

A multi-response optimization of ternary geopolymer mortar using Taguchi–GRA integrated method

Surya Teja Chinnala ^a, Sai Kumar Vindula ^{*,b}

Department of Civil Engineering, GITAM School of Core Engineering, GITAM Deemed to be University, Visakhapatnam - 530045, India

Article Info	Abstract
Article History: Received 27 Dec 2025 Accepted 17 Feb 2026 Keywords: Red mud; Geopolymer mortar; Compressive strength; Taguchi-GRA integrated method	This research addresses a critical gap in sustainable binder development by integrating experimental optimization and multi-response analysis to assess the performance of ternary Red Mud–Ground Granulated Blast Furnace Slag–Metakaolin (RM–GGBS–MK) geopolymer mortars. Although geopolymers are recognized for their potential to reduce cement consumption and CO₂ emissions, limited studies have systematically optimized ternary waste-based binders considering both fresh and hardened properties. In this study, a hybrid Taguchi–Grey Relational Analysis (GRA) framework was employed to simultaneously optimize the compressive strength, flowability, and setting times of geopolymer mortar mixes under three criteria: balanced performance, strength, and workability. The experimental design followed an L16 orthogonal array comprising five parameters—ternary composition, NaOH molarity, activator-to-binder (AL/B) ratio, Na₂SiO₃/NaOH (SS/SH) ratio, and binder-to-sand (B/S) ratio—each at four levels. The GGBS-rich mixes attained the maximum compressive strength of 49.09 MPa at 28 days, whereas the RM and MK dominant mixes demonstrated diminished strengths comparatively. ANOVA results indicated the most significant factors affecting the strength and flowability as SS/SH and Al/B ratios, whereas the binder compositions regulated initial and final setting times. Across all three criteria, GRA identified 14 M NaOH and a 1:1.5 B/S ratio as common significant parameters.

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1. Introduction

Cement production contributes to around 8% of worldwide CO₂ emissions[1]. This global challenge has prompted research into alternative binders that can diminish the carbon footprint of cement production. By utilizing industrial wastes, geopolymers have emerged as sustainable replacements[2]. Aluminosilicate-rich industrial by-products are activated with alkaline solutions to form geopolymers[3]. Compared with ordinary Portland cement (OPC), these materials exhibit enhanced physical and mechanical performance.

Red Mud (RM), an alkaline by-product of the Bayer process used in alumina production, is generated in substantial amounts globally and poses significant environmental disposal challenges [4]. In India, the annual generation of red mud is approximately 9 to 12 million metric tons [5]. RM contains high levels of Fe₂O₃ and Al₂O₃, while showing a lower concentration of reactive SiO₂, thereby limiting its geopolymer reactivity. [6] When used alone as a binder, RM often requires thermal curing and shows minimal early strength development. RM stored in landfills may pose environmental risks due to high alkalinity, which can lead to soil and water contamination [7].

*Corresponding author: svindula@gitam.edu

^aorcid.org/0000-0001-5597-4740; ^borcid.org/0000-0002-1301-4378

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Ground Granulated Blast Furnace Slag (GGBS) is an industrial by-product produced from blast furnaces utilized in iron manufacturing. This material is abundant in aluminosilicates and CaO, rendering it an appropriate source for geopolymer binders. It improves geopolymer characteristics by accelerating strength attainment and diminishing the necessity for thermal curing [8,9]. The annual production of GGBS in India is estimated at approximately 15 million tons[10]. Although majority of GGBS is used as supplementary cementitious material, unused GGBS creates significant pollution in the form of airborne particulate matter.

Proportions of oxides such as SiO₂, Al₂O₃, Fe₂O₃ and CaO strongly influence the performance of geopolymer binders [11]. Industrial by-products like RM and GGBS vary in chemical compositions, and their combined use may not always provide sufficient reactive silica and alumina for optimal geopolymerization. Metakaolin (MK), a highly reactive aluminosilicate obtained by calcining kaolinite clay at elevated temperatures, is incorporated to supplement these oxides. By enhancing reactive Si and Al, MK promotes the development of stronger and more durable geopolymer matrix[12,13].

Geopolymer mortar properties are affected by multiple factors such as molarity of the NaOH, alkaline activator to binder (Al/B) ratio, binder to aggregate proportions, and curing conditions [14]. Binary mixes comprising RM-GGBS and RM-MK have been studied previously in the literature. RM-GGBS blends benefit from calcium-induced strength gain and reduced curing temperature but can suffer from quick setting times and workability when RM content is high[15]. RM-MK blends improve the Si and Al content but lack calcium for rapid early strength [16]. Wang et.al[17] had demonstrated that mixtures containing 60–70% GGBS, with Red Mud as a secondary component, attained compressive strengths greater than 45 MPa, with enhanced thermal resistance and matrix densification. The use of Metakaolin at 60%, in conjunction with RM, has demonstrated a significant improvement in long-term strength and microstructural integrity[18,19]. In addition to these findings, RM-rich blends consisting of 60% Red Mud and 40% GGBS exhibited compressive strengths between 30 and 38 MPa [20,21]. Nevertheless, few studies have been done on the combined impact of all the three binders. The ternary mix presents a promising option for a sustainable substitute for cement [22].

The Taguchi approach along with Grey Relational Analysis (GRA), has been utilized to efficiently study and optimize multiple parameters in geopolymer systems, including strength, setting time, and workability [23,24]. Orthogonal arrays (OA) are employed in Taguchi method to identify critical factors and minimize the number of experimental trials[25–27]. The GRA enhances the Taguchi approach by facilitating multi-response optimization, aiding in the identification of parameter combinations that balance fresh state and hardened state properties [28]. The GRA consolidates various performance attributes into a singular Grey Relational Grade, hence easing the optimization procedure[29,30]. It facilitates the identification of optimal factor levels by ranking the Grey Relational Grades, consequently revealing the parameter configurations that yield superior overall performance.

This study investigates the influence of mix parameters on the performance characteristics of RM-GGBS-MK geopolymer mortar. The factors considered include the sodium silicate to sodium hydroxide (SS/SH) ratio, NaOH molarity, Al/B ratio, and binder to sand ratio, with the ternary mix composition (different proportions of binders) included as one of the factors due to its influence on aluminosilicate availability and geopolymerization. Taguchi design of experiments combined with GRA was employed to determine optimal parameter combinations under ambient curing conditions for multi-response optimization under three different optimization objectives corresponding to strength, workability, and balanced overall performance.

2. Materials

RM was obtained from NALCO, Damanjodi, Odisha. RM is predominantly composed of Fe₂O₃ and Al₂O₃ and has a characteristic red color. It was oven-dried at 80°C for a minimum of 24 hours to remove moisture, and the dried lumps were grounded and sieved through a 75-micron sieve. GGBS was sourced from Visakhapatnam. It is rich in calcium silicates and acts as a significant source of CaO, and has a greyish-white color. MK was sourced from Mumbai, India. It is a highly reactive

aluminosilicate material with good pozzolanic properties. It has an off-white colour. The chemical compositions of RM, GGBS and MK as determined by X-ray fluorescence (XRF) analysis are presented in Table 1, while their particle size distribution and XRD details are presented in Figure 1. XRD pattern of MK exhibits a large diffuse hump alongside identifiable crystalline peaks primarily attributed to quartz (Q). RM sample displays distinct diffraction peaks corresponding to gibbsite (G) and hematite (H) as the primary crystalline phases, alongside modest reflections of quartz (Q) and weak carbonate (C). The XRD pattern of GGBS is characterized by a large amorphous halo, usually found in the 2θ range of about $20\text{--}35^\circ$, indicating the prevalence of glassy amorphous phases in the slag.

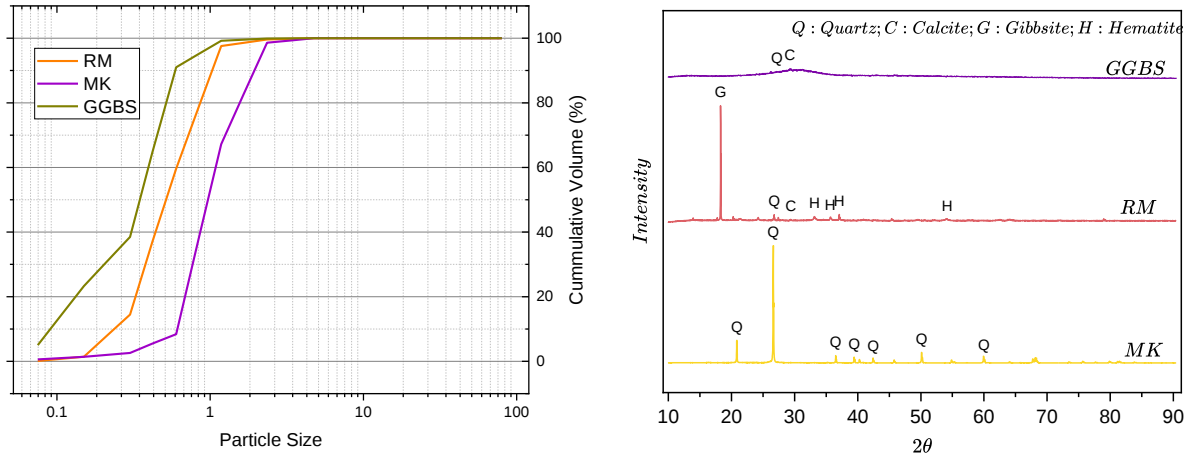


Fig. 1. Particle size distribution and XRD of the binder materials

Commercially available sodium silicate and sodium hydroxide solutions were used as alkaline activators in this study. SS/SH ratio was considered as a variable affecting the geopolymer mortar properties. Sodium hydroxide (NaOH) pellets with 99% purity were dissolved in water for 24 hours, prior to casting. Sodium silicate solution comprised of 26.5 wt% SiO_2 and 8.0 wt% Na_2O . River sand conforming to Grade 2 as per IS:383 [31] was used as fine aggregate. Binder-to-sand ratio was considered as one of the experimental factors, due to its influence on the strength of mortar.

Table 1. Chemical compositions of binder materials

Materials	Al_2O_3	CaO	SiO_2	MgO	Na_2O	K_2O	Fe_2O_3	TiO_2
RM	15.03	1.5	7.85	2.14	4.65	2.59	49.18	4.5
GGBS	10.39	38.12	32.41	8.96	0.35	0.5	0.69	1.23
MK	41.41	0.08	52.22	0.26	0.01	1.73	0.49	0.65

3. Methodology

The methodology employed for single response optimization utilizing Taguchi and multi-response optimization employing GRA is illustrated in Figure 2. In this study, five key factors influencing geopolymerization were selected based on prior literature and preliminary trials. The factors considered include the ternary mix proportions of RM, GGBS, and MK at specified ratios; NaOH at 8, 10, 12 and 14 molarity, Al/B ratio between 0.45 and 0.60, SS/SH ratio from 1.0 to 2.5 and B/S ratio from 1:1.5 to 1:3. Each parameter was chosen based on its impact on the geopolymerization process. The ternary blend ratio and B/S ratio regulates the proportions of reactive alumina, silica and calcium, whereas the molarity of NaOH influences precursor dissolution through the provision of OH^- and Na^+ ions[32–34]. The Al/B ratio ensures an adequate amount of activator in relation to the binder, while the SS/SH ratio controls the availability of soluble silica for polycondensation [22,32].

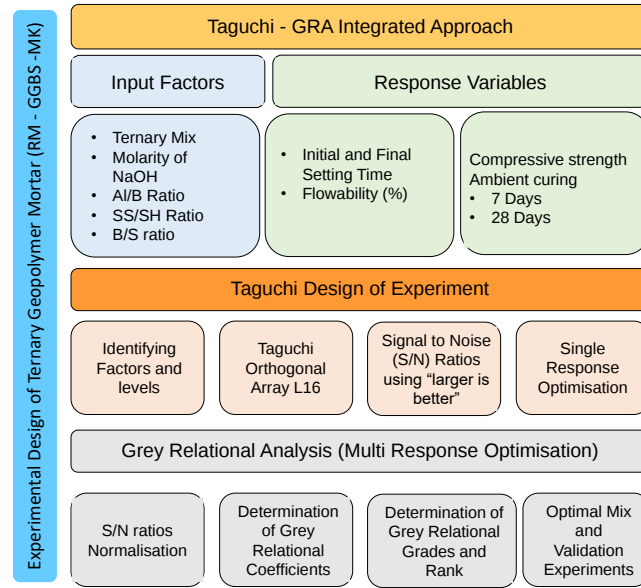


Fig. 2. Flowchart for optimisation methodology

The integrated Taguchi-GRA method is utilized to optimize various performance parameters of ternary RM-GGBS-MK geopolymer mortar. An L16 Taguchi OA is employed to investigate the main factor effects on geopolymer mortar properties. The full factorial design requires 1024 experimental combinations (4^5), making the process expensive and time-consuming. The Taguchi method enables systematic evaluation of multiple variables with a reduced number of trials through orthogonal arrays, whereas GRA facilitates multi-response optimization by consolidating different performance attributes into a single comparative index. Factors considered and the corresponding four levels are shown in Table 2. The factor assignments are presented in Table 3.

Table 2. Factors and levels for Taguchi method

Parameters	Level 1	Level 2	Level 3	Level 4
Ternary Mix	A1-20G60M20	A2-20G20M60	A3-60G20M20	A4-33G33M33
NaOH Molarity	8	10	12	14
AL/B Ratio	0.6	0.55	0.5	0.45
SS/SH Ratio	2.5	2	1.5	1.0
B/S Ratio	1:3	1:2.5	1:2	1:1.5

The Taguchi method evaluates robustness through signal-to-noise (S/N) ratios, which can be determined on the basis of "larger-the-better," "smaller-the-better," or "nominal-the-best" [36]. Since extended setting time, increased compressive strength and higher workability are targeted, the larger-the-better formulation was used for all responses as shown

$$y_{pq} = -10 \times \log_{10} \left[\frac{1}{n} \sum \frac{1}{v_{pi}^2} \right] \quad (1)$$

where, v_{pi} is the response of p^{th} trial mix for the i^{th} response and n is the number of observations, y_{pq} denotes the experiment's signal/noise ratio.

ANOVA was performed on S/N ratios to enumerate the effect of each factor. As the OA, had zero degrees of freedom. Hence, factor contributions were considered as the percentage of the sum of squares [37].

Table 3. Mix compositions and factor levels

Mix	Ternary Mix	NaOH Molarity	AL/B Ratio	SS/SH Ratio	B/S Ratio
M1	R20G60M20	8	0.6	2.5	1:3
M2	R20G60M20	10	0.55	2	1:2.5
M3	R20G60M20	12	0.5	1.5	1:2
M4	R20G60M20	14	0.45	1	1:1.5
M5	R20G20M60	8	0.55	1.5	1:1.5
M6	R20G20M60	10	0.6	1	1:2
M7	R20G20M60	12	0.45	2.5	1:2.5
M8	R20G20M60	14	0.5	2	1:3
M9	R60G20M20	8	0.5	1	1:2.5
M10	R60G20M20	10	0.45	1.5	1:3
M11	R60G20M20	12	0.6	2	1:1.5
M12	R60G20M20	14	0.55	2.5	1:2
M13	R33G33M33	8	0.45	2	1:2
M14	R33G33M33	10	0.5	2.5	1:1.5
M15	R33G33M33	12	0.55	1	1:3
M16	R33G33M33	14	0.6	1.5	1:2.5

The following equation was used to normalize the signal-to-noise ratio for each result;

$$Z_{pq} = \frac{y_{pq} - \min(y_{pq})}{\max(y_{pq}) - \min(y_{pq})}; p = 1, 2, \dots, r; q = 1, 2, \dots, n \quad (2)$$

Grey Relational Coefficient (GRC) was calculated using the following equation;

$$GRC_{opq} = \frac{\Delta_{min} + \zeta \Delta_{max}}{\Delta_{opq} + \zeta \Delta_{max}} \quad (3)$$

Δ_{opq} represents the discrepancy between the ideal and actual values of the normalized signal-to-noise ratio. The variable ζ denotes the identification or distinguishing coefficient, which ranges from 0 to 1, typically set at 0.5. [32]. Grey Relational Grade (GRG) was determined using;

$$GRG_{opq} = \frac{1}{n} \sum_{n=1}^m wGRC_{opq}; p = 1, 2, \dots, r \quad (4)$$

For various multi-response optimization objectives, suitable weighting factors were allocated to the response variables, and the Grey Relational Grade (GRG) was computed by the weighted aggregation of the respective Grey Relational Coefficients (GRCs).

3.1 Mix Procedure

The RM, GGBS, and MK were dry-mixed with fine aggregate for two minutes in a mortar mixer. The pre-prepared SS+SH alkaline solution was subsequently added, and the process was carried out for three minutes. The mortar was poured into 70.6 mm cube moulds as shown in Figure 3, compacted, and subjected to vibration for a duration of two minutes. 03 specimens for each mix were demoulded and stored at room temperature until testing at 7 and 28 days at an average temperature of 29°C. Flowability (%) for the mortar samples was determined according to IS 5512[39]. Tests for setting times were conducted as per IS 4031-Part 5[40]. Tests for compressive strength were carried out according to IS: 516[41]. The Bruker D8 Advance diffractometer is employed for X-ray diffraction investigation to examine crystalline structure and phase composition. Phase identification was achieved by correlating diffraction patterns with standard reference cards. The Bruker ALPHA-II ATR-FTIR spectrophotometer is employed for FTIR analysis.



Fig. 3. Geopolymer mortar specimens

4. Results and Discussion

S/N ratios and the experimental results for setting time, flowability, and compressive strength for all mixes are displayed in Table 4a and 4b. The results were evaluated by computing the average S/N ratio for each individual response across all the mixes with identical factors.

Table 4. (a) S/N ratios of the response variables

Mix Designation	Ternary Mix	NaOH Molarity	Al/B	SS/SH	B/S	S/N Ratios				
						Flow	IST	FST	CS-07 Days	CS -28 Days
M1	A1	8	0.6	2.5	1:3	41.41	32.67	35.99	27.74	31.37
M2	A1	10	0.55	2	1:2.5	38.59	34.96	40.91	27.02	21.42
M3	A1	12	0.5	1.5	1:2	34.81	38.59	46.24	20.87	28.63
M4	A1	14	0.45	1	1:1.5	43.52	34.32	39.09	33.25	33.82
M5	A2	8	0.55	1.5	1:1.5	43.52	47.24	50.93	24.35	28.80
M6	A2	10	0.6	1	1:2	39.65	45.80	48.13	23.33	27.95
M7	A2	12	0.45	2.5	1:2.5	43.52	36.26	41.94	28.28	30.29
M8	A2	14	0.5	2	1:3	27.96	50.32	52.42	15.04	18.57
M9	A3	8	0.5	1	1:2.5	33.06	45.58	49.13	22.15	24.88
M10	A3	10	0.45	1.5	1:3	31.36	45.58	45.34	16.22	26.82
M11	A3	12	0.6	2	1:1.5	41.18	52.67	55.71	16.83	22.29
M12	A3	14	0.55	2.5	1:2	43.52	46.44	50.26	23.89	21.18
M13	A4	8	0.45	2	1:2	34.85	33.98	40.91	30.23	29.07
M14	A4	10	0.5	2.5	1:1.5	43.52	40.83	43.81	24.06	28.74
M15	A4	12	0.55	1	1:3	43.52	39.55	47.78	26.22	27.18
M16	A4	14	0.6	1.5	1:2.5	43.52	38.79	45.85	17.01	28.82

Table 4. (b) Experimental results of response variables

Mix Designation	Setting Time		Flowability (%)	07 Days Compressive Strength			28 Days Compressive Strength		
	Initial, mins	Final, mins		Strength, MPa	Std. Deviation	Coefficient of Variation	Strength, MPa	Std. Deviation	Coefficient of Variation
M1	43	63	117.6	24.38	0.872	3.57%	37.02	1.758	4.75%
M2	56	111	85	22.45	2.227	9.92%	11.78	1.054	8.94%
M3	85	205	55	11.05	1.039	9.41%	27.02	1.453	5.38%
M4	52	90	150	45.96	2.242	4.88%	49.09	6.145	12.52%
M5	230	352	150	16.5	0.919	5.57%	27.54	2.539	9.22%
M6	195	255	96	14.67	0.544	3.71%	24.98	1.932	7.73%
M7	65	125	150	25.94	0.983	3.79%	32.71	3.903	11.93%
M8	328	418	25	5.65	0.344	6.09%	8.48	0.397	4.68%
M9	190	286	45	12.81	0.911	7.11%	17.53	1.236	7.05%
M10	190	185	37	6.47	0.13	2.01%	21.93	0.453	2.06%
M11	430	610	114.5	6.94	0.622	8.96%	13.02	1.073	8.24%
M12	210	326	150	15.65	0.283	1.81%	11.45	0.898	7.84%
M13	50	111	55.25	32.48	1.62	4.99%	28.4	1.803	6.35%
M14	110	155	150	15.95	0.64	4.01%	27.36	0.979	3.58%
M15	95	245	150	20.46	0.276	1.35%	22.86	3.055	13.36%
M16	87	196	150	7.09	0.212	2.99%	27.59	2.807	10.17%

4.2 Compressive Strength

The compressive strength test was carried out for each of the 16 mixes designed through the Taguchi method. Figure 4 shows the computed average compressive strength. At all the curing intervals, Mix M4 (60% GGBS and 20% RM & MK, Molarity: 14, Al/B ratio: 0.45, SS/SH ratio: 1, and B/S ratio: 1:1.5) demonstrated the highest compressive strength. Mix M8 (60% RM, 20% GGBS & MK, Molarity: 14, Al/B ratio: 0.55, SS/SH ratio: 2, B/S ratio: 1:3) exhibited the lowest compressive strength.

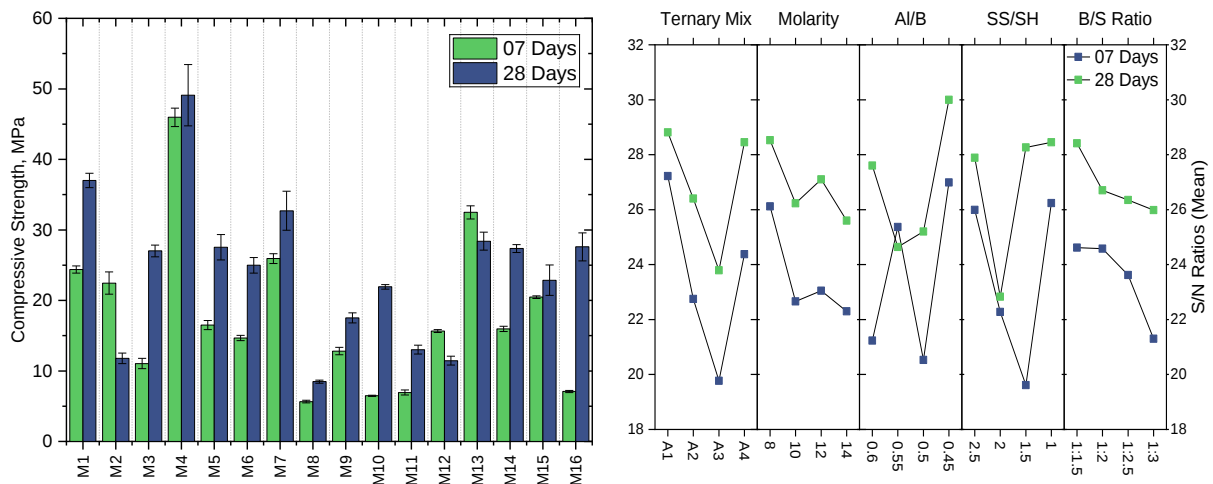


Fig. 4. Compressive strength and S/N ratios (mean)

From Figure 4, the ternary mixes with 60% GGBS had a pronounced effect on the compressive strength. Mixes comprising 60% RM and 60% MK had notable reduction in strength. As evident from Table 4, increasing the GGBS content from 20% to 60% resulted in improved compressive strength. The total calcium content of the mixes increased with increase in GGBS content. Thus, improving the solubility of raw materials which facilitates enhanced geopolymerization producing supplementary C-A-S-H, N-A-S-H and C-S-H gels [42–44].

From the previous literature, the relationship between molarity and strength is uncertain. Certain studies indicate that higher molarity of NaOH correlates with increased compressive strength whereas other studies has shown that elevated NaOH concentration may result in decreased compressive strength [45,46]. Source of aluminosilicate is a critical factor in determining the optimal NaOH concentration [47]. 8 Molar alkaline activators have exhibited higher compressive strength. In this study, increasing molarity resulted in decreased compressive strength, with the exception of 12 molar NaOH. Total amount of alkaline solution in the system is directly proportional to Al/B ratio. The maximum compressive strength was determined for Al/B ratio of 0.45. Increase in Al/B ratio results an inconsistent pattern in compressive strength. Excess alkaline activator contributed to an increased water content in the mixture, which inhibited geopolymerization[48]

Figure 4 shows the S/N ratio (mean) for various SS/SH ratios, the result doesn't follow a consistent pattern. Certain literature indicates that increased silicates due to increased SS/SH ratio leads to an increased strength whereas others indicate the opposite, reduction in strength [49,50]. In the present study, SS/SH ratio of 1 exhibited superior performance. From the mean S/N ratios for binder to sand ratio of 1: 1.5 has resulted in enhanced compressive strength. Increase in B/S ratio generally leads to decrease in the compressive strength which might be due to insufficient aluminosilicate [51] as its associated with a decrease in binder content and an increase in fine aggregate content.

Table 5 presents the results of the ANOVA for the compressive strength. The SS/SH, Al/B ratio, and binder materials together contributed to 84.41% and 87.07% of the strength at 7 and 28 days, respectively. The optimization of individual factors for compressive strength involves a geopolymer mortar mix which comprises 60% GGBS, 20% MK and RM, with 8 Molar NaOH, an Al/B ratio of 0.45, an SS/SH ratio of 1.5, and a B/S ratio of 1:1.5.

Table 5. ANOVA analysis for compressive strength

Factors	CS-07 Days				CS-28 Days			
	SS _m	SS _t	Mean SS	% Contribution	SS _m	SS _t	Mean SS	% Contribution
Ternary Mix	116.28	422.08	38.76	27.55	63.88	256.44	21.29	24.91
Molarity	36.84		12.28	8.73	19.32		6.44	7.53
Al/B	118.8		39.6	28.15	72.24		24.08	28.17
SS/SH	121.16		40.39	28.71	87.16		29.05	33.99
B/S	29		9.67	6.87	13.84		4.61	5.4
Total	422.08			100	256.44			100

4.3 Setting Time

The initial and final setting times of the 16 mixes are shown in Figure 5. Ternary Mixes (M9-M12) containing 60% RM have higher setting times and ternary mixes (M1-M4) with 60 % GGBS have the least setting times, which is in confirmatory with the literature [51]. Prolonged setting time can be attributed to an increase in the RM Content, which results in extended setting time[52] along with higher Al/B ratio[17]. An increase in the CaO owing to increased GGBS shortens the setting times[53] and higher B/S ratio which reduces the binder quantity.

S/N ratios (mean) for the initial and final setting times decreased with increase in the GGBS content (A3, A2 - A4 - A1) which is in line with previous studies[54,55]. The accessible calcium in GGBS provides heterogeneous nucleation sites, expediting the GPZ and leading to a reduced setting time. Consequently, GGBS engages with the alkaline solution more rapidly [53] [56]. The elevated alkalinity of Bayer's red mud may influence the reaction kinetics, potentially resulting in an extended setting time.[57]. From Figure 4, the setting times increased with increase in NaOH Molarity, except for the final setting time which slightly decreases after 12 Molar, which is in line with the previous studies[38] . An increase in Al/B ratio from 0.45 to 0.5 resulted in enlarged setting times[58]. However, this effect from 0.5 to 0.6 is not significant. Increase in the AL/B ratio results in dilution of the alkaline solution, potentially leading to a slowdown in the

geopolymerization and in delay of the setting time [59]. Increase in the SS/SH ratio results in increased setting times upto a threshold ratio of 2, after which a substantial decline is observed at the ratio of 2.5. An increased SS/SH and Al/B ratio enhances the soluble Na^+ ions, thereby facilitating geopolymerization and lower setting times [60]. Changing the B/S ratio from 1:2.5 to 1:1.5 led to increase in the setting times which can be due to the increased binder quantity.

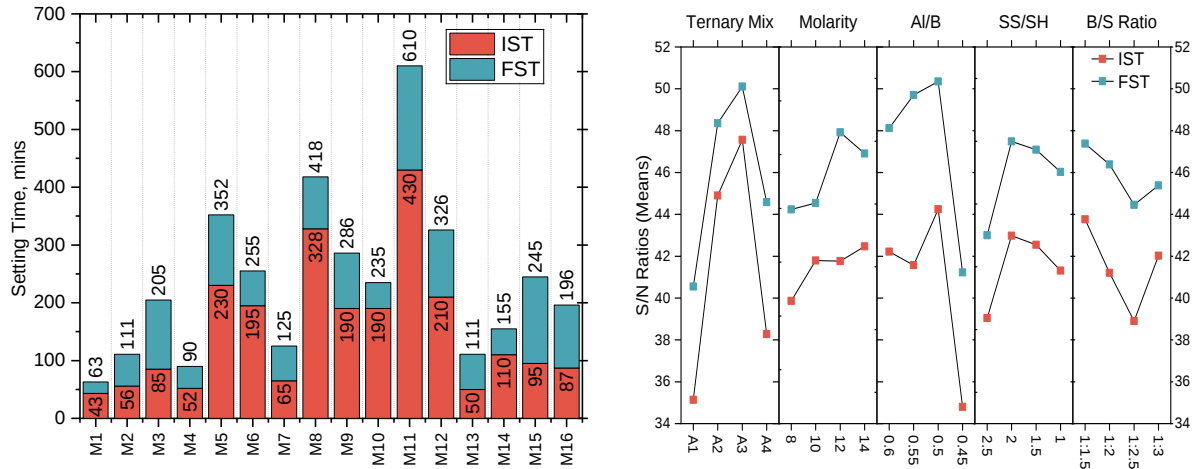


Fig. 5. Setting times of mortars and S/N ratios (means)

Table 6 demonstrates that the Ternary Binder materials is the primary factor influencing the setting times, contributing to 67.49% and 51.85% of the variation in the initial and final setting times, respectively. Al/B ratio is the second most important factor. The optimal mix for setting times is Mix: A3 - 60% RM and 20% GGBS and MK, Molarity: 12, Al/B ratio: 0.45, SS/SH: 2 and B/S ratio: 1:1.5.

Table 6. ANOVA analysis for initial and final setting times

Factors	Initial Setting Time				Final Setting Time			
	SS_m	SS_t	Mean SS	% Contribution	SS_m	SS_t	Mean SS	% Contribution
Ternary Mix	396.8	587.92	132.27	67.49	216.28	417.12	72.09	51.85
Molarity	15.08		5.03	2.56	38.68		12.89	9.27
Al/B	89.68		29.89	15.25	93.56		31.19	22.43
SS/SH	37.32		12.44	6.35	49.44		16.48	11.85
B/S	49.04		16.35	8.34	19.16		6.39	4.59
Total	587.92			100	417.12			100

4.4 Flowability

Flowability test was used to determine the workability of the geopolymer mortars. For mixes M4, M5, M7, M12, M14- M16 the spread diameter is in excess of the base plate, which is reported as 150%. The least flowability of 25% has been determined for Mix M8. The S/N ratios of flowability as shown in Figure 6 indicate ternary mix with equal proportions of all the binders exhibits the highest flow characteristics, whereas mixes with higher percentages of RM display the least flow. An increase in RM content leads to decreased workability, likely due to the high surface area of RM, which raises water demand [61]. The influence of molarity on the S/N ratio is to enhance the flow up to 12 Molar and then diminish at 14 Molar, although this change is not significant. An increase in NaOH molarity resulted in enhanced flow. An elevated molarity of NaOH results in increase of OH^- ions concentration, hence accelerating dissolution and increasing flow[62]. The S/N ratios for flow, plotted alongside the Al/B ratios, indicate a random distribution of performance. The flowability has not decreased with the decrease in the Al/B ratio, which is consistent with previous studies [63,64]. This is due to the complicated action of binders, which effect the flowability [65]. Mixes with Al/B ratio of 0.5 are stiffer compared to mixes with other Al/B ratios. The literature indicates an absence of identifiable trends regarding the influence of the SS/SH ratio. Research

indicates that flowability increases as the SS/SH ratio decreases, and conversely, decreases with an increase in the SS/SH ratio[66,67]. The current study indicates that a reduction in SS/SH from 2.5 to 2 results in a significant decrease in flow, while further reductions lead to an increase in flow. The increase in binder quantity led to an increase in flow, with a slight variation observed at a binder-to-sand ratio of 1:2. These variations can be attributed to the enhanced geopolymerization resulting from the increased availability of aluminosilicate materials[68]. Binder content influences inter-particle interactions and solidification, thereby impacting slump values.[38]

Table 7. ANOVA analysis for flowability

Factors	Flowability			
	SS _m	SS _t	Mean SS	% Contribution
Ternary Mix	35	403.76	11.67	8.67
Molarity	17.72		5.91	4.39
Al/B	137.44		45.81	34.04
SS/SH	113.56		37.85	28.13
B/S	100.04		33.35	24.78
Total	403.76			100

From Table 7, it can be concluded that the Al/B, SS/SH, and B/S ratios are the major factors influencing flowability. Al/B ratio is the primary factor influencing 34.04% of the variation. The optimal mix for setting times is Mix: A4 – 33.33% RM, GGBS and MK, Molarity: 12, Al/B ratio: 0.55, SS/SH: 2.5 and B/S ratio: 1:1.5.

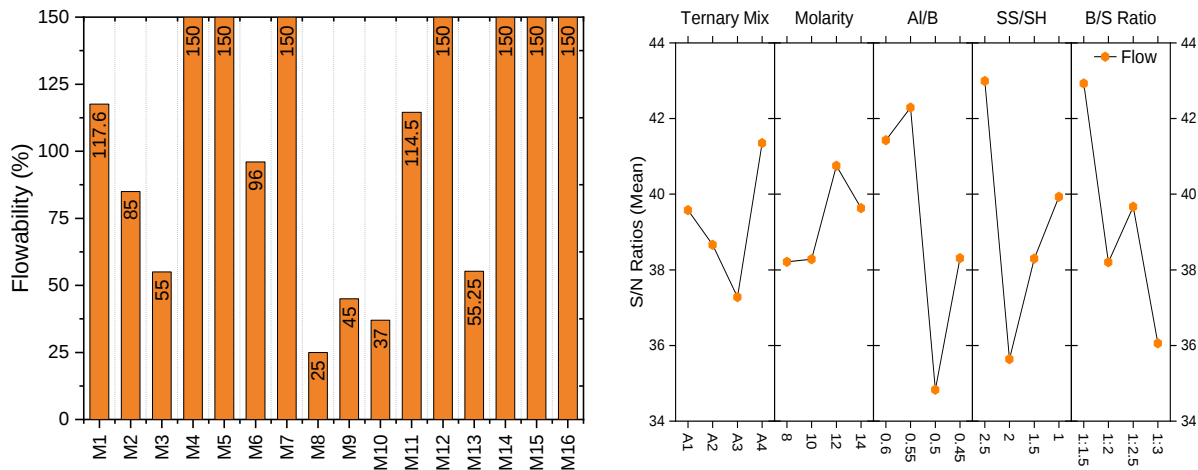


Fig. 6. Flowability of Mortars and S/N Ratios (Mean)

4.5 Multi Response Optimization by Taguchi Grey Relational Analysis

The optimal factor level combinations for each factor, that demonstrated superior performance for each of the response variables are identified on the basis of S/N ratios. Confirmatory experiments based on Taguchi Analysis were conducted for each individual response variable, and the results are shown in Table 8. The compressive strength of 51.94 MPa achieved after 28 days is 5.81% greater than the maximum strength determined using the L16 orthogonal array mixes. Additionally, this mix showed a shorter setting time of 25 minutes, which necessitates multi-factor optimization using the Taguchi-GRG method.

S/N ratios were normalized and transformed into Grey Relational Coefficients (GRCs) for multi-response comparison and the results are tabulated in Table 9 to identify optimal factor levels under different optimization objectives. Multi-response optimization was carried out using three different weights as shown in Table 10 to prioritize compressive strength, workability and balanced overall performance. Grey Relational Grades (GRGs) of the different optimization criteria are shown in Table 11.

Table 8. Taguchi - Optimum levels of each factor for response variables

Factors	Flowability	IST	FST	CS-07 Days	CS-28 Days
Ternary Mix	A4	A3	A3	A1	A1
Molarity	12	14	12	8	8
Al/B	0.55	0.5	0.5	0.45	0.45
SS/SH	2.5	2	2	1	1
B/S Ratio	1:1.5	1:1.5	1:1.5	1:1.5	1:1.5
Confirmatory Experiment	150 %	96 mins	158 mins	46.54 MPa	51.94 MPa

Table 9. Grey relational coefficients based on S/N ratios for the geopolymer mortar

Mix No	Normalized S/N Ratios					Delta					GRC				
	Flow	IST	FST	CS-07 Days	CS-28 Days	Flow	IST	FST	CS-07 Days	CS-28 Days	Flow	IST	FST	CS-07 Days	CS-28 Days
M1	0.86	0.00	0.00	0.70	0.84	0.14	1.00	1.00	0.30	0.16	0.79	0.33	0.33	0.62	0.76
M2	0.68	0.12	0.25	0.66	0.19	0.32	0.89	0.75	0.34	0.81	0.61	0.36	0.40	0.59	0.38
M3	0.44	0.30	0.52	0.32	0.66	0.56	0.70	0.48	0.68	0.34	0.47	0.42	0.51	0.42	0.60
M4	1.00	0.08	0.16	1.00	1.00	0.00	0.92	0.84	0.00	0.00	1.00	0.35	0.37	1.00	1.00
M5	1.00	0.73	0.76	0.51	0.67	0.00	0.27	0.24	0.49	0.33	1.00	0.65	0.67	0.51	0.60
M6	0.75	0.66	0.62	0.46	0.62	0.25	0.34	0.38	0.55	0.39	0.67	0.59	0.57	0.48	0.57
M7	1.00	0.18	0.30	0.73	0.77	0.00	0.82	0.70	0.27	0.23	1.00	0.38	0.42	0.65	0.68
M8	0.00	0.88	0.83	0.00	0.00	1.00	0.12	0.17	1.00	1.00	0.33	0.81	0.75	0.33	0.33
M9	0.33	0.65	0.67	0.39	0.41	0.67	0.36	0.33	0.61	0.59	0.43	0.59	0.60	0.45	0.46
M10	0.22	0.65	0.47	0.07	0.54	0.78	0.36	0.53	0.94	0.46	0.39	0.59	0.49	0.35	0.52
M11	0.85	1.00	1.00	0.10	0.24	0.15	0.00	0.00	0.90	0.76	0.77	1.00	1.00	0.36	0.40
M12	1.00	0.69	0.72	0.49	0.17	0.00	0.31	0.28	0.51	0.83	1.00	0.62	0.64	0.49	0.38
M13	0.44	0.07	0.25	0.83	0.69	0.56	0.93	0.75	0.17	0.31	0.47	0.35	0.40	0.75	0.62
M14	1.00	0.41	0.40	0.50	0.67	0.00	0.59	0.60	0.51	0.33	1.00	0.46	0.45	0.50	0.60
M15	1.00	0.34	0.60	0.61	0.57	0.00	0.66	0.40	0.39	0.44	1.00	0.43	0.55	0.56	0.54
M16	1.00	0.31	0.50	0.11	0.67	0.00	0.69	0.50	0.89	0.33	1.00	0.42	0.50	0.36	0.60

Table 10. Weighting factors for response variables under different optimization criteria's

Optimization Criteria	Flowability	IST	FST	CS-07 Days	CS-28 Days
Balanced Overall Performance	0.2	0.2	0.2	0.2	0.2
Compressive Strength	0.1667	0.1667	0.1666	0.15	0.35
Workability	0.5	0.125	0.125	0.125	0.125

Mix M4 has the highest GRG for all the three different optimizations considered. The Mix M4 has the highest reported compressive strength at the age of 7 and 28 days and flow value; nonetheless, it has quick initial and final setting times. Based on Table 12, the mean GRG analysis, distinct optimal combinations of mix parameters were identified for different optimization criteria. For balanced overall performance, the highest mean GRG was obtained at Ternary mix A2 - 60% MK, 20% GGBS, and 20%RM, 14 molar NaOH, Al/B ratio of 0.6, SS/SH ratio-1, and B/S ratio of 1:1.5, indicating a mix expected to provide balanced flowability, setting behavior, and strength

development. Under the compressive strength criteria, the optimal combination corresponded to Ternary mix- A2 - 60% MK, 20% GGBS, and 20%RM, 14 molar NaOH 14, Al/B ratio-0.45, SS/SH ratio-1, and B/S ratio of 1:1.5, suggesting enhanced compressive strength performance.

Table 11. GRG's under different optimization criteria's

Mix Designation	Balanced Overall Performance	Compressive Strength	Workability
M1	0.57	0.60	0.65
M2	0.47	0.45	0.52
M3	0.48	0.50	0.48
M4	0.75	0.79	0.84
M5	0.69	0.67	0.80
M6	0.57	0.57	0.61
M7	0.63	0.64	0.77
M8	0.51	0.48	0.44
M9	0.51	0.50	0.48
M10	0.47	0.48	0.44
M11	0.71	0.65	0.73
M12	0.63	0.58	0.77
M13	0.52	0.53	0.50
M14	0.60	0.60	0.75
M15	0.62	0.60	0.76
M16	0.58	0.59	0.74

Table 12. Mean GRG response values for different optimization criteria's

Optimization Criteria	Parameter	Level1	Level2	Level3	Level4
Balanced Overall Performance	Ternary Mix	0.57	0.60*	0.58	0.58
	Molarity	0.57	0.53	0.61	0.61*
	Al/B	0.61*	0.6	0.53	0.59
	SS/SH	0.6	0.55	0.55	0.61*
	B/S	0.68*	0.55	0.54	0.54
Strength	Ternary Mix	0.59	0.59*	0.55	0.58
	Molarity	0.58	0.53	0.60	0.61*
	Al/B	0.60	0.58	0.52	0.61*
	SS/SH	0.61	0.53	0.56	0.62*
	B/S	0.68*	0.55	0.54	0.54
Workability	Ternary Mix	0.62	0.66	0.60	0.69*
	Molarity	0.61	0.58	0.68	0.70*
	Al/B	0.68	0.71*	0.54	0.64
	SS/SH	0.73*	0.55	0.61	0.67
	B/S	0.78*	0.59	0.62	0.57

* Optimum Values

For the workability criteria, the highest mean GRG was associated with Ternary mix-A4-33.33% of RM, GGBS and MK, NaOH molarity-14, Al/B ratio-0.55, SS/SH ratio-2.5, and B/S ratio of 1:1.5, indicating improved workability characteristics. The higher mean GRG implies that the mix prepared with these levels of mix parameters would perform more favorably with respect to all the evaluated properties of geopolymer concrete. Despite variations in the optimal levels of several parameters across the three criteria, 14 M NaOH molarity and B/S ratio of 1:1.5 consistently emerged as common optimal parameters on the overall performance of the geopolymer mortar irrespective of the selected optimization objective.

6. XRD Analysis

Among the 16 Taguchi Mixes, M4 and M8, which demonstrated the highest and lowest compressive strength respectively, were analyzed using XRD spectra as shown in Figure 7. The XRD spectra revealed crystalline phases and an amorphous component. The predominant crystalline phases derived from the raw precursor materials, including quartz (SiO_2), hematite (Fe_2O_3), and minor gibbsite or mullite, remained evident in the geopolymer mortar mixes, signifying the retention of unreacted particles from the binder materials during alkali activation. Alongside these remaining phases, new diffraction characteristics linked to geopolymerization products were detected. A wide, diffuse amorphous peak ranging from roughly 20° to 35° 2θ was observed in all geopolymer mixtures, confirming the development of alkali-activated aluminosilicate gel phases. This indistinct area is usually attributed to the existence of C-(A)-S-H and/or N-A-S-H type gels generated during the dissolution and polycondensation of aluminosilicate species. Additionally, faint crystalline reflections associated with calcium-bearing phases, including calcite and calcium silicate hydrate-related phases, were seen, especially in mixtures with elevated GGBS content. The presence of remnant crystalline phases alongside newly generated amorphous aluminosilicate gels validates the heterogeneous characteristics of the geopolymerization process in the examined systems.

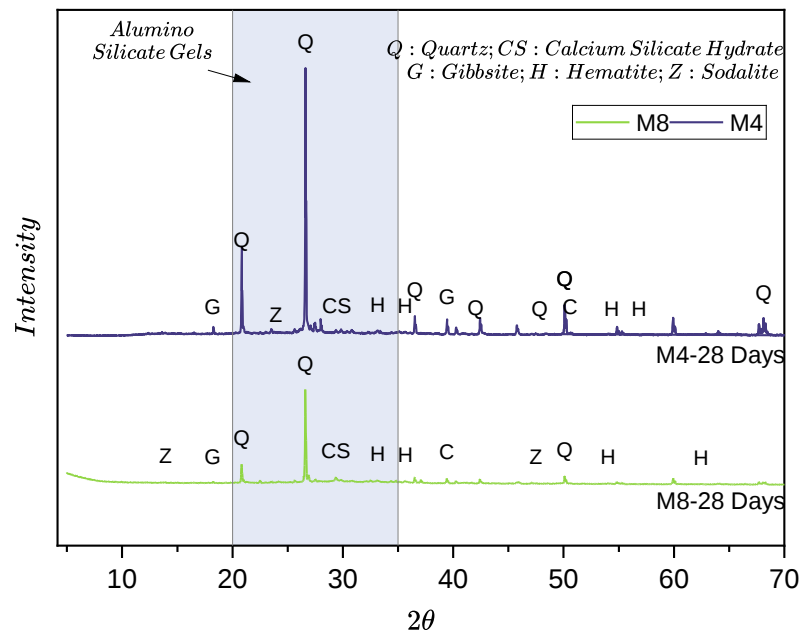


Fig. 7. XRD Spectra of GPM mixes at 28 days ambient curing

7. Conclusions

The integrated Taguchi and GRA methods were successfully used to develop an optimal geopolymer mortar mix that has superior performance in terms of compressive strength, flowability and setting times. This method aids in studying the effects of different factors and their corresponding levels on the desired response variables, and helps in identifying the optimal mix combinations which reduces the cost and time of experiments. The outcomes of the study are as follows:

- The ANOVA results of S/N ratios reveal SS/SH and Al/B ratio as significant factors affecting the flowability and compressive strength. The ternary mix combination of RM, GGBS and MK is the single most contributing factor for the setting times. From the Taguchi - GRA approach binder to sand ratio is the most influential factor when all the response variables are considered.
- The presence of GGBS accelerated the geopolymerization process, leading to reduced setting time and improved early-age compressive strength, while the inclusion of RM and MK played a crucial role in maintaining adequate workability and controlled setting behavior.

- The comparison of the XRD spectra of the binder materials RM, MK and GGBS with those of the ternary geopolymer mixes revealed the synthesis aluminosilicates which enhances compressive strength development. The heightened intensity of the amorphous halo in the ternary mixes with elevated GGBS concentration indicated increased gel formation, correlating with greater compressive strength at both early and later ages under ambient curing conditions.
- The Taguchi S/N ratio analysis revealed that the ternary mix containing 60% GGBS and 20% MK, 20% RM exhibited superior compressive strength performance. The Taguchi-GRG results for balanced overall performance and compressive strength identified the ternary mix comprising 60% MK and 20% GGBS, 20% RM as optimal, reflecting improved combined behavior in terms of workability, setting characteristics, and strength. This illustrates that the ideal proportions of ternary binders vary based on whether the performance objective emphasizes strength or overall balanced performance.
- The mean Grey Relational Grade (GRG) study indicated that various parameter combinations are ideal for achieving balanced performance, compressive strength, and workability. Nonetheless, a NaOH molarity of 14 M and a binder-to-sand ratio of 1:1.5 consistently proved to be ideal parameters across all optimization criteria.

The synthesized geopolymer mortar may serve as a substitute for conventional cement mortar and for precast applications. It also improves the visual appeal, attributed to its inherent red color.

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