Wiley
Discrete Dynamics in Nature and Society
Volume 2024, Article ID 6401595, 12 pages
https://doi.org/10.1155/2024/6401595

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Research Article

Enhancing Geopolymer Mix Optimization: Integration of the Plackett–Burman Method and Response Surface Methodology for Sustainable Construction Materials

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Received 26 December 2023; Revised 21 March 2024; Accepted 15 May 2024; Published 31 May 2024

Academic Editor: Rodica Luca

Nowadays, construction industries are using flyash as a potential alternative for cement. Due to its improved mechanical properties, ecofriendly nature, and low cost, geopolymer technology makes use of flyash as a promising future binder material. In this paper, 7 factors such as liquid-to-flyash ratio, silicate-to-hydroxide ratio, curing temperature, curing period, concentration of NaOH (molarity), rest period prior to curing, and dosage of superplasticizer that influence the compressive strength and temperature drop are screened using the Plackett–Burman method for optimization. Here, compressive strength and temperature drop are taken as the main indices of response to analyze the parameters. The significant variables determined from the Plackett–Burman design are further considered for the process of optimization using the response surface methodology. From the analysis, the optimum values of 0.4071 liquid-to-flyash ratio, 2.5 silicate-to-hydroxide ratio, and 6 hours curing period give maximum compressive strength and temperature drop of 28.87 MPa and 5.3°C under the optimized medium in the validation experiment which varies by only 3.93% and 1.85% from the observed value of 27.20 MPa and 5.4°C.

1. Introduction

Climate change, resource productivity, and industrial ecology are the three major sustainability issues which should be considered to meet the infrastructural needs. The global energy use is divided into several sectors such as building services, industry, transport, building construction, and others in which the energy consumed for building services was found to be at the highest rate of 45% as shown in Figure 1. Energy consumption may lead to a hazardous environment and hence it is very important to reduce the energy used by the buildings in order to provide safe surroundings.

Currently, our environment is under great pressure, as global cement industries are the ones that contribute to greenhouse gas emissions which is likely to increase the CO_2 emission into the atmosphere by about 37.15% in 2022 from the present to 50% in 2050 [1]. Among all greenhouse gases, about 65% of global warming is caused due to CO_2, and SO_3 and NO_x further cause the greenhouse effect and acid rain [2]. Geopolymer is an alternative technique which has a great potential to replace ordinary Portland cement in concrete. Geopolymerization is the process of formation of three-dimensional tetrahedral structures by the dissolution of solid aluminosilicate under a high alkalinity aqueous solution through the polymerization mechanism. Under high alkaline conditions, the dissolution of alumina and silica elements of aluminosilicate material occurs which releases AlO_4 and SiO_3 ions. Then, through a simultaneous process of polycondensation, gelation, and further condensation, an amorphous gel is formed, which possesses a strong capability to act as a binder [3].

Raw materials that are rich in silica and alumina, such as flyash, metakaolin, red mud, and ground granulated blast furnace slag are used to produce geopolymer. When the raw

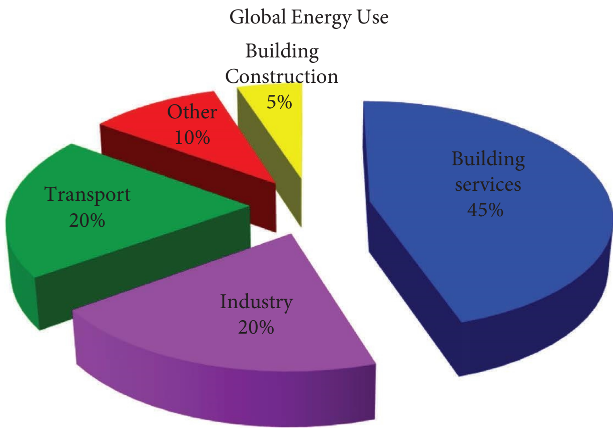


Figure 1: Global energy consumption [1].

material is mixed with sodium or potassium-based alkaline liquids, it reduces the embodied CO_2 up to 80% [4, 5]. In 1979, flyash-based geopolymer concrete was first introduced by Davidovits in which industrial flyash totally replaced cement in concrete [6]. Flyash, a waste of industrial byproduct that poses a serious problem of disposal and its usage in geopolymer leads to the development of sustainable concrete and its annual production is about 75–80% of the total ash production [7, 8]. High-quality geopolymer concrete of about 2.5 m^3 is produced using 1 tonne of low calcium flyash as there is a risk of a quick set while using high calcium flyash [9, 10]. Alkaline activators play an important role in the process of dissolution of Si and Al oxides [11]. Hence, for economical purposes, sodium-based silicate and hydroxide solutions are used along with flyash in order to achieve adequate strength through the geopolymerization process. As several factors such as flyash reactivity, liquid-to-flyash ratio, silicate-to-hydroxide ratio, dosage of superplasticizer, nature and concentration of activator solution, curing temperature, curing time, curing type, rest period, and handling time affect the strength parameter of geopolymer concrete to a great extent, till now there is no standard design procedure for preparing geopolymer concrete. The optimization process enables the efficient use of materials and energy without any wastage to obtain a proper design mix. Hence, the optimization process is carried out using the Plackett–Burman method and response surface methodology to determine the optimized mix ratio for geopolymer mortar.

Optimization of variables using classical methods involves the process of changing one independent variable by keeping all the other variables at a fixed level [12]. This method consumes more time and resources which also may give a result with increased error. Hence, it is important to adopt any optimization technique to reduce the time consumption and to obtain a good quality result. There are several optimization techniques available such as genetic algorithms, particle swarm optimization, ant colony optimization, and Taghuchi method. Here, Plackett–Burman Design and response surface methodology are the two simple methods adopted for screening and optimizing the variables [13, 14].

Plackett–Burman design is a fractional factorial design in which the main effects are calculated as the difference between the average of measurements made at a high level (+1) and low level (−1) of the factor [15, 16]. It is an efficient initial screening method to identify the active factors using a few experimental runs in the complex process [17]. It is used to identify the most important factors early in the experimentation phase when complete knowledge about the system is usually unavailable. The design has a complicated confounding relationship with two-factor interaction and it can be assumed that two-way interactions are negligible. In two-level multifactor experiments, when there are more than four factors, it is possible to economically detect large main effects without affecting the main indices. The screening process is also found to be quick. There is only very few work related to Plackett–Burman optimization design in geopolymer. Response surface methodology is an effective optimization tool to find the most significant factor that is responsible for the change in the whole system. Using response surface methodology, optimization is carried out for the development of self-compacting concrete using waste marble powder [18], mechanical properties in concrete reinforced with fibers from solid urban wastes (PET bottles) for the production of ecological concrete [19], concrete made with hybrid blends of crumb rubber and metakaolin [20], and for analysing the mix parameters of alkali-silica reactive concrete [21]. Further research has been carried out in the development of mix design and mechanical performance of alkali activated-slag concrete [22], cold bitumen emulsion mixtures [23], and concrete mixtures with hybrid blends of metakaolin and flyash [24]. However, up to now only few research studies have been performed in the development of mix design for geopolymer mortar.

Hence in this paper, the main focus is to optimize the 7 parameters such as liquid-to-flyash ratio, silicate-to-hydroxide ratio, curing temperature, curing period, concentration of NaOH (molarity), rest period prior to curing, and dosage of superplasticizer that affect the compressive strength and temperature drop of flyash-based geopolymer mortar to obtain a higher compressive strength and temperature drop. The significant variables that influence the strength of geopolymer are screened using the Plackett-Burman method and are further optimized using the response surface methodology.

2. Material and Methods

2.1. Material. Flyash is a fine residue generated from the combustion of coal. Here, class F-type flyash obtained from a coal-based thermal power plant located in Thoothukudi that satisfies the requirements of ASTM C618 is used as the source material for this research work [25, 26]. It contains substantial amounts of silicon dioxide (SiO_2) (both amorphous and crystalline), aluminium oxide (Al_2O_3), calcium oxide (CaO), and other elements in trace amounts which is shown in Table 1.

Locally available river sand that is sieved through a 4.75 mm sieve is preferred as fine aggregate and it falls under the grading zone III according to IS 383 [25, 27, 28].

Table 1: Oxide compositions of class F flyash using XRF [27].

Chemical	Component (wt%)
SiO_2	52.15
Al_2O_3	27.71
Fe_2O_3	5.09
CaO	0.51
MgO	1.01
TiO_2	3.94
K_2O	1.46
Na_2O	0.27
CuO	0.24
LOI	6.80
Total	99.18

As per the codal procedure, the specific gravity and water absorption of fine aggregate is obtained as 2.55 and 0.75% [29]. Sodium-based solutions such as sodium hydroxide pellets and sodium silicate gel prepared in solution form are used as alkaline liquids. Sodium hydroxide solution is prepared by dissolving the NaOH pellets in water to obtain the required molarity. NaOH solution with a concentration of 8 molar consists of $8 \times 40 = 320$ grams of NaOH solids per litre of the solution, where 40 is the molecular weight of NaOH. The mass of NaOH was measured as 262 grams per kg of NaOH solution with a concentration of 8 molar. Sodium silicate in gel form is thoroughly mixed with sodium hydroxide liquid one day prior to its addition in geopolymer mortar so that it can assist the polymerization process and reduce bleeding and segregation [30].

Generally in polymerization reactions, monomers are initially formed and further polymerization reactions are made faster to form a solid finished polymer as the final product. However, in geopolymerization, the process involves three steps that occur simultaneously to form a three-dimensional geopolymeric structure as shown in Figure 2.

(1) Dissolution of Si and Al atoms from the source material through the action of hydroxide ions.

(2) Then, the precursor ions are transported, oriented, and condensed into monomers.

(3) Finally, the polymerization of monomers into polymeric structures occurs as polymers are sensitive to heat, and it forms rigid chains of oxygen-bonded tetrahedral due to polycondensation.

2.2. Specimen Preparation. Dry materials such as flyash and sand are mixed thoroughly for about 4 minutes continuously. After 4 minutes, the previously mixed alkaline solution is added and the mixing process is further carried out for 3 minutes. At the end of the mixing process, this mix is separated into three equal quantities and filled as three layers in a 70.6 mm × 70.6 mm × 70.6 mm cube by giving adequate tamping for each layer using the tamping rod. Furthermore, the specimens are subjected to external vibration in order to remove the entrapped air from inside the mortar. After the completion of the vibration process, the specimens are covered with plastic sheets to avoid the evaporation of moisture. Then, the specimens are cured in a hot air oven, and after the completion of the required curing period, it is allowed to cool inside the oven itself and tested on the next day. The observed results are obtained by taking the average of three specimens which are considered to be the compressive strength of geopolymer mortar according to IS 456–2000 [31]. The temperature drop is practically determined using the infrared thermometer. In order to optimize the design, strength and temperature drop values are also predicted by adopting certain optimization techniques such as the Plackett–Burman method and the response surface method.

2.3. Optimization Techniques. Minitab 17 Statistical Software is used to design the geopolymer mix in order to optimize the variables that affect the strength and thermal properties. Here, Plackett–Burman design and response surface methodology are the two optimization techniques used for the process of screening and optimization and their methodology is shown in Figure 3.

2.3.1. Identifying the Significant Variables Using the Plackett–Burman Experimental Design. The Plackett–Burman design is the process of screening the design under the assumption that there is no interaction between the variables. Here, total 7 variables such as liquid-to-flyash ratio, silicate-to-hydroxide ratio, curing temperature, curing time, concentration of NaOH (molarity), rest period prior to curing, and dosage of superplasticizer mentioned as A, B, C, D, E, F, and G in the design that show greater influence on the strength and thermal are selected for the present study [32].

The variables and their range used for the design are shown in Table 2. The experimental design used for screening the 7 variables in 12 runs is shown in Table 3. Here, all the variables are given as numerical factors and are investigated at two widely spaced intervals such as −1 (low level) and +1 (high level).

2.3.2. Optimization of Significant Variables by Response Surface Methodology (RSM). In the response surface methodology, the optimum levels of significant values are obtained. Here, the central composite design (CCD) which is the most popular quadratic design used in response surface experiments is adopted [13]. Central composite designs are factorial or fractional factorial designs with centre points augmented with a group of axial points (also called star points) that led to estimate the curvature. It is used to study the effects of variables on their responses and subsequently in optimization studies [15]. The design adopted and the variables screened from the Plackett–Burman method and which is to be used for the response surface method is presented in Tables 4 and 5.

3. Results and Discussion

3.1. Screening of Variables Using the Plackett–Burman Design. The experiment using a two-level Plackett–Burman design of 12 runs with 7 different variables is introduced to screen the significant factor. The results obtained through the screening

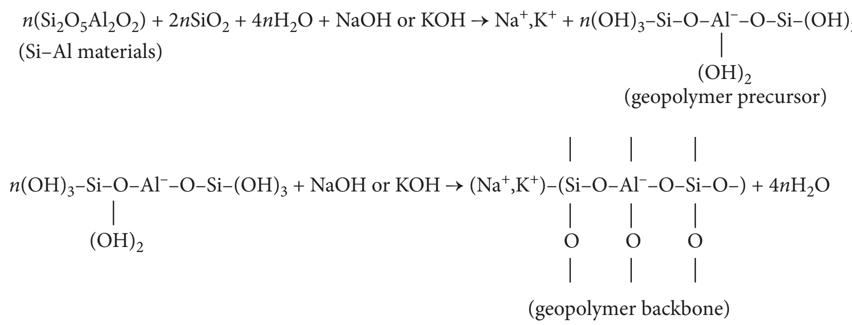


Figure 2: Formation of geopolymer [6].

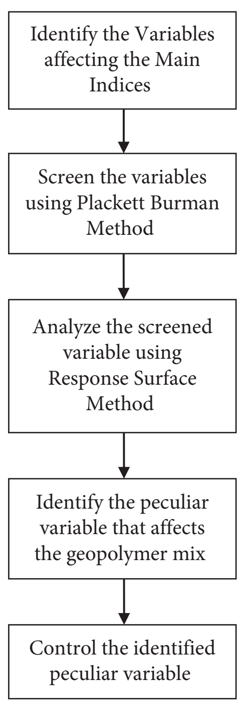


Figure 3: Optimization methodology.

process are shown in Table 6 with the observed and predicted value and it is found that there is only a slight variation of less than 5% difference between them, where DF is the degree of freedom, Adj SS is the adjusted sum of squares, Adj MS is the adjusted mean square, *F*-value is the significant difference among groups, *P* value shows whether the difference is real or random, and significant refers to whether the factor is important or not.

From Figures 4 and 5, the most significant variables that affect the compressive strength and temperature drop of geopolymer mortar are found to be A, D, and B as the effects of those variables extend beyond the reference line. The other variables such as E, G, C, and F are found to be not significant when compared to A, D, and B as their effect on compressive strength and temperature drop are only at a lower level. The critical value representing the statistically significant effect of factors at a 95% confidence level is 2.78. In Tables 7 and 8, the analysis of variance clearly shows that the model is statistically significant as the *F*-value is 65.97 and 79.36, while $P < \alpha$ where α is 0.05. Thus, the model with an R^2 value of 99.14% and 99.29% has been obtained.

3.2. Optimization Using Response Surface Methodology (RSM). As a second phase, the optimization is carried out for the significant variables using response surface methodology by maximizing the compressive strength and temperature drop of the geopolymer mortar and the result of observed and predicted values is presented in Table 9. As the *P* value is less than the α-value (i.e., 0.05), the model is found to be significant. The analysis of variance results is presented in Tables 10 and 11. It is concluded that A and D are the most significant variables that affect the strength and thermal property greatly and B is found to be not significant. The maximum strength (27.20 MPa) and temperature drop of (5.4°C) of geopolymer mortar are produced only when the constituents are set as follows: liquid-to-flyash ratio (0.39), curing period (6 hours), and silicate-to-hydroxide ratio (2.5).

Equations (1) and (2) are the second-order regression equation that represent the levels of strength and temperature drop as a function of liquid-to-flyash ratio, curing period, and silicate-to-hydroxide ratio.

$$\begin{aligned}\text{Compressive strength (MPa)} = {} & -58.52 + 394.3A - 1.449D + 8.66B - 526.1A * A + 0.05337D * D \\ & - 1.02B * B + 0.519A * D + 8.15A * B - 0.3099D * B,\end{aligned} \tag{1}$$

$$\begin{aligned}\text{Temperature drop (°C)} = {} & -2.34 + 53.76A - 0.6035D - 0.54B - 75.69A * A + 0.018486D * D \\ & - 0.104B * B + 0.0675A * D + 3.000A * B + 0.00295D * B,\end{aligned} \tag{2}$$

Table 2: Variables used for the Plackett–Burman design.

S.No	Variables code	Variables	Unit	Minimum value	Maximum value
1	A	Liquid-to-flyash ratio	—	0.3	0.5
2	B	Silicate-to-hydroxide ratio	—	1.5	2.5
3	C	Curing temperature	°C	80	100
4	D	Curing period	Hour	6	24
5	E	Concentration of NaOH	M	8	12
6	F	Rest period	Hour	24	48
7	G	Dosage of superplasticizer	%	1	2

Table 3: Experimental design for screening variables using the Plackett–Burman design for 7 variables.

Runs	A	B	C	D	E	F	G
1	−1	−1	+1	+1	+1	−1	+1
2	−1	+1	−1	−1	−1	+1	+1
3	−1	+1	+1	−1	+1	−1	−1
4	−1	−1	−1	−1	−1	−1	−1
5	−1	−1	−1	+1	+1	+1	−1
6	+1	+1	+1	−1	+1	+1	−1
7	+1	−1	+1	−1	−1	−1	+1
8	+1	+1	−1	+1	+1	−1	+1
9	+1	−1	−1	−1	+1	+1	+1
10	−1	+1	+1	+1	−1	+1	+1
11	+1	+1	−1	+1	−1	−1	−1
12	+1	−1	+1	+1	−1	+1	−1

Table 4: Experimental design for response surface methodology.

Runs	A	D	B
1	−1	+1	−1
2	0	−1	0
3	0	0	0
4	+1	−1	−1
5	0	0	−1
6	0	−1	−1
7	−1	−1	−1
8	0	+1	0
9	0	−1	+1
10	0	+1	+1
11	−1	+1	+1
12	+1	+1	+1
13	0	+1	−1
14	+1	−1	+1
15	0	0	+1
16	+1	0	0
17	−1	0	0
18	−1	−1	+1
19	−1	−1	0
20	+1	+1	−1

Table 5: Variable for response surface methodology.

S.No	Variables code	Variables	Unit	−1	0	+1
1	A	Liquid-to-flyash ratio	—	0.3	0.4	0.5
2	B	Silicate-to-hydroxide ratio	—	1.5	2.0	2.5
3	D	Curing period	Hour	6	12	24

Table 6: Observed and predicted response using the Plackett–Burman design.

Runs	Compressive strength (MPa)		Temperature drop (°C)	
	Observed	Predicted	Observed	Predicted
1	13.32	13.53	1.70	1.75
2	20.13	20.29	3.20	3.20
3	21.45	21.01	2.80	2.83
4	16.56	16.28	2.70	2.65
5	12.34	12.84	1.90	1.87
6	26.50	26.94	3.90	3.87
7	22.39	22.90	3.60	3.57
8	23.36	23.03	3.30	3.20
9	23.64	23.24	3.60	3.68
10	16.67	16.50	2.30	2.30
11	21.67	22.00	3.10	3.20
12	18.98	18.42	2.80	2.78

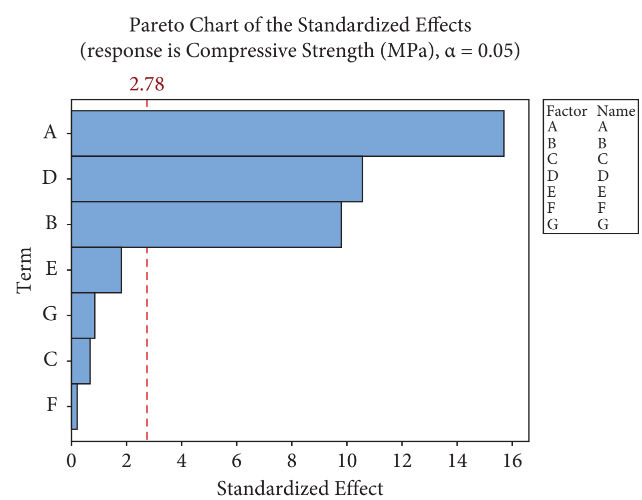


Figure 4: Pareto chart showing the effect of variables on compressive strength (A: liquid-to-flyash ratio, D: curing period, and B: silicate-to-hydroxide ratio).

where A is the liquid-to-flyash ratio, D is the curing period (hour), and B is the silicate-to-hydroxide ratio.

Within the experimental range, the interdependence of liquid-to-flyash ratio and curing period is predicted using the contour plot and is shown in Figures 6 and 7. A contour plot is like a topographical map in which values are plotted instead of longitude, latitude, and elevation. The shape of the contour plot indicates the interaction between the most

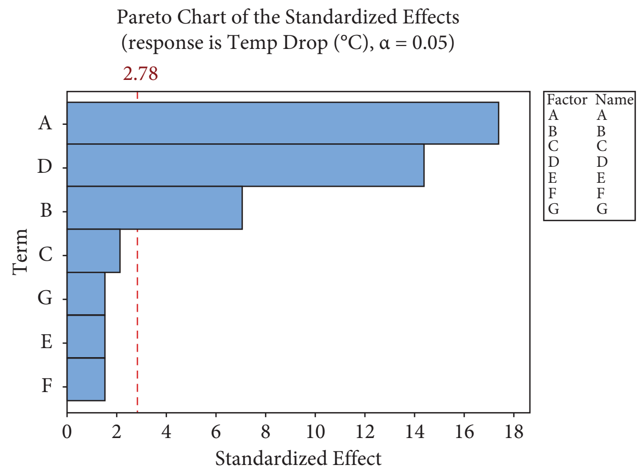


Figure 5: Pareto chart showing the effect of variables on temperature drop (A: liquid-to-flyash ratio, D: curing period, and B: silicate-to-hydroxide ratio).

Table 7: Analysis of variance of the Plackett–Burman design for compressive strength.

Source	DF	Adj SS	Adj MS	*F* value	*P* value	Significant
Model	7	202.174	28.882	65.970	0.001	Yes
Linear	7	202.174	28.882	65.970	0.001	Yes
A	1	108.420	108.420	247.660	≤0.001	Yes
B	1	42.375	42.375	96.800	0.001	Yes
C	1	0.216	0.216	0.490	0.521	No
D	1	49.329	49.329	112.680	≤0.001	Yes
E	1	1.477	1.477	3.370	0.140	No
F	1	0.020	0.020	0.050	0.841	No
G	1	0.337	0.337	0.770	0.430	No
Error	4	1.751	0.438	—	—	—
Total	11	203.925	—	—	—	—

Table 8: Analysis of variance of the Plackett–Burman design for temperature drop.

Source	DF	Adj SS	Adj MS	*F* value	*P* value	Significant
Model	7	5.09250	0.72750	79.36	≤0.001	Yes
Linear	7	5.09250	0.72750	79.36	≤0.001	Yes
A	1	2.70750	2.70750	295.36	≤0.001	Yes
B	1	0.44083	0.44083	48.09	0.002	Yes
C	1	0.04083	0.04083	4.45	0.102	No
D	1	1.84083	1.84083	200.82	≤0.001	Yes
E	1	0.02083	0.02083	2.27	0.206	No
F	1	0.02083	0.02083	2.27	0.206	No
G	1	0.02083	0.02083	2.27	0.206	No
Error	4	0.03667	0.00917	—	—	—
Total	11	5.12917	—	—	—	—

significant variables and the potential relationship between the two variables. The following plot shows how the liquid-to-flyash ratio (x) and curing period (y) affect the compressive strength (contours) of geopolymer mortar. The A and D variables are plotted on the x and y scales and the response values are represented by contours. There are clear peaks which indicate that the maximum strength is obtained

Table 9: Observed and predicted response using the response surface method.

Runs	Compressive strength (MPa)		Temperature drop (°C)	
	Observed	Predicted	Observed	Predicted
1	15.16	15.34	4.00	4.03
2	25.94	25.55	5.00	5.20
3	20.39	20.15	3.80	3.77
4	15.84	15.93	4.20	4.10
5	17.96	17.83	3.50	3.60
6	22.67	22.31	5.00	5.04
7	17.76	18.17	4.50	4.48
8	20.83	20.87	4.90	4.91
9	27.20	28.28	5.40	5.30
10	20.01	20.81	5.10	5.04
11	15.16	14.92	4.00	4.05
12	16.78	16.19	4.50	4.51
13	21.14	20.42	4.90	4.72
14	23.01	22.71	4.60	4.66
15	22.06	21.95	3.90	3.89
16	14.21	14.49	3.10	3.01
17	15.10	15.29	3.00	3.01
18	23.99	23.32	4.40	4.43
19	20.89	21.00	4.60	4.48
20	14.46	14.97	3.80	3.90

Table 10: Analysis of variance result of RSM for compressive strength.

Source	DF	Adj SS	Adj MS	*F* value	*P* value	Significant
Model	9	289.642	32.182	75.870	≤0.001	Yes
Linear	3	116.468	38.823	91.530	≤0.001	Yes
A	1	100.410	100.410	236.730	≤0.001	Yes
D	1	22.913	22.913	54.020	≤0.001	Yes
B	1	0.901	0.901	2.120	0.176	No
Square	3	158.644	52.881	124.670	≤0.001	Yes
A ∗ A	1	131.835	131.835	310.820	≤0.001	Yes
A ∗ B	1	45.298	45.298	106.800	≤0.001	Yes
D ∗ B	1	0.225	0.225	0.530	0.483	No
2-Way interaction	3	26.944	8.981	21.170	≤0.001	Yes
A ∗ A	1	1.906	1.906	4.490	0.060	No
A ∗ B	1	1.328	1.328	3.130	0.107	No
D ∗ B	1	23.710	23.710	55.900	≤0.001	Yes
Error	10	4.242	0.424	—	—	—
Total	19	293.884	—	—	—	—

only when A is around (0.40, 6 hours), (0.40, 24 hours). The maximum drop in temperature is obtained when A is by considering the energy consumption, 0.40 with 6 hours curing periods is selected.

Surface plots are diagrams that display the three-dimensional data, rather than showing the individual data points, and they show a functional relationship between a designated dependent variable (Y) and two independent variables (X and Z). It is useful for establishing response values and operating conditions the same as contour but in 3D view and it can provide a clearer concept of the response surface than contour plots. The plot is a companion plot to

Table 11: Analysis of variance result of RSM for temperature drop.

Source	DF	Adj SS	Adj MS	*F* value	*P* value	Significant
Model	9	8.28936	0.92104	61.97	≤0.001	Yes
Linear	3	5.68170	1.89390	127.42	≤0.001	Yes
A	1	1.86618	1.86618	125.55	≤0.001	Yes
D	1	3.97552	3.97552	267.47	≤0.001	Yes
B	1	0.00351	0.00351	0.24	0.638	No
Square	3	7.73863	2.57954	173.55	≤0.001	Yes
A * A	1	2.72877	2.72877	183.59	≤0.001	Yes
D * D	1	5.43439	5.43439	365.62	≤0.001	Yes
B * B	1	0.00235	0.00235	0.16	0.699	No
2-Way interaction	3	0.21441	0.07147	4.81	0.025	Yes
A * D	1	0.03226	0.03226	2.17	0.171	No
A * B	1	0.18000	0.18000	12.11	0.006	Yes
D * B	1	0.00215	0.00215	0.14	0.712	No
Error	10	0.14864	0.01486	—	—	—
Total	19	8.43800	—	—	—	—

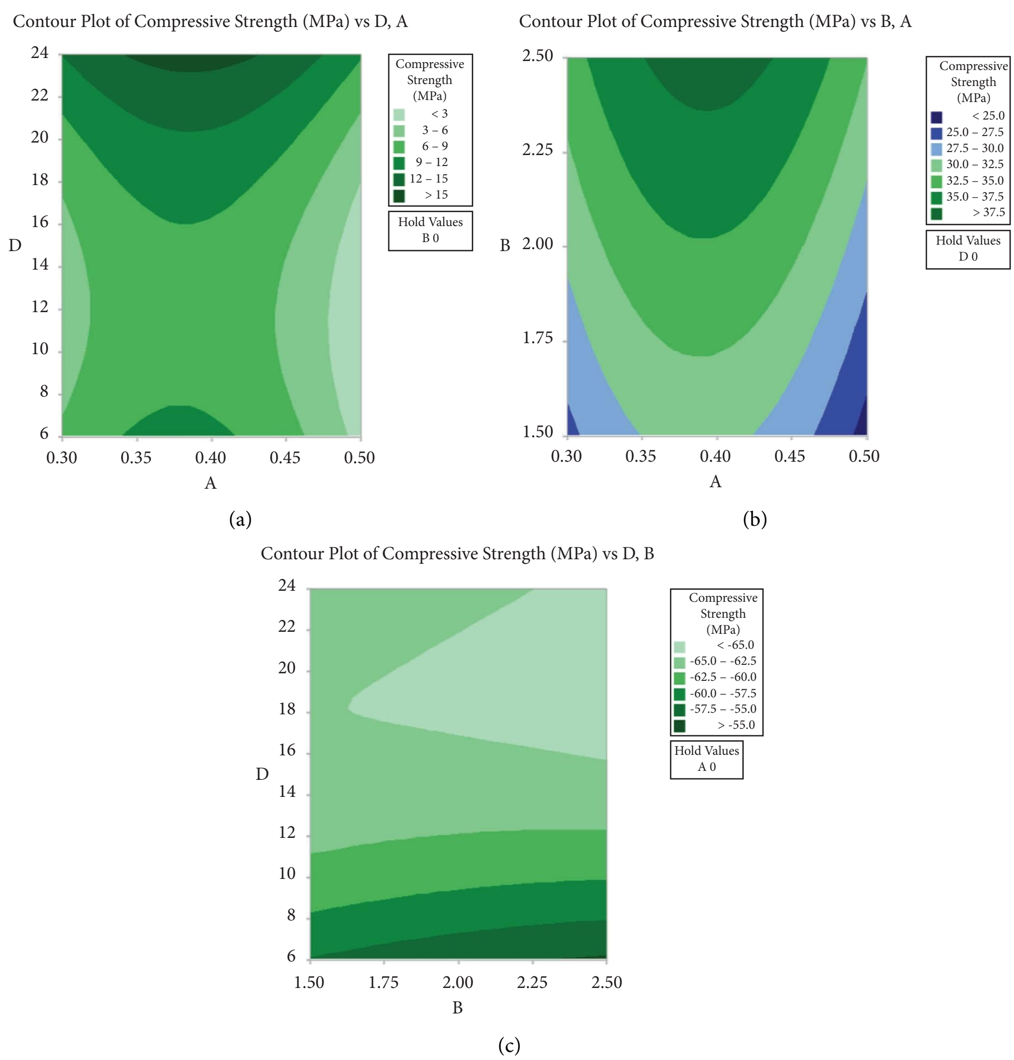
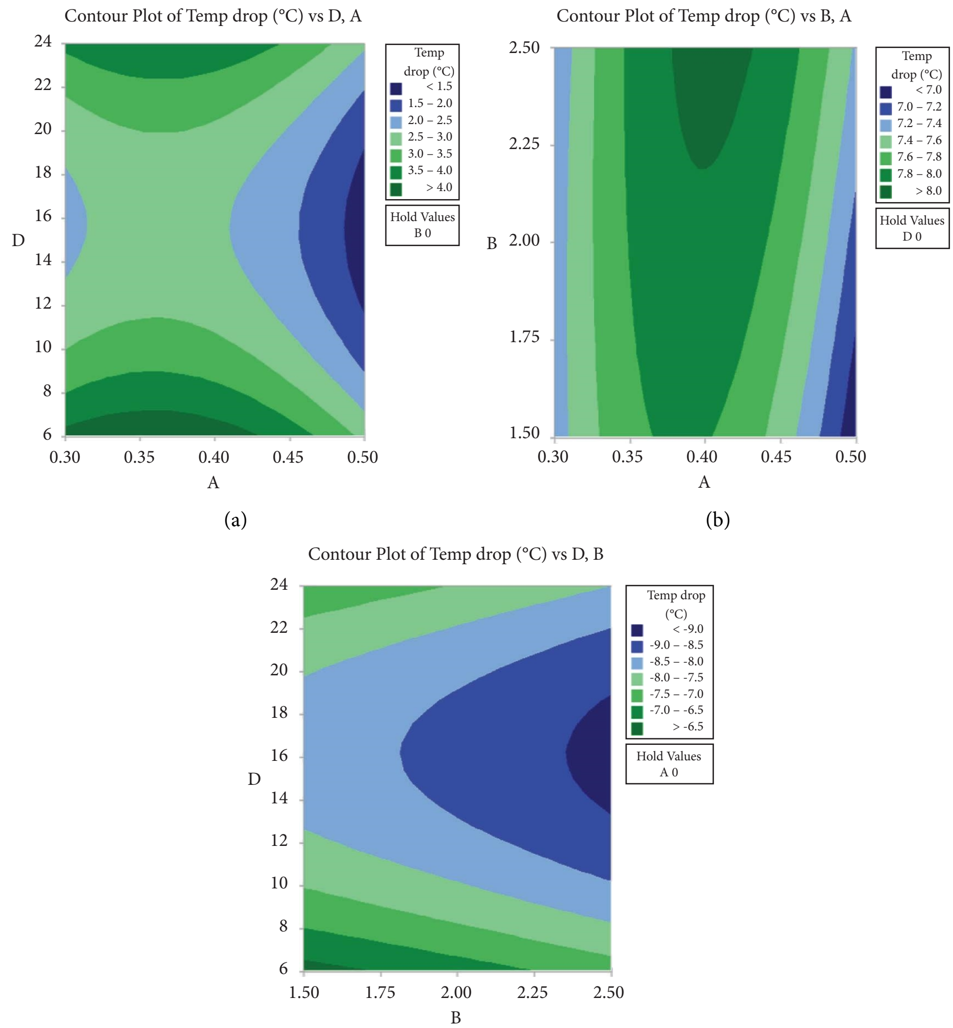
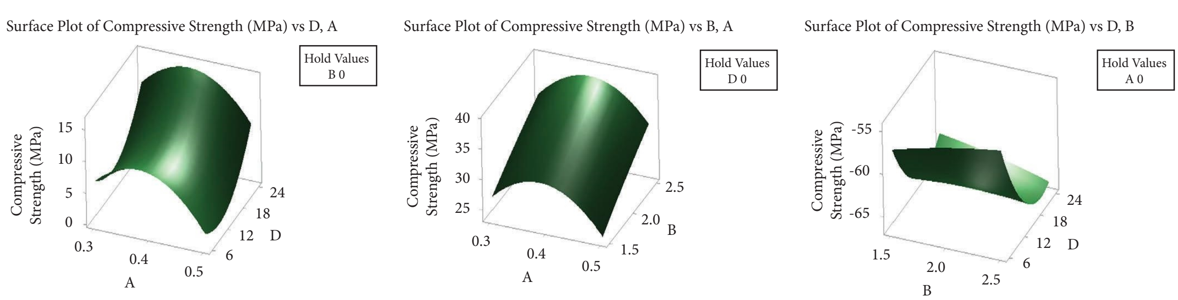


Figure 6: Contour plot between variables (a) A and D, (b) A and B, and (c) B and D on compressive strength.



(c)

Figure 7: Contour plot between variables (a) A and D, (b) A and B, and (c) B and D on temperature drop.



(a) (b) (c)

Figure 8: Surface plot between variables (a) A and D, (b) A and B, and (c) B and D on compressive strength.

the contour plot. In Figures 8 and 9, there is a rise in the strength at 0.4 liquid-to-flyash ratio from 6 hours curing till 24 hours, beyond that there is a decrease in strength. On the basis of energy consumption into account, 6 hours curing period is taken as the optimum value.

Figures 10 and 11 show the main effects plot for the compressive strength and temperature drop of geopolymer mortar with respect to B. Here, there is a rise in the strength value up to 2.5, and the larger value is always better and hence the silicate-to-hydroxide ratio can be fixed as 2.5. A

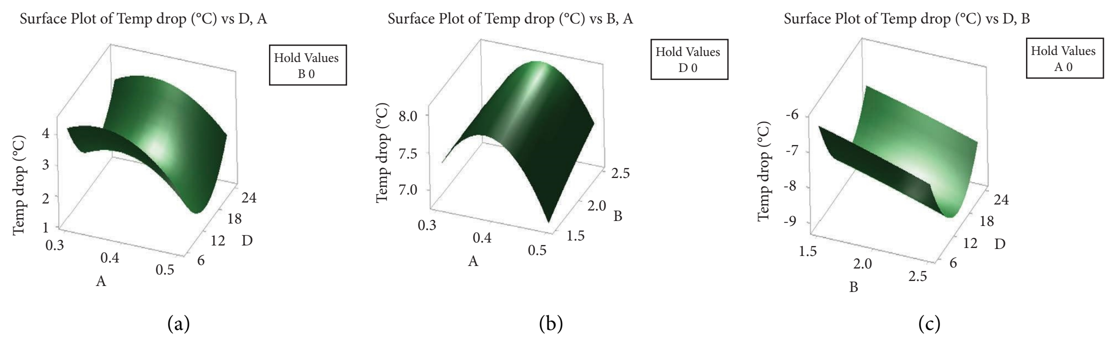


Figure 9: Surface plot between variables (a) A and D, (b) A and B, and (c) B and D on temperature drop.

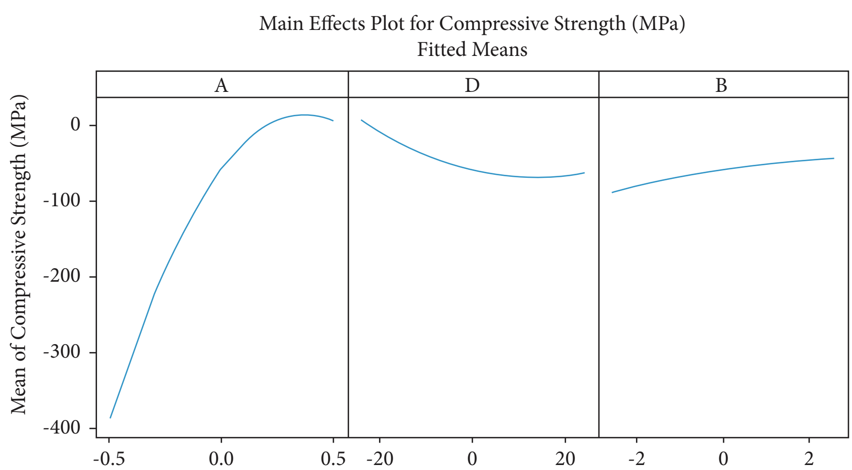


Figure 10: Main effects plot for compressive strength.

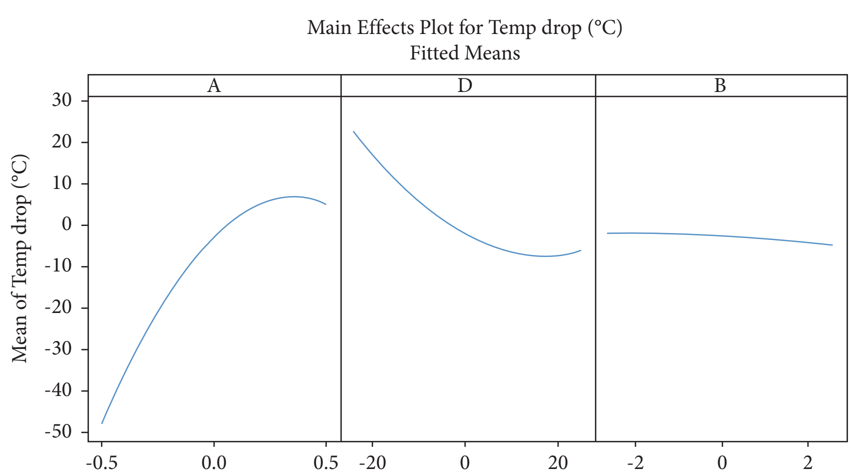


Figure 11: Main effects plot for temperature drop.

main effects plot is used in conjunction with ANOVA and DOE to examine differences among level means for one or more factors. It connects the response means for each factor level, which are connected by a line.

From Figure 12, the optimized value of compressive strength and temperature drop has been obtained as 28.23 MPa and 5.3°C with the desirability of 1 and 0.96, when the variables are set as 0.4071 liquid-to-flyash ratio, with 6 hours of curing period and 2.5 silicate-to hydroxide ratio. The desirability function was selected to find the suitable values for the factors. The observed value through experimentation is found to be 27.20 MPa and 5.4°C at 0.4 liquid-to-flyash ratios, with 6 hours of curing period and 2.5 silicate-to-hydroxide ratios. The variation in the result between

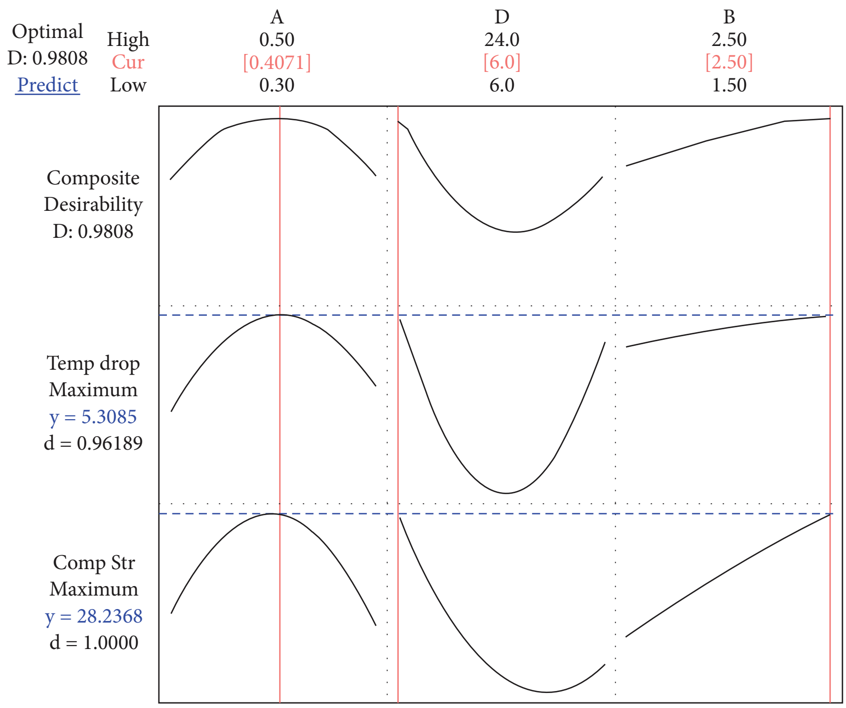


FIGURE 12: Optimization plot.

the observed and optimized value is almost 3.93% and 1.85%, which is less than 5% that makes the optimization process effective in applying.

4. Conclusion

As there is no standard mix design procedure for geopolymer, it is important to optimize various factors such as liquid-to-flyash ratio, silicate-to-hydroxide ratio, curing temperature, curing period, concentration of NaOH (molarity), rest period, and dosage of superplasticizer which have a great influence on the compressive strength of flyash-based geopolymer mortar. The present study involves in screening the seven variables in 12 runs using the Plackett–Burman design and then optimizing the obtained significant variables in 20 runs using central composite design in response surface methodology. From the analysis, the following conclusions can be drawn:

(1) Among the seven variables, only three variables such as liquid-to-flyash ratio (A), curing period (D), and silicate-to-hydroxide ratio (B) are identified as significant using the Pareto chart in Plackett–Burman design as they influence the compressive strength property to a great extent.

(2) From the analysis, the observed and predicted value is found to have only a slight variation of less than 5% in its value.

(3) The ANOVA table of Plackett–Burman designs shows that the model is significant as the P value < 0.05 and also the variables A, D, and B are found to be significant.

(4) These three significant variables are further optimized using the response surface methodology and it is concluded that liquid-to-flyash ratio and curing period are the most significant variable and silicate-to-hydroxide ratio is not significant.

(5) Among the three, the curing period plays a significant role as per sensitivity analysis. As its variation is from 6 to 24 hours even in optimistic, pessimistic, and most likely time depictions, only the curing period shows variation at a great extent which has to be controlled further in the process.

(6) The observed and predicted results using RSM are found to be significantly similar. There is a high similarity in the observed and predicted results, which shows the accuracy and applicability of RSM to optimize the geopolymer process.

(7) The contour and surface plot depict the interaction between the variables where there is an increase in compressive strength at 0.4 liquid-to-flyash ratios from 6 hours curing till 24 hours, further it tends to decrease. In order to reduce the energy consumption, 6 hours curing period is taken as the optimum value.

(8) The optimized value of maximum compressive strength (28.289 MPa) of geopolymer mortar is produced only when the constituents are set as follows: liquid-to-flyash ratio (0.397), curing period (6 hours), and silicate-to-hydroxide ratio (2.5), which varies only by 3.85% from the observed value of 27.20 MPa with the desirability of 1.

(9) There are also some drawbacks while using Plackett–Burman designs that practitioners should be

aware of: they do not verify if the effect of one factor depends on another factor. If you run the smallest design you can, it does not follow that enough data have been collected to know what those effects are precisely. However, in this research work to balance the demerit of the Plackett–Burman method, the response surface method is used.

The process of applying the statistical experimental design method to optimize the mix design of geopolymer mortar by maximizing the strength value is found to be an efficient method to find the interaction among different variables in a reduced number of experiments. The Plackett–Burman method and the response surface method are found to be adequate methods to design and optimize the geopolymer mortar. Furthermore, the changing climatic condition affects the strength development in geopolymer mortar. In the future, it is suggested to carry out some research works regarding the strength development under various climatic conditions to make the mix design a standardized one.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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