Journal of Engineering and Technology (JET),
Volume 2, Issue 2, Page 35-50, 2026

Optimization of Strength Characteristics of Incinerator Bottom Ash-Based Geopolymer Concrete Using Response Surface Methodology

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ABSTRACT

Growing populations and industrial expansion have led to increased municipal waste generation and environmental concerns, as well as substantial greenhouse gas emissions from the cement industry. In response, Geopolymer concrete (GPC) has emerged as a promising, more sustainable alternative to Ordinary Portland Cement (OPC). This study employs Response Surface Methodology (RSM) to optimize four critical parameters affecting the compressive strength of Incinerator Bottom Ash (IBA): curing temperature, curing duration, activator ratio, and activator molarity. The research objectives include analyzing the oxide composition of IBA, assessing the specific gravities of materials, and developing a predictive model with three-dimensional surface plots, with Analysis of Variance (ANOVA) employed for data analysis. Results demonstrate the alumino-silicate content of IBA at 76.88%, confirming its viability as a pozzolanic material. The achieved optimal compressive strength was 21.30 N/mm² at an activator ratio of 60%, a curing temperature of 100°C, an 18 M KOH molarity, and a curing duration of 6 hours. ANOVA results indicate that all parameters significantly influence strength development ($p < 0.0001$), exhibiting a strong model fit with a high coefficient of determination ($R^2 = 0.9945$). Furthermore, a desirability function value of 0.99 indicates effective optimization, while a low prediction error of 1.74% confirms the accuracy and reliability of the developed model. This research emphasizes RSM's effectiveness in process optimization and supports advancements in eco-efficient geopolymer technologies, promoting the transition towards sustainable construction materials.

Keywords— **Geopolymer, IBA, Parameters, Responses, RSM, and Sustainable**

I. INTRODUCTION

The fast expansion of worldwide infrastructure has sharply raised demand for Ordinary Portland Cement (OPC), the main binding agent in traditional concrete. Producing OPC, however, consumes large amounts of energy and generates significant carbon dioxide (CO_2) emissions, driving climate change and harming the environment. This has driven the development of sustainable alternatives capable of reducing environmental impact while maintaining structural performance [1], [2], [3], [4].

Geopolymer technology has emerged as a viable alternative binder system. First proposed by Davidovits (1979), Geopolymers are produced by activating aluminosilicate precursors with an alkaline solution, forming a three-dimensional polymeric network. These materials exhibit high compressive strength, low permeability, and enhanced resistance to chemical attack. In addition, their production from industrial and agricultural wastes supports resource efficiency and circular economy principles [5]. Incinerator bottom ash (IBA), a major by-product of municipal solid waste (MSW) incineration, has gained attention as a potential geopolymer precursor. Representing approximately 80–90% of the total residues produced during incineration, IBA is rich in silica and alumina, which are essential constituents for geopolymerisation processes [6]. Its utilization in construction reduces landfill disposal and promotes sustainable waste management.

Previous studies have investigated IBA as a partial cement replacement and as an aggregate in concrete. Improvements in incineration technologies have enhanced the physicochemical properties of IBA, increasing its suitability for construction applications [7], [8], [9], [10], [11]. Nevertheless, challenges remain, including variability in composition, potential contaminants, and limited long-term durability data [12].

Response Surface Methodology (RSM) is an advanced statistical method that enhances conventional experimental approaches through the application of structured designs such as the Central Composite Design (CCD). It enables the systematic evaluation and quantification of both the individual and interactive effects of multiple independent variables on one or more response variables, while significantly reducing the number of experimental runs required by traditional one-factor-at-a-time methods [13]. In geopolymer systems, material performance is strongly influenced by key parameters, including curing temperature, curing duration, activator composition (e.g., silicate-to-hydroxide ratio), and alkaline solution molarity. These factors govern the reaction kinetics, degree of geopolymerization, microstructural development, and ultimately the mechanical properties of the material [14].

Despite existing studies, limited research has systematically addressed the simultaneous optimization of key processing parameters that affect the performance of IBA-based geopolymers. To address this gap, the present study employs IBA calcined at 800°C to produce a more reactive, amorphous, and carbon-free precursor suitable for geopolymer synthesis. Response Surface Methodology (RSM) was applied to investigate the effects of the activator-to-source material ratio (30–60%), alkaline solution molarity (12–

18 M), oven-curing temperature (60–100°C), and curing duration (6–8 hours) on the compressive strength of potassium-activated geopolymer binders. Predictive models were then developed to identify parameter combinations that maximize compressive strength while minimizing material and processing costs. This optimization enables precise proportioning and curing regimes, thereby improving process efficiency, reducing experimental burden, and facilitating the cost-effective production of potassium-activated IBA-based geopolymer binders.

II. MATERIALS AND METHODS

A. Materials

The study involved three components: aggregates, Incinerator Bottom Ash (IBA), and an alkaline activator, as shown in Figures 1 (a-d). The IBA was calcined at 800°C to produce aluminosilicate for geopolymerization. Solid potassium hydroxide (KOH) pellets with a 96% purity, and potassium silicate (K_2SiO_3) possessing a grade of 1.34 and a molecular mass of 154.28 g/mol, with a modulus ratio (SiO_2/K_2O) of 2.04, were sourced from the Lagos market. The GPC mixtures included crushed granite (coarse aggregate) and clean natural sand (fine aggregate), adhering to ASTM C136 [15].

B. Design of Experiment Using RSM

The interactions and effects of the constituent components on the compressive strength of geopolymer concrete were systematically investigated in this study. Four key factors (see Table 1) were considered as independent variables: the activator to source material ratio (A), molarity of the alkaline solution (B), oven curing temperature (C), and curing duration (D). These variables were selected due to their significant influence on the geopolymerization process and the resulting compressive strength (response). To facilitate statistical analysis and model development, predictive coded levels for each factor were established.

Figure 1: (a) Sand (b) Granite (c) IBA (d) Potassium hydroxide and potassium silicate

Table 1: Variables, coded levels and experimental treatment symbols

Variables	Codes	Unit	Level		
			Coded Low (-1)	**Coded Mean (0)**	**Coded High (+1)**
Activator ratio	A	%	30	45	60
Molarity	B	M	12	15	18
Oven curing	C	^{0}C	60	80	100
Duration	D	Hrs.	6	7	8

In this study, the Central Composite Design (CCD) approach within RSM was utilized to identify key analytical factors and generate the required experimental runs. CCD was chosen because it minimizes the total number of experiments while allowing for effective estimation of main effects, interaction effects, and quadratic terms. This method also accommodates practical constraints on mixture proportions, ensuring that unrealistic or overly concentrated formulations are avoided.

Compressive strength was defined as the primary response variable, while temperature, activator ratio, molarity, and curing duration served as the independent variables. RSM was employed to statistically analyze the compressive strength results and establish predictive relationships among these influencing factors. Equation (1) presents the functional relationship, which was established using both linear and quadratic polynomial models, with particular emphasis on a second-degree polynomial equation.

$$Y = K + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_1^2 + \beta_4 X_2^2 + \beta_5 (X_1 X_1) \quad (1)$$

In this model, β represents the regression coefficients, X denotes the independent variable, and K is the intercept constant. The response variable Y corresponds to the output obtained from the experimental tests. A total of thirty experimental runs were conducted using the selected factor levels at their respective low and high settings.

An experimental framework was developed to optimize the mix parameters for geopolymer concrete. The CCD method was employed, incorporating four independent variables for mixture synthesis, as detailed in Table 2. Based on the design matrix, a total of 30 experimental runs were prepared according to the specified mix combinations.

Table 2: **Geopolymer synthesis design**

Runs	Activator Ratio (%)	Molarity (M)	Oven Curing (^{0}C)	Duration (Hrs)
1	60	12	60	8
2	60	18	100	8
3	60	18	100	6
4	60	18	60	8
5	60	12	100	6
6	30	12	100	8
7	30	18	100	8
8	45	15	100	7
9	60	12	60	6
10	60	15	80	7
11	45	15	80	7
12	45	15	80	6
13	45	15	60	7
14	45	15	80	8
15	30	18	60	6
16	30	12	60	8
17	45	15	80	7
18	45	12	80	7
19	45	15	80	7
22	30	15	80	7
23	45	15	80	7
24	30	12	100	6
25	45	15	80	7
26	45	15	80	7
27	30	18	100	6
28	60	18	60	6
29	60	12	100	8
30	45	18	80	7

C. Preparation of Alkaline Solutions

The alkaline activator was prepared by dissolving potassium hydroxide (KOH) pellets in potable water to reach the target molarity. The mixture was stirred and left to cool to room temperature to release the heat produced during dissolution. Potassium silicate (K_2SiO_3) solution was then added to the KOH solution in a 2.5:1 ratio. and mixed until uniform. The combined activator was prepared at least 24 hours before use to allow it to reach equilibrium and stabilize before blending with other geopolymer constituents.

D. Mixing of the Constituents

Ingredients for the geopolymer paste were prepared following BS 8500-2 [16] standards, with mix proportions set according to the activator ratio, alkali concentration, and aggregate design. Specimens were produced by first dry-mixing the aggregates to ensure uniformity, then gradually incorporating a pre-made alkaline activator solution of potassium hydroxide (KOH) and potassium silicate (K_2SiO_3), as illustrated in Figure 2. Mixing continued until a uniform geopolymer slurry was achieved. The fresh mixture was cast into moulds, adequately compacted to remove entrapped air, and the tops leveled before curing under the prescribed conditions. The overall mixing and casting sequence for geopolymer concrete (GPC) closely mirrored that used for Ordinary Portland Cement (OPC) concrete, as described in BS 8500-2 [16].

E. Casting and Curing of Specimens

The freshly prepared geopolymer concrete was cast into clean, oiled steel moulds of 50m size and compacted to remove entrapped air and achieve consistent density. Compaction was performed by manual rodding or vibration, according to the mix's workability. Each experimental run was repeated three times to ensure the experimental data and ensuing statistical analysis were reliable and valid, with their top surfaces carefully smoothed and leveled (Figure 3a). The specimens were then oven-cured at varying temperatures and durations (Figure 3b). After curing, the cubes were allowed to cool naturally to room temperature before undergoing compressive strength testing using a compression testing machine. All procedures were conducted in accordance with ASTM C192/C192M [17] to facilitate the determination of optimal curing conditions.

F. Compressive Strength Tests

The compressive strength of the geopolymer concrete samples was measured with a compression testing machine, as depicted in Figure 4, following ASTM C39/C39M [18]. Before testing, cured samples were brought to room temperature and inspected to confirm clean, defect-free surfaces. Each specimen's size was measured to calculate its cross-sectional area. Specimens were positioned at the center of the testing machine's lower platen and subjected to a steady, continuous load applied at a constant rate until they failed. The maximum load at failure was recorded, and compressive strength was calculated by dividing that peak load by the specimen's cross-sectional area. For each test condition, the mean compressive strength was calculated from three replicate specimens to ensure the reliability and accuracy of the results.

Figure 2: Mixing of the constituent materials

Figure 3: (a): Cast geopolymer concrete (b) Oven machine

Figure 4: Compression machine

III. RESULTS AND DISCUSSION

A. Chemical Composition of IBA

Table 3 presents the major oxide composition of incinerator bottom ash (IBA), showing a silica (SiO_2) content of 56.74%. The combined percentage of SiO_2, Al_2O_3, and Fe_2O_3 is 76.89%, which exceeds the minimum requirement of 70% specified by ASTM C618 [19] for pozzolanic materials. This elevated combined oxide content demonstrates the significant pozzolanic potential of IBA and its ability to participate in cementitious and geopolymeric reactions, corroborating the findings of Tang et al. [20]. Consequently, IBA can be effectively used as a supplementary cementitious material in blended cements and geopolymer concrete, contributing to sustainable construction practices by enabling the beneficial reuse of industrial waste and reducing environmental burdens associated with waste disposal.

B. The Specific Gravity Results

Table 4 lists the specific gravity of the tested materials. The IBA had a specific gravity of 2.31, while the fine and coarse aggregates measured 2.58 and 2.63, respectively. These values lie within the ASTM C128 [21] acceptable range of 2.1–2.9, confirming that the materials meet the standard criteria for use in concrete.

C. Analysis of Variance (ANOVA) and Significance of Terms

Table 5 presents the ANOVA results for the developed model; significance was taken as $p < 0.050$ and insignificance as $p > 0.100$ [22], [23]. The regression model effectively captures the relationship between the response and the predictors, demonstrated by a highly substantial overall F-value of 343.47 ($p < 0.0001$). The model accounts for a large portion of the response variation, indicated by a very low residual (0.1013) and a large model sum of squares (18.31).

Although interaction terms BC, BD, and CD were not statistically significant, they were retained to enhance predictive accuracy. Considerable factors affecting the response include A, B, C, D and the interactions AB, AC, and AD [24]. The model fits the experimental data well, shown by minimal pure error and a no significant lack-of-fit. In summary, the IBA-based GPC response was accurately predicted, confirming the model's statistical strength and reliability.

D. Regression Model Analysis

Experimental results from the design matrix were used to construct a second-order regression model for forecasting geopolymer concrete compressive strength. The resulting regression equation, presented in

Equation 2, reflects the actual values of the mathematical model and summarizes the associated statistical effects of the independent variables and their interactions.

$$\textbf{\textit{Response}} = +2.91 + 0.4472A + 0.4457B + 0.7617C + 0.1594D + 0.0839AB - 0.0423AC - 0.0638AD - 0.0308BC - 0.0181BD - 0.0173CD \quad (2)$$

Table 3: Chemical Composition of IBA

Materials	SiO_2	AL_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	Lol
IBA	56.74	8.12	12.02	9.67	0.29	0.67	0.72	0.96	1.12

Table 4: Specific gravity of the IBA and aggregate materials

	MATERIALS		
	IBA	**Fine**	**Coarse**
Specific Gravity	2.31	2.58	2.63

Table 5: Analysis of variance (ANOVA) of response surface model

Source	**Sum of Squares**	**Df**	**Mean Square**	***F*-value**	***P*-value**	
Model	18.310	10	1.8300	343.47	< 0.0001	significant
A	3.6000	1	3.6000	675.23	< 0.0001	significant
B	3.5800	1	3.5800	670.56	< 0.0001	significant
C	10.450	1	10.450	1959.75	< 0.0001	significant
D	0.4572	1	0.4572	85.74	< 0.0001	significant
AB	0.1127	1	0.1127	21.14	0.0002	significant
AC	0.0286	1	0.0286	5.36	0.0319	significant
AD	0.065	1	0.0650	12.2	0.0024	significant
BC	0.0151	1	0.0151	2.84	0.1084	insignificant
BD	0.0052	1	0.0052	0.9828	0.3340	insignificant
CD	0.0048	1	0.0048	0.893	0.3565	insignificant
Residual	0.1013	19	0.0053			
Lack of Fit	0.1013	14	0.0072			
Pure Error	0.0000	5	0.0000			
Cor Total	18.420	29				

E. Development of Validation of the Model Response

The variability analysis of the developed model demonstrates strong agreement between the experimental and predicted values, as evidenced by a very low standard deviation and a coefficient of variation (C.V.) below 10%, indicating good precision and reproducibility. The coefficient of determination ($R^2 = 0.9945$) shows excellent agreement with the predicted and adjusted R^2 values, confirming the model's high predictive capability and reliability. Furthermore, the adequate precision value exceeded 80, signifying a strong signal-to-noise ratio and the model's fitness for navigating the design space. Collectively, these statistical indicators affirm that the model is robust, accurate, and highly effective for predicting and optimizing the effects of input variables.

F. Validation of Model Adequacy

The model's adequacy was assessed using diagnostic plots, including predicted versus actual values, normal probability plot of residuals, residuals versus predicted response, and Cook's distance versus run number, as shown in Figures 5(a–d). The model demonstrated strong predictive capability, with predicted compressive strength values closely aligning with experimental results. The normal probability plot of residuals indicates that the errors are approximately normally distributed. Additionally, the residuals versus predicted response plot reveals a random pattern, confirming no violation of the independence assumption. Together, the developed model and experimental findings provide valuable guidance for optimizing the preparation parameters of IBA-based geopolymer concrete.

Table 6: Summary statistical data on the quadratic model selection for Mixtures

Source	Std. Dev.	Mean	C.V. %	R^2	Adjusted R^2	Predicted R^2	Adeq. Precision
Values	0.0730	2.910	2.510	0.9945	0.9916	0.9679	82.0606

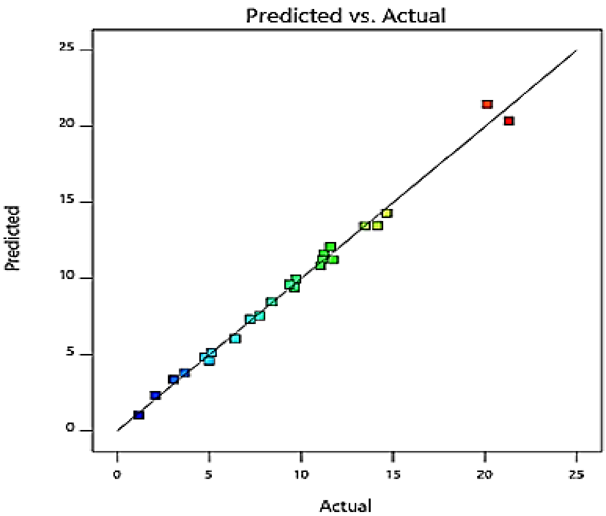


Figure 5a: Plot of predicted and actual values

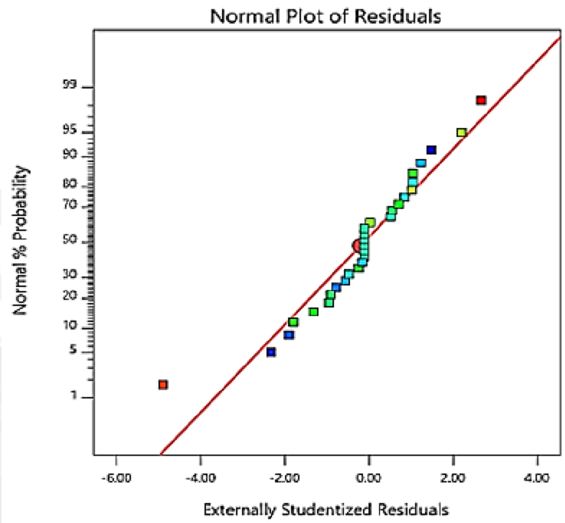


Figure 5b: Normal probability plot from the residuals

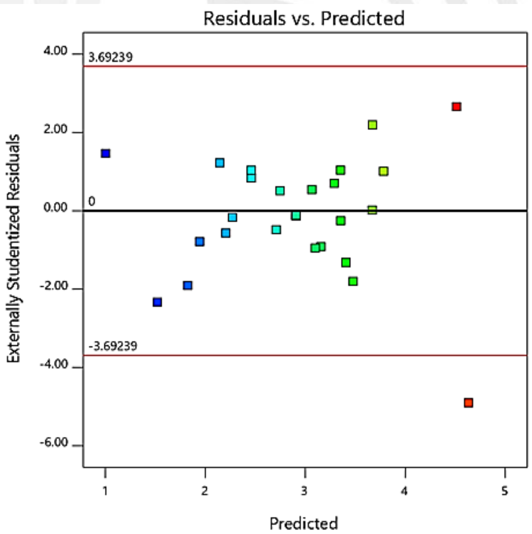


Figure 5c: Plot of residual against predicted response

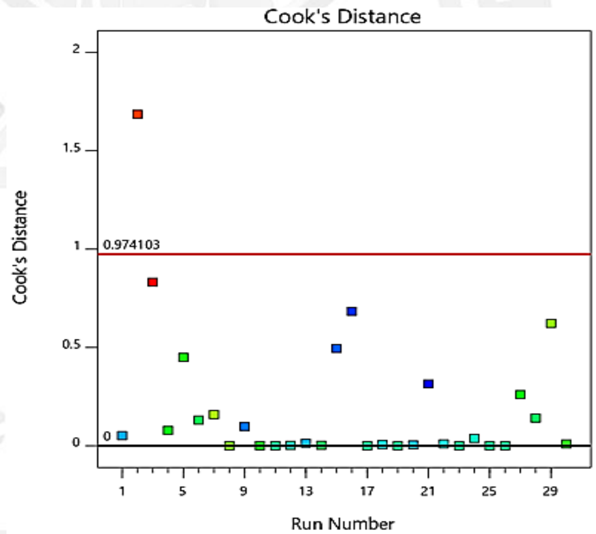
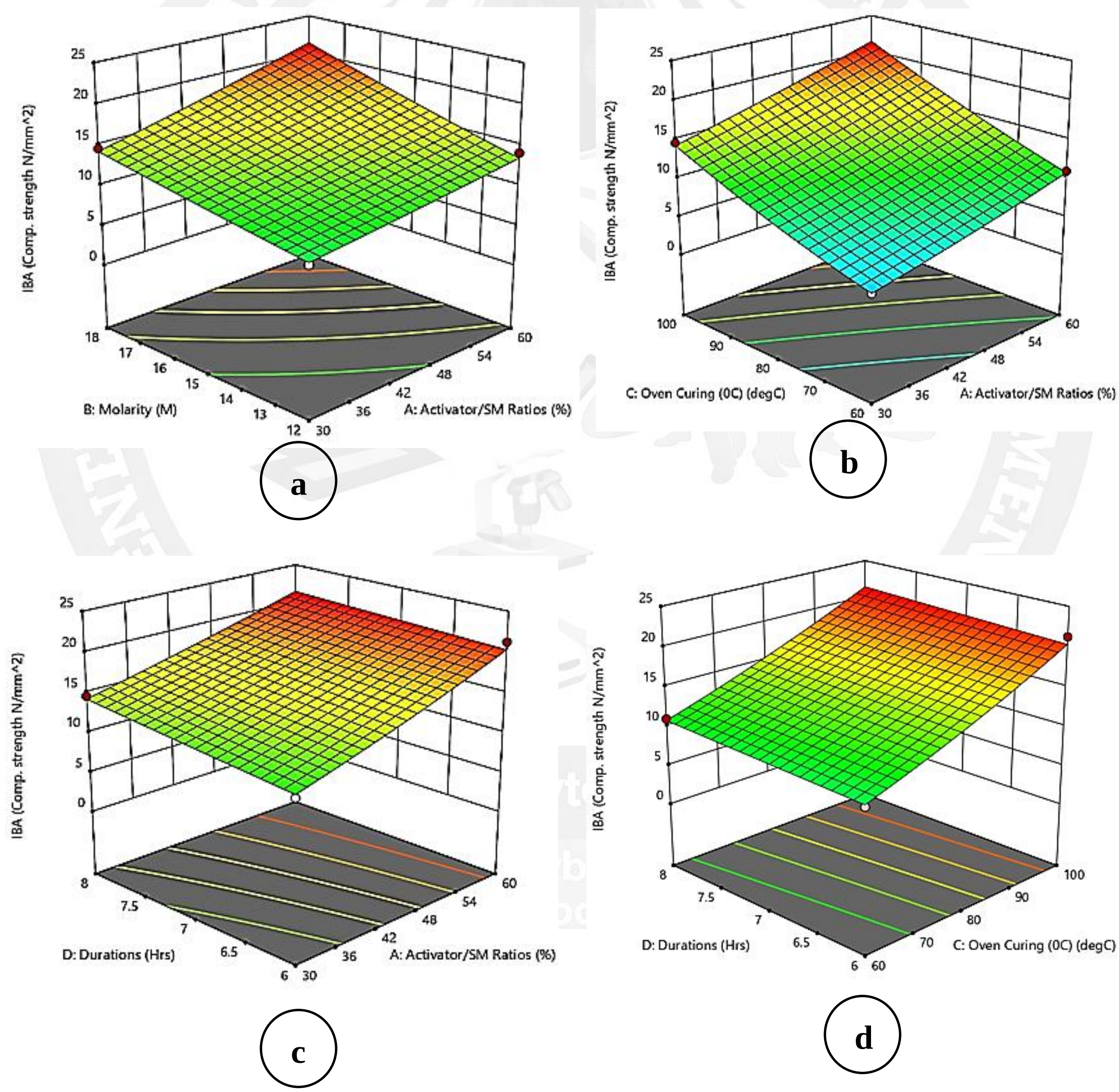


Figure 5d: Plot of cook's distance against run number

G. 3D Plots Model on Responses for IBA-based geopolymers

The interactions between the independent variables and their combined effects on the compressive strength (response) of geopolymer concrete (GPC) are shown by the 3D surface plots in Figures 6 (a–f). The findings show that strength development is greatly impacted by changes in alkaline concentration, curing temperature, activator ratio, and curing time. Higher alkaline concentrations, higher curing temperatures, greater activator ratios, and longer curing times are all associated with a constant rise in compressive strength. Notably, a potassium hydroxide (KOH) concentration of 18 M yields the best compressive strength. For example, the IBA-based GPC achieved a compressive strength of 21.30 N/mm² at an activator-to-source material ratio of 60%, a curing temperature of 100°C, and a curing time of 6 hours. These results are consistent with the findings of Fang et al. [25] and Ghafoor et al. [26]. Overall, these 3D plots provide valuable insights into the synergistic effects of these parameters on the compressive strength of IBA-based geopolymer concrete.



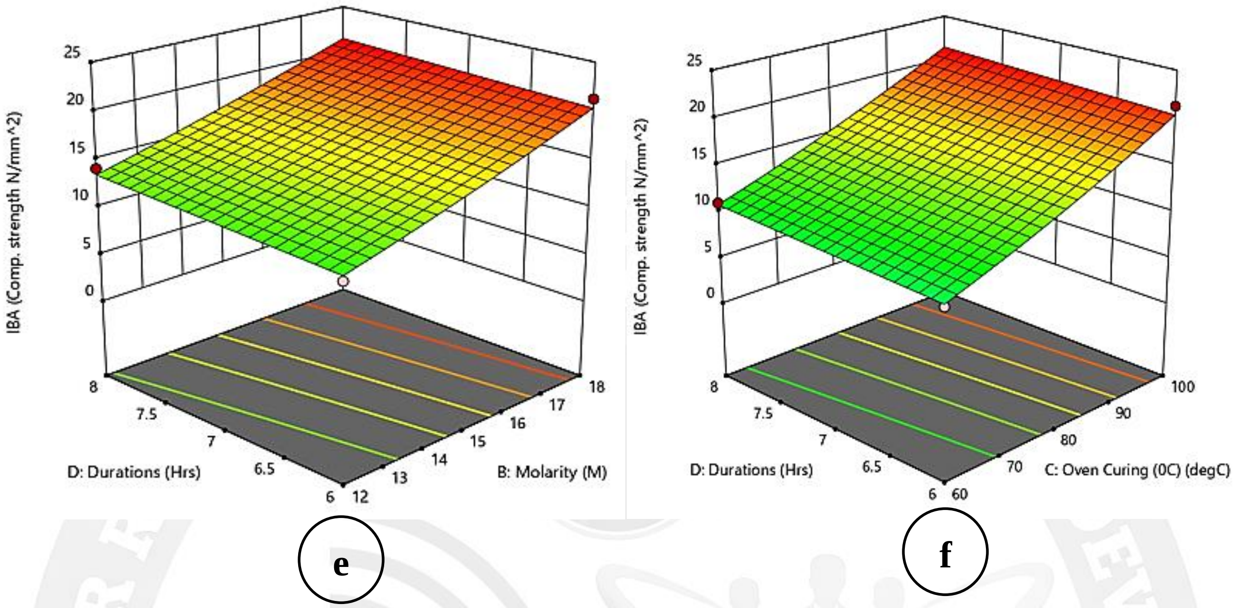


Figure 6a-f: 3D plots illustrating the interaction effects between pairs of variables and the response

H. Optimization Conditions

The validation results of the response, shown in Table 7, indicate that the IBA-based geopolymer concrete (GPC) achieved a compressive strength of 21.30 N/mm². This is in close agreement with the predicted value of 21.67 N/mm². The resulting error is minimal and well within acceptable limits for experimental modeling. This close correlation confirms that the input variables reached near-optimal conditions, demonstrating the robustness of the developed model and its potential applicability in future geopolymer concrete research.

Table 7: Experimental results validation

Response			
Compressive strength (N/mm^2)	**Predicted Value**	**Experimental Value**	**Error %**
IBA GPC	21.67	21.30	1.74

IV. CONCLUSION

The experimental work described in this study allowed for the extraction of the following specific conclusions:

i. The Incinerator Bottom Ash (IBA) was characterized based on its physicochemical properties and found to meet the combined oxide criterion ($SiO_2 + Al_2O_3 + Fe_2O_3 > 70\%$). According to ASTM C618-19, this composition classifies IBA as a suitable and sustainable pozzolanic material.

ii. The specific gravities of the IBA, fine aggregate, and coarse aggregate were determined as 2.31, 2.58, and 2.63, respectively. These values fall within the acceptable range of 2.1–2.9 specified by ASTM C128 -15, confirming the materials' suitability for concrete production.

iii. The optimal compressive strength of the experimental samples was recorded at 21.30 N/mm², closely matching the predicted value of 21.67 N/mm². This optimum was achieved under an activator-to-source material ratio of 60%, curing temperature of 100°C, KOH concentration of 18 M, and curing duration of 6 hours.

iv. ANOVA results show that all parameters significantly affect GPC strength development, achieving a high coefficient of determination ($R^2 = 0.9945$). The desirability function value of 0.99 indicates effective optimization, and a low prediction error of 1.74% confirms the model's accuracy and reliability\

V. RECOMMENDATION

The study investigates the geopolymerization using Response Surface Methodology (RSM), and the following recommendations are proposed:

i. Further research is essential to investigate industrial and agricultural waste as potential source materials and to assess their suitability and reactivity as binders in geopolymer concrete.

ii. Comprehensive studies are essential to establish clear relationships between the chemical composition, microstructural characteristics, and mechanical performance of GPC, thereby enabling optimized mix design and reliable performance prediction.

iii. The comprehensive adoption of GPC in major structural projects and infrastructures necessitates a thorough assessment of its long-term performance, cost-effectiveness, and standardization

REFERENCES

[1] H. Chen, M. L. Ling, B. Hencz, H. Y. Ling, G. Li, Z. Lin, and S. Zhang, "Exploring chemical, mechanical, and electrical functionalities of binders for advanced energy-storage devices," Chem. Rev., vol. 118, no. 18, pp. 8936–8982, 2018.

[2] F. Zou and A. Manthiram, "A review of the design of advanced binders for high-performance batteries," Adv. Energy Mater., vol. 10, no. 45, Art. no. 2002508, 2020.

[3] M. Mili, S. A. R. Hashmi, M. Ather, V. Hada, N. Markandeya, S. Kamble, and S. Verma, "Novel lignin as natural-biodegradable binder for various sectors: A review," J. Appl. Polym. Sci., vol. 139, no. 15, Art. no. 51951, 2022.

[4] Q. He, J. Ning, H. Chen, Z. Jiang, J. Wang, D. Chen, and W. Huang, "Achievements, challenges, and perspectives in the design of polymer binders for advanced lithium-ion batteries," Chem. Soc. Rev., vol. 53, no. 13, pp. 7091–7157, 2024.

[5] H. S. Rajan and P. Kathirvel, "Sustainable development of geopolymer binder using sodium silicate synthesized from agricultural waste," J. Cleaner Prod., vol. 286, Art. no. 124959, 2021.

[6] S. Alnezami, G. Lamaa, M. F. C. Pereira, R. Kurda, J. de Brito, and R. V. Silva, "A sustainable treatment method to use municipal solid waste incinerator bottom ash as cement replacement," Constr. Build. Mater., vol. 423, Art. no. 135855, 2024.

[7] S. Kumar and D. Singh, "Municipal solid waste incineration bottom ash: A competent raw material with new possibilities," Innov. Infrastruct. Solut., vol. 6, no. 4, Art. no. 201, 2021.

[8] M. N. Alderete, M. A. Joseph, P. Van den Heede, S. Matthys, and N. De Belie, "Effective and sustainable use of municipal solid waste incineration bottom ash in concrete regarding strength and durability," Resour. Conserv. Recycl., vol. 167, Art. no. 105356, 2021.

[9] P. Shen, H. Zheng, J. Lu, and C. S. Poon, "Utilization of municipal solid waste incineration bottom ash (IBA) aggregates in high-strength pervious concrete," Resour. Conserv. Recycl., vol. 174, Art. no. 105736, 2021.

[10] C. H. Wang, L. Fang, D. T. T. Chang, C. J. Hsu, and Y. T. Hu, "Evaluating the strength characteristics of mixtures of municipal solid waste incineration bottom ash and reddish laterite clay for sustainable construction," Heliyon, vol. 10, no. 18, 2024.

[11] M. Kasina, A. Telk, and M. Wendorff-Belon, "Comprehensive characterization and environmental implications of industrial and hazardous incineration ashes: Insights into chemistry, mineralogy, elements' fractionation and leaching potential," Sci. Rep., vol. 14, no. 1, Art. no. 29010, 2024.

[12] R. Kumar, A. Srivastava, and R. Lakhani, "Industrial wastes-cum-strength enhancing additives incorporated lightweight aggregate concrete (LWAC) for energy efficient building: A comprehensive review," Sustainability, vol. 14, no. 1, Art. no. 331, 2022.

[13] R. H. Myers, D. C. Montgomery, and C. M. Anderson-Cook, Response Surface Methodology: Process and Product Optimization Using Designed Experiments, 4th ed. Hoboken, NJ, USA: Wiley, 2016.

[14] S. G. K. M. Kumar, J. M. Kinuthia, J. Oti, and B. O. Adeleke, "Geopolymer chemistry and composition: A comprehensive review of synthesis, reaction mechanisms, and material properties oriented with sustainable construction," Materials, vol. 18, no. 16, Art. no. 3823, 2025.

[15] ASTM International, ASTM C136/C136M: Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates. West Conshohocken, PA, USA: ASTM International, 2014.

[16] British Standards Institution, BS 8500-2: Complementary British Standard to BS EN 206—Specification for Constituent Materials and Concrete. London, U.K.: British Standards Institution, 2023.

[17] ASTM International, ASTM C192/C192M: Standard Practice for Making and Curing Concrete Test Specimens. West Conshohocken, PA, USA: ASTM International, 2020.

[18] ASTM International, ASTM C39/C39M: Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50 mm] Cube Specimens). West Conshohocken, PA, USA: ASTM International, 2024.

[19] ASTM International, ASTM C618: Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. West Conshohocken, PA, USA: ASTM International, 2019.

[20] P. Tang, W. Chen, D. Xuan, Y. Zuo, and C. S. Poon, "Investigation of cementitious properties of different constituents in municipal solid waste incineration bottom ash as supplementary cementitious materials," J. Cleaner Prod., vol. 258, Art. no. 120675, 2020.

[21] ASTM International, ASTM C128: Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate. West Conshohocken, PA, USA: ASTM International, 2015.

[22] M. Mohammed, N. Shafiq, N. A. W. Abdallah, M. Ayoub, and A. Haruna, "A review on achieving sustainable construction waste management through application of 3R (reduction, reuse, recycling): A lifecycle approach," in IOP Conf. Ser.: Earth Environ. Sci., vol. 476, no. 1, Art. no. 012010, 2020.

[23] K. A. Buyondo, P. W. Olupot, J. B. Kirabira, and A. A. Yusuf, "Optimization of production parameters for rice husk ash-based geopolymer cement using response surface methodology," Case Stud. Constr. Mater., vol. 13, Art. no. e00461, 2020.

[24] Stat-Ease, Design-Expert 11 User's Guide: Response Surface Methods (RSM) Tutorials—Section 6. Minneapolis, MN, USA: Stat-Ease, 2023.

[25] S. Fang, E. S. S. Lam, B. Li, and B. Wu, "Effect of alkali contents, moduli and curing time on engineering properties of alkali activated slag," Constr. Build. Mater., vol. 249, Art. no. 118799, 2020.

[26] M. T. Ghafoor, Q. S. Khan, A. U. Qazi, M. N. Sheikh, and M. N. S. Hadi, "Influence of alkaline activators on the mechanical properties of fly ash based geopolymer concrete cured at ambient temperature," Constr. Build. Mater., vol. 273, Art. no. 121752, 2021.