



Assessing the Influence of Calcium-Based Alkaline Activators and Metakaolin on the Compressive Strength Development of Geopolymer Concrete for Different Mix Design Parameters

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ABSTRACT

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Geopolymer concrete (GPC) represents an innovative alternative to traditional Portland cement concrete. The alkaline activators and precursors play pivotal roles in making GPC environmentally sustainable. This study delves into the positive effects of applying metakaolin (MK) as precursor in combination with an alkaline activator solution (AAS), consisting of calcium hydroxide (Ca(OH)₂) and sodium silicate (Na₂SiO₃) on the strength enhancement. This study involves the exploration of several key factors, including water-to-solid binder ratios (W/B), Na₂SiO₃ to Ca(OH)₂ ratios, alkaline activating solution to MK (AAS/ MK) ratios, superplasticizer dosages, MK quantities, curing temperature degrees, and heat curing durations. The objective of this article is to assess the consequences of optimizing MK with AAS on the Compressive strength (CS) of GPC. The experimental results demonstrated that optimization of GPC was achieved with a W/B of 0.75, a Na₂SiO₃ to Ca(OH)₂ ratio of 1.5, a AAS to MK ratio of 1, a superplasticizer dosage of 1.5%, a MK quantity of 400 kg m⁻³, and an oven curing temperature of 80°C for 24 hours, at a standard air curing duration of 28 days. Additionally, with an increasing curing age of the GPC specimens from 2 to 28 days, the CS increases from 14.74 MPa to 31.62 MPa. This reflects the successful formulation of GPC through the polycondensation process involving MK as a geopolymeric precursor and alkali polysilicates. The significance of this study lies in its contribution to the development of more environmentally friendly concrete solutions, promoting the use of alternative materials in the construction industry.

1. INTRODUCTION

The rapid growth of the world's population and the construction of tall buildings and structures have generated a higher demand for Portland cement, a widely utilized material in the construction industry. Regrettably, the production of Portland cement is a significant source of global CO₂ emissions, constituting approximately 30% of the total emissions [1]. Notably, OPC manufacturing alone is responsible for roughly 5% of greenhouse gas emissions worldwide, raising environmental problem [2]. This is mainly due to the substantial energy consumption and CO₂ release during the production process, with approximately 0.53 tons of CO₂ emitted per ton of OPC manufactured. If carbon fuel is utilized in producing 1 ton of OPC, about 0.45 tons of CO₂ are discharged. These factors exacerbate environmental concerns and have led to an escalated demand for eco-friendly materials with minimal CO₂ emissions in the construction industry. As a result, there is a pressing need for expedited research in this area [3].

In recent times, there has been extensive research focusing on environmentally friendly and safer alternatives to Portland

cement [4]. Among these alternatives is geopolymer cement, a cleaner material that offers a substitute for conventional Portland cement. Geopolymer cement is designed to minimize its carbon footprint by utilizing limited natural resources or industrial waste products, while also demonstrating durable properties that address the issues encountered with traditional concrete. Like Portland cement, geopolymer cement is a binder for construction materials that undergo curing at room temperature [5]. The process of creating the geopolymer binder involves a chemical reaction between specific raw materials rich in aluminosilicates such as MK, fly ash (FA), and ground granulated blast furnace slag (GGBS), along with an alkaline activating solution. This alkaline solution aids in dissolving the glassy phase present in the raw materials, resulting in the formation of different solid phases, including calcium aluminate silicate hydrate gels (C-A-S-H). These phases play a crucial role in influencing the microstructure, durability, and mechanical properties of the geopolymer binder [6, 7].

MK-based GPC offers considerable advantages over OPC and other geopolymer alternatives such as fly ash or slag-based GPC. One significant advantage is its excellent durability and

chemical resistance, making it suitable for harsh environments. MK GPC emits fewer greenhouse gases during manufacture than OPC due to calcining kaolin to MK, which uses less energy than OPC's energy-intensive clinker production. Alsaif et al. [8] found that MK-based GPC outperforms fly ash and slag-based geopolymers in terms of long-term durability to chemical and thermal stress.

MK, sourced from kaolin clay, is critical for promoting sustainable construction methods due to its widespread availability and low environmental impact. Its existence in numerous places decreases dependence on nonrenewable resources, making it an attractive and environmentally friendly alternative for GPC. Furthermore, MK increases the durability and chemical resistance of GPC, making it ideal for sustainable building solutions. This combination of sustainability and performance indicates MK's crucial importance in promoting green construction practices [9].

The sustainability of GPC faces challenges, particularly concerning the energy requirements for its curing process. Elevated temperatures are often necessary to achieve optimal curing, which can lead to increased energy consumption. To mitigate this issue, it is essential to explore energy-efficient curing methods, such as optimizing curing temperatures and applying insulation. Nurrudin et al. [10] present a thorough examination of several curing processes for GPC. They address the need for optimizing curing conditions, such as temperature control and the use of insulation, to improve strength and durability while reducing energy usage. Their findings show that efficient curing procedures can significantly lower GPC's environmental impact, giving it a more sustainable option to traditional OPC concrete.

The process of geopolymerization is solely dependent on alkaline activation and the degree of dissolution of silica and alumina species in the alkaline solution. Previous research has commonly employed alkaline solutions formed by combining sodium hydroxide (NaOH) or potassium hydroxide (KOH) with sodium silicate (Na_2SiO_3) or potassium silicate (K_2SiO_3) [11, 12]. However, GPC of NaOH based alkaline activation is subjected to efflorescence due to movement of salt to its surface, causing a whitish layer of coating to be present on it. Corrosive compounds such as NaOH and KOH must be handled with care, utilizing protective equipment such as gloves, safety glasses, and masks, especially in large-scale applications [5]. To offset these issues, an attractive option to NaOH is the combination of $\text{Ca}(\text{OH})_2$ and Na_2SiO_3 as an alkaline solution to alkali-activate GPC. Hydrated lime, such as calcium hydroxide ($\text{Ca}(\text{OH})_2$), which is classed as an irritant, does not necessitate significant protective measures and can be utilized in large proportions without extreme caution. Alkaline reagents in this category are referred to as "friendly" [5].

Yang et al. [13] studied the performance of calcium hydroxide ($\text{Ca}(\text{OH})_2$) as an activator in ground granulated blast furnace slag (GGBS). To stabilize C-S-H gel over time, $\text{Ca}(\text{OH})_2$ was used at 7.5% of the total binder. Na_2SiO_3 and Na_2CO_3 were added at 1% and 2%, respectively, as auxiliary activators. $\text{Ca}(\text{OH})_2$ has been shown to improve workability, increase strength, and reduce costs. The experiment included three groups of GPC, each with a different activator combination, water-to-binder ratio (W/B), and sand-to-binder ratio (S/B). The study found that compressive strength results with $\text{Ca}(\text{OH})_2$ and Na_2CO_3 outperformed those with $\text{Ca}(\text{OH})_2$ and Na_2CO_3 .

This study focuses on the strength behavior of GPC using MK as a precursor. It evaluates the strength of GPC based on

the optimal reactivity between the calcium-based alkaline solution and MK, providing crucial insights into its ability to withstand loading pressure through bonding and intactness. The research includes a comprehensive experimental assessment of CS for GPC.

2. MATERIALS AND METHODS

2.1 Physical and chemical properties of the raw materials under study

The raw materials used for the making of the GPC are calcium hydroxide, sodium silicate, MK, gravel, river sand, and polycarboxylate superplasticizer. All the raw materials were ordered from local suppliers. MK, produced from kaolin clay, is commonly obtained as an industrial byproduct and is widely available in established mining regions. Its sustainable procurement and the environmental impact of extraction and processing are critical for assessing the overall sustainability of geopolymer concrete (GPC), which reinforces its benefits in construction applications. MK, and calcium hydroxide were tested to have bulk density of 1580, and 480kg m^{-3} respectively. Their respective specific gravity values were evaluated to be 2.560, and 2.120. Calcium hydroxide has the lowest bulk density and specific gravity among all the raw materials due to its porous and lightweight nature. During geopolymerization, calcium hydroxide transitions into a finely powdered form characterized by loosely arranged particles, resulting in the formation of voids within the material. This porous structure facilitates enhanced air retention within the substance, thereby leading to its reduced bulk density, defined as the material's mass divided by its volume. The findings suggest that MK has a greater Blaine fineness than calcium hydroxide. To be specific, MK was measured at $6631.0\text{ cm}^2\text{ g}^{-1}$, while calcium hydroxide showed a Blaine fineness value of $3189.0\text{ cm}^2\text{ g}^{-1}$. The chemical composition of MK under the study was investigated. As expected, the MK is predominated by very fine silica, alumina, and ferric oxide with the total sum of the chemical compound is 93.84%, thereby qualifying it to be a precursor for the concrete's geopolymerization. The amounts of Al_2O_3 and SiO_2 were found to be 40.80% and 51.80%, respectively. MK is regarded an excellent precursor for GPC because of its significant proportions of silica in the amorphous state, alumina, and ferric oxide, contributing to its reactivity and capacity to establish robust chemical bonds upon activation with alkaline solutions. A very high content of silica of 96% in river sand was observed, which provides an indication that it is comprised of quartz as its majority chemical composition. Silica sand functions as a fine aggregate within GPC, enhancing its structural integrity, density, and mechanical characteristics through the optimization of packing density and reduction of porosity. The sodium silicate (Na_2SiO_3) was found to contain 51.00% water, and total silicon dioxide (SiO_2), and sodium oxide (Na_2O) of 49.00%, with a ratio of 1 Na_2O to 2 SiO_2 .

2.2 Mix designs and methods of testing

The trial mix designs for the GPC specimens under study are depicted in Table 1. It is notable that the reference mix design (Series 1) was set at 400 kg m^{-3} MK, 200 kg m^{-3} sodium silicate, 200 kg m^{-3} calcium hydroxide, 366 kg m^{-3} sand, 732 kg m^{-3} gravel, 400 kg m^{-3} water, 6 kg m^{-3} polycarboxylate

superplasticizer based on an alkaline activator to MK ratio of 1. In series 2, the trial mix designs for the GPC were varied at water to solid binder ratios of 0.65, 0.7, 0.75, 0.8, and 0.1. It is imperative to comprehend the influence of the water-to-binder ratio on the strength of GPC, as this knowledge is vital for enhancing its structural robustness and efficiency, thus informing the development of resilient and environmentally friendly construction materials. After that, the study of the trial mix designs was concentrated on sodium silicate to calcium hydroxide ratios which varied from 0.67, 1, 1.5, and 2 (series 3). Analyzing the ratio between sodium silicate and calcium hydroxide in GPC is vital, as it directly impacts the creation of the geopolymer gel, thereby influencing mechanical characteristics, setting duration, and durability, ultimately guaranteeing superior performance and longevity in construction applications. In series 4, the alkaline activator to MK ratios were varied at 0.5, 1, 1.5, and 2 in the trial mix

designs. The need to vary the ratios is justified by the importance of finding the most optimal condition for the geopolymerization process to take place in the concrete. Finally, the strength development of the GPC was studied by varying the dosages of superplasticizer and MK quantities, as indicated in series 5 and 6 respectively of Table 1. The GPC molds were filled in three layers. Each layer was compacted with 35 strokes of a tamping rod. The cubes from all trial mix designs were initially cured in an oven at 60°C for 24 hours before determining the optimal heat curing conditions.

Figure 1(a) shows the placement of the fresh GPC in the molds, and the molds vibrated for 30 seconds on a mechanical vibrating table. The molds were then wrapped in plastic film and set aside for one day to allow the GPC to harden. Figure 1(b) depicts the demolding of GPC samples, 24 hours after they were cast. All samples were then wrapped in aluminum sheets (Figure 1(c)) and cured in an oven.

Table 1. Trial mix designs for the GPC specimens under study

Mix Design ID	MK (kg m ⁻³)	Na ₂ SiO ₃ (kg m ⁻³)	Ca(OH) ₂ (kg m ⁻³)	Sand (kg m ⁻³)	Gravel (kg m ⁻³)	Water (kg m ⁻³)	SP (kg m ⁻³)	AAS/MK
Series 1								
Reference mix design S1(GPC)	400	200	200	366	732	400	6	1
Series 2								
S2(GPC)0.65	400	200	200	366	732	390	6	1
S2(GPC)0.7	400	200	200	366	732	420	6	1
S2(GPC)0.75	400	200	200	366	732	450	6	1
S2(GPC)0.8	400	200	200	366	732	480	6	1
S2(GPC)1	400	200	200	366	732	600	6	1
Series 3								
S3(GPC)0.67	400	160	240	366	732	480	6.4	1
S3(GPC)1	400	200	200	366	732	450	6	1
S3(GPC)1.5	400	240	160	366	732	420	5.6	1
S3(GPC)2	400	266	133	366	732	400	5.3	1
Series 4								
S4(GPC)0.5	400	120	80	366	732	360	4.8	0.5
S4(GPC)1	400	240	160	366	732	420	5.6	1
S4(GPC)1.5	400	360	240	366	732	480	6.4	1.5
S4(GPC)2	400	480	320	366	732	540	7.2	2
Series 5								
S5(GPC)1	400	240	160	366	732	420	5.6	1
S5(GPC)1.5	400	240	160	366	732	420	8.4	1
S5(GPC)2	400	240	160	366	732	420	11.2	1
S5(GPC)3	400	240	160	366	732	420	16.8	1
S5(GPC)4	400	240	160	366	732	420	22.4	1
Series 6								
S6(GPC)200	200	240	160	366	732	270	5.4	2
S6(GPC)300	300	240	160	366	732	345	6.9	1.3
S6(GPC)400	400	240	160	366	732	420	8.4	1



(a)



(b)



(c)

Figure 1. (a) The samples after casting; (b) The samples after demolding; (c) The samples after wrapped in aluminum sheet

Compression tests were carried out on the GPC specimens to optimize their CS following BS EN 12390-3:2019 [14] standard. Under each test, GPC cube with dimensions of 100 mm was positioned at the lower platen of the Universal Testing Machine. This was done carefully to ensure it was positioned at the center of the loading axis. In the test, a continual and uniform pressure at 0.5 MPa per second was applied on the GPC cube until failure. The compressive loading sustained by the GPC cube over vertical displacement was recorded with the maximum compressive loading converted to CS by dividing it with cross-sectional area of the GPC cube. The slump tests were conducted to evaluate the workability of the GPC admixtures, following the standard of BS EN 12390-2:2009 [15]. The initial and final setting times of the GPC admixtures were determined in accordance with ASTM C-266-89 [16].

3. RESULTS AND DISCUSSIONS

3.1 Fresh properties of geopolymer mixes

Figure 2 shows the relationship between the slump and water to solid binder ratio of the GPC mix. As shown in Figure 2, the slump value increased with increasing water to solid binder (W/B) ratio. When the W/B ratio was raised from 0.65 to 1, the slump value increased from 75 to 85 mm. This shows that the best workability for the GPC mix was achieved at a W/B ratio of 1. The workability of GPC is enhanced by incorporating MK and $\text{Ca}(\text{OH})_2$. MK's fine reactive particles improve particle packing and optimize water demand, while $\text{Ca}(\text{OH})_2$ reacts with MK to generate extra binding phases. These interactions result in a mix that is more fluid and easier to handle, simplifying the placement process. This result is comparable with previous study of slag/fly ash geopolymer blends [17], which emphasized that the huge surface area of slag demanded a lot of water, leading to a slump reduction.

The initial and final setting times of the geopolymer mixes were investigated. The geopolymer mix has initial and final setting time of 18 and 70 minutes, respectively. With an initial setting time of 18 minutes, the geopolymer mix containing MK and $\text{Ca}(\text{OH})_2$ hardened quickly, necessitating prompt placement and finishing. A final setting time of 70 minutes revealed that the mixture rapidly attained the necessary hardness for subsequent construction work. This expedited setting process is attributed to the reactive nature of MK, and the additional binding phases formed through its interaction with $\text{Ca}(\text{OH})_2$. The low initial setting time of geopolymer mix is attributable to the high fineness of MK resulting in which reduces the dormant period, enhances the hydration, and accelerates the geopolymerization and rapid hardening of geopolymer with MK [18].

Workability, setting time, and scalability are important considerations in the actual use of calcium-based GPC. Optimising the water-to-binder ratio and utilising superplasticizers can increase workability, while controlling alkaline activator ratios and MK quantity aids in achieving appropriate setting times [19]. Scaling up production of calcium hydroxide ($\text{Ca}(\text{OH})_2$) does not necessitate significant protective measures and can be utilised in large proportions without extreme caution compared to alternative GPC [5]. Furthermore, a comprehensive cost analysis comparing calcium-based GPC to conventional concrete and alternative GPC systems, taking into consideration raw material costs,

manufacturing efficiency, and long-term savings from durability and reduced maintenance, must be undertaken to determine its economic feasibility and competitiveness.

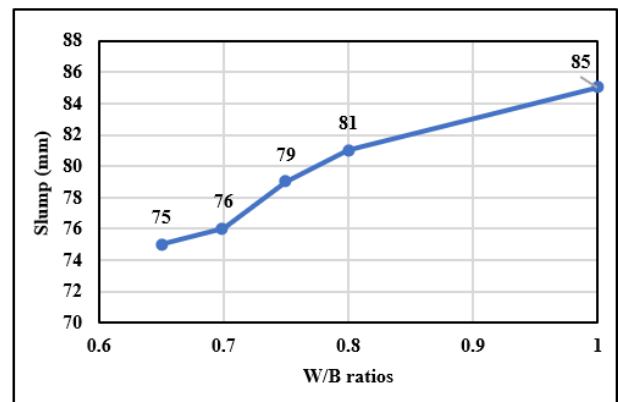


Figure 2. Slump results of the optimum GPC mix at various water to solid binder ratios

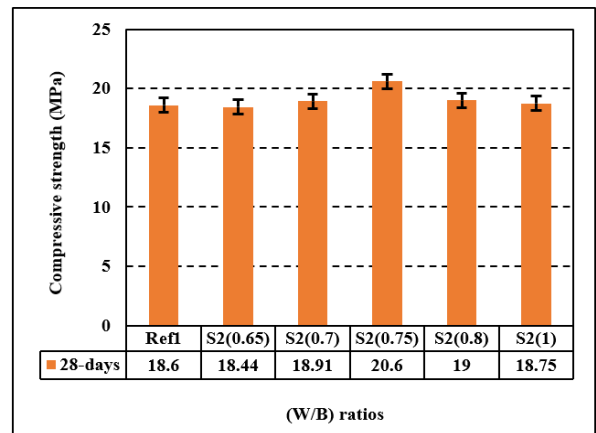


Figure 3. CS of different W/B ratios

3.2 Compressive strength development of geopolymer concrete

3.2.1 Effect of different water to solid binder ratios

The CS of GPC was investigated by evaluating its performance at various water-to-solid binder ratios. Figure 3 shows the CS data from the GPC mix design. After 28 days of curing, the reference mix (S1) had a CS of 18.6 MPa. In contrast, a mix with a W/B ratio of 0.75 demonstrated a significant improvement, attaining a CS of 20.6 MPa, a 10.8% increase over the reference mix. A range of W/B ratios, including 0.65, 0.7, 0.75, 0.8, and 1, were tested, yielding CSs of 18.44 MPa, 18.91 MPa, 20.6 MPa, 19 MPa, and 18.75 MPa, respectively. It is significant that the optimal W/B ratio of 0.75 outperformed earlier research on GPC. This enhancement can be due to the increased solid binder component, which contained MK and $\text{Ca}(\text{OH})_2$ powder. However, increasing the W/B ratio from 0.75 to 1 resulted in a decrease in CS from 20.6 MPa to 18.75 MPa. This observation is similar to the finding of Ou et al. [20]. The mix with a W/B ratio of 0.65 had a CS of 18.44 MPa, indicating a slight decrease from the reference mix. A minor improvement was noticed with the 0.7 ratio, resulting in a CS of 18.91 MPa. When the W/B ratio was increased to 0.8, the CS decreased slightly to 19 MPa, while raising the ratio to 1 resulted in a CS of 18.75 MPa. The mix's

enhanced performance with a W/B ratio of 0.75 can be attributed to the sufficient water content for the higher proportion of solid binders. Specifically, the combination of MK, $\text{Ca}(\text{OH})_2$ powder, and Na_2SiO_3 generates extra calcium silicate hydrate (C-S-H) gel, providing a denser microstructure and increasing the GPC's overall strength. Conversely, the decrease in CS with increasing W/B ratios (from 0.75 to 1) emphasizes the negative consequences of excess water. The added water allows for more evaporation during oven curing, resulting in increased porosity and, as a result, reduced strength. Several researchers have confirmed the reverse relationship between water content and CS, including Ou et al. [20] and Wang et al. [21].

3.2.2 Effect of different sodium silicate to calcium hydroxide ratios

The relation between the Na_2SiO_3 to $\text{Ca}(\text{OH})_2$ ratio and CS in GPC was investigated, and the results are shown in Figure 4. The figure shows that the best ratio of 1.5 Na_2SiO_3 to $\text{Ca}(\text{OH})_2$ resulted in a maximum CS of 23.4 MPa. This indicates a 25.8% improvement over the reference (S1) mix, demonstrating the importance of the correct ratio. The CS increased gradually as the Na_2SiO_3 to $\text{Ca}(\text{OH})_2$ ratio increased from 0.67 to 1.5, with values ranging from 18 MPa to 23.4 MPa. This improvement can be attributed to the increased concentration of Na_2SiO_3 , which aided in the generation of reaction products with high Si content. The increased Si concentration expedited the polymerization process, resulting in greater CS. Sathonsaowaphak et al. [22] found similar results, confirming that increased Na_2SiO_3 concentrations have a favorable impact on CS. In contrast, increasing the Na_2SiO_3 to $\text{Ca}(\text{OH})_2$ ratio to 2 resulted in a CS of 22.32 MPa, which was 4.8% lower than the 1.5 ratio. This pattern is consistent with the findings of Sathonsaowaphak et al. [22] and Karith and Mohan [23], who also evidence the importance of the Na_2SiO_3 to $\text{Ca}(\text{OH})_2$ ratio. Both studies emphasized that a Na_2SiO_3 -to- NaOH ratio of 1.5 is required for high CS. These consistent findings across research emphasize the necessity of maintaining the proper Na_2SiO_3 to $\text{Ca}(\text{OH})_2$ ratio in GPC for optimal CS. Pangdaeng et al. [24] found 1.5 to be the optimal Na_2SiO_3 to NaOH ratio for maximum CS, supporting the findings. $\text{Ca}(\text{OH})_2$ reacts with the Na_2SiO_3 solution to generate additional calcium silicate hydrate (C-S-H) gel, contributing further to the overall strength and durability of the GPC. Increasing the Na_2SiO_3 to $\text{Ca}(\text{OH})_2$ ratio to 2, resulting in a decrease the quantity of $\text{Ca}(\text{OH})_2$, influencing the generation of calcium silicate hydrate (C-S-H) gel, thus decreasing the CS.

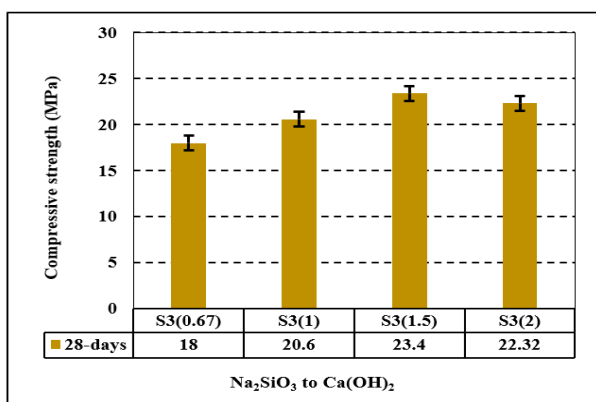


Figure 4. CS of GPC with different Na_2SiO_3 to $\text{Ca}(\text{OH})_2$ ratios

3.2.3 Effect of different alkaline activator solution to MK ratios

Figure 5 depicts the findings of a comprehensive investigation on the effect of the alkaline activator solution-to-MK ratio (AAS/MK) on the CS of GPC. The figure clearly shows that an optimal AAS/MK ratio of 1 result in a maximum CS of 23.4 MPa. This is a significant improvement over the other evaluated ratios. The CS rose significantly as the AAS/MK ratio was elevated from 0.5 to 1, with values ranging from 15.23 MPa to 23.4 MPa. However, raising the AAS/MK ratio beyond 1 resulted in a reduction in CS. Specifically, CSs of 20.3 MPa and 17 MPa were recorded at AAS/MK ratios of 1.5 and 2, respectively, indicating a decrease from an optimal ratio of 1. The increase in CS up to an AAS/MK ratio of 1 can be attributed to a higher proportion of Na_2SiO_3 , which raises the $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio and causes stronger Si-O-Si bonds to form. Al Bakri Abdullah et al. [25] showed that these bonds are stronger than Si-O-Al bonds. The findings of this work are consistent with this of Albidah et al. [26], who also emphasized the importance of the activator alkaline solution to precursor ratio, especially when sodium hydroxide (NaOH) is present in the alkaline activator solution. Their study showed ideal alkaline activator solution-to-precursor ratios of roughly 0.88 and 1.25, respectively, emphasizing the importance of this ratio and the favorable influence of sodium silicate on CS in GPC. Further validating these findings, Kampli et al. [27] investigated various alkaline activator solution-to-precursor ratios ranging from 0.25 to 0.7 and discovered that a ratio of 0.7 produced the highest CS. This emphasizes the importance of maintaining the optimum AAS/MK ratio and the considerable influence of sodium silicate in increasing the CS of GPC. The reduction in CS beyond the AAS/M of 1% can be attributed to insufficient MK dosage in the alkali-activator, which does not provide an optimal alkali environment for the geopolymer reaction, resulting in becoming unable to generate a sufficient number of N-A-S-H gels in the geopolymer reaction, Zhang et al. [28]. When the AAS/MK ratio exceeds 1%, the excess Na_2SiO_3 in the alkali-activator is unable to react with the free SiO_2 in the paste, resulting in the production of hardened crystals in the GPC. Simultaneously, excess Na_2SiO_3 in the air may combine with CO_2 and H_2O to produce sodium carbonate crystals deposited on the surface of the silica-aluminate, influencing the density of the GPC and its strength.

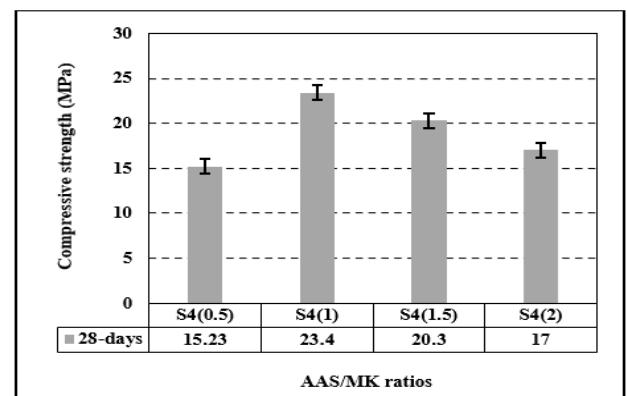


Figure 5. CS of GPC with different AAS/MK ratios

3.2.4 Effect of different superplasticizer dosages

The relation between superplasticizer dosage and CS in GPC was thoroughly investigated, and the results are

presented in Figure 6. The data show that an ideal superplasticizer dosage of 1.5% results in a maximum CS of 28.36 MPa. This demonstrates a significant improvement over previous dosage. Notably, CS increased significantly from 23.4 MPa to 28.36 MPa as the superplasticizer dosage was increased from 1% to 1.5%, demonstrating a positive influence of the high dosage. However, increasing the superplasticizer dosage above 1.5% resulted in a decrease in CS. Concentrations of 2%, 3%, and 4% produced CSs of 26.18 MPa, 21.68 MPa, and 18.91 MPa, respectively, emphasizing the adverse effects of high dosages. These findings are similar to Karthik and Mohan [23], which also identified 1.5% as the optimal superplasticizer dosage, emphasizing the significance of this exact dosage for increasing CS. The consistency of these findings emphasizes the need to select the right superplasticizer concentration for optimal CS in GPC. The use of superplasticizers in GPC attributed to increasing the material's workability and flowability [29]. This results in dispersing cement particles and increasing particle packing in the GPC mix. The best concentration for achieving high CS was found to be 1.5%, with substantial improvements over previous dosages. Conversely, high superplasticizer concentrations have a negative impact on CS. These findings emphasize the need for careful selection of the proper superplasticizer content to optimize GPC performance. Pham et al. [30] discovered that, with a water-to-binder ratio of 0.39 and superplasticizer dosages of 1.5% and 2%, the 1.5% dosage generated superior results than 2%. Verma and Dev [31] investigated the effect of several superplasticizer dosages ranging from 0.5% to 2% on CS of GPC using NaOH and Na₂SiO₃ and determined that the 1% concentration produced the highest CS. The reduction in CS with increasing of superplasticizer with dosage more than 1.5% can be attributed due to the instability of high superplasticizer dosage in multi-compound activator as a very high alkaline activator solution (Na₂SiO₃/Ca(OH)₂=1.5) [32].

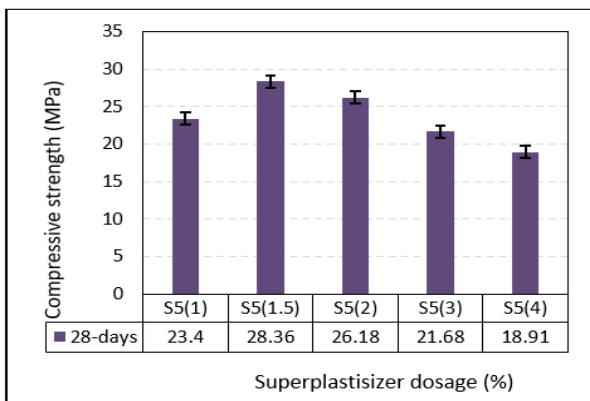


Figure 6. CS of GPC with different SP ratios

3.2.5 Effect of different MK quantities

The effects of MK content on the CS of GPC were investigated, and the results are shown in Figure 7. The research shows that a MK amount of 400 kg/m³ produces the highest CS. Increasing the amount of MK from 200 to 400 kg/m³ resulted in a considerable increase in CS, from 22 to 28.36 MPa. This reveals that an increased MK improves the CS of GPC. Using 300 kg/m³ of MK increased CS to 25.57 MPa, exceeding the dosage of 200 kg/m³. This provides support for the idea that raising the MK amount improves the CS of GPC. Increasing the amount of MK to 400 kg/m³

improves CS due to increased aluminosilicate components, which react with Na₂SiO₃ and Ca(OH)₂ to generate an amorphous gel. This gel is the principal binding phase of GPC, giving it strength and stability, resulting in enhanced CS. The reduction in strength with low amount of MK can be attributed to insufficient MK dosage in the alkali-activator, which does not provide an optimal alkali environment for the geopolymer reaction, resulting in becoming unable to generate a sufficient number of N-A-S-H gels in the geopolymer reaction, Zhang et al. [28].

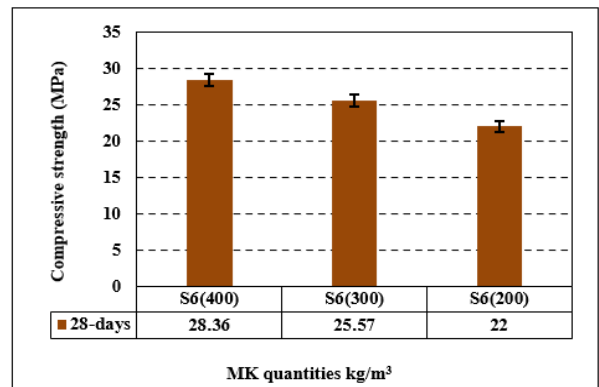


Figure 7. CS of GPC with different MK quantities

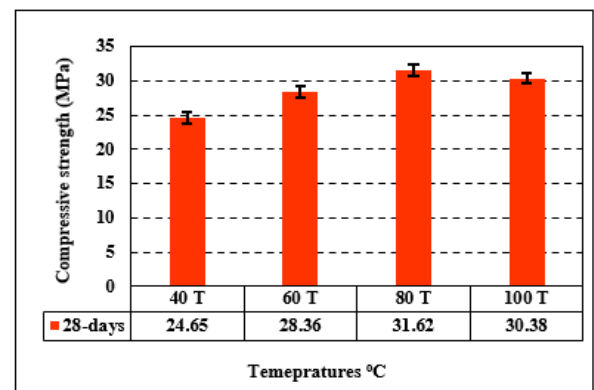


Figure 8. Effect of temperatures degrees curing for 24 hours on the 28-days CS of GPC

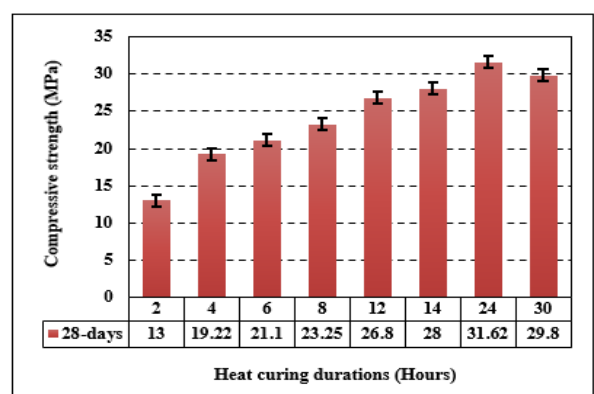


Figure 9. Effect of heat curing hours on the 28-days CS of GPC

3.2.6 Effect of different heat curing temperature degrees and durations

Figures 8 and 9 illustrate the effect of heat curing

temperatures and duration on the CS of GPC. Figure 8 shows that the 28-days CSs at oven curing temperatures of 40, 60, 80, and 100°C for 24 hours were 24.65 MPa, 28.36 MPa, 31.62 MPa, and 30.38 MPa, respectively, with the greatest strength of 31.62 MPa at 80°C. Figure 9 shows the CS development over curing times of 2, 4, 6, 8, 12, 14, 24, and 30 hours at 80°C, with strength values of 13 MPa, 19.22 MPa, 21.1 MPa, 23.25 MPa, 26.8 MPa, 28 MPa, 31.62 MPa, and 29.8 MPa, respectively, with the optimum strength remaining at 31.62 MPa after 24 hours. According to Posi et al. [33], the increase in CS at 80°C and 24 hours is attributed to heat assisting the geopolymerization process, which improves binder activation and strength. Beyond these settings, strength decreases, possibly due to moisture loss from the GPC at higher temperatures, the porous microstructure of the samples allows heat to easily penetrate, resulting in the evaporation or migration of moisture from the sample's interior areas as indicated by Görhan and Kürklü [34]. Previous investigations on GPC using NaOH solution by Krishnaraj et al. [35] confirm the finding that 80°C is the optimal oven curing temperature. Similarly, Görhan and Kürklü [34] reveal that 24 hours is the ideal cure duration. It is crucial to note that the optimal curing temperature and duration might vary depending on the exact composition of the GPC mix; therefore, these parameters should be tailored to each individual application. These findings demonstrate the importance of curing conditions in determining the CS of GPC.

3.2.7 Average CS of GPC with different curing ages of test

Figure 10 depicts the average CS values of GPC samples after a 24-hour curing period at 80°C and evaluation at various ages. The figure demonstrates a clear trend of rising CS as the testing age continues, from 14.74 MPa at 2 days to 31.62 MPa after 28 days. The average CS values measured were 14.74 MPa at 2 days, 18.81 MPa at 5 days, 23.38 MPa at 7 days, 24.82 MPa at 14 days, 28.1 MPa at 21 days, and 31.62 MPa at 28 days. The study found a positive relationship between testing age and CS in GPC samples, with strength rising over time due to the continuous hydration process. The continued hydration of the cementitious components promotes the creation of stronger bonds, which increases CS. This behaviour is typical of cement-based materials and is required to ensure the structural integrity and durability of construction projects. Hassan et al. [36] also observed that the CS of GPC rises with curing age. These findings highlight the need to provide GPC samples with enough curing time to obtain appropriate CS. Extending the testing age can greatly improve GPC's CS, providing important information about its performance and long-term behavior.

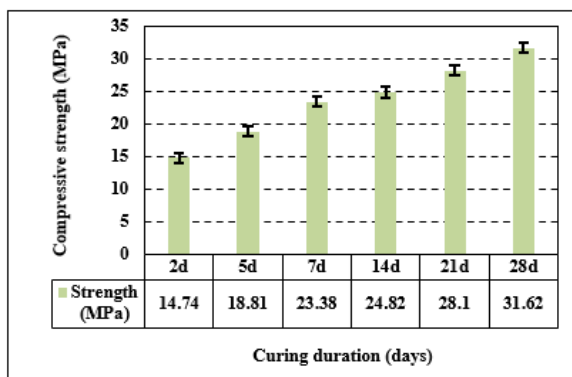


Figure 10. CS of GPC with different ages

3.2.8 The optimal mix design parameters

Based on the study's findings and experimental results, it is possible to conclude that specific parameters have a considerable influence on the compressive strength of geopolymer concrete mixtures. The geopolymer concrete mix with a water-to-solid binder ratio (W/B) of 0.75 had a compressive strength of 20.6 MPa. Furthermore, a sodium silicate to calcium hydroxide ratio (Na_2SiO_3 to $\text{Ca}(\text{OH})_2$) of 1.5 produced a compressive strength of 23.4 MPa. Similarly, a 1% alkaline activator solution/metakaolin ratio (AAS/M) yielded a compressive strength of 23.4 MPa. The dosage of superplasticizer (SP) had a significant impact on compressive strength; a 1.5% dosage increased strength to 28.36 MPa. The amount of MK in the mix directly affects compressive strength, with 400 kg/m³ of MK resulting in a compressive strength of 28.36 MPa. Curing conditions further influenced the compressive strength, as samples cured at 80°C for 24 hours exhibited the highest compressive strength of 31.62 MPa. Overall, these findings indicate that the optimum mix design achieved a maximum compressive strength of 31.62 MPa.

The optimization of the mix design can result in increased compressive strength while minimizing material inputs. This promotes GPC as a cost-effective alternative to standard concrete, which is particularly useful for large-scale construction projects with high material costs. The adaptability of GPC allows for its formulation to be tailored to fit a wide range of construction requirements, from residential buildings to large infrastructure projects. This adaptability improves its scalability, making it a suitable choice for a wide range of applications. Using industrial byproducts in GPC significantly decreases the carbon footprint of traditional cement production. This aligns with the industry's growing focus on sustainability, as GPC can effectively minimize greenhouse gas emissions while providing a durable building material.

3.3. Microstructure analysis

3.3.1 SEM analysis and EDX analysis

Figure 11 shows the SEM image of samples containing MK and $\text{Ca}(\text{OH})_2$. The SEM result of the combination shows a homogenous, compacted, and dense microstructure in general. Furthermore, Figure 11 provides important insights into the microstructural complexities of the GPC mix. In the alkaline activation of MK GPC, Na_2SiO_3 and $\text{Ca}(\text{OH})_2$ play critical roles in a number of different reactions. Sodium silicate, or water glass, dissolves in MK, releasing silicate species that combine with the aluminum in MK to generate an amorphous aluminosilicate gel. This gel serves as the primary binding phase in the GPC, providing both strength and stability. $\text{Ca}(\text{OH})_2$ combines with Na_2SiO_3 solution to produce more calcium silicate hydrate (C-S-H) gel, contributing further to the overall strength, durability, and dense microstructure of the GPC. The combination of these reactions leads to the transformation of MK into a solid and compacted material, showcasing the synergistic role of Na_2SiO_3 and $\text{Ca}(\text{OH})_2$ in the geopolymerization process specific to MK-based systems. Yang et al. [13] reported that the incorporation of $\text{Ca}(\text{OH})_2$ -based GGBS with Na_2SiO_3 showed denser product as indicated by SEM analysis. The C-S-H gels and smaller hydration products, such as C_2ASH_8 and C_4AH_{13} , formed rapidly, indicating that hydration products are developing.

The combination of calcium silicate hydrate (C-S-H) and

calcium-aluminium silicate hydrate (C-A-S-H) improves the performance of geopolymer concrete (GPC). C-S-H acts as the major binding phase, increasing strength and durability while decreasing porosity, therefore improving resistance to environmental effects and cracking. Its fibrous structure significantly boosts load-bearing capability, allowing for faster construction due to rapid early strength rise. At the same time, C-A-S-H serves as an additional binding phase, increasing mechanical properties. Its globular morphology promotes uniform distribution of binding phases, contributing to the overall stability and chemical resistance of GPC. In combination, these hydrates have a synergistic effect that improves the strength and durability of geopolymer concrete for a variety of building applications [37].

In the hybrid geopolymer system, the interaction between calcium-aluminum-silicate-hydrate (C-A-S-H) and sodium-aluminosilicate-hydrate (N-A-S-H) gels is important. C-A-S-H gel is formed in the presence of calcium, whereas N-A-S-H gel is formed via sodium silicate activation. This synergistic interaction improves the performance characteristics of geopolymer concrete through enhanced bonding strength and structural integrity, resulting in a more durable and resilient material [38]. The balanced presence of both gels enables optimised mechanical properties and overall performance in building applications.

Calcium incorporation enhances strength gain when compared to traditional sodium-based geopolymers. Calcium promotes faster gel formation and denser microstructure, resulting in significant early strength growth.

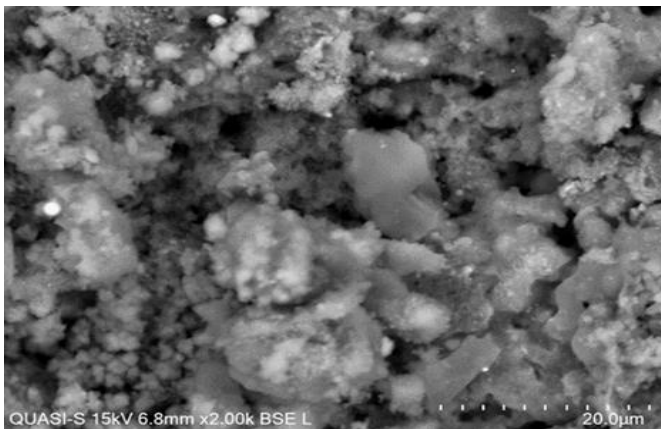


Figure 11. SEM of MK GPC

Table 2. Element weights based on the energy dispersive X-ray (EDX) graphical plot of GPC sample at 28-day curing

Element	Weight %
Al	11.590
Si	14.140
Ca	12.020
O	43.490
C	15.890
Na	2.170
K	0.230
Ti	0.470

The result of an EDX investigation on samples containing MK and Ca(OH)₂ after 28 days of curing has been investigated, which revealed some interesting findings. The principal elemental components found in the GPC were silicon (Si), calcium (Ca), and aluminium (Al), as shown in Table 2.

These three ingredients are required for the synthesis of C-A-S-H and C-S-H gels, which serve as the primary binder in GPC. Similarly, Zhang et al. [39] found strong peaks of these elements in EDX spectroscopy of GPC made with surface-modified fly ash cenosphere waste as an internal curing ingredient. Table 2 demonstrates that the GPC samples had significant levels of calcium, silicon, and aluminium, which are important components of calcium-aluminium-silicate-hydrate (C-A-S-H) gel, crucial for enhancing the mechanical properties of GPC. The sample contained 37.75% of silicon, calcium, and aluminium. The identification of these elements, reinforcing the critical role of these elements in the geopolymerization process. This, in turn, underscores the compatibility of the elemental composition with the mixture's mechanical properties. It indicates that the GPC samples exhibit the expected chemical signatures necessary for achieving the desired geopolymerization and mechanical performance, highlighting the suitability of the GPC for its intended application. The high percentage of these elements, coupled with the homogeneous and compact microstructures seen in Figure 11, indicates the efficiency of Ca(OH)₂ and MK in promoting the production of C-S-H and C-A-S-H gels. This process lowers porosity and strengthens the GPC [40].

4. CONCLUSIONS AND RECOMMENDATIONS

Based on the experimental finding, the following conclusions have been made:

1. The slump value of the GPC increases with an increase in the water-to-solid binder (W/B) ratio. Specifically, as the W/B ratio is raised from 0.65 to 1, the slump value also increases, going from 75 mm to 85 mm, respectively. This relationship between the W/B ratio and slump value is commonly observed in GPC mixtures. A higher W/B ratio means more water is used in proportion to the binder, which leads to a more workable and fluid GPC mix. As a result, the GPC becomes easier to pour and shape, and the slump value increases. Conversely, a lower W/B ratio produces a stiffer and less workable GPC mix, leading to a lower slump value. The use of MK and Ca(OH)₂ in GPC contributes to its low initial and final setting times. This is primarily due to the high fineness of MK, which reduces the dormant period and accelerates the geopolymerization process, leading to rapid hardening. The high surface area of fine particles in MK provides more sites for the geopolymerization reaction to occur with Ca(OH)₂, which leads to faster hydration and binding of the materials in the GPC mixture.

2. The results of the GPC mix design demonstrate that the optimal parameters for GPC are as follows: Water to solid binder ratio: 0.75, Sodium silicate to calcium hydroxide ratio: 1.5, Alkaline activator to MK ratio: 1, Superplasticizer dosage: 1.5, MK amount: 400 kg/m³, curing temperature: 80°C, and heat curing period: 24 hours. These optimized parameters were determined through the study, and they represent the ideal MK based geopolymer mix proportions and curing conditions for the GPC.

3. The CS properties of the MK-based geopolymer exhibit a consistent improvement with the curing age. This indicates that the GPC gains strength over time as the curing process progresses. Furthermore, the results show that the use of Ca(OH)₂ as an activator in the MK-based geopolymer has a positive impact on its characteristics. The presence of Ca(OH)₂ facilitates the geopolymerization process, leading to improved

bonding and enhanced strength development in the GPC. This positive influence is evident in the measured mechanical properties, which demonstrate higher CS. SEM and EDX analyses indicated the positive influences of the incorporation of Ca(OH)₂ in GPC.

4. The synergistic impacts of several critical parameters, working together to optimize the material's performance and workability, influence the design of geopolymer concrete (GPC). A lower water-to-solid binder ratio increases strength but decreases workability, which can be offset by the addition of superplasticizers. The sodium silicate to calcium hydroxide ratio improves the binder phase, while the alkaline activator to metakaolin ratio controls geopolymerization. Higher metakaolin quantities increase aluminosilicates for polymerization but require careful adjustment of activators and superplasticizers to maintain workability. By optimizing these factors together, the performance of GPC in terms of strength, durability, and workability can be enhanced.

5. The findings highlight geopolymer concrete (GPC) as a sustainable alternative to traditional concrete, with the potential to lower the construction industry's environmental impact. By utilising industrial by-products like metakaolin, GPC minimises carbon emissions associated with conventional cement production. This makes GPC a key player in promoting eco-friendly building practices.

Although our study effectively identifies optimal mix design parameters, it is important to acknowledge certain limitations inherent in our approach, particularly concerning the specific materials and curing conditions employed. Based on the obtained findings, researchers recommended investigating a wider variety of precursors and binders, as well as evaluating the performance of geopolymer concrete (GPC) across diverse environmental conditions. Conducting long-term durability assessments beyond 28 days will be crucial for completely validating the efficiency of GPC in real-world applications, ensuring its reliability and sustainability as a construction material. Additionally, incorporating additional characterization techniques such as X-ray diffraction (XRD) to identify crystalline phases, Fourier-transform infrared spectroscopy (FTIR) to investigate chemical bonding, and mercury intrusion porosimetry (MIP) to analyze pore structure.

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NOMENCLATURE

GPC Geopolymer Concrete

MK
CS
OPC

Metakaolin
Compressive Strength
Ordinary Portland Cement