates (SiO<sub>2</sub>), and alkali oxides (Na, Ca, K), it is a promising raw material for geopolymer synthesis. However, the composition generally features a limited amount of alumina alongside predominantly non-reactive silica [27]. Therefore, it is commonly combined with supplementary sources of alumina and active silica, including fly ash, GGBFS, silica fume, rice husk ash, and metakaolin [28].

#### 1.2.2 Ground Granulated Blast Furnace Slag (GGBFS)

Ground granulated blast furnace slag (GGBFS) is a by-product of the iron manufacturing industry, created when iron ore, coke, and limestone are combined in a blast furnace. The resultant molten slag, which floats

above the molten iron at temperatures of approximately 1500°C to 1600°C [29], contains roughly 30% to 40% SiO<sub>2</sub> and around 40% CaO, resembling the chemical composition of OPC. Rapid quenching produces glassy granules, which are subsequently dried and ground into a fine powder to produce GGBFS.

GGBFS contains more than 85% glass by volume, rendering it highly reactive. Its specific gravity (2.7 to 2.9) is lower than that of OPC with a bulk density of 1200 kg/m<sup>3</sup>–1300 kg/m<sup>3</sup> [30]. These properties make the GGBFS an ideal binder material for the development of GPC. GGBFS consists of sufficient quantities of silica and alumina, which are activated by alkaline solution. Geopolymer paste is formed during the geopolymerization process, which in turn acts as a strong binder for aggregates. Adding GGBFS as a binder material will contribute to develop higher compressive strength and better resistance to environmental degradation [31].

### 1.2.3 Automotive Glass Waste Powder (AGWP)

Automotive glass waste powder (AGWP) is prepared from the waste glass products of the automotive industry. It consists mainly of soda-lime glass, which is mostly made up of silica (SiO<sub>2</sub>) and other additives like lime, sodium carbonate, and other oxides to make it stronger [32]. Glass is a material that is brittle, clear, and not crystalline. Because it is strong and clear, it is widely used in the car industry. Laminated glass is often used for windshields, and tempered glass is often used for side and back windows. In the late 1930s, automakers started using tempered glass for the side and rear windows of cars [33,34].

Inert glass can be recycled in a number of ways without changing its chemical makeup through proper methods [35]. Around 130 million metric tons of glass are made around the world every year, and about 100 million metric tons are thrown away as trash [36,37]. Only 21% of this waste is recycled [38], and the rest goes to landfills because of the colors, materials composition and sorting difficulties. To reduce the environmental impact of glass waste, it is important to recycle and use it properly.

AGWP has shown that it could be a good partial binder replacement in concrete. When mixed with alkalis, its pozzolanic properties and amorphous structure make cementitious reactions better, which makes sodium silicate gel, which makes the mechanical performance better [39,40]. Adding AGWP to geopolymer concrete makes the concrete matrix denser, less porous, and stronger and more durable [41–43]. In addition, adding AGWP to GPC production is in line with the Sustainable Development Goals because it keeps waste out of landfills and encourages the use of other materials as binders in the construction sector. But more research is needed to identify the best way to integrate it and see how well it works overtime in different environments.

This study aims to develop high-strength GPC. RM, AGWP, and GGBFS were utilized as the sources of

alumina, calcium oxide, and silica, while SS and SH solutions were used as alkaline reagents. The physical, microstructural, and mechanical performances were investigated by characterizing the raw materials using X-ray fluorescence (XRF), X-ray diffraction (XRD), scanning electron microscopy (SEM), and particle size analysis (PSA). Furthermore, testing focused on the density, workability, and compressive strength, complemented by morphological analysis of the hardened GPC.

## 2. Methodology

### 2.1 Materials and Methods

The physical appearances of RM, AGWP, and GGBFS are shown in Fig. 1. The main waste material used to develop the sustainable GPC was red mud (RM), which was collected from the eastern province of the Kingdom of Saudi Arabia. The pH was 10.5, and the bulk density was 0.93 g/cc. The Bayer process uses alkali to treat bauxite ore, which causes this by-product to have a high alkalinity value. The collected dry RM was pulverized and then used a No. 60 (250 μm) sieve to ensure homogeneity and to get rid of any lumps.



**Fig. 1.** Binder materials: (a) RM, (b) AGWP, and (c) GGBFS

For AGWP preparation, waste glass fragments were sourced from the automotive industry and processed into powder in the laboratory using a Los Angeles abrasion machine that contained 11 steel balls (48 mm diameter, weighing 395–445 grams each). Approximately 5 kg of glass pieces were pulverized at 30 rpm for six hours. The resulting glass powder was sieved through a No. 60 (250 μm) sieve to ensure homogeneity and remove oversized particles. Fig. 2 illustrates the preparation of AGWP using a grinding machine.

Commercially available GGBFS was sourced from a private firm located in the same province within the Kingdom of Saudi Arabia. It was supplied as a grey powder. The bulk densities of AGWP and GGBFS were determined to be 1.30 g/cc and 1.09 g/cc, respectively. Sodium silicate (Na<sub>2</sub>SiO<sub>3</sub>, commonly known as water glass) – alkaline grade, specific gravity 1.5- and sodium hydroxide (NaOH flakes, 99% purity) were utilized as alkaline reagents. Fig. 3 illustrates the physical



**Fig. 2.** Preparation of materials (a) Automotive glass waste (b) Grinding machine

appearance of the sodium hydroxide solution, while Fig. 4 shows the sodium hydroxide flakes.

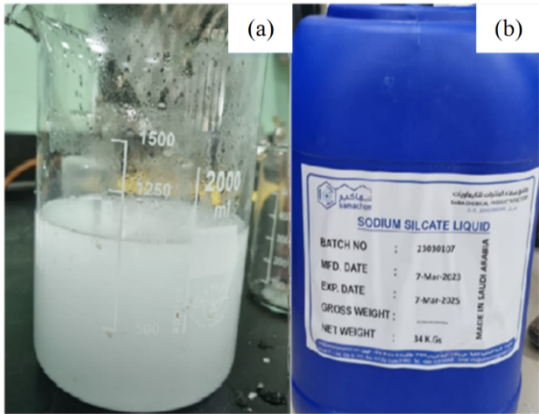


**Fig. 3.** (a) Sodium hydroxide solution (b) Sodium silicate liquid



**Fig. 4.** Sodium hydroxide flakes

The chemical compositions of the binder materials were analysed using X-ray fluorescence (XRF) with a Perkin Elmer FL 6500 instrument. Particle size distribution was determined using dynamic light scattering (DLS) with the ZEN3600 system. Morphological characteristics were examined using a desktop scanning electron microscope (SEMscope IEM 11+ desktop scanning electron microscope (SEM), Invenso, Waltham, MA, USA). Quantitative phase compositions were analyzed through X-ray diffraction (XRD) using Shimadzu XRD-6000 diffractometer, from Kyoto, Japan.

The sodium hydroxide solution was prepared by dissolving SH flakes in distilled water. The molarity (M) of the solution was varied across five levels (6, 8, 10, 12, and 14), with 10 M being prepared by dissolving 400 grams of SH flakes in distilled water to achieve one liter of solution. The SH solution was stored for 24 hours to allow the exothermically heated solution to dissipate and reach room temperature before mixing with sodium silicate to form the alkaline solution. The SS: SH ratios tested were 0.75, 1.0, 1.5, 2, 2.5, 3, and 3.5.

## 2.2 Preparation and Testing of GPC Cubes

To prepare the GPC cubes, binder materials, fine aggregates, and coarse aggregates were weighed according to the proportions for C<sub>30</sub> grade concrete. The mix proportions were determined according to the ACI mix design method. The resulting ratio of binder materials: fine aggregates: coarse aggregates was 1:1.72:2.56.

The mixing of geopolymer concrete ingredients was conducted in accordance with ASTM C 192 with modifications necessitated by the absence of a specific standard for GPC. Manual mixing was used due to the limited volume of concrete prepared. Initially, dry binder materials were blended in a clean metal pan for approximately 2 to 3 minutes to ensure homogeneity. The prepared alkaline solution was then gradually added to the mixture, in two portions, to promote a uniform blend. Mixing continued for 3 to 4 minutes until the alkaline solution was fully incorporated. Subsequently, a final mix was performed for 1 to 2 minutes until a homogeneous texture and uniform color were obtained, resulting in a total mixing time of approximately 8 minutes.

The workability of the fresh GPC was assessed using a slump test in accordance with ASTM C143 standards, as illustrated in Fig. 5. The test employed a metal mould in the shape of a conical frustum, with a top diameter of 10 cm, a bottom diameter of 20 cm, and a height of 30 cm.



**Fig. 5.** Workability test of fresh GPC

Fresh concrete was cast into oiled steel moulds in three layers, with each layer compacted using 25 strokes of a tamping rod (16 mm diameter, 600 mm length with a bullet-nosed end). Excess concrete was removed, and the surface was levelled with a trowel.

The GPC cube specimens (100 mm × 100 mm × 100 mm) were cured at ambient temperature (27 °C – 31 °C). Specimens containing the ternary binder combination (RM + AGWP + GGBFS) were demoulded after 24 hours. However, for the binary combination (RM + AGWP), demoulding was delayed to 96 hours due to slower strength development. Fig. 6 illustrates the various stages of GPC preparation.

Compressive strength tests were conducted using a universal testing machine in accordance with the ASTM C39 (ASTM C39/C39M) standard. The loading was applied continuously at a stress rate of 0.25 ± 0.05 MPa. The tests were performed at intervals of 7, 14 and 28 days. To compare the performance of binary and ternary



**Fig. 6.** Casting process (a) Dry mixture of binder materials, (b) Dry mixture of GPC ingredients, (c) Mixing of GPC ingredients with alkaline solution, (d) Fresh GPC cubes in the moulds, (e) Ambient curing of GPC cubes after demoulding

binder combinations under different curing conditions, selected specimens were oven-cured at 90 °C for 24 hours after demoulding, followed by ambient curing at a temperature of 27–31 °C. For these comparisons, compressive strength was measured after 28 days of curing. Fig. 7 illustrates the compressive strength testing setup.



**Fig. 7.** Compressive strength test of GPC cube

### 2.3 Microstructure Examination

The SEM images of synthesized geopolymers were acquired after 28 days of curing. Geopolymer paste was prepared for the ternary GPC (RM+AGWP+GGBFS) and binary GPC (RM+AGWP) under the same con-

ditions of F/B, SS/SH & molarity (refer to Table 3). The SEM analysis was conducted at a magnification of 1K to assess microstructural features. The results are discussed in Section 3.6 and SEM morphology images in Fig. 16.

## 3. Results and Discussion

### 3.1 Characterization of Materials under Microstructure Examination

#### 3.1.1 X-ray Fluorescence Analysis

Table 1 presents the chemical composition of the primary raw materials - RM, AGWP, and GGBFS, as determined by XRF analysis. The results highlight the complementary roles of these materials in the production of geopolymer concrete. RM, with its significant alumina and silica content, acts as a dominant material for initiating the geopolymerization process and therefore ideal for producing geopolymer concrete. AGWP, rich in SiO<sub>2</sub>, enhances the matrix's pozzolanic activity, while GGBFS contributes cementitious components such as alumina, silica, and CaO, improving overall performance.

The Table shows RM has enough alumina, silica, and even calcium oxide for the geopolymerization process and to achieve the mechanical strength. But its elemental balance is not enough for producing high-grade concrete. Adding GGBFS as supplementary binder material helps to overcome this limitation because it contains essential oxides to facilitate the development of high strength. Also, the high silica content of AGWP makes up for the lack of silica in RM, making it a useful precursor in both binary (RM + AGWP) and ternary (RM + AGWP + GGBFS) binder systems.

#### 3.1.2 X-ray Diffraction Analysis

The XRD diffractograms for RM, AGWP, and GGBFS are shown in Fig. 8. The XRD pattern for RM does not have any clear broad humps, which means that there are very few amorphous phases. Instead, it has high-intensity peaks that show that it is mostly crystalline, which is in line with the high alumina content found in the XRF analysis. The GGBFS pattern, on the other hand, shows a broad hump between 23° (2θ) and 37° (2θ), which shows the confirmation of significant amorphous phases. This amorphous nature of GGBFS makes this binder material an ideal precursor for enhancing mechanical strength during the geopolymerization process. The AGWP pattern also doesn't have any sharp, high-intensity peaks, which means there are no crystalline phases. It has wide humps that suggest an amorphous structure, which fits with the high SiO<sub>2</sub> content found in the XRF results.

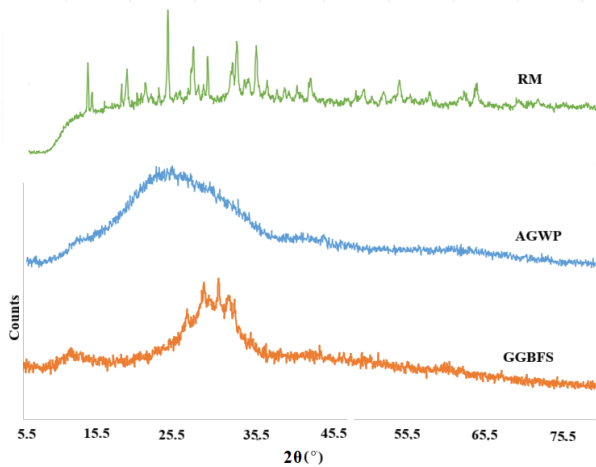
#### 3.1.3 Scanning Electron Microscopy

The SEM micrographs for RM, AGWP, and GGBFS are shown in Fig. 9. The morphology of RM is charac-

**Table 1**

XRF results of binder materials.

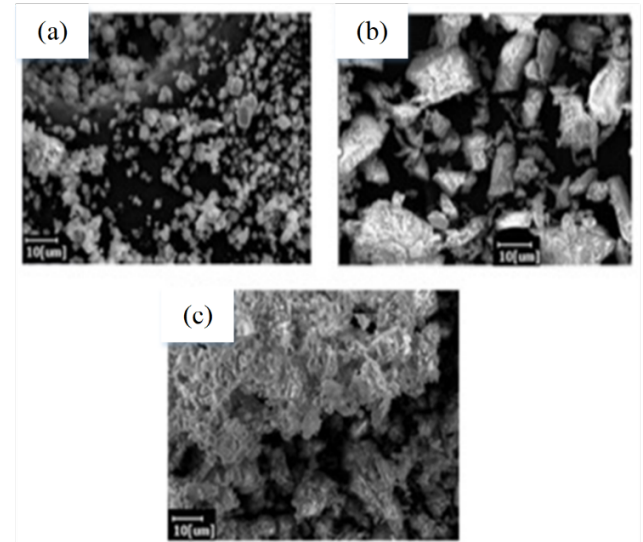
| Symbol                         | RM<br>Concentration | AGWP<br>Concentration | GGBS<br>Concentration |
|--------------------------------|---------------------|-----------------------|-----------------------|
| Al <sub>2</sub> O <sub>3</sub> | 22.27               | 0.1241                | 15.39                 |
| SiO <sub>2</sub>               | 14.38               | 70.01                 | 14.76                 |
| P <sub>2</sub> O <sub>5</sub>  | 0.3253              | 0.026                 | 0.166                 |
| K <sub>2</sub> O               | 0.08188             | 0.3092                | 0.3918                |
| CaO                            | 5.323               | 8.36                  | 37.69                 |
| TiO <sub>2</sub>               | 5.425               | 0.03468               | 0.5572                |
| Fe <sub>2</sub> O <sub>3</sub> | 16.7                | 0.8585                | 1.441                 |

**Fig. 8.** XRD analysis of binder materials

terized by smooth, dense surfaces, which correspond to the crystalline nature observed in XRD analysis. This compact structure contributes to its stability within the geopolymer matrix. The AGWP micrograph, on the other hand, shows angular glass grains with a polydisperse size distribution, which is typical of an amorphous material. These shapes that aren't perfect and particles that are different sizes make the surface area bigger, which makes the geopolymerization process more reactive. GGBFS also has a mix of angular and irregular glassy particles. Like AGWP, this disordered shape makes good reaction sites, which helps the binder become more reactive and stronger overall.

#### 3.1.4 Particle Size Analysis

The binder materials particle size distributions are shown in Fig. 10. The average size of the particles was found to be 380 nm for RM, 48 nm for AGWP, and 500 nm for GGBFS. AGWP's extreme fineness is thought to greatly improve the reactivity of the geopolymer matrix. Also, these very small particles fill in gaps between other particles, which makes the packing denser and improves bonding at the microstructural level. This densification is expected to reduce porosity and may improve durability, though the effect was not directly measured in this study. The RM and GGBFS particles, on the other hand, help keep the system stable. The RM particles are not too fine, which makes sure that geopolymerization starts off right. The GGBFS particles are relatively larger, which helps keep the matrix

**Fig. 9.** SEM morphology images (a) RM, (b) AGWP, and (c) GGBFS

stable and improve mechanical performance because they are naturally cementitious.

#### 3.2 Effect of Various Control Parameters on the Density of Geopolymer Concrete

The variation of GPC densities under different control parameters such as binder proportions, alkaline solution molarity, SS to SH ratio, and F/B are presented in Table 2. The GP<sub>1</sub> was recorded as the lowest density, approximately 2254 kg/m<sup>3</sup>. It was developed with 100% RM. However, the incorporation of GGBFS and AGWP increased the density range from 2310 kg/m<sup>3</sup> to 2420 kg/m<sup>3</sup>, which is comparable to that of ordinary concrete. The maximum density of 2420 kg/m<sup>3</sup> (GP<sub>18</sub>) was achieved under the following optimal conditions: M=10, SS/SH=2.5, F/B=0.5, RM: AGWP: GGBFS=50:10:40. This high density indicates a compact matrix structure, which is a precursor to enhanced mechanical properties.

#### 3.3 Effect of Control Parameters on the Workability of Fresh Geopolymer Concrete

Table 2 further illustrates the impact of control parameters on the workability of fresh GPC. The experiments indicate that, while all parameters impact workability to some extent, variations in the fluid-to-binder (F/B) ratio have the most significant effect. For instance, at F/B = 0.5 (GP<sub>18</sub>), the workability of fresh GPC was 80

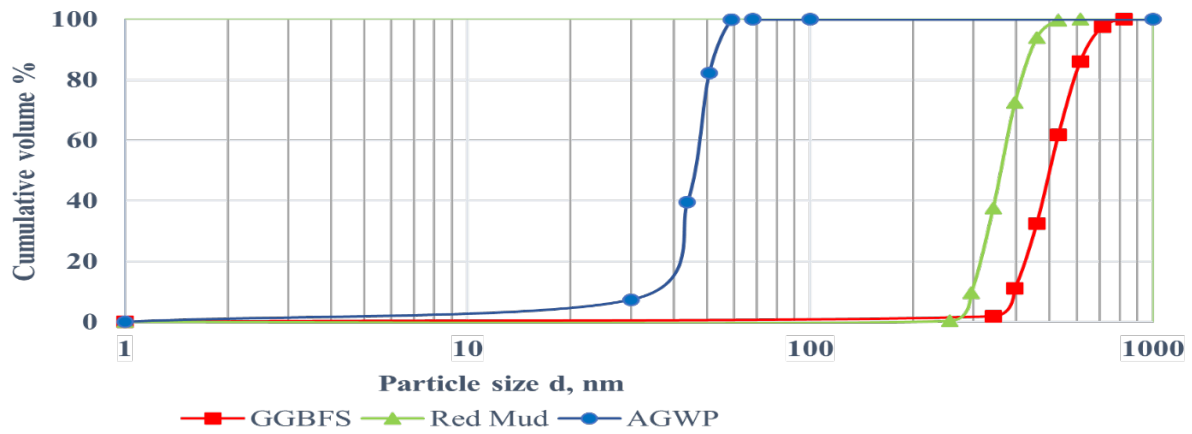


**Fig. 10.** Particle size distribution curve of RM, AGWP, and GGBFS

**Table 2**

Control parameters, density of GPC and workability

(F/B = fluid to binder ratio, SS/SH = sodium silicate to sodium hydroxide ratio, M = molarity)

| Designation      | RM (%) | AGWP (%) | GGBFS (%) | Alkaline Solution (M) | F/B  | SS/SH | Density of GPC (kg/m <sup>3</sup> ) | Workability (mm) |
|------------------|--------|----------|-----------|-----------------------|------|-------|-------------------------------------|------------------|
| GP <sub>1</sub>  | 100    | 0        | 0         | 12                    | 0.5  | 2.5   | 2254                                | 250              |
| GP <sub>2</sub>  | 90     | 10       | 0         | 12                    | 0.5  | 2.5   | 2360                                | 230              |
| GP <sub>3</sub>  | 80     | 20       | 0         | 12                    | 0.5  | 2.5   | 2350                                | 80               |
| GP <sub>4</sub>  | 60     | 20       | 20        | 12                    | 0.5  | 2.5   | 2380                                | 100              |
| GP <sub>5</sub>  | 50     | 20       | 30        | 12                    | 0.5  | 2.5   | 2410                                | 80               |
| GP <sub>6</sub>  | 50     | 10       | 40        | 12                    | 0.5  | 2.5   | 2400                                | 30               |
| GP <sub>7</sub>  | 50     | 5        | 45        | 10                    | 0.5  | 2.5   | 2410                                | 70               |
| GP <sub>8</sub>  | 50     | 10       | 40        | 10                    | 0.55 | 2.5   | 2410                                | 200              |
| GP <sub>9</sub>  | 50     | 10       | 40        | 10                    | 0.45 | 2.5   | 2400                                | 10               |
| GP <sub>10</sub> | 50     | 10       | 40        | 10                    | 0.4  | 2.5   | 2320                                | 0                |
| GP <sub>11</sub> | 50     | 10       | 40        | 14                    | 0.5  | 2.5   | 2390                                | 100              |
| GP <sub>12</sub> | 50     | 10       | 40        | 8                     | 0.5  | 2.5   | 2380                                | 50               |
| GP <sub>13</sub> | 50     | 10       | 40        | 6                     | 0.5  | 2.5   | 2310                                | 80               |
| GP <sub>14</sub> | 50     | 10       | 40        | 10                    | 0.5  | 0.75  | 2350                                | 100              |
| GP <sub>15</sub> | 50     | 10       | 40        | 10                    | 0.5  | 1     | 2370                                | 150              |
| GP <sub>16</sub> | 50     | 10       | 40        | 10                    | 0.5  | 1.5   | 2410                                | 125              |
| GP <sub>17</sub> | 50     | 10       | 40        | 10                    | 0.5  | 2     | 2390                                | 100              |
| GP <sub>18</sub> | 50     | 10       | 40        | 10                    | 0.5  | 2.5   | 2420                                | 80               |
| GP <sub>19</sub> | 50     | 10       | 40        | 10                    | 0.5  | 3     | 2380                                | 110              |
| GP <sub>20</sub> | 50     | 10       | 40        | 10                    | 0.5  | 3.5   | 2410                                | 110              |

mm. When the F/B ratio increased to 0.55 (GP<sub>8</sub>), the workability improved significantly to 200 mm. Conversely, reducing the F/B ratio to 0.4 resulted in zero workability, highlighting the sensitivity of GPC workability to F/B variations. When the RM content is increased to 100%, it provided the highest workability at 250 mm. However, increasing the proportions of other binder materials, such as AGWP and GGBFS, reduced the slump values of fresh GPC. This suggests that while AGWP and GGBFS contribute to the mechanical properties of hardened GPC, their inclusion reduces the workability of fresh concrete. In summary, the workability of fresh GPC is highly dependent on the F/B ratio and proportion of binder materials.

### 3.4 Mechanical Properties of Geopolymer Concrete

The mechanical properties of GPC were evaluated by analyzing the effect of control parameters, such as the proportion of binder materials, SS to SH ratio, molarity of the alkaline solution, and F/B ratio, on compressive strength.

Fig. 11 through 14 illustrate the variations in compressive strength under the specified conditions. Fig. 11 highlights the compressive strength corresponding to the binder proportion (6), which includes RM, AGWP, and GGBFS in a 50:10:40 ratio. This proportion yielded satisfactory results, with strength exceeding 39 MPa. Proportion (1), containing 100% RM, yielded a

compressive strength of 7.5 MPa, confirming that while RM can initiate geopolymerization, it is insufficient for producing high-grade concrete.

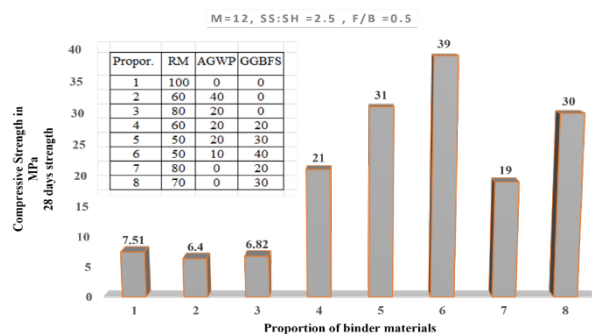


**Fig. 11.** Compressive strength versus proportion of binder materials

Fig. 12 examines the influence of alkaline molarity on the compressive strength of the optimized binder (Proportion 6). While strength generally trended upward with increased alkalinity, a non-linear behavior was observed: a distinct reduction in strength occurred at  $M=12$ , followed by a recovery at  $M=14$ . The strength drops at  $M=12$  is caused by too many salt ions and too much iron oxide, which probably slowed down the pace of polymerization at moderate alkalinity levels. On the other hand, the increase to  $M=14$  made the alkaline environment strong enough to get rid of this influence. This high concentration made it easier for unreacted aluminosilicate phases to dissolve, which made the geopolymer matrix denser and stronger [7]. It was determined from the figure that molarities of 10 and 14 produced high strengths, with molarity 10 being favored to mitigate excessive corrosiveness.

In Fig. 13, the compressive strength for varying F/B ratios was analysed with a fixed molarity of 10 for proportion (6). The maximum strength was achieved at an F/B ratio of 0.5; however, at F/B = 0.55, the strength declined sharply. This occurs because excess fluid increases porosity, weakening the matrix and reducing strength despite improving workability [9, 10].

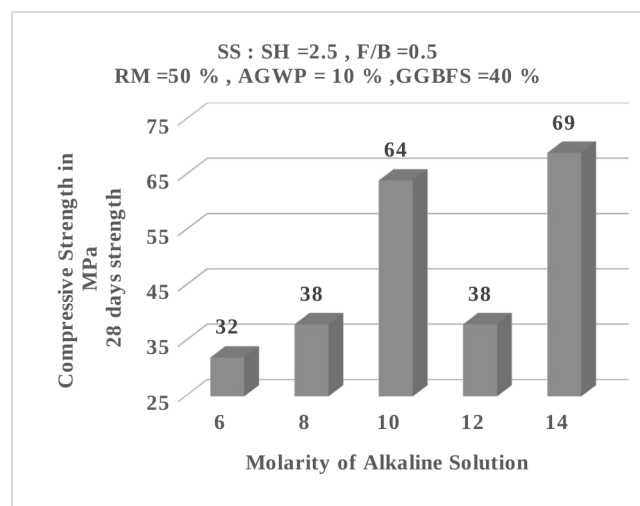


**Fig. 12.** Compressive strength versus molarity

Fig. 14 explores the effect of SS to SH ratios on compressive strength, with a molarity of 10 and an F/B ratio of 0.5, for the proportion (6). The highest strength,

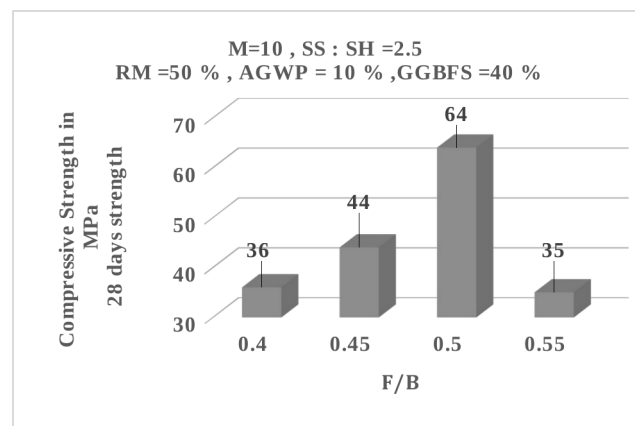


**Fig. 13.** Compressive strength versus F/B

approximately 64 MPa, was achieved when the ratio was 2.5. Strengths exceeding 40 MPa were observed across most ratios, except at a ratio of 3.0, which exhibited a strength of 34 MPa. Therefore, depending upon the strength requirements as per the structural design of concrete structures, the proper ratio can be selected. Experimental findings demonstrate the strength enhances as the SS/SH ratio increases. The strength reaches its peak value at SS/SH = 2.5. But a decline in strength was observed at SS/SH = 3, followed by a recovery at SS/SH = 3.5, though it remains significantly lower than the peak. The decrease in strength at SS/SH = 3 was due to high viscosity, poor workability, and the heterogeneous gel formation caused by the low reactivity of specific red mud components. At higher activator ratios, a greater amount of silicate gradually participates in the geopolymerization process during curing, improving the reaction efficiency. This densification of the microstructure led to a partial recovery of strength [8].

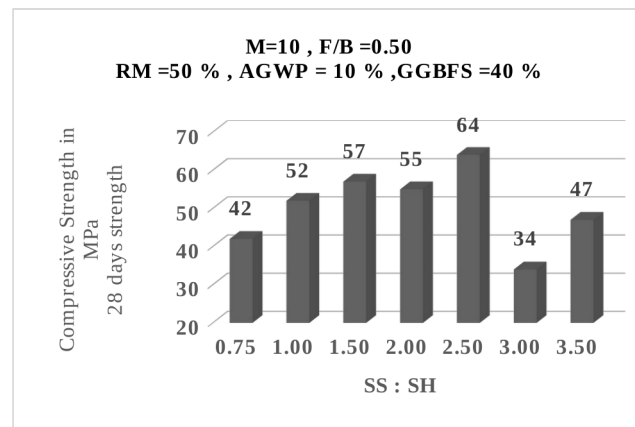


**Fig. 14.** Compressive strength versus SS: SH

### 3.5 Binary Binder Performance

The binary GPC (AGWP + RM) was prepared to assess the impact of AGWP specifically. As shown in Fig. 15, under ambient temperature, the strength was very low, approximately 7.0 MPa. This is 65% lower than the binary GPC cured at elevated temperature, which has reached 21 MPa at 90°C. This result highlights that silica becomes more reactive at elevated temperatures, and enhances geopolymerization [32, 44, 45]. However, further detailed investigation is required to assess the performance of these geopolymers in terms of mechan-

ical and microstructural properties at various elevated temperatures.

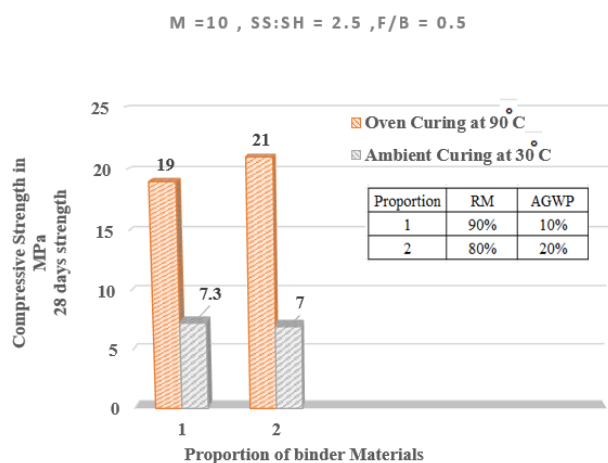


**Fig. 15.** Compressive strength versus proportion of binder materials (binary)

**Table 3**

Conditions of synthesised geopolymers

| Sample (1)                                                                     | Sample (2)                                                    |
|--------------------------------------------------------------------------------|---------------------------------------------------------------|
| RM = 50 %,<br>GGBFS = 40 %<br>AGWP = 10%<br>SS : SH = 1.5<br>M = 10, F/B = 0.5 | RM = 80 %,<br>AGWP = 20%<br>SS: SH = 1.5<br>M = 10, F/B = 0.5 |

### 3.6 Microstructural Analysis After Curing

Fig. 16 (a) shows fewer pores and gel deposits because it has reached the third stage of geopolymerization, crystallization. In contrast to Fig. 16 (a), Fig. 16 (b) lacks complete crystallization and exhibits more gel deposits and visible pores.

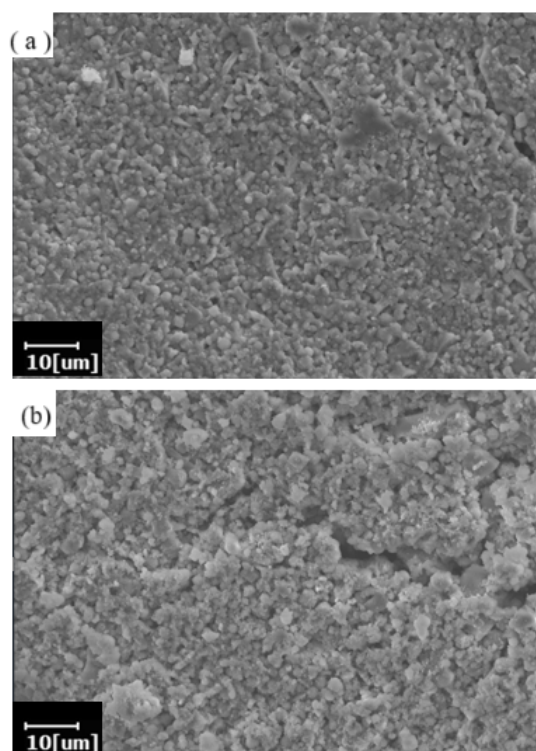


**Fig. 16.** SEM morphology images of geopolymers at 28 days curing (a) sample 1, (b) sample 2

## 4. Conclusions

This study demonstrated that the maximum compressive strength of geopolymer concrete (GPC) reached 64 MPa under ambient curing for the C<sub>30</sub> grade. This high value was achieved by optimizing parameters such as binder proportions, F/B ratio, alkaline solution molarity, and SS to SH ratio. Although the 14 M SH concentration gave the higher compressive strength of 69 MPa, the 10 M, which achieved approximately 64 MPa, was chosen as the practical optimum due to the corrosiveness and handling concerns of the more concentrated SH solutions.

These findings suggest the potential for achieving even higher values than 64 MPa depending on the concrete grade. The mix design for red mud-based GPC was adapted from conventional concrete due to the absence of standardized guidelines.

A limitation of the present study is that the binder proportion, SH molarity, F/B ratio, and SS/SH ratio were optimized sequentially using a one-factor-at-a-time approach. Future studies employing factorial or response surface methodology (RSM) could provide a more comprehensive assessment of parameter interactions and enable multi-variable optimization of the RM–GGBFS–AGWP geopolymer concrete system.

This study also reveals that binary GPC (RM + AGWP) can only achieve higher strength at elevated temperatures, as the silica in the AGWP becomes more reactive at these temperatures. Additionally, the density of GPC, ranging from 2310 to 2420 kg/m<sup>3</sup>, closely matches that of ordinary concrete, with the highest density recorded under ideal parameters.

Furthermore, this study underscores the sensitivity of GPC workability to the F/B ratio. A slight increase could enhance workability. However, while higher RM content improved workability, increased AGWP and GGBFS contents had an adverse effect. This study also indicates that, through microstructural observations, ternary blends result in denser gels and less porous GPC. In conclusion, this research established a foundation for incorporating and optimizing the use of geopolymer concrete made from crystalline material red mud into higher-grade GPC, paving the way for sustainable and high-strength, ambient-cured RM based geopolymer concrete.

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## Disclosure statement

The authors declare that they have no competing financial interests. The research was undertaken solely to enhance the scientific understanding of sustainable concrete.

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