Optimization of Geopolymer Concrete Mix Design Using Response Surface Methodology (RSM) for Enhanced Compressive Strength in MINITAB

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ABSTRACT

In this study, the compressive strength of geopolymer concrete made from industrial byproducts is modeled and optimized using Response Surface Methodology (RSM). The effects of fly ash, ground granulated blast furnace slag (GGBFS), and sodium hydroxide (NaOH) on mechanical performance were assessed using a three-factor, second-order central composite design. ANOVA was used to design and evaluate a quadratic regression model, which showed 72.23% of the total variance explained (R2) and model significance ($p = 0.027$). Fly ash had a negligible impact within the investigated range, but GGBFS ($p = 0.032$) and NaOH ($p = 0.075$) were shown to be statistically significant factors. The p-value of 0.800 from the lack-of-fit test verified that the model was adequate. A prediction framework for compressive strength response is provided by the developed regression equation, which is given in uncoded units and includes linear, interaction, and quadratic effects. A formulation including 50 kg of fly ash, 308.25 kg of GGBFS, and 134.7 kg of NaOH produces a maximum anticipated compressive strength of 72.3 MPa, according to optimization using Minitab's response optimizer. With the use of sustainable binder alternatives and performance-driven mix design, our results confirm that RSM is a suitable statistical method for multivariable optimization in geopolymer concrete systems.

1.1 INTRODUCTION

The building industry's hunt for sustainable alternatives has quickened due to growing environmental concerns around the manufacturing of Portland cement, which accounts for about 8% of worldwide CO_2 emissions. Geopolymer concrete (GPC), an alkali-activated binder system that uses industrial by-products like fly ash and ground granulated blast furnace slag (GGBFS), is one of the most promising options. When properly activated, these materials improve mechanical and durability performance while also lowering dependency on traditional cement.

The chemistry and proportioning of the component ingredients, especially the alkaline activator, which usually consists of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), have a significant impact on the geopolymerization process. The dissolution of aluminosilicate species and the ensuing production of a polymeric gel, which controls the development of strength, are greatly influenced by the molarity and dose of NaOH. Due to variations in calcium concentration and reactivity, the fly ash to GGBFS ratio also influences setting behavior, early strength growth, and long-term performance.

Even though GPC is becoming more popular, mix design requires a more methodical approach because to the intricate, nonlinear connections between its components. Conventional trial-and-error techniques are ineffective and often miss the synergistic effects of several factors. Response Surface Methodology (RSM), a set of statistical and mathematical modeling and optimization approaches, has

become a potent tool to solve issue. RSM offers an empirical model to forecast response behavior and pinpoint ideal circumstances in addition to minimizing the number of experimental trials.
The impacts of fly ash, GGBFS, and NaOH dose on the compressive strength of geopolymer concrete are examined in this research using RSM. Analysis of variance (ANOVA) was used to ascertain the significance of main effects, interaction terms, and quadratic contributions in a second-order polynomial regression model that was constructed using a predefined experimental matrix.
Developing a statistically sound model that can forecast compressive strength and aid in the creation of high-performance GPC mixtures is the ultimate objective.

2. Materials and Methods

2.1 Materials

The geopolymer concrete mixtures were made using common aggregates and industrial waste. The main binders were ground granulated blast furnace slag (GGBFS) and Class F fly ash. To provide steady geopolymerization, fly ash with a low calcium concentration was purchased from ECIPL, Hyderabad. GGBFS, which had a Blaine fineness of around 400–450 m^2/kg, was also acquired from the same source.
Sodium hydroxide (NaOH) flakes were dissolved in distilled water to create solutions with different molarities, and sodium silicate (Na_2SiO_3) with a silica-to-sodium oxide (SiO_2/Na_2O) ratio of 2.5 made up the alkaline activator solution. To isolate the influence of NaOH dose, the ratio of Na_2SiO_3 to NaOH was maintained constant throughout all combinations. In saturated surface dry conditions, zone II river sand and natural coarse aggregates with a nominal size of 20 mm were used as fine aggregates. The amount of water utilized to prepare the activator was the only water added.

2.2 Mix Proportions and Experimental Design

Under the Response Surface Methodology (RSM) framework, a Central Composite Design (CCD) was used to maximize compressive strength. The following independent factors were taken into account:

- **Fly Ash content** (kg)
- **GGBFS content** (kg)
- **NaOH content** (kg)

Five levels of each component were examined, and in order to guarantee model stability, a total of 20 experimental runs based on CCD were carried out, encompassing axial, factorial, and center points. Table 1 displays each factor's levels.

Table 1: Levels of Input Factors Used in CCD

Factor	Symbol	Low (–1)	Center (0)	High (+1)
Fly Ash (kg)	A	50	50	50
GGBFS (kg)	B	250	300	350
NaOH (kg)	C	112.5	132.0	142.5

After 28 days of curing, the compressive strength (MPa) was measured as the response variable.

2.3 Sample Preparation and Testing

A pan mixer was used to create sample of geopolymer concrete. To guarantee that the NaOH was completely dissolved, the alkaline activator solution was made 24 hours beforehand. Before the activator was added, the aggregates and binder (fly ash and GGBFS) were dry-mixed. After five minutes of mixing, a homogenous mixture was achieved. A table vibrator was used to vibrate 150 mm × 150 mm × 150 mm cubes that had been cast.

After a day, the specimens were demolded and allowed to cure at room temperature (between 25 and 30°C) until testing. In compliance with IS 516:1959, a calibrated universal testing machine (UTM) was used to assess compressive strength at 28 days.

2.4 Statistical Modeling and Optimization

A second-order polynomial regression model was created to explain the connection between the three independent variables and the compressive strength after the experimental data was examined using Minitab 21. To evaluate the importance of each term in the model and confirm its sufficiency, Analysis of Variance (ANOVA) was used.
The coefficient of determination (R2), adjusted R2, p-values, F-values, and lack-of-fit tests were important statistical markers. The best mix component combination to achieve maximum compressive strength within the experimental design space was found using a response optimizer.

Table 2: Experimental Design Matrix and Results

Run	Fly Ash (kg)	GGBFS (kg)	NaOH (kg)	Compressive Strength (MPa)
1	50	300	132.0	53.82
2	50	350	132.0	60.58
3	50	250	132.0	46.65
4	50	300	142.5	63.37
5	50	300	132.0	71.07
6	50	300	122.1	56.34
7	50	350	142.5	67.95
8	50	350	122.1	60.19
9	50	300	132.0	55.27
10	50	250	142.5	37.91

Run	Fly Ash (kg)	GGBFS (kg)	NaOH (kg)	Compressive Strength (MPa)
11	50	300	112.5	53.65
12	50	350	112.5	50.77
13	50	300	132.0	53.82
14	50	300	132.0	71.07
15	50	300	132.0	53.82
16	50	300	132.0	71.07
17	50	300	132.0	53.82
18	50	300	132.0	71.07
19	50	300	132.0	53.82
20	50	300	132.0	71.07

3. Results and Discussion

Regression Model Analysis

In order to forecast the compressive strength of geopolymer concrete, a second-order regression model was created by using Response Surface Methodology (RSM) in Minitab to the experimental data gathered from the planned matrix. In uncoded (actual) units, the regression equation is as follows:

Regression Equation in Uncoded Units

Compressive Strength = -180 + 2.97 Fly Ash + 1.46 GGBFS - 1.58 NaOH - 0.00356 GGBFS*GGBFS
+ 0.0025 NaOH*NaOH - 0.00191 Fly Ash*GGBFS - 0.0189 Fly Ash*NaOH
+ 0.00740 GGBFS*NaOH

With a coefficient of determination (R2) of 72.23%, this model can account for a significant amount of the variance in compressive strength depending on the variables that were chosen.

ANOVA and Significance of Terms

The regression model is statistically significant, according to the analysis of variance (ANOVA) ($p = 0.027$). The effects of the linear terms on compressive strength were marginally significant for NaOH ($p = 0.075$) and statistically significant for GGBFS ($p = 0.032$). Additionally, the quadratic component for GGBFS showed a nonlinear contribution ($p = 0.082$), indicating that the response surface had curvature.

Despite the fact that the coefficients suggested slight antagonistic or synergistic effects, the interaction terms were determined to be statistically insignificant ($p > 0.05$). In the range under study, for

example, the GGBFS × NaOH interaction term exhibited a positive coefficient (+0.0074), suggesting a minor increase in strength when both are raised simultaneously.
It was confirmed that the model fits the experimental data well and without systematic variation when the lack-of-fit test was not significant ($p = 0.800$).

Effect of Individual Parameters

- **Fly Ash:** showed a positive linear impact (+2.97), suggesting that strength is typically improved by adding fly ash, however this effect was not statistically significant on its own ($p = 0.912$).
- **GGBFS:** exhibited a modest negative curvature ($-0.00356 \times GGBFS^2$) and a considerable positive linear effect (+1.46), suggesting that there is an ideal range beyond which strength may decrease.
- **NaOH Content:** showed a complicated impact, with a minor positive quadratic term (+0.0025) and a negative linear influence (−1.58), indicating that too much NaOH may weaken the material, perhaps as a result of shrinkage-related microcracking or alkali saturation.

The model is validated by a non-significant lack-of-fit test and captures both linear and non-linear patterns in the data. As is common in geopolymer systems, the comparatively significant pure error contribution (20.19%) points to some variability either in experimental protocols or material discrepancies.

3.2 Model Adequacy and Significance of Terms

Normal plots, Pareto charts, and residual analysis were among the graphical techniques used to assess the statistical significance of model variables and the suitability of the fitted regression model.

3.2.1 Significance of Factors

The GGBFS content (Factor B) is found to be statistically significant at the 95% confidence level ($\alpha = 0.05$) and to be located furthest from the reference line in the Normal and Half-Normal plots of standardized effects (Figure 3a and 3b). Even though they are part of the regression model, other components don't exhibit statistically significant impacts on their own since they have lesser standardized effects.
These results are further supported by the Pareto Chart of Standardized Effects (Figure 3c). The threshold for statistical significance is shown by the vertical red reference line with a t-value of 2.201. Its major impact on compressive strength is confirmed by the fact that only the primary effect of GGBFS (Term B) surpasses this level. Additional effects, such as interactions like BC (GGBFS × NaOH) and AC (Fly Ash × NaOH), stay below the significance level, suggesting that their contributions are either statistically unimportant or less significant under the experimental circumstances.

Figure 3a

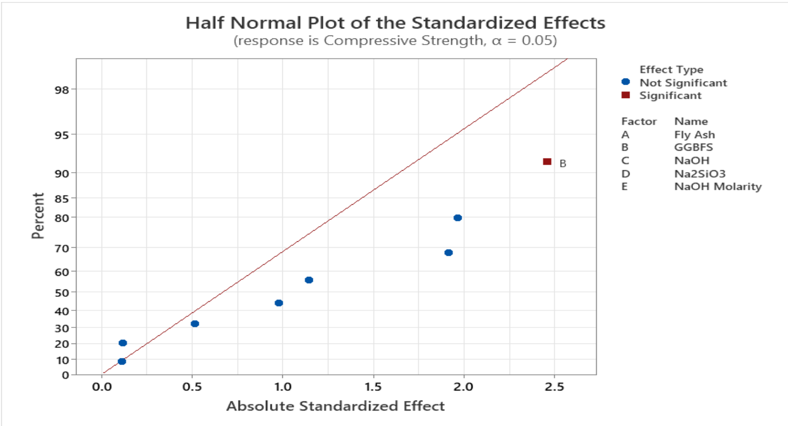

Figure 3 b

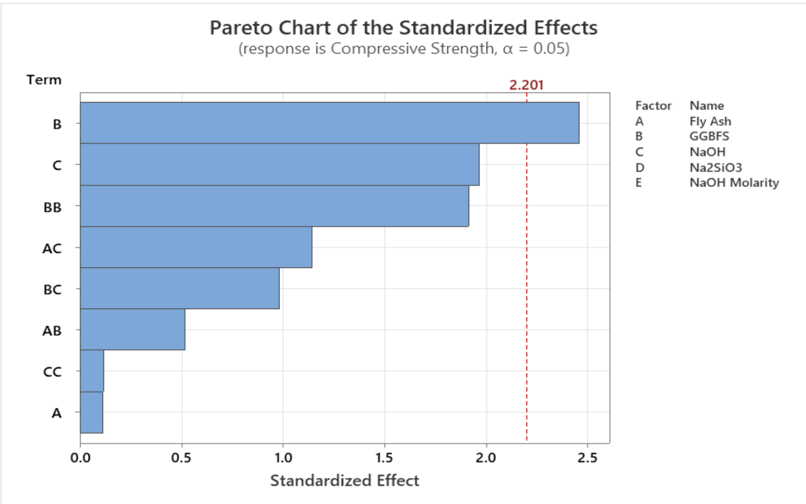

Figure 3c

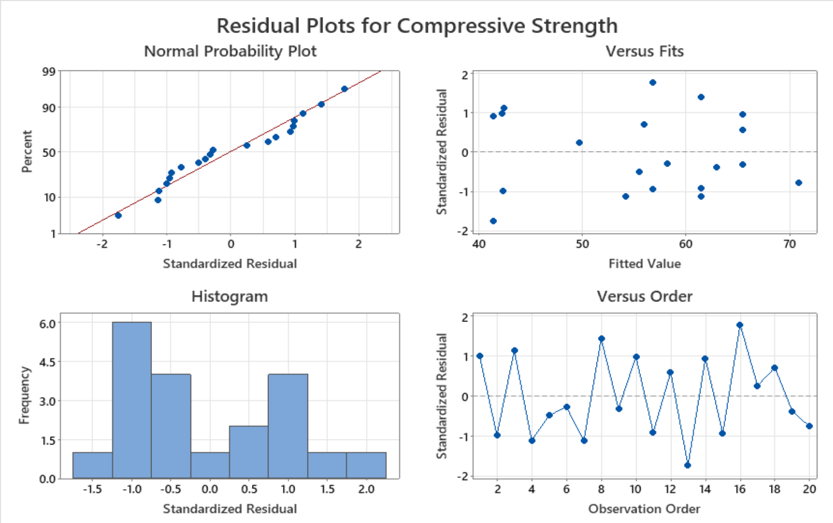

Figure 3d

3.2.2 Residual Analysis

Remaining diagnostic plots were used to assess the model's appropriateness (Figure 3d):

- The Normal Probability The plot of residuals suggests a normal distribution of errors since the residuals closely resemble a straight line.
- A random scatter is seen in the Residuals vs. Fitted plot, suggesting homoscedasticity (constant variance) and the lack of nonlinearity.
- • The notion of normalcy is further supported by the normalized residuals histogram, which roughly resembles a bell-shaped distribution.
- There is no obvious pattern in the Residuals vs. Order figure, indicating that the residuals are independent and dispersed at random throughout time.

When taken as a whole, these diagnostics verify that the regression model meets the requirements of ANOVA and is suitable for both prediction and optimization.

3.3 Contour Plot Analysis for Compressive Strength

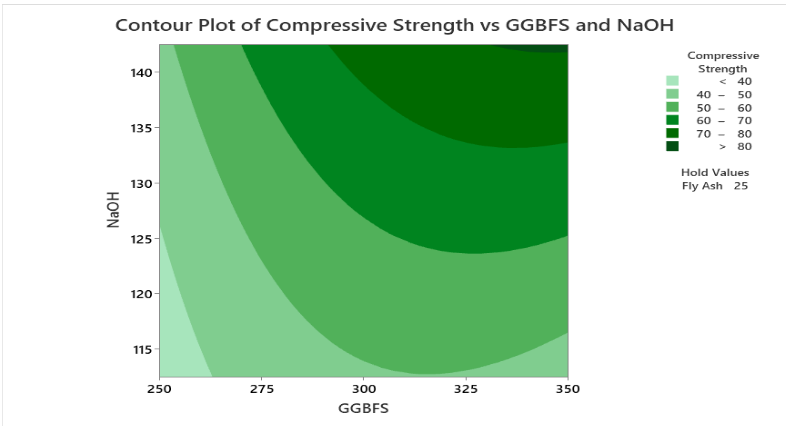

Figure 3e: *Contour Plot of Compressive Strength vs GGBFS and NaOH (Fly Ash held constant at 25 kg/m³)*

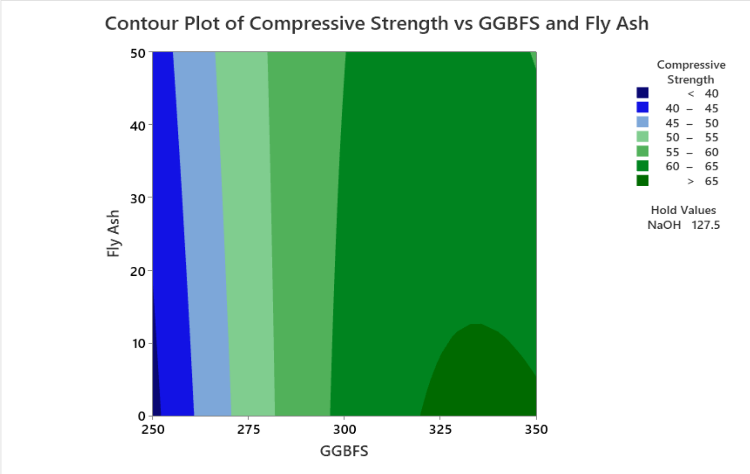

Figure 3f: *Contour Plot of Compressive Strength vs GGBFS and Fly Ash (NaOH held constant at 127.5 kg/m³)*

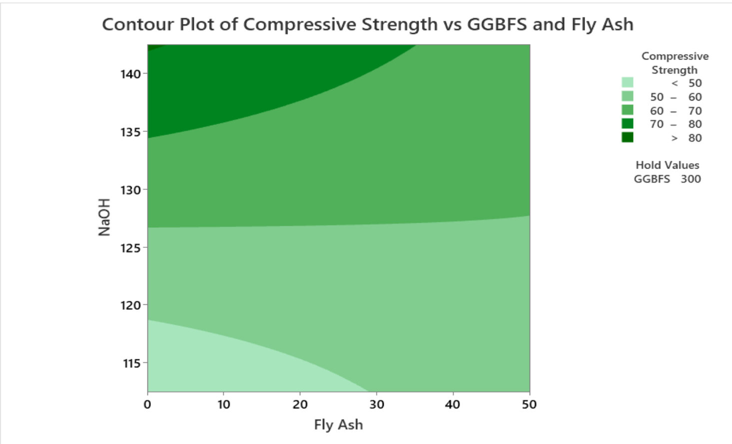

Figure 3g: *Contour Plot of Compressive Strength vs Fly Ash and NaOH (GGBFS held constant at 300 kg/m³)*

To visually grasp how different elements interact to affect compressive strength, contour plots were created. Compressive strength increased significantly when both GGBFS and NaOH were increased, especially above 130 kg of NaOH, as seen in Figure 3e. Regardless of the quantity of fly ash, Figure 3f demonstrates that a larger GGBFS content significantly increases strength, which is in line with the Pareto chart findings. On the other hand, Figure 3h indicates a positive but smaller contribution than GGBFS and NaOH, suggesting that increasing the Fly Ash content somewhat increases strength at higher NaOH levels.

4. Conclusion

Using fly ash, GGBFS, and NaOH concentration as the primary variables, this research effectively used Response Surface Methodology (RSM) to model and assess the compressive strength of geopolymer concrete. More than 72% of the variation in the data was explained by the statistically significant regression model that was created.
Key findings include:

- GGBFS has a large quadratic and linear impact on strength.

- There is an optimal level at which strength decreases, and NaOH adds to strength in a nonlinear manner.
- Within the investigated range, fly ash has a positive but statistically less significant influence.

The lack-of-fit study validates the model's suitability for the experimental data and shows that it may be used to forecast and optimize compressive strength.

4.2 Response Optimizer

To find the ideal mixture composition that optimizes the compressive strength of geopolymer concrete, the response optimizer was used. The input parameters (Fly Ash, GGBFS, and NaOH) were limited within the experimental design range, and the optimization goal was set to "maximize" compressive strength.

The maximum compressive strength of 72.3 MPa was estimated by the optimizer with the given input conditions:

- **Fly Ash**: 50 kg
- **GGBFS**: 308.25 kg
- **NaOH**: 134.7 kg

These optimized values validate the model's prediction power since they are inside the feasible zone. A perfect match with the optimization goal was confirmed by the desirability function, which showed a value of 1.00.

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