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Evaluating the Performance of Low Carbon GGBS & Metakaolin Geopolymer (Cement Free) Concrete: Impact of Binder Composition, Curing Methods, and Activator Ratios on Compressive Strength

Noor Alawi, Aye Myat Mon, An Huynh, Ash Ahmed* and Habiba El-Gharably

School of Built Environment and Engineering, Leeds Beckett University, Leeds, United Kingdom.

***Corresponding author**

Ash Ahmed,
School of Built Environment and Engineering,
Leeds Beckett University,
Leeds, United Kingdom.

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Abstract

Concrete production's reliance on traditional Portland cement is a significant contributor to global construction and development. Concrete production's reliance on traditional Portland cement is a significant contributor up to 10% global CO_2 emissions, prompting a need for sustainable alternatives. This study explores the use of geopolymer binders, composed of industrial and agricultural by-products ground granulated blast furnace slag (GGBS) and metakaolin (MK), as a low-carbon alternative to conventional cement. An experimental investigation has been conducted to assess the workability and compressive strength of various cement free concrete mixes, tested at intervals of 5, 7, 28, and 91 days. The study also examined the impact of different curing methods (air and water curing) and activator-to-binder (a/b) ratios on the concrete's mechanical properties. The findings revealed that both the binder composition and curing method significantly influence the compressive strength, with certain mixes demonstrating superior long-term performance, particularly those with optimized a/b ratios and higher GGBS content. These insights underscore the potential of geopolymer binders as a sustainable alternative to Portland cement, offering a viable path to reducing the carbon footprint of concrete production while maintaining structural integrity.

Keywords: Geopolymer concrete, GGBS, Metakaolin, Compressive strength, Sustainable construction, Activator-to-binder ratio, Curing method.

Introduction

A crucial role in infrastructure development and urbanization is played by concrete all over the world, and it is the most frequently used material in building sector. The manufacturing process of traditional Portland cement used for producing concrete accounts for up to 7-10% of worldwide CO_2 emissions (Ahmed et al., 2019). The most significant factor contributing to these emissions is calcium carbonate decomposition in limestone during production of cement, which involves heat-intensive operation. Almost 90% of all embedded emissions in an average cubic meter of this building material come from such processes (Ahmed et al., 2019; Ahmed & Sturges, 2014; Heidelberg Materials, 2023) because production requires large amount of CO_2 to be released into surroundings. To achieve sustainable concrete production, the amount of cement produced needs to be reduced globally. Geopolymer cement, composed of aluminosilicate materials, an alkaline reagent like sodium or potassium silicates, water, and often calcium from blast furnace slag, forms three-dimensional zeolitic frameworks through geopolymerization, creating a high-alkali (K-Ca)-Poly (sialate-siloxo) structure (Davidovits, 2013; Davidovits, 1994; Davidovits, 2015). Geopolymer concrete, made from minimally processed or industrial by-products, is ideal for infrastructure and construction due to its lower carbon footprint. Incorporating aluminosilicate materials and an alkaline activator, it offers notable advantages over conventional concrete, including reduced carbon emissions, lower energy use, and enhanced durability, fire resistance, and chemical resistance. This sustainable alternative to Portland cement, made from minimally processed natural materials or industrial by-products, is used in various industries for transportation, construction, and offshore projects (Davidovits, 2013; Davidovits, 1994).

The term "geopolymer," introduced in the 1970s by Professor Joseph Davidovits, refers to a solid and stable material formed when an aluminosilicate powder reacts with an alkaline solution, such as alkali hydroxide or alkali silicate (Davidovits, 2015). Geopolymers are inorganic polymers formed through a chemical reaction between silicon (Si) and aluminium (Al) in a source material and an alkaline activator. This process involves dissolving Si and Al atoms, followed by the rapid polymerization of precursor ions, resulting in a three-dimensional polymeric structure with Si-O-Al-O bonds. The product is a hard, high-strength binder that forms the geopolymer material (Davidovits, 1994; Hardjito & Rangan, 2005). Geopolymers are being used as an environmentally friendly substitute for Portland cement, with a commercial interest in replacing its aluminosilicate sources, for instance, blast furnace slag and fly ash among others. Sodium hydroxide (NaOH), potassium hydroxide (KOH), water and sodium silicate (Na_2SiO_3) are used to integrate aluminosilicate sources with alkali activators. This approach offers a lower carbon footprint, improved mechanical properties, and enhanced resistance to environmental factors (Hardjito & Rangan, 2005; Huynh, 2023). To address CO_2 challenges in the cement and concrete industry, geopolymer cement and concrete offer a promising solution by using environmentally friendly materials like industrial and agricultural by-products. Their use has expanded to major construction projects, including airports, pavements, and railways (Joshua et al., 2021). Aluminosilicate sources such as ground granulated blast furnace slag (GGBS), fly ash (PFA), silica fume (SF), metakaolin (MK), rice husk ash (RHA), and palm ash (PA) are categorized either as pozzolans or industrial by-products provide finely powdered siliceous and aluminous compounds. They also come with other advantages including lower CO_2 emissions when producing, industrial waste utilization for cost-effectiveness among others that have led to minimal heating requirements. These sources also improve concrete durability, contributing to longer-lasting structures (Ahmed et al., 2019; Hardjito& Rangan, 2005; Joshua et al., 2021).

In this paper, GGBS, with a high CaO content (44.7%) was chosen to combine with MK, providing a distinct advantage. In the manufacture of geopolymer mixes, a high proportion of CaO significantly accelerates the reactions (Kabirova et al., 2022; Nadir et al., 2024). GGBS, a by-product of iron production with over 44.7% calcium oxide, is considered hazardous due to environmental concerns (Nadir et al., 2024). However, it is an effective component for slag-based geopolymers. When combined with an alkali activator, GGBS hardens rapidly at room temperature, offering high strength and lower CO_2 emissions compared to conventional concrete (Huynh, 2023; King, 2012; Nadir & Ahmed, 2021). Consequently, Metakaolin (MK) was selected due to its primary compositions (Nadir et al., 2024). Metakaolin is manufactured by calcination of kaolinite clay at 650-850°C and ground into a fineness of 700-900 m²/kg. It is highly reactive pozzolanic material improving the durability of concrete. The chemical composition of metakaolin is: 52.1% SiO_2 and 45.1% Al_2O_3, hence it is very reactive material with more than 90% pozzolanic elements (Nadir et al., 2024; Nadir & Ahmed, 2021; Narmatha & Felixkala, 2016). Alkali activators, essential in geopolymer synthesis, typically include sodium or potassium hydroxides and sodium or potassium silicates. Sodium hydroxide (NaOH) is most used due to its cost-effectiveness and availability, while sodium silicates, though more adhesive and challenging to achieve flowability, are preferred for their effectiveness in forming geopolymers. These activators create an alkaline environment that dissolves silicon and aluminum from source materials, facilitating their polymerization into a three-dimensional network. The strength, setting time, and durability of the geopolymer are all influenced by the composition and concentration of these activators, thus choosing them carefully is critical to maximizing performance (Provis & Van Deventer, 2009; Hardjito & Rangan, 2005). Geopolymers are produced by combining an alkali activator with an aluminosilicate source, producing a disordered alkali aluminosilicate gel that serves as the binder. This gel incorporates unreacted particles and retains water from the mixing solution. Unlike traditional C-S-H gel, the water in geopolymer binders is not chemically integrated, influencing the properties of material (Hardjito & Rangan, 2005; Joshua et al., 2021).

The synthesized process known as geopolymerization involves dissolving aluminosilicate sources in an alkali activator solution, which forms an amorphous phase and builds a three-dimensional network of silicoaluminate structures (Joshua et al., 2021) and the process comprises two main stages, as illustrated in Figure 1. First, alkaline dissolution of solid aluminosilicate oxides, resulting in the creation of highly reactive silica and alumina particles. In the subsequent stage, polycondensation process, which facilitates the transformation of these particles into amorphous to semicrystalline polymers (Mabroum et al., 2020).

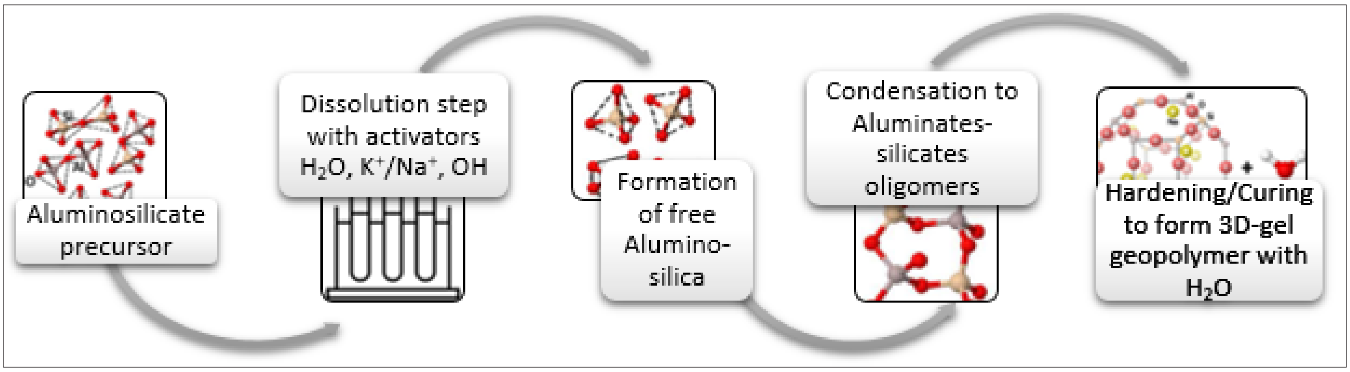

Figure 1: Basic Geopolymerisation Pathway (Mabroum et al., 2020)

This paper is a study of how geopolymer concrete can be used to reduce the carbon footprint of the civil engineering industry through sustainable construction practices. The research concentrates on workability as well as compressive strengths of geopolymer binders (MK/GGBS) that are activated with portion of alkali. The aim of this research is to develop workable mix designs for geopolymer concretes which will satisfy structural performance requirements and to determine the compressive strengths at short term (5, 7, 28 days) and long term (91 days) intervals. The research has also analyzed the effect of different curing regimes (air, water) and various activator-to-binder (a/b) ratios on concrete mechanical properties.

Methodology

This study investigates the development of cementless concrete mixes utilizing geopolymer binders, aiming to reduce the embodied carbon associated with traditional Portland cement. The methodology is organized into distinct phases, as detailed in the below sections:

Geopolymer Binder Mix Design

The geopolymer binders used are composed of GGBS and MK, shown in table 1, selected for their high aluminosilicate content and reactivity. The binder combinations are designed to explore varying ratios of GGBS and MK to optimize the mechanical properties of the resulting concrete. Fine and coarse aggregates are consistently maintained across all mixes to ensure comparability. The aggregate proportions are fixed at 554 kg/m^3 of fine aggregate (FA) and 1293 kg/m^3 of coarse aggregate (CA), translating to 6.65 kg of fine and 15.52 kg of coarse aggregate per batch (table 1), providing a stable base for the concrete formulation. Geopolymer binder compositions with a consistent activator proportion by weight consist of 12 kg/m^3 of solid/pellet NaOH mixed with 18 kg/m^3 of water and 120 kg/m^3 of Na_2SiO_3 solution.

Based on the embodied carbon factor data provided by the Institution of Structural Engineers and Adesina (The Institution of Structural Engineers, 2022; Adesina, 2020), it was found out that the use of superplasticizer increases embodied carbon due to its high carbon factor. As a result, superplasticizer was omitted from the GGBS/MK binders, requiring adjustments to the water content in each mix. Additionally, another contributing factor for not using superplasticizer is to optimize the strength development by employing three curing methods including water curing, air drying, and air curing under the proposed MK/GGBS binder type as using superplasticizer may interfere with the curing process.

The water content was adjusted to determine final activator-to-binder ratio, ranging from 0.58 to 1.27 in this study. The a/b ratio in geopolymer concrete mixes is defined as the ratio of alkaline activator to binder. The alkaline activator consists of sodium silicate solution combined with sodium hydroxide solution, which is mixed with addition water during the mixing process. Similarly, the binder is the total content of MK and GGBS under proposed combination such as 0% MK and 100% GGBS. The below example of the calculation has been used to process a/b ratio.

$$\text{0\% MK and 100\% GGBS, a/b ratio} = \frac{Activator}{Binder}$$

$$= \frac{12\,\frac{kg}{ms}\text{ of solid NaOH } + 18\,\frac{kg}{ms}\text{ of water } + 120\,\frac{kg}{ms}\text{ of } Na_2SiO_3\text{ solution } + 24\,\frac{kg}{ms}\text{ of additional water}}{0\,\frac{kg}{ms}\text{ of MK} + 300\,\frac{kg}{ms}\text{ of GGBS}} = 0.58$$

Binder Combinations	Activator to Binder Ratio (a/b)		
	GGBS	MK	
GGBS + MK	20	80	0.58, 0.7, 0.75, 0.76, 0.77, 0.8, 0.82, 0.84, 0.99, 1.07 and 1.27
	50	50	
	80	20	
	100	0	

Table 1: Mix Design for Different Geopolymer Binders and a/b Ratios

Specimen Preparation

Several batches of geopolymer specimens were prepared and assessed according geopolymer mixes with various binder combinations conducted in this experimental investigation. To create the alkaline activator for the geopolymer concrete, a 10 Molarity NaOH solution was prepared by dissolving 98% pure NaOH pellets in water to produce NaOH solution. This solution was then mixed with Na_2SiO_3 solution 24 hours in advance. During the first mixing phase, coarse and fine aggregates were mixed for 2 minutes. Binder components were added next, followed by the gradual addition of the alkali activator and extra water, determining a/b ratios. The mixture was then mixed for an additional 3 minutes. To ensure uniformity, the freshly formed geopolymer concrete was mixed for another 2 minutes. The production procedure for the geopolymer concrete is illustrated in Figure 2 (Mohmmad et al., 2023).

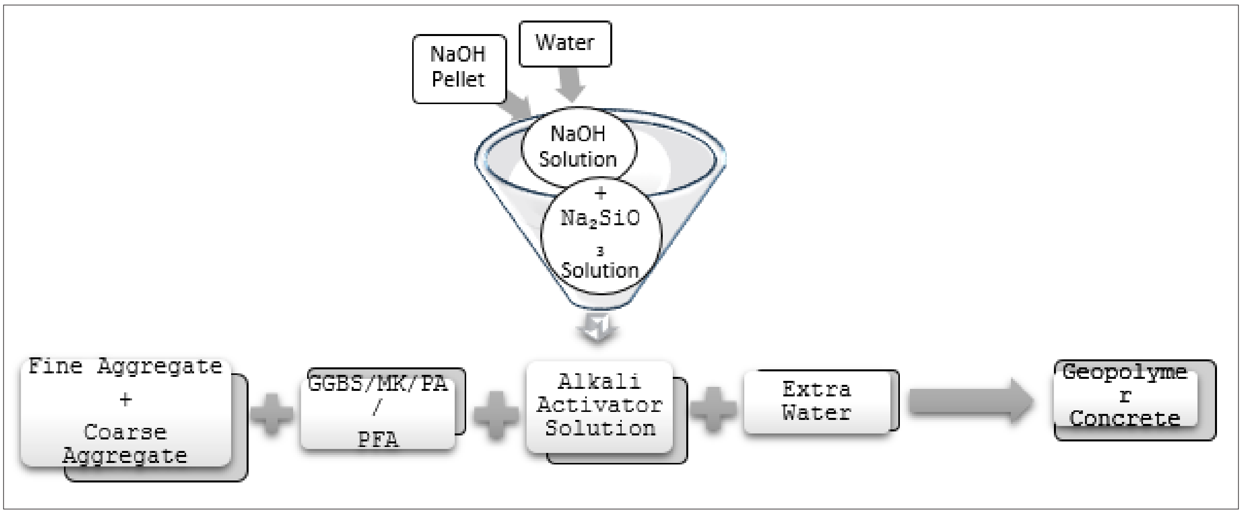

Figure 2: Geopolymer Concrete Formation Process

Casting and Curing Methods

For every mix, eight cube specimens measuring 100 x 100 x 100 mm were created (Figure 3a). The specimens were compacted using a mechanical vibrating machine in compliance with BS EN 12390-2:2019 to minimize air voids (British Standards Institution, 2019). After casting, specimens were stored under laboratory condition maintained at room temperature (20°C) for 24 to 48 hours before being removed from the molds with the specimens covered in heavy-duty polythene plastic sheets to prevent evaporation of the alkaline solution, as shown in Figure 3b. Additionally, humidity levels were controlled to facilitate the chemical reactions necessary for effective geopolymer hardening and structure formation.

Figure 3: (a) 100 x 100 x 100 mm Specimens (b) Prevention of Alkaline Solution Evaporation (c) Water Curing (d) Air Drying (e) Air Curing

The specimens were cured under controlled conditions according to BS EN 12350-2:2019. This study employed three curing methods including water curing, air drying, and air curing, specifically for GGBS and MK mixes. Water curing (Figure 3c) involved keeping the concrete continuously wet at a controlled temperature of 20°C ± 2°C, as detailed for MK0GS100, MK20GS80, MK50GS50, and MK80GS20. For air drying (Figure 3d), the specimens were dried in open air without additional moisture, applied for 5 days at 7, 28, and 91 days for ACMK0100GS, ACMK2080GS, ACMK5050GS, and ACMK8020GS. Air curing (Figure 3e) was conducted under controlled conditions, with moisture maintained by spraying water on polythene sheets (covering the specimens) three times a week. Air curing was done for 2 days at 7-day age, 23 days at 28-day age, and 86 days at 91 -day age as presented in Table 2.

Table 2: Details of Curing Method for MK and GGBS Mixes

Mixes	7-day Age			Curing Method 28-day Age			91-day Age		
	Water Curing (days)	Air Drying (days)	Air Curing (days)	Water Curing (days)	Air Drying (days)	Air Curing (days)	Water Curing (days)	Air Drying (days)	Air Curing (days)
MK0GS100	7	-	-	28	-	-	91	-	-
MK20GS80	7	-	-	28	-	-	91	-	-
MK50GS50	7	-	-	28	-	-	91	-	-
MK80GS20	7	-	-	28	-	-	91	-	-
ACMK0100GS	-	5	2	-	5	23	-	5	86
ACMK2080GS	-	5	2	-	5	23	-	5	86
ACMK5050GS	-	5	2	-	5	23	-	5	86
ACMK8020GS	-	5	2	-	5	23	-	5	86

Testing Procedure

Slump Testing

The slump test was carried out according to BS EN 12350-2:2019 (British Standards Institution, 2019) with several procedures. First, the sample was shovelled into a heap, turned over three times, and then flattened with a vertical shovel once the mixer had been emptied and cleaned. The slump cone and base plate were cleaned, dampened, and placed on a solid, level base. The cone was filled in three equal layers, each rodded 25 times with a standard rod. Before rodding the third layer, the concrete was heaped above the top of the cone, ensuring the rod penetrated the previous layer. The rod was then used to strike the concrete level with the top of the cone. Spillage was cleaned off while maintaining foot pressure on the cone. The cone was lifted straight up within 5 to 10 seconds. Finally, the rod was laid across the upturned cone, and the distance between the underside of the rod and the highest concrete point was measured to the nearest 10mm to determine the slump (Figure 4a) reflecting workability, stability and flowability. In this research, the slump test was classified into categories from S1 (10-40mm) to S4 (160-210mm) as specified in the standard of BS EN 206-1:2000 (British Standards Institution, 2000).

Density

The selection of binder types in geopolymer concrete production significantly affects the density of the final product. To analyse this, density testing was conducted using four 100 x 100 x 100 mm cube specimens for each mix (Figure 4b and 4c). Before testing the compressive strength, hardened density was measured using Eq. 1 both at short-term (5, 7, and 28 days) and long-term (91 days) intervals, in accordance with BS EN 12390-7:2019 (British Standards Institution, 2019).

$$Density = \frac{Mass\ Dry}{(Mass\ Dry - Mass\ Wet)} \times 1000 \quad (\text{in kg/m}^3) \qquad (1)$$

Compressive Strength Testing

Compressive strength testing was performed at 5, 7, 28 and 91 days, following the BS EN 12390-3:2019 (British Standards Institution, 2019) standard. Specimens were subjected to axial loading until failure, with the maximum load recorded by using the apparatus shown in Figure 4d. This provided the failure value, representing the maximum compressive strength of the concrete and compressive strength of the specimens was determined using Eq.2 (British Standards Institution, 2019) [25].

$$f_c = \frac{F}{A_c} \quad (\text{in N/mm}^2 \text{ or MPa}) \qquad (2)$$

Where, F = failure load in Newtons (N) and Ac = 100mm x 100mm (cross-sectional area of the specimen subjected to the compressive force)

Figure 4: Geopolymer Concrete Specimens (a) Under Slump Testing (b) Under Density Testing (Mass Dry) (c) Under Density Testing (Mass Wet) (d) Under Testing of Compressive Strength

Results and Discussion

All the experimental work done and recorded for this paper have been done in accordance with the British standards and European standards. Manual handling, health and safety as well as the Code of Practice have been considered and followed. All environmental conditions for each mix have been consistent throughout the experiment duration to minimize external variables that could affect the results.

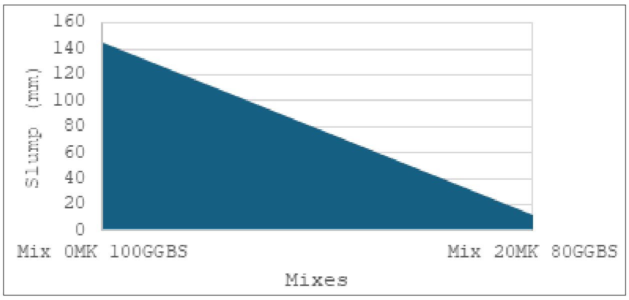

Figure 5: Variation of MK addition to GGBS mixes on slump properties

It's worth noting that the mixes with the same activator to binder ratios of 0.5 but different MK and GGBS proportions have exhibited varying slumps as seen in figure 5. For example, the mix compromising of 100% GGBS mix had a slump of 140mm, whereas the mix containing 20%MK and 80%GGBS has resulted a slump of 12mm. This proves that introducing MK to a GGBS based mix reduced the slump and that is mainly due to the fact that MK's higher surface area improves the cohesiveness and workability of the mix.

Compressive Strength

Compressive strength of MK and GGBS mixes.

In figure 6, the effect of metakaolin and the way MK can contribute to the early strength is mainly due to its high pozzolanic reactivity. It can also be noted that high MK content tends to slow down the initial strength gain as seen in the 80MK20GGBS mixes. In the 80MK20GGBS mixes show an increase in strength from 28 MPa at 7 days to 58MPa at 28 days and further reaches to 46MPa at 91 days. This high initial strength indicates that there is a good initial reactivity and the strength gain over time suggests the continuity of the pozzolanic reaction.

GGBS significantly enhances the long-term strength due to its latent hydraulic properties, which are activated over time. Having a high GGBS content mixes show a marked increase in the compressive strength from 29 to 91 days which suggests that GGBS is highly beneficial for long-term durability.

On the other hand, mixes with a balanced ratio of MK and GGBS such as 50MK50GGBS tend to show good strength development at all ages. The combination of an early pozzolanic activity from MK and the long-term strength effect of GGBS creates a cooperative effect.

As highlighted in Figure 6 below, the results indicate that the compressive strength of concrete mixes is highly influenced by the proportions of MK and GGBS. Higher GGBS content leads to a significant long-term strength development. Whereas MK contributes mostly at the initial stages of strength gain and developments. The optimal mixes having a balance of 50-50 of both components have achieved the best performance and recorded results in term of long and short curing periods.

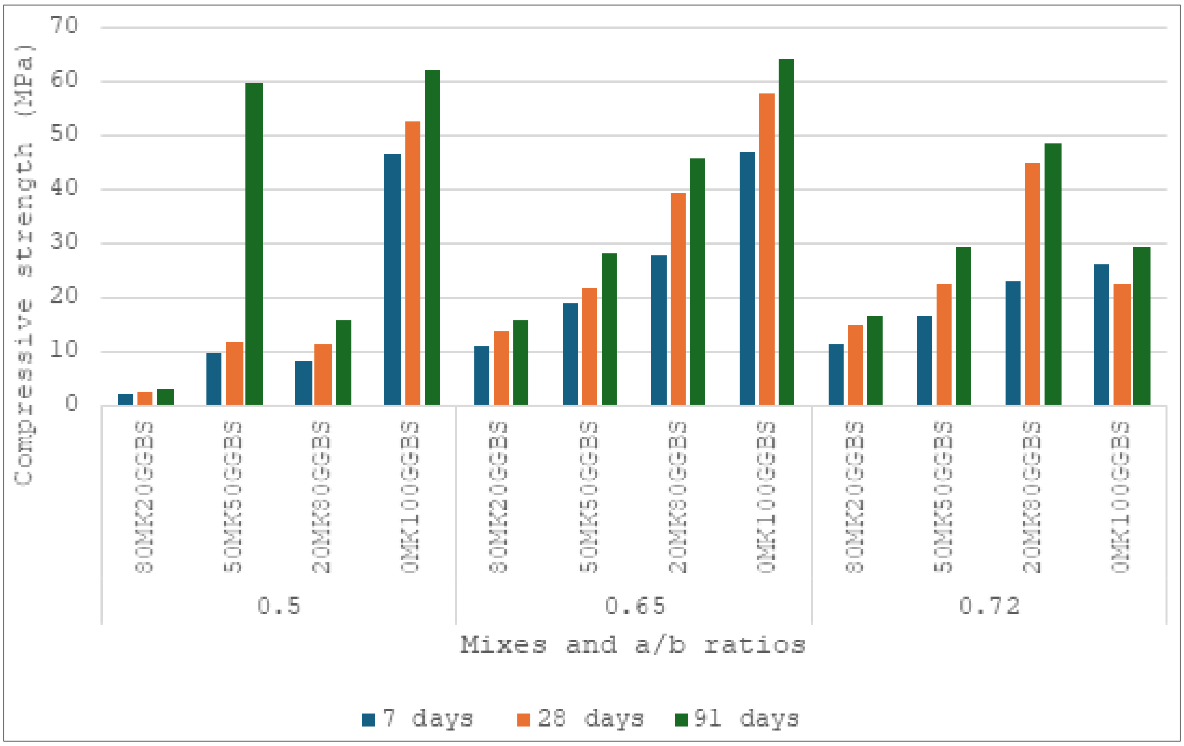

Figure 6: MK and GGBS Compressive strength at 7, 28 and 91 days (after standard water curing).

Compressive strength of MK and GGBS mixes at different curing methods

A total of 30 mixes of MK and GGBS were tested by different curing methods. 15 Mixes were subjected to water curing throughout the curing process till the testing days on 7,28 and 91 days. The other 15 mixes were subjected to air drying for a week before being subjected to air curing for the remainder of the curing period.

When comparing the results highlighted in Figure 6 (water cured) and the results in Figure 7 (air cured), it can be noted that the general trend in Figure 7 to be that the compressive strengths are generally low when compared to the water cured samples. The strength gain is more gradual over time with a noticeable increase at 28 to 91 days. Water cured samples have compressive strengths that are consistently higher compared to the air cured samples. It can also be noted that there is a more rapid strength gain especially between 7 and 28 days. Moreover, the strengths at 91 days are significantly higher for most mixes indicating the effectiveness of water curing the samples.

Its worth noting that the 80MK20GGBS mix at the 0.5 water-cement ratio shows extremely low compressive strength at all tested ages (7, 28, and 91 days). This makes it essentially useless in terms of strength, with compressive values far below what's viable for structural applications. It's ineffective for construction projects requiring durable and strong concrete. Moreover, the extremely low strength suggests poor workability. The high proportion of Metakaolin (80%) likely causes difficulties in mixing, placing, and finishing the concrete, further reducing its practical utility.

Specimens that were subjected to water curing had a more conducive environment of cementitious materials which has resulted in a higher compressive strength. Having a consistent presence of moisture which has facilitated the environment for the pozzolanic reactions to take place and for the formation of the hydration products leading to improved strength development.

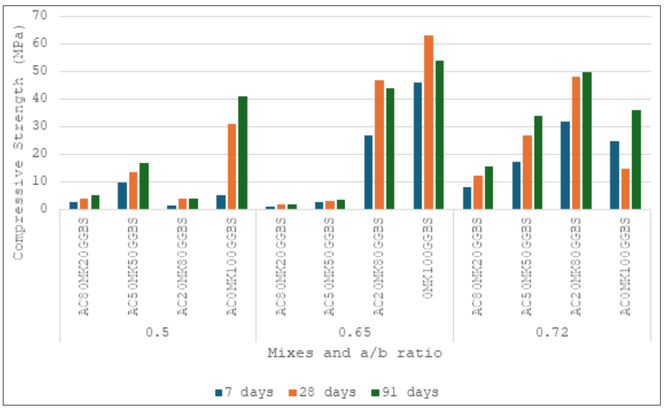

Figure 7: Compressive strength of MK and GGBS Mixes subjected to air drying and curing at 7, 28 and 91 days

On the other hand, specimens that were subjected to air curing were limited to the availability of moisture which has slowed done the rate of the hydration process resulting in lower compressive strengths. It can be noted that water curing is evidently the optimal method of curing as it has shown a consistency in the yielding of higher compressive strengths across all mixes by having a more efficient hydration process leading to a bettering early and long-term strength development. Air curing on the other hand, has been noted to be less effective especially with mixes having high content of MK which rely mostly on the moisture for the pozzolanic activity.

It can be summarized that mixes with a balanced proportions of MK and GGBS benefit significantly from water curing by showing a strength increase at all ages. Where as pure GGBS mixes had a consistent performance and performed well under both curing conditions, but the advantage of water curing is still apparent in the higher compressive strength achieved. Mixes with a high MK content have shown limited strength development under air drying which highlights the importance of water curing for their strength gain.

Figures 6 and 7 clearly indicate that water curing is the optimal method of developing compressive strength in concrete mixes containing MK and GGBS. The continuous availability of moisture enhances the hydration process and pozzolanic reaction which leads to a higher and more consistent strength gain. However, air curing still allows strength gain and development but will result in a lower overall strength and is less effective for mixes with high MK content.

Influence of Increasing Binder Mass (via a/b ratio) on Performance of Compressive Strength

Figures 8 to 15 summarizes the strengths measured at 7,28 and 91 days. The mixes are labelled with their respective MK and GGBS percentages and compared across different a/b ratios.

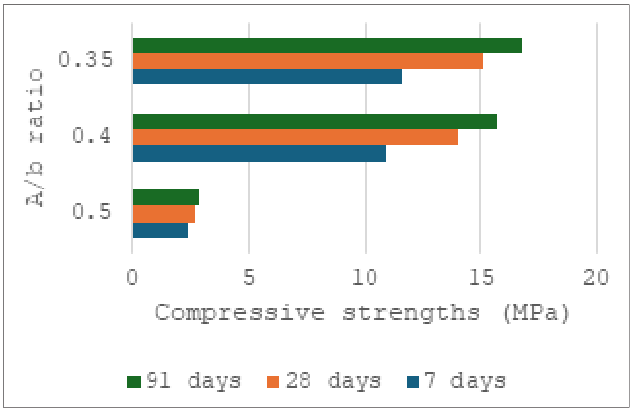

Figure 8: MIX 80MK 20GGBS compressive strengths at different a/b ratios

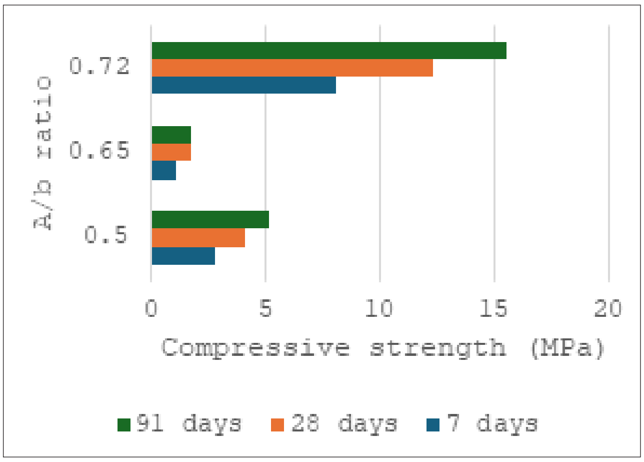

Figure 9: Mix AC 80MK 20GGBS compressive strength at different a/b ratio

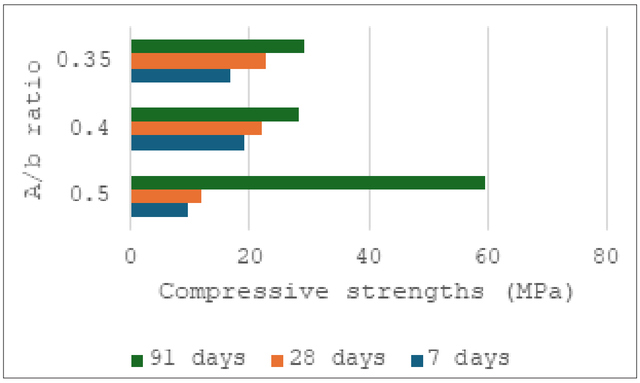

Figure 10: MIX 50MK 50GGBS compressive strengths at different a/b ratios

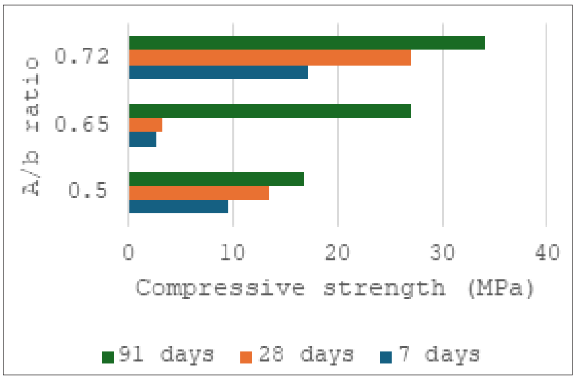

Figure 11: MIX AC50MK 50GGBS compressive strengths at different a/b ratios

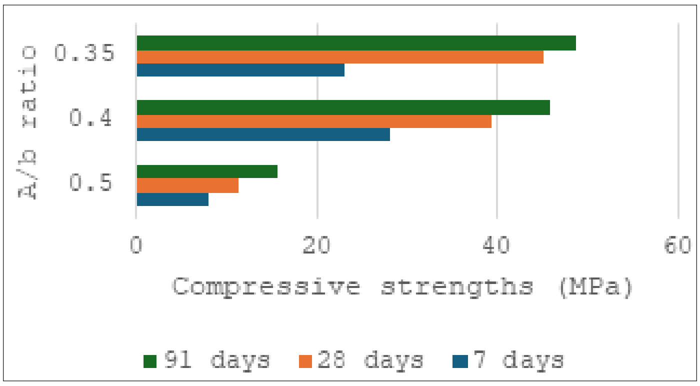

Figure 12: MIX 20MK 80GGBS compressive strengths at different a/b ratios.

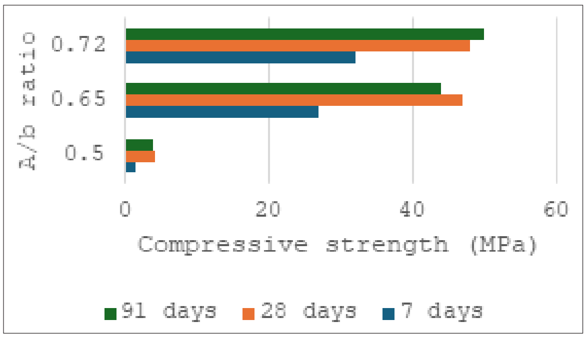

Figure 13: MIX AC20MK 80GGBS compressive strengths at different a/b ratios

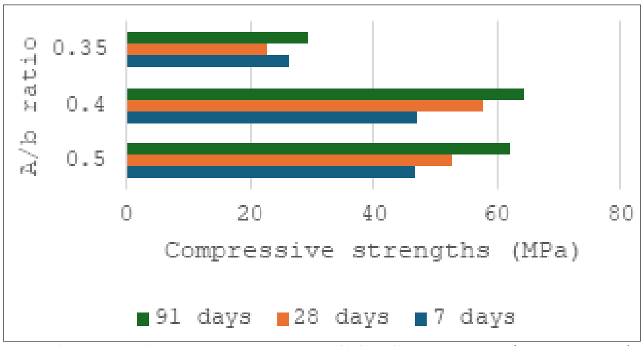

Figure 14: MIX 0MK 100GGBS compressive strengths at different a/b ratios

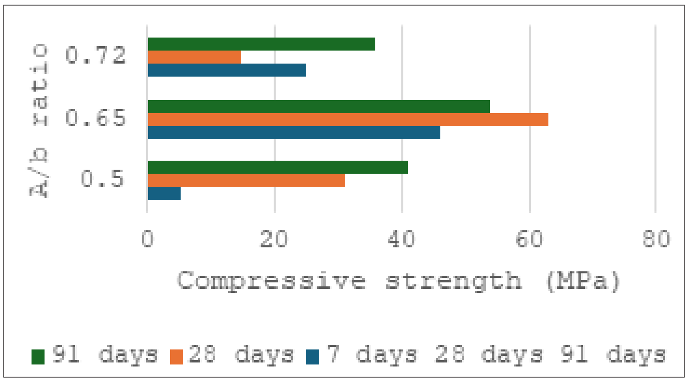

Figure 15: MIX AC0MK 100GGBS compressive strengths at different a/b ratios

The analysis done and results recorded and displayed in figures 8 to 15 show that the compressive strength results across the different mixes and curing methods can be summarised in a few key trends being mixes with higher metakaolin content such as those with 80%MK and 20%GGBS have shown a general trend of a greater compressive strength at a lower-activator to binder ratio, most importantly the best and optimal strengths have been recorded for these samples when subjected to water curing. On the other hand, mixes that were air cured have shown a significant decrease in the compressive strength when compared to the water cured samples which highlights the important role water has in relation to the compressive strength. In mixes with an equal amount of 50%MK and 50% GGBS the strength development has been noted to be more stable with higher strengths being achieved at lower a/b ratios and the most optimal results are the ones that were subjected to water curing. Moreover, specimens with lower MK content and a higher GGBS content have shown a long-term strength gain most particularly at a lower a/b ratio benefiting from the hydraulic properties of GGBS. Finally, mixes with 100% GGBS demonstrate the potential for very high compressive strength, especially under water curing and low a/b ratios, but this potential is significantly diminished under air curing, underscoring the importance of proper curing practices for optimal strength development.

Impact of Binder Content and Curing Regime on Geopolymer Mixes with Fixed Activator Mass

Around the world not many have the facility and the luxury of having water being always facilitated whenever required for construction purposes. An investigation has taken place to study the possibility of producing a more sustainable solution to concrete using air curing method. Results are summarised in figure 16 below.

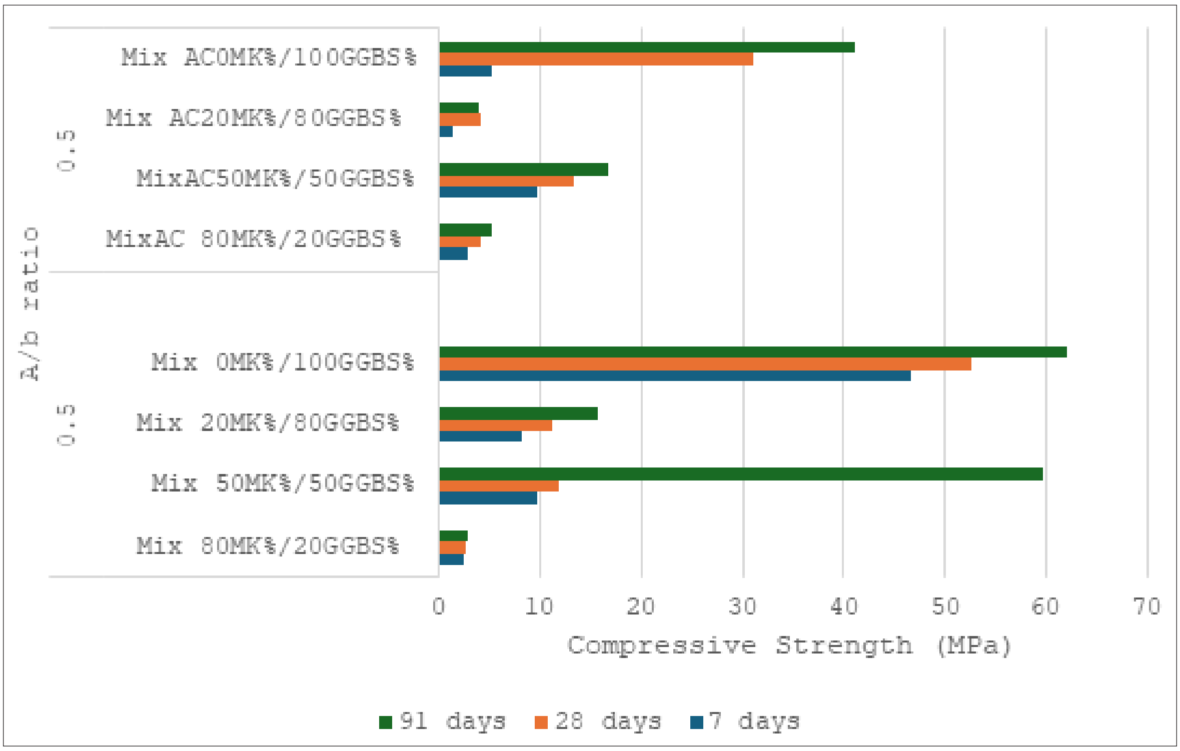

Figure 16: Comparison of MK and GGBS mixes with similar a/b ratio

Figure 16 above compares the compressive strengths of various mixes of MK and GGBS having a similar a/b ratio over 7, 28 and 91 days. The water cured mixes labelled as ''Mix MK% GGBS%, generally have shown a trend of a higher compressive strength when compared to the air cured mixes. For instance, the Mix 0%MK 100%GGBS nearly reached 60MPa at 91 days which has outperformed the air cured mix having the same a/b ratio and the same mix component. A similar trend is consistent across the water-cured mixes which can be interpreted as the water curing is more effective as it initiates and promotes the hydration process for the geopolymerization process to take place which is a big contributor to the strengthening of the mix.

Moreover, air cured mixes which were labelled as ''Mix AC MK% GGBS%'' generally have shown a lower compressive strength. For instance, Mix AC 0%MK 100%GGBS has achieved just around 30MPa at 91 days, which is almost half of the strength that was achieved by the mixes that had the same mix components and the a/b ratio but have been subjected to water curing. The difference in strength highlights the importance and the effectiveness curing has on the strength as its most likely that the air curing leads to an incomplete hydration process which effects the overall strength negatively.

Results and Analysis of the Impact of Curing Method and MK percentage on Concrete Strength using ANOVA variance analysis

ANOVA variance analysis have been used to study the effects of different curing methods and percentages of MK on the compressive strength of concrete over 91-day curing period. The factors examined include two curing methods being air curing and water curing and four levels of MK content

(0%,20%,50%,80%). This statistical method of analysis partitions the total variances in a dataset into components associated with specific sources of variation, which helps in the assessment and analysis of the impact of different factors within the model. The results obtained from the ANOVA analysis are summarised in figure 17 below.

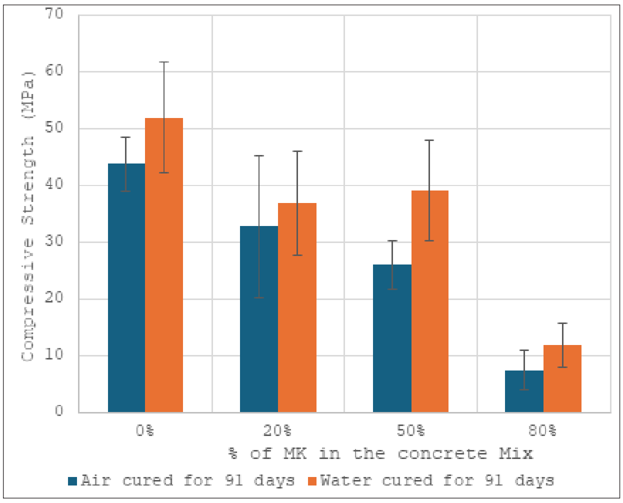

Figure 17: Analysis of variance (ANOVA) for different MK percentages in the MK and GGBS Mixes

Main Effects

The ANOVA results obtained as seen in figure 17 above indicate that the percentage of MK in concrete has a huge impact on the compressive strength, this can be supported by the P-value calculate as seen in Table 3 below having a value of 0.005 which is below the 0.05 threshold. This suggests and proves that the difference in MK percentage in the mix plays a crucial role in determining the overall strength of concrete. It can also be noted from Table 3 that the curing method has an impact on the compressive strength of concrete with a P-value of 0.257, this shows that the variations between air curing and water curing can be considered as impactful factors on concrete but as the P-value of the MK% is lower this suggests that the percentage of MK in the concrete mix has the most powerful impact on the compressive strength of concrete.

Table 3: ANOVA Two-Factor with Replication analysis

ANOVA: Two-Factor with Replication						
SUMMARY	0	0.2	0.5	0.8	Total	
Air cured for 91 days						
Count	3	3	3	3	12	
Sum	131	98	77.8	22.3	329.1	
Average	43.66667	32.66667	25.93333	7.433333	27.425	
Variance	86.33333	625.3333	74.81333	51.69333	341.4384	
Water cured for 91 days						
Count	3	3	3	3	12	
Sum	155.63	110.47	117.113	35.4	418.613	
Average	51.87667	36.82333	39.03767	11.8	34.88442	
Variance	383.1072	334.4202	321.1956	59.8491	429.5501	
Total						
Count	6	6	6	6		
Sum	286.63	208.47	194.913	57.7		
Average	47.77167	34.745	32.4855	9.616667		
Variance	207.9975	389.0848	209.9206	50.33731		
ANOVA						
Source of Variation	ss	df	MS	F	P-value	F crit
Curing Method	333.8574	1	333.8574	1.379045	0.257447	4.493998
% of MK in concrete mix	4528.03	3	1509.343	6.234556	0.005232	3.238872
Interaction	79.35258	3	26.45086	0.109259	0.953448	3.238872
Within	3873.491	16	242.0932			
Total	8814.731	23				

Table 4: ANOVA variances analysis

Curing Method	% of MK in Concrete Mix	Mean Strength	Var	SD	SE
Air cured for 91 days	0%	43.66666667	86.33333	9.291573	4.645787
	20%	32.66666667	625.3333	25.00667	12.50333
	50%	25.93333333	74.81333	8.64947	4.324735
	80%	7.433333333	51.69333	7.189808	3.594904
Water cured for 91 days	0%	51.87666667	383.1072	19.57313	9.786563
	20%	36.82333333	334.4202	18.28716	9.14358
	50%	39.03766667	321.1956	17.92193	8.960965
	80%	11.8	59.8491	7.73622	3.86811

The main effect of MK percentage content on the concrete strength is very evident and clear from the results recorded in Tables 3 and 4. It can be noted there is a directly proportional relationship between the decrease in strength as the percentage of MK increases. It can also be noted in Figure 17 that the slope effect is negative, this is an indicator that the higher levels of MK affected the concrete samples negatively, especially concrete samples made up of more than 20% of MK. The other factor studied in this analysis was the curing method. It can be noted that water curing has a general trend of higher results of the compressive strength when compared with the air cured samples.

Interaction Effects

The ANOVA analysis also studied the interaction between the curing method and MK content in order to determine whether the combination of these two factors differed from their individual effects. The ANOVA results have shown that the interaction between the two factors suggested was not statistically of any significance, with a P-value of 0.953 as recorded in Table 4. The P-value recorded is high and can be used and analysed as an indicator that the impact of one factor for instance the curing method on the strength of concrete is independent of the percentage of MK used in the concrete mix. In short, the effectiveness of the air curing method versus the water curing method does not change significantly across the different levels or percentages of MK used.

This can also be proven as graphically, as seen in figure 17, each trend line representing a factor are parallel to one another and there is no intersection point. As there is no intersection point it simply implies that each factor can be adjusted and customized independently to achieve the desired strength.

Conclusion

In study has been a comprehensive exploration of the influence of MK and GGBS on the compressive strength of concrete with a focus on varying mix compositions, a/b ratios and curing methods. Through the application of Analysis of Variance (ANOVA), it was determined that both MK and GGBS has a significant role, and both have an impact on the compressive strength, while the curing method plays the secondary role within the 91 day period.

The results recorded from the experimental investigations indicated that the MK, particularly at contents up to 20% have a significant role in enhancing the pozzolanic reactions and so resulting in good compressive strengths. However, increasing the MK content beyond the 20% threshold can reduce the strength due to the potential distribution in the mix's optimal balance. Whereas, GGBS has been shown to be consistently improving the long-term strength especially with mixes made of higher GGBS contents.

Curing methods also plays a crucial role, particularly in the context of water curing, which generally resulted in higher compressive strengths compared to air curing. This was especially evident in mixes with 100% GGBS, where water curing led to nearly double the compressive strength compared to air curing. The findings highlight the importance of adequate curing practices, particularly water curing, in promoting hydration and enhancing the geopolymerization process, thereby optimizing the overall strength of the concrete.

In conclusion, while MK and GGBS content are key determinants of concrete strength, curing methods, especially water curing, are vital for maximizing these benefits. This study provides valuable insights into optimizing concrete mixes for both short-term and long-term performance, laying a solid foundation for future research aimed at achieving more sustainable and effective construction practices. Future studies should explore the impact of extended curing periods and varying environmental conditions to further refine these findings.

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