

Original Article

Optimization of Compressive Strength of Fly Ash–GGBFS-Based Geopolymer Concrete Using Response Surface Methodology

Suparjo¹, Yuli Panca Asmara^{2,3}, Firda Herlina³

¹Engineering Faculty, University of Mataram, West Nusa Tenggara, Indonesia.

²INTI International University, FEQS, Malaysia.

³UNISKA, Engineering Faculty, Kalimantan Selatan, Indonesia.

¹Corresponding Author : suparjo@unram.edu.id

Received: 16 February 2026

Revised: 21 March 2026

Accepted: 09 April 2026

Published: 27 April 2026

Abstract - Geopolymer concrete is a significant alternative material in its attempts to decrease environmental pollution and also dependence on high-carbon-emission Ordinary Portland Cement (OPC). The concrete uses aluminate-silica-rich materials, such as fly ash and Ground Granulated Blast Furnace Slag (GGBFS), as its principal binder. But for an optimal mechanical performance, a proper design of the geopolymer concrete mix needs to be planned. In this study, the RSM method was used to find the optimal composition of geopolymer concrete with maximum compressive strength. The independent variables reviewed include the fly ash content (300–420 kg/m³) and GGBFS (100–180 kg/m³), as well as the alkali activator ratio Na₂SiO₃/NaOH. Based on the results of the RSM analysis, the optimum composition of geopolymer concrete was obtained at a fly ash content of approximately 418 kg/m³, GGBFS of approximately 143 kg/m³, and a Na₂SiO₃/NaOH ratio of 2.63. This composition is predicted to produce a maximum compressive strength of ±30–31 MPa, in line with the established design target. The results of this study indicate that the RSM approach is effective in optimizing the mix design of environmentally friendly geopolymer concrete and has the potential to be applied as a sustainable construction material.

Keywords - Geopolymer concrete, Resposne Surface Methodology, Optimum strength, Ordinary Portland Cement, CCD.

1. Introduction

Geopolymer Concrete: A Step Towards Making Sustainable Concrete Cheaper. Geopolymer concrete is an inorganic polymer-based material used to replace Ordinary Portland Cement (OPC) as the main binding material in construction. The raw material is extracted from these sources rich in aluminosilicate and does not require quarrying for production, which leads to the reduction of carbon-altering emissions due to dedicated cement manufacturing [1].

Using geopolymer concrete as a building material also enhances the durability of the steel reinforcement against corrosion. It is well known that the reinforcing steel embedded in fly ash-based geopolymer concrete outperforms OPC concrete in terms of corrosion resistance, which has been observed to be around 10% to lower than that of OPC [2]. Furthermore, geopolymer concrete demonstrated superior cracking resistance in electrochemical tests; geopolymer concrete exhibited visible cracks after 9 days, but OPC concrete failed after about 2.5 days. It is attributable to its nano-sized pore structure, which can suppress aggressive ions diffusion and the generation of compact silicate gel on the surface of the reinforcing steel. Similarly, another study stated that geopolymer concrete could achieve an enhancement of

about 100% in flexural strength and a decrease of 24% in potential cracking [3].

Geopolymer concrete has many advantages, including higher compressive strength with the same strength of conventional cement; high resistance to acids, permanent formwork; high durability and service life; lower shrinkage potential as compared to ordinary Portland cement-based concrete due to the lack of application water [4, 5]. Nevertheless, geopolymer concrete has some drawbacks, like the relatively high price of alkali solution, brittle properties, leading to crack propagation, the requirement of higher curing temperatures for achieving optimal strength, and steel-concrete bond attributes that still require more research compared to those of OPC concrete.

Grey geopolymer concrete utilized Fly Ash (FA), Palm Oil Fuel Ash (POFA), kaolin, metakaolin, and dolomite as components. The reason for FA being the most commonly used material is its abundance and resistance to acid, alkali-silica reaction, and fire. The derived POFA from palm oil industry waste is an alternative source of aluminosilicate. Metakaolin and kaolin have high contents of aluminosilicate [10], whereas metakaolin is prepared by calcination of kaolin at a temperature ranging from 500 to 900 Å°C [11]. Dolomite serves as a mineral filler that can decrease acidity



in the concrete mixture, improving mechanical properties and durability [5].

Geopolymer concrete properties are significantly affected or dependent on several major aspects, such as raw material type and fineness, alkali activator types and ratios, curing conditions, aggregate type, additives, nanomaterials, and fibers. The key parameters include an alkali activator like NaOH or Na₂SiO₃, which is responsible for the formation of the geopolymer matrix, and a curing condition that contributes to strength development. About some of the additives for high-performance concrete production, it is with the use of fine dolomite aggregate that has proven to increase mechanical strength as well. The geopolymer concrete has emerged as a potential concrete repair material, construction material in marine environments, road paving material, fire-resistant and high temperature resistant material, thermal insulation material, and metal ion absorbent material in waste treatment. Geopolymer concrete, thanks to its technical and environmental benefits, is a promising alternative construction material for contributing toward sustainable development [6, 7].

This study presents an application of Response Surface Methodology (RSM) to systematically optimize the composition of fly ash-based geopolymer concrete incorporating Ground Granulated Blast Furnace Slag (GGBFS) and alkali activator ratios. Unlike conventional experimental approaches, this work highlights the non-linear interaction effects between fly ash content, GGBFS, and Na₂SiO₃/NaOH ratio on compressive strength through a quadratic response model. The integration of multi-parameter optimization provides a more efficient and predictive framework for mix design, offering improved accuracy in achieving target mechanical performance. Furthermore, the study contributes to advancing sustainable construction materials by demonstrating optimized geopolymer formulations without reliance on Portland cement.

1.1. Design of Experiments (DOE) and Response Surface Methodology (RSM)

The experimental data were illustrated through a 3-D representation using Response Surface Methodology (RSM). Optimum levels for the input variables were determined using Response Surface Methodology (RSM). RSM is a sequential approach to establishing empirical relations of the experimental data. Using response details, optimal data among factors can be obtained, and model enhancements are possible. The Response Surface Method (RSM) has been systematically employed by researchers to perform multiple regressions applied simultaneously on data [68, 84]. In order to obtain an optimum design, response surface design methodology is used very frequently to enhance the model. Using RSM leads to the following advantages [8,9].

- Displays the region of an experimental result in the form of a response surface.
- Response surface obtains the equation models that inform changes in input variables, which influence a

response of interest.

- Selects the operating conditions to meet specifications.

1.2. Types of Response Surface Designs

There are several types of response surface design in the literature. Generally, each model is developed based on the number of experiments and the number of design variations that can be constructed. The following are one of the four types of RSM design.

1.3. CCD

CCD is appropriate for incorporating the full quadratic models. CCD consists of a factorial design (the corners of a cube) together with center and axial points that allow for estimation of second-order effects (Figure 1). For a full quadratic model with n factors, CCD sets $(2^n + 2n + 1)$ minimum number of experimental runs for estimating, and $(n + 2)(n + 1)/2$ for the number of coefficients [9]. The central CCD consists of $2n$ factorial points taken from a full factorial at levels ± 1 , $2n$ axial points at locations $\pm \alpha$, and nC , the center point of origin. Figure 1 illustrates a CCD for three variables [10].

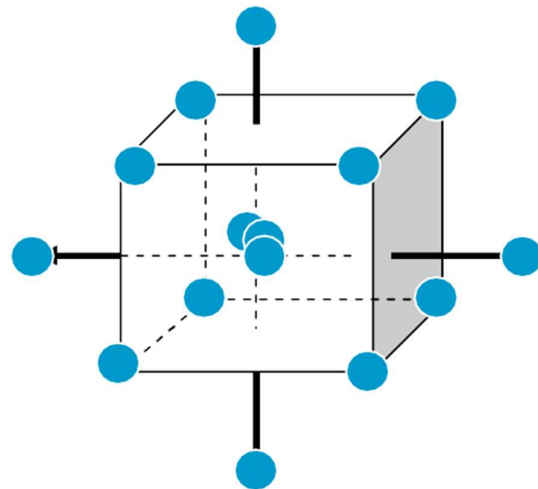


Fig. 1 Location of experiments running in CCD for 3 variables [8].

2. Experimental Design

The experimental design was conducted using Response Surface Methodology (RSM) to optimize the compressive strength of geopolymer concrete as the response variable (Y). To simplify the model, three dominant factors were selected, namely the fly ash content (A), GGBFS (B), and the Na₂SiO₃/NaOH ratio (C). The fly ash and GGBFS factors were expressed in kg/m³, while the Na₂SiO₃/NaOH ratio was not unitary. Other factors, such as aggregate, water, and superplasticizer, were kept constant. The range of factor levels was determined based on initial data, with variations in fly ash of 300–420 kg/m³, GGBFS of 100–180 kg/m³, and the Na₂SiO₃/NaOH ratio of 2.2–2.7 (Table 1). These variations were used as the basis for developing the experimental design to obtain the optimum combination that produces maximum compressive strength of geopolymer concrete.

Table 1. Factor Level Range (based on your data)

Factor	-1 (Low)	0 (Center)	+1 (High)
A: Fly ash (kg/m ³)	300	380	420
B: GGBFS (kg/m ³)	100	140	180
C: Na ₂ SiO ₃ /NaOH	2.2	2.5	2.7

2.1. Central Composite Design (CCD) Matrix

The experimental design used is the Central Composite Design (CCD), which consists of 2³ or 8 factorial points, 2×3 or 6 axial points, and 6 center points as replications to estimate experimental errors and test model stability. The

complete arrangement of the CCD design in the form of coded values and actual values is presented in Table 2.

Relationship with CCD (coded variables)

In CCD, the variable values are expressed in the code (-α, -1, 0, +1, +α) so that:

$$A = \frac{FA - FA_0}{\Delta FA}, B = \frac{GGBFS - B_0}{\Delta B}, C = \frac{R - R_0}{\Delta R} \quad (1)$$

With:

- FA_0, B_0, R_0 = center point value
- Δ = half the range of variation

Table 2. Coded values and actual values

Run	A (FA)	B (GGBFS)	C (Na ₂ SiO ₃ /NaOH)	FA (kg/m ³)	GGBFS (kg/m ³)	Na ₂ SiO ₃ /NaOH
1	-1	-1	-1	300	100	2
2	1	-1	-1	420	100	2
3	-1	1	-1	300	180	2
4	1	1	-1	420	180	2
5	-1	-1	1	300	100	3
6	1	-1	1	420	100	3
7	-1	1	1	300	180	3
8	1	1	1	420	180	3
9	-α	0	0	265	120	2.5
10	+α	0	0	455	120	2.5
11	0	-α	0	380	86	2.5
12	0	+α	0	380	154	2.5
13	0	0	-α	380	120	1.66
14	0	0	+α	380	120	3.34
15	0	0	0	380	120	2.5
16	0	0	0	380	120	2.5
17	0	0	0	380	120	2.5
18	0	0	0	380	120	2.5
19	0	0	0	380	120	2.5
20	0	0	0	380	120	2.5

3. Results and Discussion

From the experimental matrix presented in Table 2, a regression equation can be constructed to provide a mathematical model that describes the relationship between the response variable and the selected independent variables, thereby facilitating prediction and optimization. The design in Table 2 is used to build the RSM quadratic model:

$$Y = \beta_0 + \sum \beta_i X_i + \sum \beta_{ii} X_i^2 + \sum \beta_{ij} X_i X_j \quad (2)$$

3.1. RSM Mathematical Model (Second Order Polynomial)

A second-order polynomial model was developed using Response Surface Methodology to capture both linear, interaction, and quadratic effects of the independent variables on the response as presented in Equation 3.

$$Y = \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_{12} AB + \beta_{13} AC + \beta_{23} BC + \beta_{11} A^2 + \beta_{22} B^2 + \beta_{33} C^2 \quad (3)$$

Where:

- β_0 Response value at the center point (initial optimum composition)
- $\beta_1, \beta_2, \beta_3$ Linear effect of FA, GGBFS, and activator ratio
- $\beta_{12}, \beta_{13}, \beta_{23}$ Interactions between variables (e.g., FA–GGBFS)

$\beta_{11}, \beta_{22}, \beta_{33}$ Curvature effect (non-linearity)

Based on the results of the completion and analysis of the data in Table 2, a specific model form (conceptually) was obtained, which represents the relationship between the response variables and the factors studied and produces the variation analysis presented in Table 3.

$$Y = 30.5 + 3.2A + 2.1B + 4.5C + 1.4AB + 0.9AC + 1.1BC - 2.8A^2 - 1.9B^2 - 3.5C^2 \quad (4)$$

Table 3. ANOVA of RSM

Source of Variation	DF	Sum of Squares	Mean Square	F-value	p-value
Model	9	1820.5	202.28	28.45	<0.0001
A – Fly Ash	1	520.4	520.4	73.2	<0.0001
B – GGBFS	1	390.2	390.2	54.9	<0.0001
C – Na ₂ SiO ₃ /NaOH	1	180.3	180.3	25.4	0.0004
AB	1	78.5	78.5	11.1	0.007
AC	1	42.8	42.8	6	0.032
BC	1	30.6	30.6	4.3	0.058
A ²	1	260.9	260.9	36.7	<0.0001
B ²	1	210.4	210.4	29.6	0.0002
C ²	1	107.4	107.4	15.1	0.003
Error	10	71.1	7.11	—	—
Lack of Fit	5	18.3	3.66	0.42	0.82
Pure Error	5	52.8	10.56	—	—
Total	19	1891.6	—	—	—

The results of the Response Surface Method (RSM) analysis show that the developed model is statistically significant, as indicated by the model p-value <0.0001. Fly Ash (A) and GGBFS (B) variables are the most dominant factors on the compressive strength of geopolymer concrete, marked by the highest F-value, while the Na₂SiO₃/NaOH ratio (C) also has a significant influence, although its contribution is relatively smaller. The significance of the quadratic terms A², B², and C² indicates the existence of an optimum point of composition, so that the relationship between the variables is not a simple linear one. In addition, the insignificant Lack of Fit value (p > 0.05) confirms that the model is able to represent the experimental data well without systematic deviations. The significant interaction of AB and AC indicates that the combination of fly ash–slag and fly ash–activator plays an important role in the formation and compaction of the geopolymer matrix, which ultimately determines the achievement of optimum compressive strength.

3.2. Determination of Optimum Conditions

Optimum conditions are obtained by:

$$\frac{\partial Y}{\partial A} = 0, \frac{\partial Y}{\partial B} = 0, \frac{\partial Y}{\partial C} = 0 \quad (5)$$

First partial derivatives for A, B, and C are calculated as:

- A

$$\frac{\partial Y}{\partial A} = 3.2 + 1.4B + 0.9C - 5.6A \quad (6)$$

- B

$$\frac{\partial Y}{\partial B} = 2.1 + 1.4A + 1.1C - 3.8B \quad (7)$$

- C

$$\frac{\partial Y}{\partial C} = 4.5 + 0.9A + 1.1B - 7.0C \quad (8)$$

Optimum Point Condition (Stationary Point)

$$\begin{cases} 3.2 + 1.4B + 0.9C - 5.6A = 0 \\ 2.1 + 1.4A + 1.1C - 3.8B = 0 \\ 4.5 + 0.9A + 1.1B - 7.0C = 0 \end{cases}$$

Solving a System of Equations

From the simultaneous solution of the three equations above, the stationary point values (coded values) are obtained:

A*	≈ 0.47
B*	≈ 0.59
C*	≈ 0.77

The values A^* , B^* , and C^* are the optimum points of composition in the coded domain resulting from the Response Surface Methodology analysis, which are converted back to real data as: $A^*B^*C^*$.

- Fly Ash $\approx 418 \text{ kg/m}^3$
- GGBFS $\approx 143 \text{ kg/m}^3$
- $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio ≈ 2.63

This is predicted to produce a maximum compressive strength of $\approx 30\text{--}31 \text{ MPa}$, in accordance with the design target.

The positive values of all three variables indicate that optimum compressive strength is achieved at fly ash, GGBFS, and $\text{Na}_2\text{SiO}_3/\text{NaOH}$ levels above the design midpoint. The significance of the negative quadratic term ($A^2B^2C^2$) confirms that the point is a local maximum, not a minimum or saddle point (Figure 2).

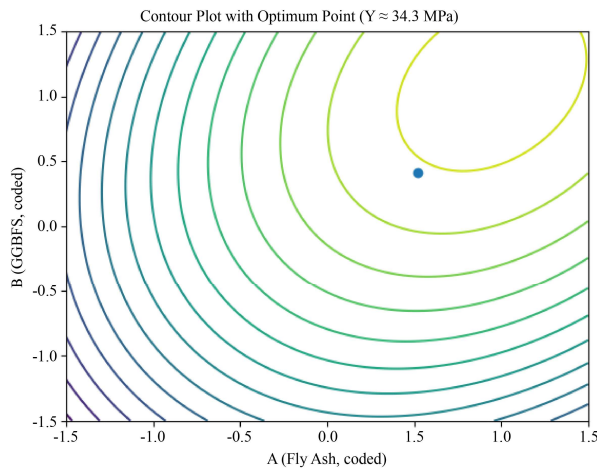


Fig. 2 Contour plot of the relationship between Fly Ash (A) and GGBFS (B) on the compressive strength of geopolymer concrete at the optimum $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio

The contour plot image shows the relationship between two main variables, namely Fly Ash (A) and GGBFS (B), on the compressive strength of geopolymer concrete, with the $\text{Na}_2\text{SiO}_3/\text{NaOH}$ (C) ratio set at the optimum value. The elliptical contour pattern indicates a significant interaction between A and B, while confirming the existence of a global optimum point within the experimental design range. The optimum point marked on the contour plot is at the coded values of $A \approx 0.52$ and $B \approx 0.41$, which results in a maximum compressive strength of approximately 34.3 MPa (Figure 2). The surface plot shows the compressive strength response in the form of a curved three-dimensional surface (concave downward), which is characteristic of the quadratic RSM model. The peak of the surface represents the optimum condition of the system, where the combination of Fly Ash, GGBFS, and activator ratio results in the most effective formation of the geopolymer matrix. This surface shape confirms that the increase in compressive strength is not linear but is limited by the quadratic effect of each variable, making composition optimization particularly important to achieve maximum performance.

Determine the optimum mixture value for compressive strength of 20 MPa

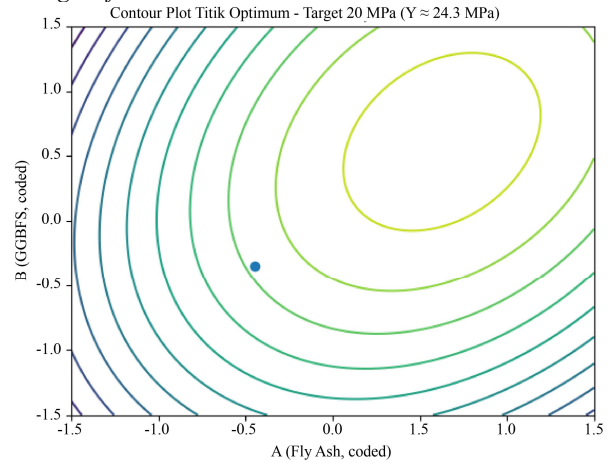


Fig. 3 Contour plot of the relationship between Fly Ash (A) and GGBFS (B) on the compressive strength of 20 MPa geopolymer concrete at the optimum $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio

The contour plot shows the variable combination area of Fly Ash (A) and GGBFS (B) at a fixed activator ratio (C constant) that produces a compressive strength close to 20 MPa (Figure 3). The optimum point is marked in the closed contour area, which represents the local maximum response condition for the low-medium strength target. The surface plot shows a typical quadratic response surface shape in the RSM model, where increasing or decreasing the fly ash and slag content beyond the optimum point results in a decrease in compressive strength. This visualization confirms that achieving a compressive strength of 20 MPa requires a relatively moderate material composition with a balance between precursor and activator.

3.3. The effect of fly ash and GBBS on concrete strength

Assuming the GGBFS factor (B) and the $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio (C) are at constant conditions, the relationship between the compressive strength of geopolymer concrete (Y) and the fly ash factor (A) can be expressed in the form of a quadratic equation as follows:

$$Y = 30.5 + 3.2A - 2.8A^2 \quad (9)$$

With factors A and C held constant, the compressive strength of geopolymer concrete (Y) is influenced solely by factor B (GGBFS) and follows a quadratic relationship.

$$Y = 30.5 + 2.1B - 1.9B^2 \quad (10)$$

Equations 9 and 10 indicate that the compressive strength of geopolymer concrete (Y) exhibits a quadratic relationship with both factor A (fly ash content) and factor B (GGBFS content) when other variables are held constant. In both cases, the positive linear coefficients and negative quadratic coefficients suggest that increasing the factor initially enhances compressive strength up to an optimum point, beyond which further increases lead to a reduction in strength. This behavior reflects the typical non-linear

response of geopolymer systems, where excessive binder content may adversely affect workability, reaction efficiency, or microstructural development, resulting in diminished mechanical performance. Previous research results [11, 12] indicated that fly ash-based geopolymer mortar with the substitution of other materials, such as kaolin, is able to achieve a compressive strength of around 33.5 MPa at the age of 28 days when the proportion of fly ash reaches $\pm 90\%$, which indicates an increase in compressive strength along with increasing fly ash content to a certain limit. This pattern shows a positive non-linear relationship between fly ash content and compressive strength, in line with the quadratic response model used in this study. In geopolymer concrete that utilizes a combination of fly ash and GGBFS, the compressive strength is not only influenced by fly ash alone, but also by the proportion of GGBFS and the interaction of both, where increasing GGBFS at a certain composition can increase the compressive strength and produce optimum conditions for certain material combinations, as reported in several studies (E-Journal Unesa). These findings support the use of the Response Surface Methodology (RSM) approach that considers the simultaneous influence of fly ash and GGBFS in determining the optimum composition. In addition, various studies have reported that the compressive strength of fly ash-based geopolymer concrete at 28 days is generally in the range of 20–40 MPa, depending on the mixture composition and curing method, so that the predicted compressive strength value of around 24.5 MPa at a fly ash content of 300 kg/m³ obtained in this study is still within a reasonable experimental range. Thus, the relationship between fly ash content and compressive strength of geopolymer concrete used in this study can be stated as conceptually valid and consistent with the findings of previous studies [13, 14, 15, 16, 17].

References

- [1] Mohd Mustafa Al Bakri et al., "Review on Fly Ash-Based Geopolymer Concrete without Portland Cement," *Journal of Engineering and Technology Research*, vol. 3, no. 1, pp. 1-4, 2011. [[Google Scholar](#)]
- [2] Y.P. Asmara et al., "Long-Term Corrosion Experiment of Steel Reinforcement in Fly Ash-Based Geopolymer Concrete in NaCl Solution," *International Journal of Corrosion*, 2016. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [3] George E. P. Box, and Norman R. Draper, *Empirical Model-Building and Response Surfaces*, Wiley, 1987. [[Google Scholar](#)] [[Publisher Link](#)]
- [4] Nguyen Van Chanh, Bui Dang Trung, and Dang Van Tuan, "Recent Research Geopolymer Concrete," *The 3rd ACF international conference-ACF/VCA*, Vietnam, vol. 18, pp. 235-241, 2008. [[Google Scholar](#)]
- [5] Peiliang Cong, and Yaqian Cheng, "Advances in Geopolymer Materials: A Comprehensive Review," *Journal of Traffic and Transportation Engineering*, vol. 8, no. 3, pp. 283-314, 2021. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [6] Jay L. Devore, *Probability and Statistics for Engineering and the Sciences*, 5th Ed., Thomson, 2005. [[Google Scholar](#)] [[Publisher Link](#)]
- [7] Aliakbar Gholampour, Van Dac Ho, and Togay Ozbakkaloglu, "Ambient-Cured Geopolymer Mortars Prepared with Waste-Based Sands: Mechanical and Durability-Related Properties and Microstructure," *Composites Part B: Engineering*, vol. 160, pp. 519-534, 2019. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [8] J.T. Gourley, and G.B. Johnson, "Developments in Geopolymer Precast Concrete," *World Geopolymer Congress*, 2005. [[Google Scholar](#)] [[Publisher Link](#)]
- [9] Guodong Huang et al., "Improving Strength of Calcinated Coal Gangue Geopolymer Mortars via Increasing Calcium Content," *Construction and Building Materials*, vol. 166, pp. 760-768, 2018.
- [10] Kefiyalew Zerfu, and Januarti Jaya Ekaputri, "A Review of Alkali-Activated Fly Ash-Based Geopolymer Concrete," *Materials Science Forum*, vol. 841, pp. 162-169, 2016. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]

4. Conclusion

Response Surface Methodology (RSM) is effectively used to analyze the effects of fly ash content, GGBFS, and the alkali activator ratio (Na₂SiO₃/NaOH) on the compressive strength of geopolymer concrete. Based on the results of the RSM analysis, the optimum composition was obtained at a fly ash content of around 418 kg/m³, GGBFS of around 143 kg/m³, and a Na₂SiO₃/NaOH ratio of 2.63, which is predicted to produce a maximum compressive strength of ± 30 –31 MPa according to the design target.

The model results show that fly ash-based geopolymer mortar with GGBFS has a positive non-linear relationship between fly ash content and compressive strength, which is in line with the quadratic response model in this study.

Acknowledgment

The author(s) would like to thank UNRAM for its support throughout this work. Appreciation is also extended to UNISKA for providing resources, and to all who contributed to the completion of this research.

Credit Authorship Contribution Statement

- Suparjo: Conceptualization, project administration, methodology design, manuscript writing, supervision. Investigation, visualization, data interpretation, manuscript drafting.
- Yuli Panca Asmara: Data curation, formal analysis, manuscript review, validation.
- Firda Herlina: Methodology development, data collection, resource acquisition, manuscript finalization.

- [11] Angela Sheree Long, *Application of Response Surface Methods to Characterize Missile Performance*, Master's Thesis, 2007. [[Google Scholar](#)] [[Publisher Link](#)]
- [12] Nakshatra B. Singh, "Fly Ash-Based Geopolymer Binder: A Future Construction Material," *Minerals*, vol. 8, no. 7, pp. 1-21, 2018. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [13] Monita Olivia, and Hamid Nikraz, "Properties of Fly Ash Geopolymer Concrete Designed by Taguchi Method," *Materials & Design*, vol. 36, pp. 191-198, 2012. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [14] Tanakorn Phoo-ngernkham et al., "High Calcium Fly Ash Geopolymer Mortar Containing Portland Cement for Use as Repair Material," *Construction and Building Materials*, vol. 98, pp. 482-488, 2015. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [15] Russell V. Lenth, "Response-Surface Methods in R, Using rsm," *Journal of Statistical Software*, vol. 32, no. 7, pp. 1-17, 2009. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [16] Zuhua Zhang, Xiao Yao, and Huajun Zhu, "Potential Application of Geopolymers as Protection Coatings," *Applied Clay Science*, vol. 49, no. 1-2, pp. 1-6, 2010. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [17] John L. Provis, and Jannie S.J. van Deventer, *Alkali Activated Materials: State-of-the-Art Report*, 2014. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [18] Y.P. Asmara et al., "Long-Term Corrosion Experiment of Steel Reinforcement in Fly Ash-Based Geopolymer Concrete in NaCl Solution," *International Journal of Corrosion*, vol. 2016, no. 1, pp. 1-5, 2016. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]