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Research Paper

Response Surface Model for Predicting the Compressive Strength of Metakaolin Geopolymer Concrete

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ABSTRACT
This paper focuses on developing a response surface model (RSM) to predict and optimize the compressive strength of Metakaolin-based Geopolymer Concrete (MKGPC). The materials used include metakaolin (MK) as the precursor, granite, river sand, and an activator solution consisting of sodium hydroxide and sodium silicate. The mix design was created using the face-centered central composite design of RSM. Key factors influencing strength included the alkali activator-MK ratio, sodium silicate to sodium hydroxide ratio, sodium hydroxide concentration, curing time and curing temperature. The optimization of compressive strength was performed with RSM with desirability function. Experimental results revealed significant variations in compressive strength, ranging from 11.31 MPa to 19.67 MPa, with a 73.92% difference across the trials. Some mixtures achieved strengths over 17 MPa, indicating MKGPC's potential for lightweight construction. The RSM model developed for compressive strength prediction showed a high R^2 value of 89.98%, reflecting its accuracy in capturing the influence of mix parameters. The optimization process determined the ideal conditions for maximum compressive strength: an activator-to-metakaolin ratio of 0.2, a sodium silicate-to-sodium hydroxide ratio of 2.05, a sodium hydroxide concentration of 11.15, a curing time of 66.51 hours, and a curing temperature of 100.61°C, yielding a compressive strength of 19.44 MPa and a desirability function value of 97.32%. The results emphasize the importance of careful mix design and curing conditions to enhance MKGPC's mechanical properties, with potential applications in low-strength structural elements and lightweight construction.
Keywords; Response Surface model, prediction, optimization, metakaolin, geopolymer concrete, desirability function

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I. Introduction

Over the past few decades, the construction industry has encountered growing demands to minimize its environmental impact, especially regarding the substantial carbon dioxide (CO_2) emissions produced during the manufacture of ordinary Portland cement (OPC). In response to this challenge, geopolymer concrete (GPC) has gained attention as a sustainable alternative. This innovative material is formed through the alkaline activation of aluminosilicate-rich precursors, eliminating the need for traditional clinker-based cement (Davidovits, 2011).

Among the various source materials for geopolymer synthesis, metakaolin, a calcined and dehydroxylated derivative of kaolinite clay, has emerged as a particularly promising option due to its high purity, uniform composition, and excellent reactivity (Zawrah & Gado, 2011). Metakaolin-based geopolymer concrete (MK-GPC) exhibits enhanced mechanical strength, superior durability, and improved resistance to thermal degradation compared to conventional OPC-based concrete (Zhang et al., 2013).

A key performance indicator of MK-GPC is its compressive strength, which is influenced by several interrelated factors, including the concentration of the alkaline activator, the sodium silicate-to-sodium hydroxide ($Na_2SiO_3/NaOH$) ratio, the solid-to-liquid ratio, and curing parameters such as temperature and duration (Hardjito & Rangan, 2005). Optimizing these variables is essential for tailoring the structural performance of MK-GPC to meet specific engineering requirements.

Given the complexity and non-linear behavior of these mix parameters, traditional trial-and-error approaches often fall short in accurately predicting or optimizing compressive strength outcomes. To address this limitation, Response Surface Methodology (RSM) has been widely adopted. RSM is a statistical and mathematical tool that facilitates the development of predictive models, process optimization, and the analysis of variable interactions while minimizing the number of experimental trials required (Myers et al., 2016). It typically utilizes second-order polynomial equations to model responses, such as compressive strengthbased on data generated through structured Design of Experiments (DoE), including Central Composite Design (CCD) and Box–Behnken Design (BBD).

Numerous studies have demonstrated the effectiveness of RSM in optimizing geopolymer formulations. For instance, Temuujin et al. (2009) applied RSM to analyze the influence of NaOH concentration and curing conditions on the properties of fly ash-based GPC. Nath and Sarker (2014) used RSM to optimize mechanical and durability characteristics in slag-metakaolin geopolymer blends. More recently, Sharma and Chaurasia (2023) utilized RSM to examine how aggressive environmental exposures, such as acidic and sulfate-rich conditions, affect the durability of metakaolin-based geopolymer concrete. Their findings highlighted the importance of factors like curing temperature, sand-to-metakaolin ratio, and exposure duration in preserving residual compressive strength.

Zareei et al. (2023) also employed RSM to create a predictive model for the compressive strength of geopolymer concrete using varying proportions of metakaolin and slag. They identified optimal mix parameters, including a Na_2SiO_3/NaOH ratio of 2.5 and a reduced metakaolin-to-slag ratio, which yielded higher compressive strengths. Their regression models achieved R^2 values above 0.90, underscoring the reliability of RSM in capturing complex variable interactions.

Building on this foundation, the present study aims to develop an RSM-based predictive model for estimating the compressive strength of metakaolin-based geopolymer concrete. The research focuses on evaluating the combined effects of key mix design parameters, including the alkali activator-to-metakaolin (AA/MK) ratio, Na_2SiO_3/NaOH ratio, NaOH molarity, curing temperature, and curing time, to identify optimal conditions for enhanced structural performance.

II. Materials and Methods

2.1 Materials

The materials used in this study were locally sourced from within Port Harcourt City.

i. Coarse aggregate;Uniformly graded granite with maximum sizes of 19 mm and 12.5 mm was used as the coarse aggregate in this study. The granite was sourced from a building material shop in Ozuoba, Port Harcourt, with the original supply coming from the Akamkpa quarry in Calabar. For the experimental purposes, the two granite sizes were mixed in a 60:40 ratio. This mixture produced a coarse aggregate with a fineness modulus of 4.06 and a specific gravity of 2.77.

ii. Fine aggregate;River sand was utilized as the fine aggregate in this study. It was sourced from a construction site in Port Harcourt, with the Choba River identified as the main origin. The sand underwent sun-drying for 48 hours to eliminate moisture, followed by sieving through a 4.5 mm mesh to remove impurities and organic matter. Subsequent sieve analysis indicated that the sand was uniformly graded, falling within the Zone 1 gradation category. The analysis also showed a fineness modulus of 2.18 and a specific gravity of 2.43.

iii. Geopolymer Precursor; The geopolymer binder in this study was created using metakaolin (MK) as the precursor, which was derived from kaolin clay, often referred to as white clay. This clay was obtained from a sand fill site in Choba, Port Harcourt. After sun-drying the kaolin for 48 hours to remove moisture, it was heated in a muffle furnace at 800°C for three hours to convert it into metakaolin. The resulting metakaolin was then ground into a fine powder and sieved through a 75 μm (No. 200) sieve before being used in the mix.

iv. Activators; To activate the metakaolin, a mixture of sodium hydroxide and sodium silicate solutions was used. The sodium hydroxide, a commercial-grade flake product with 98% purity and a particle size of 3 mm, was sourced from H-Chemicals Ltd in Ozuoba. It was dissolved in water to achieve the required molar concentrations, such as an 8M solution, which contained 320 grams of NaOH per liter of water. The sodium silicate powder, also from H-Chemicals, had 98% purity and a specific gravity of 1.27. It was mixed with water in a 70:30 ratio, resulting in a solution with a specific gravity of 1.61.

v. Cement; Ordinary Portland Cement (OPC) of the Dangote brand (R. 425, CB 4227), conforming to BS 12 (1996) standards, was also used in the study. This cement was sourced from a local building materials supplier in Ozuoba, Port Harcourt.

vi. Water; water with a pH of approximately 6.9, free from organic matter and impurities, was used in preparing all concrete mixtures.

2.2 Methods

2.2.1 Face Centered- Central Composite Design (FC-CCD)

In building the design of experiment (DoE), five factors were considered to contribute to the compressive strength of the MK based geopolymer concrete (MKGPC). These factors are; Alkaline-Metakaolin ratio

(AA/MK), Sodium hydroxide-sodium silicate ratio, Sodium hydroxide concentration, the curing period, and curing temperature. From experience and extensive reviews, the following parameter ranges were adopted for building the DoE of this study. The alkaline activator-MK (Activator/MK) content was limited within 0.20-0.40, sodium silicate-hydroxide ratio (SS/SH) was limited to 1-3, sodium hydroxide(SH) concentration was limited to 8M-14M, curing time (CT) was varied between 4-72 hours, and finally curing temperature (CTemp) was varied between 40-120^{0}C. Using the face centred-central composite design (via Minitab software) results to a total of thirty-two (32) experimental runs as presented by Table 1.

Table 1. FC-CCD for MKGPC

RunOrder	Activator/MK	SS/SH	SH Conc	C.T	C.Temp
1	0.3	1	11	38	80
2	0.4	3	14	4	40
3	0.3	2	11	38	80
4	0.4	1	14	72	40
5	0.2	3	8	72	120
6	0.3	2	11	38	80
7	0.4	2	11	38	80
8	0.3	2	11	38	80
9	0.3	2	14	38	80
10	0.4	1	8	72	120
11	0.3	2	8	38	80
12	0.4	3	8	4	120
13	0.3	2	11	38	40
14	0.2	3	14	72	40
15	0.3	2	11	72	80
16	0.2	2	11	38	80
17	0.4	1	14	4	120
18	0.4	1	8	4	40
19	0.2	1	8	72	40
20	0.2	1	14	72	120
21	0.2	3	8	4	40
22	0.3	2	11	38	80
23	0.3	3	11	38	80
24	0.2	1	8	4	120
25	0.2	3	14	4	120
26	0.3	2	11	38	80
27	0.3	2	11	38	120
28	0.2	1	14	4	40
29	0.3	2	11	38	80
30	0.4	3	8	72	40
31	0.3	2	11	4	80
32	0.4	3	14	72	120

2.2.2 Preparation of MKGPC Samples

A predetermined mix ratio of 1:2:4 was used to produce MKGPC with a characteristic compressive strength of 15 MPa, and a consistent rest period of 3 hours was allowed for the mixture after production. The amount of NaOH solids in the activator solution varied according to the molar concentration (M), as specified by the experimental design. For example, an 8M NaOH solution contained 320 grams of NaOH flakes per liter, with the molecular weight of NaOH being 40 g/mol. The sodium silicate powder, with 98% purity, was dissolved in water at a 70:30 ratio to form the sodium silicate solution. These solutions were left to stand for 24 hours before being used in the experiments. Materials for the different MKGPC mixtures were calculated based on the Design of Experiments (DoE) and weighed, then placed in nylon bags before the practical work began. The materials were mixed in the laboratory using an electrically powered mixer.

2.2.3 Compressive Strength Investigation of MKGPC

The compressive strength of hardened MKGPC sampleswas carried out in accordance to appropriate specifications (BS 1881:Part 115, 1983). The concrete cube was placed at the center of the bottom plate of the compressive strength testing machine and subjected to a continuous loading rate of 0.4 MPa/sec until it failed. The compressive strength was calculated by dividing the maximum load at failure by the cross-sectional area of the cubic mold (Equation 1).

$$\text{Compressive strength} = \frac{\text{load at failure (N)}}{\text{Cross sectional area (mm}^2\text{)}} \quad (1)$$

2.2.4 Response Surface Model (RSM)

The Central Composite Design (CCD) analyzes experimental data and generates a response model, which is represented by Equation (2).

$$Y = \beta_0 + \sum_{i=1}^{n}(\beta_i Z_i) + \sum_{i=1}^{n}(\beta_{ii} Z_i^2) + \sum_{i=1}^{n}\sum_{j=1}^{n}(\beta_{ij} Z_i Z_j) + e \quad (2)$$

Where; β_0 is the constant term, β_i represents the linear coefficients, β_{ii} denotes the quadratic coefficients, and β_{ij} refers to the interaction coefficients. By utilizing the derived mathematical model, it becomes possible to determine the specific combinations of independent variables (factors) that result in optimal concrete performance.

For a five-factor design as used in this study, Equation (2) becomes;

$$Y = \beta_0 + \beta_1 Z_1 + \beta_2 Z_2 + \beta_3 Z_3 + \beta_4 Z_4 + \beta_5 Z_5 + \beta_{11} Z_1^2 + \beta_{22} Z_2^2 + \beta_{33} Z_3^2 + \beta_{44} Z_4^2 + \beta_{55} Z_5^2 + \beta_{12} Z_1 Z_2 + \beta_{13} Z_1 Z_3 + \beta_{14} Z_1 Z_4 + \beta_{15} Z_1 Z_5 + \beta_{23} Z_2 Z_3 + \beta_{24} Z_2 Z_4 + \beta_{25} Z_2 X_5 + \beta_{34} Z_3 Z_4 + \beta_{35} Z_3 Z_5 + \beta_{45} Z_4 Z_5 \quad (3)$$

Where,

Y = compressive strength of MKGPC

Z_1 = Alkali activator to MK ratio (Activator/MK)

Z_2 = Sodium silicate to sodium hydroxide ratio (SS/SH)

Z_3 = Sodium hydroxide concentration (SH Conc)

Z_4 = Curing time in hours (CT)

Z_5 = Curing temperature in ^{0}C (CTemp)

In a simplified mathematical or matrix form, Equation (3) can be expressed as;

$$Y = Z\beta \quad (4)$$

Where;

Z= shape function vector showing interaction between considered factors

β = coefficient vector function

3

By multiplying both sides of Equation (4) by a weighting factor, which is the transpose of the shape function vector, Equation (5) was derived.

$$Z^T * Y = Z^T * Z\beta \quad (5)$$

Rewriting Equation (5) in the form of Equation (6);

$$M = P * \beta \quad (6)$$

Where, M and P are defined by Equations (7) and (8) respectively;

$$M = Z^T * Y \quad (7)$$

$$P = Z^T * Z \quad (8)$$

From Equation (8);

$$\beta = P^{-1} * M \quad (9)$$

Due to the complexity and magnitude of the matrixes involved in this analysis, Microsoft excel was adopted in solving Equation (9) in order to estimate the model coefficients. The developed RSM for compressive strength prediction of MKGPC was verified using the coefficient of determination (R^2) via the graphical approach.

2.2.5 Optimization of Compressive Strength of MKGPC

The Response Optimizer tool which is based on Response Surface Methodology (RSM) with the desirability function, was used in this analysis to identify the optimal combination of factors for maximizing the compressive strength of MKGPC. The results are presented in descending order of desirability, which indicates how closely the response matches its ideal value. Desirability is a dimensionless value between 0 and 1, with higher values indicating that the response falls within the desired range (Nwaobakata et al., 2023).

III.Results and Discussion

3.1 Compressive Strength of MKGPC

The compressive strength of MKGPC, as shown in Figure 1, ranges from 11.31 MPa at run order 2 to 19.67 MPa at run order 26, reflecting a substantial variation of 73.92% across the experimental runs. This variability is influenced by several factors in the experimental design, such as the concentration of the alkali activator, curing time, temperature, and material mix ratios. Notably, certain mixtures achieved compressive strengths above 17 MPa, meeting the criteria for light-load-bearing elements as defined by Ahmed and Hoque (2020). This suggests that MKGPC has potential as a viable material for lightweight construction applications.

When compared to other studies, the compressive strength values in this research are similar to those reported in similar work but show a wider range, likely due to differing mix designs and experimental conditions. For instance, Zhang et al. (2013) observed MKGPC compressive strengths between 10 MPa and 30 MPa, depending on the mix proportions and curing conditions, though their observed variation was smaller than in this study. The greater variability in this study suggests that factors such as curing temperature, activator concentration, and metakaolin content have a more significant impact on MKGPC's performance compared to other geopolymer systems.

Additionally, Hardjito and Rangan (2005) studied fly ash-based geopolymer concrete, finding compressive strengths of up to 25 MPa under optimal curing conditions. Although their study used a different precursor material, the trend of enhancing strength by optimizing curing parameters is consistent with the current study's results. The findings here underscore the importance of adjusting curing conditions and other factors to achieve the desired structural properties in MKGPC.

In contrast, some studies have reported lower compressive strengths for geopolymer concrete made exclusively with metakaolin as the binder. For instance, Zawrah and Gado (2011) found strengths between 8 MPa and 15 MPa for metakaolin-based geopolymer concrete, suggesting that improvements in activator mix and curing conditions could enhance mechanical performance. The current study's results, with certain formulations exceeding 17 MPa, demonstrate that MKGPC can be optimized to meet the needs of specific applications, such as low-strength structural elements.

The variation in compressive strength values in this study highlights MKGPC's adaptability, making it suitable for a range of construction applications based on specific design requirements. Future optimization of activator ratios, curing times, and temperatures could further improve its compressive strength.

Figure 1. Compressive Strength of MKGPC

3.2 RSM Development for Compressive Strength Prediction of MKGPC

Table 2 presents the matrix of the shape function of MKGPC. On application of Equation (7), M was obtained as shown in Equation (10).

$$M = [514.18\ \ 152.28\ \ 1025.94\ \ 5650.4\ \ 19904.68\ \ 41565.20\ \ 47.72\ \ 2308.48\ \ 64457.32\ \ 1075071\ \ 3780624303.35\ \ 1673.43\ \ 5893.66\ \ 12312.52\ \ 11276.40\ \ 39756.16\ \ 82861.60\ \ 218792.50\ \ 457474\ \ 1613287]^T \quad (10)$$

Also, P being a 21 X 21 matrix was determined on the application of Equation (8). With the help of matrix M and matrix P, and application of Equation (9), the coefficient matrix of the compressive strength model is illustratedin Equation (11).

$$\beta = [-4.7519\ \ 25.2938\ \ 6.9902\ \ 1.9430\ \ 0.0316\ \ 0.0538\ \ -51.253\ \ -1.5625 - 0.1036\ \ -0.0004\ \ -0.0005\ \ -2.9625\ 0.05\ \ -0.01400\ \ 0.0047\ \ 0.0154\ \ 0.0021 - 0.0029\ \ \ 0.0003\ 0.0031\ 0.0002\ ]^T \tag{11}$$

Substituting these coefficient values into Equation (3), the RSM optimization model for predicting the compressive strength of MKGPC was obtained as presented in Equation (12).

$$Y_{C.S} = -4.7519 + 25.2938\ Z_1 + 6.9902\ Z_2 + 1.9430\ Z_3 + 0.0316\ Z_4 + 0.0538\ Z_5 - 51.253\ Z_1^2 - 1.5625\ Z_2^2 - 0.1036\ Z_3^2 - 0.0004\ Z_4^2 - 0.0005\ Z_5^2 - 2.9625\ Z_1Z_2 + 0.05\ Z_1Z_3 - 0.0140\ Z_1Z_4 + 0.0047\ Z_1Z_5 + 0.0154\ Z_2Z_3 + 0.0021\ Z_2Z_4 - 0.0029\ Z_2Z_5 + 0.0003\ Z_3Z_4 + 0.0031\ Z_3Z_5 + 0.0002\ Z_4Z_5 \tag{12}$$

On verification of the model using the coefficient of determination (R^2) at 5 % level of significance, a R^2 value of 89.98 % was obtained as presented in Figure 2. This indicates that over 89 % of the data set within the design space is explained by the optimization model. This verification outcome is excellent as the deduced R^2 is very close to a 100 %.

In the present study, the optimization model was verified using the coefficient of determination (R^2) at a 5% level of significance, yielding an impressive R^2 value of 89.98%, as illustrated in Figure 2. This indicates that the model successfully explains over 89% of the variance within the design space. The high R^2 value suggests that the optimization model is highly reliable and accurate in predicting the behavior of the system, with only a small portion of the data unexplained. Given that R^2 values closer to 100% indicate better model performance, the result in this study is considered excellent, as it is very close to a perfect fit. This R^2 value of 89.98% is indicative of strong model performance. In similar studies using optimization models for concrete and geopolymer mix design, high R^2 values are often sought after to ensure that the model effectively captures the relationship between input variables and output properties such as compressive strength. For example, in studies applying Response Surface Methodology (RSM) to optimize geopolymer concrete mix proportions, R^2 values exceeding 80% are commonly reported. For instance, Zareei et al. (2023) achieved an R^2 of 92.7% when developing predictive models for compressive strength in geopolymer concrete containing metakaolin and slag, suggesting a similarly high degree of accuracy in their model predictions. In this case, their R^2 value is slightly higher than the current study, but still demonstrates a high level of precision.

Furthermore, in the optimization of fly ash-based geopolymer concrete by Nath and Sarker (2014), the R^2 value achieved was 85.5%, which, while slightly lower than the 89.98% obtained here, still indicates a reasonably high correlation between experimental data and the model's predictions. These studies suggest that R^2 values above 80% are typically considered acceptable in experimental optimization models, particularly when multiple interacting variables are involved, as is the case in geopolymer concrete mix design.

On the other hand, certain studies report lower R^2 values, especially when the modeling approach is not as refined or when the system's behavior is complex. For instance, Temuujin et al. (2009) reported an R^2 of around 75% in their work on fly ash-based geopolymer concrete, indicating that while their model was useful, it did not explain as much of the variance in the experimental data. This suggests that the optimization model in the current study is comparatively more robust and offers a better fit to the experimental data.

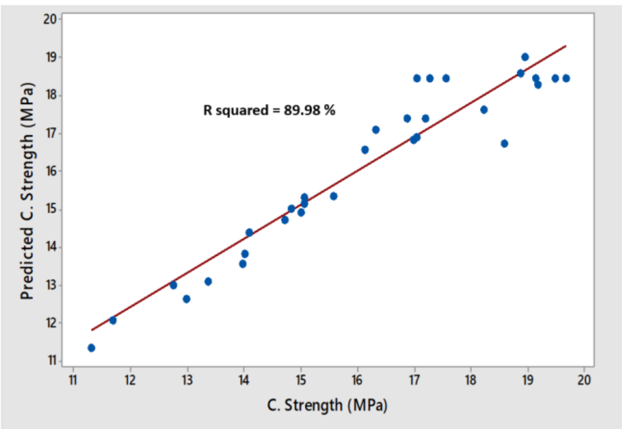

Figure 2. Predicted Compressive strength Vs Experimental Compressive Strength (R^2 statistics of Developed Compressive strength model)

Table 2. Matrix of Shape Function, Z of MKGPC

Intercept	Z_1	Z_2	Z_3	Z_4	Z_5	Z_1^2	Z_2^2	Z_3^2	Z_4^2	Z_5^2	Z_1Z_2	Z_1Z_3	Z_1Z_4	Z_1Z_5	Z_2Z_3	Z_2Z_4	Z_2Z_5	Z_3Z_4	Z_3Z_5	Z_4Z_5
1	0.3	1	11	38	80	0.09	1	121	1444	6400	0.3	3.3	11.4	24	11	38	80	418	880	3040
1	0.4	3	14	4	40	0.16	9	196	16	1600	1.2	5.6	1.6	16	42	12	120	56	560	160
1	0.3	2	11	38	80	0.09	4	121	1444	6400	0.6	3.3	11.4	24	22	76	160	418	880	3040
1	0.4	1	14	72	40	0.16	1	196	5184	1600	0.4	5.6	28.8	16	14	72	40	1008	560	2880
1	0.2	3	8	72	120	0.04	9	64	5184	14400	0.6	1.6	14.4	24	24	216	360	576	960	8640
1	0.3	2	11	38	80	0.09	4	121	1444	6400	0.6	3.3	11.4	24	22	76	160	418	880	3040
1	0.4	2	11	38	80	0.16	4	121	1444	6400	0.8	4.4	15.2	32	22	76	160	418	880	3040
1	0.3	2	11	38	80	0.09	4	121	1444	6400	0.6	3.3	11.4	24	22	76	160	418	880	3040
1	0.3	2	14	38	80	0.09	4	196	1444	6400	0.6	4.2	11.4	24	28	76	160	532	1120	3040
1	0.4	1	8	72	120	0.16	1	64	5184	14400	0.4	3.2	28.8	48	8	72	120	576	960	8640
1	0.3	2	8	38	80	0.09	4	64	1444	6400	0.6	2.4	11.4	24	16	76	160	304	640	3040
1	0.4	3	8	4	120	0.16	9	64	16	14400	1.2	3.2	1.6	48	24	12	360	32	960	480
1	0.3	2	11	38	40	0.09	4	121	1444	1600	0.6	3.3	11.4	12	22	76	80	418	440	1520
1	0.2	3	14	72	40	0.04	9	196	5184	1600	0.6	2.8	14.4	8	42	216	120	1008	560	2880
1	0.3	2	11	72	80	0.09	4	121	5184	6400	0.6	3.3	21.6	24	22	144	160	792	880	5760
1	0.2	2	11	38	80	0.04	4	121	1444	6400	0.4	2.2	7.6	16	22	76	160	418	880	3040
1	0.4	1	14	4	120	0.16	1	196	16	14400	0.4	5.6	1.6	48	14	4	120	56	1680	480
1	0.4	1	8	4	40	0.16	1	64	16	1600	0.4	3.2	1.6	16	8	4	40	32	320	160
1	0.2	1	8	72	40	0.04	1	64	5184	1600	0.2	1.6	14.4	8	8	72	40	576	320	2880
1	0.2	1	14	72	120	0.04	1	196	5184	14400	0.2	2.8	14.4	24	14	72	120	1008	1680	8640
1	0.2	3	8	4	40	0.04	9	64	16	1600	0.6	1.6	0.8	8	24	12	120	32	320	160
1	0.3	2	11	38	80	0.09	4	121	1444	6400	0.6	3.3	11.4	24	22	76	160	418	880	3040
1	0.3	3	11	38	80	0.09	9	121	1444	6400	0.9	3.3	11.4	24	33	114	240	418	880	3040
1	0.2	1	8	4	120	0.04	1	64	16	14400	0.2	1.6	0.8	24	8	4	120	32	960	480
1	0.2	3	14	4	120	0.04	9	196	16	14400	0.6	2.8	0.8	24	42	12	360	56	1680	480
1	0.3	2	11	38	80	0.09	4	121	1444	6400	0.6	3.3	11.4	24	22	76	160	418	880	3040
1	0.3	2	11	38	120	0.09	4	121	1444	14400	0.6	3.3	11.4	36	22	76	240	418	1320	4560
1	0.2	1	14	4	40	0.04	1	196	16	1600	0.2	2.8	0.8	8	14	4	40	56	560	160
1	0.3	2	11	38	80	0.09	4	121	1444	6400	0.6	3.3	11.4	24	22	76	160	418	880	3040
1	0.4	3	8	72	40	0.16	9	64	5184	1600	1.2	3.2	28.8	16	24	216	120	576	320	2880
1	0.3	2	11	4	80	0.09	4	121	16	6400	0.6	3.3	1.2	24	22	8	160	44	880	320
1	0.4	3	14	72	120	0.16	9	196	5184	14400	1.2	5.6	28.8	48	42	216	360	1008	1680	8640

Z_1= Activator/MK; Z_2 = SS/SH; Z_3 = SH conc.; Z_4 = Curing Time; Z_5 = Curing Temperature

3.3 Optimization of Compressive Strength of MKGPC

The optimization results for the compressive strength of MKGPC, as shown in Figure 3, highlight the ideal combination of factors that yield the maximum compressive strength. The optimal conditions for achieving the highest compressive strength were found to be: an activator-to-metakaolin (Z_1) ratio of 0.2, a sodium silicate-to-sodium hydroxide (SS/SH) ratio (Z_2) of 2.0505, a sodium hydroxide concentration (Z_3) of 11.1515, a curing time (Z_4) of 66.5057 hours, and a curing temperature (Z_5) of 100.6061°C. Under these conditions, a maximum compressive strength of 19.4384 MPa was achieved. Additionally, the optimization process produced a desirability function value of 0.9732 (97.32%), indicating an excellent optimization result.

Optimizing compressive strength by adjusting mix parameters has been a key focus in geopolymer concrete (GPC) research. Similar optimization studies on geopolymer concrete have aimed to maximize compressive strength by manipulating factors such as activator-to-precursor ratios, curing temperature, and curing time. The optimal parameters and resulting compressive strength of 19.4384 MPa in this study are in line with findings from other research using similar optimization models.

For instance, Zhang et al. (2013) optimized metakaolin-based geopolymer concrete by varying the sodium hydroxide and sodium silicate solutions, alongside curing conditions. Their results showed that a sodium silicate-to-sodium hydroxide ratio of 2.0 and curing at elevated temperatures around 85°C achieved a compressive strength of up to 20 MPa, which closely aligns with the 19.4384 MPa found in this study. This confirms the importance of curing temperature and activator solution ratios in obtaining desirable mechanical properties, as demonstrated in both studies.

Another significant study by Nath and Sarker (2014) used response surface methodology (RSM) to optimize fly ash-based geopolymer concrete. They achieved the highest compressive strength with a sodium hydroxide concentration of around 10 M and a curing temperature of 80°C, which is similar to the optimal conditions identified in this study. Their compressive strength reached 18.2 MPa, and the trends observed in both studies indicate that elevated sodium hydroxide concentration and curing temperature are crucial for enhancing compressive strength.

In an optimization study by Temuujin et al. (2009), the highest compressive strength for fly ash-based geopolymer concrete was found to be highly sensitive to the molar concentration of sodium hydroxide and the curing temperature, with optimal values close to those used in this study. The study concluded that a sodium hydroxide molarity of around 10 M and a curing temperature of 85°C significantly improved compressive strength, reinforcing the findings of this study.

The desirability function value of 0.9732 (97.32%) in this study further validates the success of the optimization process. The desirability function measures how closely the obtained results meet the desired target or objective. In optimization studies with multiple variables, such as geopolymer mix design, a desirability function close to 1 (or 100%) indicates that the selected combination of factors is optimal for achieving the desired outcome (Myers et al., 2016).

For instance, in the study by Zareei et al. (2023), a desirability function value of 0.95 was reported for the optimization of compressive strength in geopolymer concrete using a blend of metakaolin and slag. While slightly lower than the 0.9732 found in this study, this still indicates an excellent optimization process. The relatively high desirability function values across both studies emphasize the reliability and effectiveness of the optimization models used to enhance the properties of geopolymer concrete.

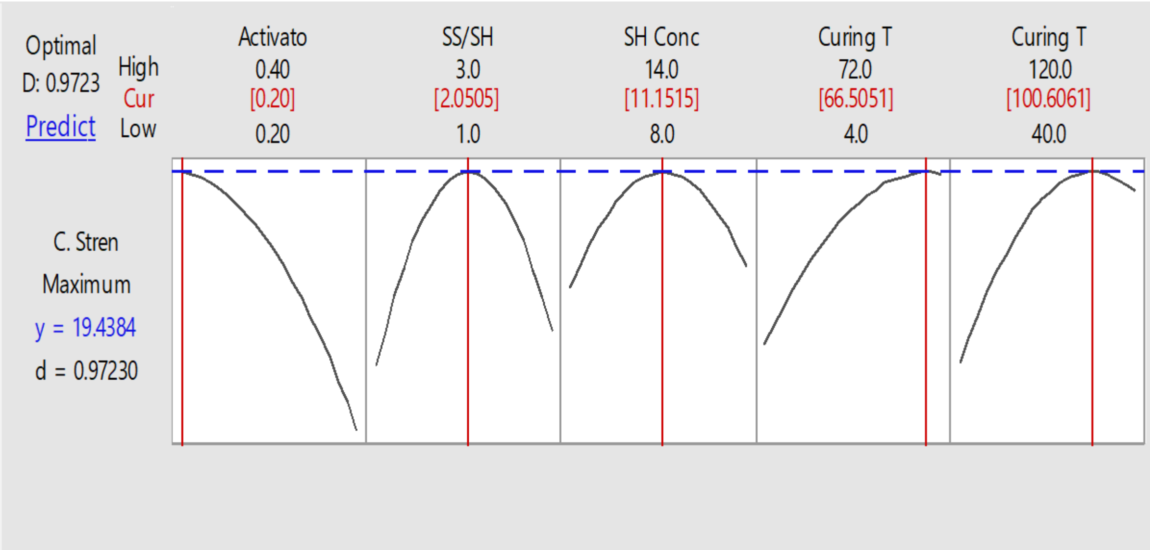

Figure 3. Optimization (Maximization) of the compressive strength of MKGPC

IV.Conclusions

The following key conclusions can be drawn from this study;

i. The compressive strength of MKGPC varied substantially across the experimental runs, with a range from 11.31 MPa to 19.67 MPa, reflecting a 73.92% difference. This variability is primarily attributed to factors such as the concentration of the alkali activator, curing time, temperature, and the material mix ratios. The findings suggest that MKGPC has potential for lightweight construction applications, with certain mixtures achieving compressive strengths above 17 MPa, aligning with criteria for light-load-bearing elements. However, optimizing curing conditions and mix design is crucial to achieving consistent and enhanced compressive strength.

ii. The RSM developed for predicting compressive strength demonstrated a high degree of accuracy, with an R^2 value of 89.98%. This indicates that the model can explain over 89% of the variance in compressive strength, highlighting the reliability of the model in predicting the outcomes based on various input parameters. The high R^2 value is consistent with other similar studies that utilized optimization models, showcasing that RSM is a robust tool for optimizing geopolymer concrete mix designs.

iii. The optimization process revealed that the maximum compressive strength of 19.44 MPa can be achieved under specific conditions: an activator-to-metakaolin ratio of 0.2, a sodium silicate-to-sodium hydroxide ratio of 2.05, a sodium hydroxide concentration of 11.15, a curing time of 66.51 hours, and a curing temperature of 100.61°C. This outcome reflects the successful optimization of the mix design parameters, which aligns with similar studies that emphasize the role of curing temperature and activator solution ratios in achieving high compressive strength in geopolymer concrete.

iv. The optimization process resulted in a desirability function value of 97.32%, indicating that the selected combination of factors was highly effective in achieving the desired compressive strength. This value is close to the ideal value of 100%, confirming the success of the optimization process. Comparable studies report desirability values in the range of 90-95%, further reinforcing that the optimization approach used in this study is both reliable and effective in improving the mechanical properties of geopolymer concrete.

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