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Development of GGBS-Based Geopolymer Concrete Incorporated with Polypropylene Fibers as Sustainable Materials

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Abstract: Geopolymer concrete, because of its less embodied energy as compared to conventional cement concrete, has paved the way for achieving sustainable development goals. In this study, an effort was made to optimize its quality characteristics or responses, namely, workability, and the compressive and flexural strengths of Ground Granulated Blast-furnace Slag (GGBS)-based geopolymer concrete incorporated with polypropylene (PP) fibers by Taguchi's method. A three-factor and three-level design of experiments was adopted with the three factors and their corresponding levels as alkali ratio ($NaOH:Na_2SiO_3$) (1:1.5 (8 M NaOH); 1:2 (10 M NaOH); 1:2.5 (12 M NaOH)), percentage of GGBS (80%, 90%, and 100%) and PP fibers (1.5%, 2%, and 2.5%). M25 was taken as the control mix for gauging and comparing the results. Nine mixes were obtained using an L9 orthogonal array, and an analysis was performed. The analysis revealed the optimum levels as 1:2 (10 molar) alkali ratio, 80% GGBS, and 2% PP fibers for workability; 1:2 (10 molar) alkali ratio, 80% GGBS, and 2.5% PP fibers for compressive strength; and 1:2 (10 molar) alkali ratio, 80% GGBS, and 1.5% PP fibers for flexural strength. The percentage of GGBS was found to be the most effective parameter for all three responses. The analysis also revealed the ranks of all the factors in terms of significance in determining the three responses. ANOVA conducted on the results validated the reliability of the results obtained by Taguchi's method. The optimized results were further verified by confirmation tests. The confirmation tests revealed the compressive and flexural strengths to be quite close to the strengths of the control mix. Thus, optimum mixes with comparable strengths were successfully achieved by replacing cement with GGBS and thereby providing a better path for sustainable development.

Keywords: geopolymer concrete; Taguchi method; ANOVA; Ground Granulated Blast-furnace Slag (GGBS); polypropylene (PP) fibers; L9 orthogonal array; sustainability

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1. Introduction

Many emerging nations' economies depend heavily on the construction sector, which also serves as the backbone of their development. However, cement, a conventional binding material, used widely in construction because of its high-embodied energy and CO_2 emissions, hinders the achievement of the UN Sustainable Development Goals (SDGs). The huge manufacturing and usage of Ordinary Portland Cement (OPC) has a negative influence on the environment [1], and 5–7% of global CO_2 emissions are attributable to its massive production [2]. Recent advancements have assisted in providing an imperative sustainable solution by partially utilizing industrial wastes such as fly ash, GGBS, silica fume, and rice husk ash in place of cement and minimizing the embodied energy and CO_2 emissions [3,4]. Partial replacement by the optimum amount of these industrial wastes in concrete has been reported to enhance the mechanical properties such as flexural, compressive, and tensile strength, and limit the chloride ion penetration with time [5–8]. Utilizing these industrial wastes has also been reported in substantial cost savings together with benefits to the environment [9,10].

As compared to conventional cement-based concrete, observations of better physical and durability properties obtained by partially replacing OPC with fly ash, GGBS, and silica fume are reported [11]. However, replacing cement completely by these materials is incongruous due to the economic cost and changes in mechanical behavior. Providentially, Davidovits' description of the inorganic aluminosilicate polymers known as geopolymers has offered a feasible option for their complete replacement [12]. These inorganic aluminosilicate polymers are generally industrial waste such as GGBS, fly ash, etc., which, when activated by alkali, are realized into geopolymer binders. Hence, these industrial by-products can be realized as useful construction materials [13]. The concrete, thus obtained, is called geopolymer concrete. Geopolymer concrete has shown to exhibit better physical and durability properties than OPC-based conventional concrete [14–18]. The enhancement is attributed to the denser hydration product as compared to cement paste [14]. The geopolymer binder also exhibits better binding characteristics, which results in a considerably stronger Interfacial Transition Zone (ITZ) and microstructure [17,18]. Geopolymer concrete has proved to be a viable alternative to Portland cement-based concrete because of the reduction in the embodied energy and carbon footprint [19,20]. Literature study reveals a lesser impact of geopolymer concrete on the environment as compared to concrete with higher amounts of cement. This environmental impact of the geopolymer concrete was assessed by determining the Environmental Impact Factor (P) through a Life Cycle Assessment (LCA) [21]. Thus, geopolymer concrete resonates with the UN Sustainable Development Goals related to energy, climate, and infrastructure.

Upon combining fly ash and GGBS, the strength of geopolymer concrete was discovered to be improved with an increase in the proportion of GGBS, as opposed to fly ash, suggesting that GGBS is a better replacement for cement than fly ash [22–26]. This enhancement due to GGBS as compared to fly ash can be contributed to the high alumina, calcium oxide content, and comparable silica content of GGBS, compared to that of fly ash. Additionally, the dissolution of GGBS in an alkaline medium is more than that of fly ash [27]. Hence, the sole replacement by GGBS can drastically reduce the cost. However, because of the higher particle size of GGBS compared to fly ash, partial and full replacement of cement by GGBS alone results in no or minimal improvement in the compressive strength [28,29]. To overcome this limitation, research has been conducted by incorporating reinforcing fibers such as glass fibers, carbon fibers, steel fibers, basalt fibers, and polypropylene fibers into the geopolymer concrete, and improved properties are reported [30]. Waste fibers have also been incorporated into concrete to obtain sustainable concrete and improved properties. Waste PP fibers have been reported to enhance the tensile strength and sound insulation coefficient of Prepacked Aggregates Fiber Reinforced Concrete (PAFRC) while waste metalized film food packaging fibers in concrete have shown improved tensile strength and reduced carbonation and drying shrinkage [31,32]. Hybrid fibers such as the combination of steel fibers and polypropylene fibers have also resulted in improved properties, but their cost effectiveness remains questionable [33].

Polypropylene fibers are reported to improve the mechanical properties, sulfate resistance, and post-cracking behavior and increase the yield stress of geopolymer concrete, i.e., improvement in the mechanical and durability-related properties and their low cost combined with thermal stability, easy dispersal, and chemical inertness in alkaline environments make them suitable for use in concrete [34–36]. Hence, the combination of polypropylene fibers with higher percentages of GGBS might result in better compressive and flexural strengths, and related studies can be made in this field. The literature seems silent on the topic of GGBS-based geopolymer concrete incorporated with polypropylene fibers while much research is taking place on the effect of hybrid fibers or polypropylene fibers in fly-ash-based geopolymer concrete with the percentage incorporation varying from 0.05% to 2% by weight of concrete [37,38]. These studies have revealed better physical properties with lesser percentages of polypropylene fibers (less than or around 1% by weight of concrete). Different alkali ratios ($NaOH:Na_2SiO_3$) also evidently affect the compressive and flexural strengths with a higher alkali ratio of 1:3 (others being 1:2 and 1:2.5), exhibiting maximum strengths due to the crystalline nepheline formation and uniformity of polymer products [39]. Thus, lower alkali ratios seem to be unexplored.

The fresh and hardened properties of alkali-activated geopolymer concrete differ considerably for different quantities of the constituents such as alkali ratio ($NaOH:Na_2SiO_3$), percentage of GGBS, percentage of incorporated fibers, etc. The properties of geopolymer concrete may differ widely country-wise even for the same mix proportion because of the high sensitivity to the variation in the constituent materials. Therefore, in this work, an effort has been made to use Taguchi's method to achieve the optimal amounts of the components of alkali-activated geopolymer concrete and to investigate using Analysis of Variance (ANOVA) the key factors influencing the workability, and compressive and flexural strengths of concrete. Literature study revealed the use of full as well as the fractional factorial method of design of experiments followed by other methods of optimization such as the Taguchi method, response surface analysis, Principal Component Analysis, and AI-based predicted models such as the Genetic Algorithm (GA) and AI-based regression techniques such as Genetic Programming (GP), Enhanced Polynomial Regression (EPR), and Artificial Neural Networks (ANN) [40–43]. The Taguchi method has successfully been implemented to the derive optimum design mix for geopolymer concrete [44]. A lot of research on optimizing the process parameters for geopolymer concrete has been conducted with the research mainly taking place for fly ash-added geopolymer concrete [45,46]. Optimization of a geopolymer concrete mix incorporated with a combination of GGBS, fly ash, and silica fume have also taken place [47]. Scarce literature is available regarding the implementation of the Taguchi method for only GGBS-based geopolymer concrete and that too reinforced with fiber material [48]. The Taguchi method is also implemented to optimize the compressive strength of geopolymer concrete with palm oil fuel ash [49]. Steel fiber-incorporated GGBS-based geopolymer concrete has been optimized by the Taguchi method for better spilt tensile strength [50]. The use of the Taguchi method to determine the optimum process parameters for GGBS-based geopolymer concrete reinforced with polypropylene fibers appears to be undocumented in the literature.

In this study, an analysis of the results of the combined usage of different levels of GGBS, polypropylene fibers, and alkali ratio ($NaOH:Na_2SiO_3$) to further improve the fresh state property, viz., workability and hardened state properties, and compressive and flexural strengths of the GGBS-based geopolymer concrete incorporated with polypropylene fibers, was made. By using Taguchi's method, this study also intends to determine the optimum levels of the three factors: the alkali ratio ($NaOH:Na_2SiO_3$), the percentage of GGBS, and the percentage of polypropylene fibers. Three levels were adopted for each factor, based on the above literature review. Nine mixes for three factors and three levels were obtained by employing the L9 orthogonal array (3^4). Experiments were conducted on nine mixes to investigate optimum levels of each factor or process parameter for the responses, namely, workability, and compressive and flexural strengths. Significant factors and their ranks were also derived by using Taguchi's method. ANOVA was also performed on the data to find the factor parameter with least and most significant influence on the responses and optimum levels of each factor, and the results of Taguchi's method and ANOVA were compared.

Significance of the Present Study

With the world striving towards sustainable development goals, energy conservation has become one of the most important aspects in this direction. Geopolymer concrete with cement replaced by industrial waste has paved the way to achieving sustainable development goals because of its low embodied energy as compared to cement-based concrete. As discussed above, sole GGBS-based geopolymer concrete is cost effective and with the incorporation of polypropylene fibers, a concrete with desirable fresh and hardened state properties can be achieved. However, these properties differ considerably for the different quantities of the constituents. The properties of geopolymer concrete may differ widely country-wise even for the same mix proportion because of the high sensitivity to the variation in the constituent materials. Therefore, in this work, efforts have been made to:

- Use Taguchi's method to achieve the optimal amounts of process parameters, viz., alkali ratio ($NaOH:Na_2SiO_3$), percentage of GGBS, and percentage of polypropylene fiber for workability, and compressive and flexural strengths of alkali-activated GGBS-based geopolymer concrete incorporated with polypropylene fibers.
- Study the contribution of the process parameters or to investigate the key factors influencing the responses, viz., workability, and compressive and flexural strengths.
- Validate the reliability of the results obtained by the Taguchi method through ANOVA.
- Confirm the predicted optimized responses by confirmation tests.
- Obtain an optimized GGBS-based concrete mix with comparable strength as that of a pure cement-based control mix.
- Provide a guide to identify the key factor and choose the best concrete mix based on the present study's statistical analyses.
- Demonstrate that both fresh and hardened properties of concrete can be tuned for an optimal response for a given set of controlling process parameters or factors.
- Section 2 below discusses the materials and their characteristics used in the study to make geopolymer concrete along with the results of tests conducted on them.

2. Materials and Methods

2.1. Ground Granulated Blast-Furnace Slag (GGBS)

When molten iron slag obtained from the blast furnace is quenched in water or steam, glassy and granular waste material is obtained, which, upon grinding, gives Ground Granulated Blast-furnace Slag, commonly known as GGBS. The GGBS produced by JSW Cements, with a specific gravity of 2.82 and chemical composition listed in Table 1, was used in the current investigation.

Table 1. Chemical Composition of GGBS [1].

Parameter	GGBS	IS: 12089-1987 [51]
SiO_2	37.73%	-
Al_2O_3	14.42%	-
CaO	37.34%	-
Fe_2O_3	1.11%	-
MgO	8.71%	Max. 17%
MnO	0.02%	Max. 5.5%
Glass Content (%)	92.00%	Min. 85%
Insoluble Residue	1.59%	Max. 5%
Loss of Ignition	1.41%	-
Sulfide Sulphur	0.39%	Max. 2%

[1] Data correspond to the product brochure from the supplier.

2.2. Cement

For the fabrication of test specimens, Portland Pozzolana Cement (PPC) from ACC complying with IS: 1489-1 (2015) [52] was employed. The cement, before use, was tested for various properties, as shown in Table 2, to check the suitability to be used in the study. The tests on the cement revealed the observed values to be well within the limits.

Table 2. Properties of cement.

Tests	Apparatus Used	Testing Procedure as Per	Results
Standard Consistency	Vicat Apparatus (conforming to IS 5513:1996) [53]	IS 4031 (Part 4): 1988 [54]	34%
Fineness	Blaine's Permeability Test	IS 4031 (Part 1): 1996 [55]	432.4 m^2/kg
Soundness	Le-Chatelier's Apparatus (conforming to IS 5514:1969) [56]	IS 4031 (Part 3): 1988 [57]	8 mm
Initial Setting Time	Vicat Apparatus (conforming to IS 5513:1996)	IS 4031 (Part 5): 1988 [58]	32 min
Final Setting Time	Vicat Apparatus (conforming to IS 5513:1996)	IS 4031 (Part 5): 1988	300 min
Compressive Strength	Cube mold of 70.6 mm (conforming to IS: 10080-1982) [59]	IS 4031 (Part 6): 1988 [60]	7 Days—20.3 MPa 28 Days—37.8 MPa

2.3. Fine Aggregate

The mixes were created using readily accessible river coarse sand from the area. According to IS: 383–1970 [61], the sieve analysis results conducted on sand (Table 3) conformed well within the parameters of zone II, as shown in Figure 1. Table 4 displays the fine aggregate's physical characteristics.

Table 3. Results of sieve analysis of sand used.

IS Sieve Size	Sieve Size (mm)	Weight of Empty Sieve (gm)	Weight of Sieve + Retained Sand (gm)	Weight of Retained Sand (gm)	Limits for Zone II as per IS: 383-1970		Cumulative Weight Retained (gm)	Cumulative % Weight Retained	Cumulative % Passing
					Lower	Upper			
10 mm	10	435	435	0	100	100	0	0	100
4.75 mm	4.75	425	485	26	90	100	26	5.2	95
2.36 mm	2.36	385	420	29	75	100	55	11	89
1.18 mm	1.18	410	465	80	55	90	135	27	73
600 microns	0.6	380	500	141	35	59	276	55.2	45
300 microns	0.3	345	555	144	8	30	420	84	16
150 microns	0.15	355	365	70	0	10	490	98	2
Lower Pan		425	430	10			500		

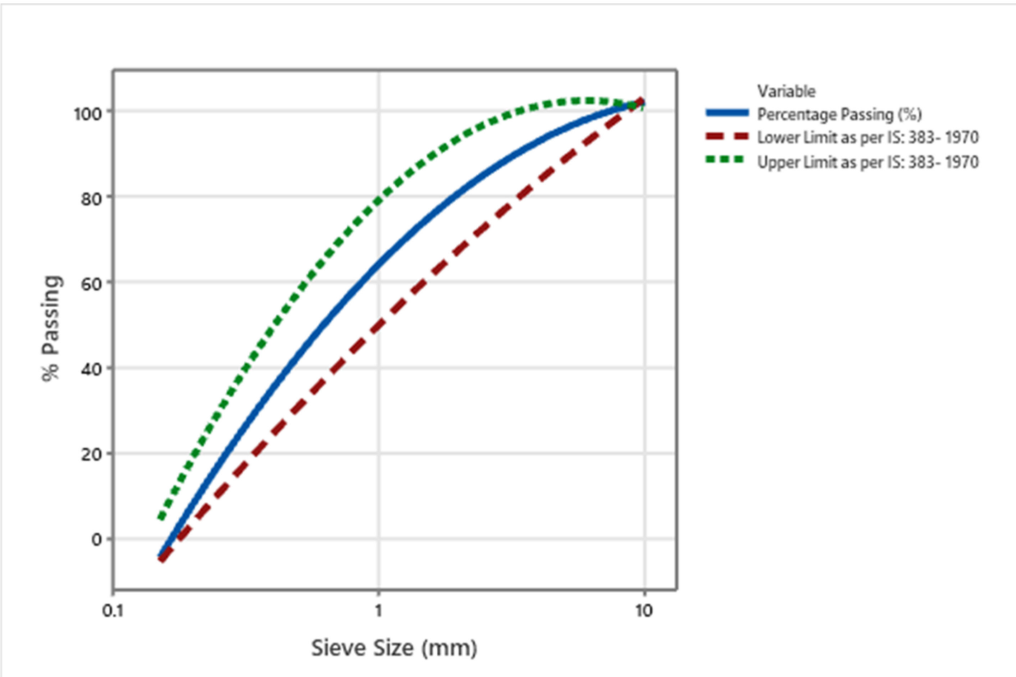

Figure 1. Gradation curve (semi-log graph) of sand used.

Table 4. Physical characteristics of fine aggregates.

Tests	Apparatus Used	IS Code Used	Results
Fineness Modulus	Standard IS sieves and shaker (Conforming to IS: 460 (Part 2)-1985) [62]	IS 2386 (Part 1): 1963 [63]	3.09
Specific Gravity	Pycnometer of about 1-liter capacity	IS 2386 (Part 3): 1963 [64]	2.51
Apparent Specific Gravity	Pycnometer of about 1-liter capacity	IS 2386 (Part 3): 1963	2.60
Water Absorption	Pycnometer of about 1-liter capacity	IS 2386 (Part 3): 1963	1.051%
Bulk Density	Pycnometer of about 1-liter capacity	IS 2386 (Part 3): 1963	1668 kg/m^3

2.4. Coarse Aggregate

For creating the necessary mixes, coarse aggregates with a nominal size of 20 mm were employed. Table 5 shows the physical characteristics of the coarse aggregates used.

Table 5. Physical characteristics of coarse aggregates.

Characteristics	Values
Type	Crushed
Bulk Density	1765 kg/m^3
Specific Gravity	2.71
Nominal size	20 mm
Fineness Modulus	6.45
Water Absorption	1.5%
Flakiness Index	12.90%
Elongation Index	12.92%

2.5. Polypropylene Fibers

Polypropylene fibers, a synthetic carbon polymer, were used as fiber reinforcement in the present study as shown in Figure 2. The present study utilizes polypropylene fibers with an aspect ratio (L/D) of 200 and 0.91 g/cm^3 density, in the form of continuous monofilaments of length 4 mm with a circular cross-section having a diameter of 20 micrometers (μm). The characteristics of polypropylene fibers used are listed in Table 6.

Figure 2. Polypropylene fibers used in the study.

Table 6. Characteristics of Polypropylene fibers [2].

Fibers	Melting Point (Degree Celsius)	Diameter (mm)	Density (gm/cm^3)	Tensile Strength (kN/mm^2)
Polypropylene	164	0.29	0.91	0.67

[2] Data correspond to the product brochure from the supplier.

2.6. Alkaline Activators Solution

The combination of sodium hydroxide and sodium silicate (available as sodium meta silicate nonahydrate) is used as alkaline activators. NaOH available in the form of flakes and crystalline Na_2SiO_3, purchased from Central Drug House (P) Ltd. (CDH), were used in the present study. The product specifications of the chemicals used as alkaline activators are given in Table 7. Sodium hydroxide has a purity of 97.84% and the purity of sodium meta silicate is above 99%. These alkaline activators are used to activate a source of reactive alumino-silicates such as GGBS, fly ash, and metakaolin. This alumna and silica, upon the addition of alkaline activators, set up a geopolymerization reaction including dissolution of alumina and silica in water along with alkali coming from the activators [65]. The activation reaction yields an alumino-silicate glass phase containing a three-dimensional network of interlinked $SiO4^{-4}$ and $AlO4^{-5}$ tetrahedral units [66]. Section 3 below elaborates on the experimental program covering the three factors and their levels adopted for the study, nine mixes obtained by an L9 orthogonal array, and the preparation of specimens and tests conducted on them. The process of preparation of alkaline activators solution is discussed in Section 3.2.

Table 7. Specifications of the chemicals used as alkaline activators [3].

Chemical	CASR No.	Molecular Formula	Molecular Weight (g/mol)	Description	Solubility	Assay
Sodium Hydroxide	1310-73-2	NaOH	40	White deliquescent flakes	10% solution in water is clear	96%
Sodium Meta Silicate Nonahydrate (or Sodium Meta Silicate)	13517-24-3	$Na_2SiO_3{\cdot}9H_2O$	284.2	White crystals (moistened)	Soluble in mixture of water and hydrochloric acid	Abt. 95%

[3] Data correspond to the product brochure from the supplier.

2.7. Taguchi Method of Optimization

The Taguchi method is a statistical method used to improve a response by optimizing the process parameters affecting the response. The conventional methods for the design of experiments, such as the full factorial method followed by response surface analysis, encompass numerous experiments as the number of factors and their levels increase. Thus, making a study uneconomical and time consuming. This analysis method has the potential to highlight the importance of the control factors in affecting the desired responses. The Taguchi method tends to optimize the process parameters or factors with a lesser number of experiments with the help of a signal-to-noise (S/N) ratio, thus saving time and money. The Taguchi method follows four approaches to calculate the S/N ratio based on the requirement, viz., larger-the-better, nominal-the-better, and smaller-the-better. As maximum workability, and maximum compressive and maximum flexural strengths are the target functions in this study, the larger-the-better approach has been employed to evaluate the optimal levels of the factors for these properties. The S/N ratio for the larger-the-better approach is given by Equation (1):

$$\mathrm{S/N} = -10\log_{10}\frac{1}{n}\sum_{i=1}^{n} y_i^2 \quad (1)$$

where n = total number of responses for the given factor level combination and y = responses.

2.8. Analysis of Variance (ANOVA)

One statistical method for determining the contribution ratio and consequently the rank of each parameter based on the study of the data is the Analysis of Variance (ANOVA). In other words, the level of significance of the process parameters on the response can also be determined by ANOVA. To assess the contribution and rank of each factor for various responses, this statistical method uses the degree of freedom (DOF), sum-of-squares (SS), mean-of-squares (MS), F-value, p-value, and contribution ratios of each process parameter. This study uses ANOVA to compare the results of Taguchi's method and, hence, establishes the reliability of the results obtained. ANOVA was performed on the data to find the factor parameter with the least and most significant influence on the responses and optimum levels of each factor and the results of Taguchi's method and ANOVA were compared.

3. Experimental Program

3.1. Factors and Their Levels

The present study aimed at obtaining the optimum levels of different factors affecting the fresh and hardened properties of alkali-activated GGBS-based geopolymer concrete incorporated with polypropylene fibers. The Taguchi method was adopted for the optimization of process parameters of factors influencing the properties (responses) of fresh concrete, viz., workability and hardened concrete, and compressive and flexural strengths. Three factors and three levels were selected for optimization by the Taguchi method. Three factors were taken as the alkali activators ratio ($NaOH$:Na_2SiO_3), percentage of GGBS (or % replacement of cement), and percentage of polypropylene fibers by total weight of binding material. The three levels, as per the discussion made in the introduction section, were taken as 1:1.5 (8 Molar NaOH), 1:2 (10 Molar NaOH), 1:2.5 (12 Molar NaOH) for alkali ratio; 80%, 90%, and 100% for the percentage of GGBS; and 1.5%, 2%, and 2.5% for the percentage of polypropylene fibers, as given in Table 8. Many of the past studies, as discussed in Section 1, have adopted the total weight of the concrete as the basis for the percentage of polypropylene fibers, which is quite an inefficient and inaccurate method of gauging the amount of polypropylene fiber. Therefore, in this study, the percentage of polypropylene fibers is taken with respect to the total weight of the binding materials. Thus, in the present study, 2.5% of polypropylene fibers by total weight of binding material is approximately 0.6% of polypropylene fibers by total weight of concrete. Keeping in mind the strength and durability parameters, a fixed water-binder ratio of 0.35 was chosen.

Table 8. Factors and their levels.

Factors	Levels		
	1	2	3
Alkali-Activators Ratio ($NaOH$:Na_2SiO_3)	1:1.5 (8 Molar NaOH)	1:2 (10 Molar NaOH)	1:2.5 (12 Molar NaOH)
% of GGBS	80%	90%	100%
% of Polypropylene Fiber	1.5%	2%	2.5%

A control mix corresponding to the M25 concrete mix was designed for a water-binder ratio of 0.35 as per IS 10262:2009 [67], and the quantity of the constituent materials was derived as 563.31 kg/m^3 of cement, 698.07 kg/m^3 of fine aggregates, 911.14 kg/m^3 of coarse aggregates, and 197.16 kg/m^3 of water.

L9 orthogonal array was used to obtain design mixes for the three-factor and three-level design of experiments. A typical L9 orthogonal array given by Taguchi is given in Table 9. Nine mixes, thus obtained, were used to produce concrete specimens for workability, and compressive and flexural strengths tests. All the replacements of cement with GGBS and addition of polypropylene fibers were undertaken with respect to the control mix. The composition along with the quantities of each material for each mix is given in Table 10.

Table 9. A typical Taguchi's L9 orthogonal array.

Mix	Control Factors (CF) and Their Levels			
	CF1	CF2	CF3	CF4
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Table 10. Mixes obtained as per Taguchi's L9 orthogonal array and quantities of materials for each mix.

Mix No.	Factor A (Alkali Ratio)	Factor B (% of GGBS)	Factor C (% of PPFibers)	Alkali Ratio	% of GGBS	% of PPFibers	Cement (kg/m^3)	GGBS (kg/m^3)	PP Fibers (kg/m^3)	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)
M1	1	1	1	1:1.5 (8 Molar)	80	1.5	112.66	450.65	8.45	698.07	911.14
M2	1	2	2	1:1.5 (8 Molar)	90	2	56.33	506.98	11.27	698.07	911.14
M3	1	3	3	1:1.5 (8 Molar)	100	2.5	0.00	563.31	14.08	698.07	911.14
M4	2	1	2	1:2 (10 Molar)	80	2.5	112.66	450.65	14.08	698.07	911.14
M5	2	2	3	1:2 (10 Molar)	90	1.5	56.33	506.98	8.45	698.07	911.14
M6	2	3	1	1:2 (10 Molar)	100	2	0.00	563.31	11.27	698.07	911.14
M7	3	1	3	1:2.5 (12 Molar)	80	2	112.66	450.65	11.27	698.07	911.14
M8	3	2	1	1:2.5 (12 Molar)	90	2.5	56.33	506.98	14.08	698.07	911.14
M9	3	3	2	1:2.5 (12 Molar)	100	1.5	0.00	563.31	8.45	698.07	911.14

3.2. Mixing

For analyzing the results of compressive and flexural strength testing, three specimens were created for each mix for each of the following responses. To evaluate the compressive and flexural strengths of GGBS-based geopolymer concrete mixes incorporated with polypropylene fibers in accordance with IS 516:1959 [68], cube specimens of size 150 mm and beam specimens measuring 150 mm × 150 mm × 700 mm were made, respectively.

The process of preparation of concrete as described in IS 516:1959 was adopted for the manufacture of geopolymer concrete. For each mix, binder, fine aggregates, coarse aggregates, and polypropylene fibers were weighed as per the respective mix and then dried mix by machine mixing as per the calculated quantities of materials given in Table 10. For this, the skip is loaded with half of the coarse aggregates with the subsequent addition of fine aggregates, cement (if any), GGBS, and polypropylene fibers, and lastly with the remaining half of the coarse aggregates at the top followed by water with alkali activator solution.

An 8 molar NaOH solution was obtained by dissolving 320 gm (8 M × 40 gm/mol) of NaOH flakes in 1 L of distilled water to form a 1 L solution. Similarly, 10 molar and 12 molar NaOH solutions were obtained by dissolving 400 gm (10 M × 40 gm/mol) and 480 gm (12 M × 40 gm/mol) of NaOH flakes in 1 L of distilled water, respectively. The alkali activator solution was then obtained by mixing NaOH and Na_2SiO_3 in the required mass ratio. For example, in an alkali ratio ($NaOH:Na_2SiO_3$) of 1:1.5 (8 M NaOH), the mass of Na_2SiO_3 will be 1.5 times the mass of NaOH added for 8 M NaOH and so on for other ratios. All the constituent materials in the drum are then mixed until the resulting concrete is uniform in appearance, with the period of mixing being not less than 2 min.

3.3. Preparation of Specimens and Testing

By using the compaction factor test in accordance with IS 1199-1959 [69], the prepared concrete was immediately evaluated for workability. Cubes with side dimensions of 150 mm were cast for the compressive strength test. Three layers of concrete, each about 5 cm thick, were poured into the mold. Each mold was compacted fully with the help of a vibrating table without segregation or excessive laitance. The surface of the concrete in the mold was then troweled to an even finish and covered with a plastic sheet to prevent evaporation. The molds were then opened after 24 h and kept submerged in water having a temperature of 27 ± 2 °C for curing before being tested for compressive strength at 7 and

28 days. To evaluate the flexural strength of concrete, beams measuring 700 mm × 150 mm × 150 mm were cast. The filling, compacting, and curing of the concrete were performed in the same manner as those adopted for the fabrication of cubes.

According to the procedure outlined in IS 516:1959, a compression test was performed on the cube specimens at 7 and 28 days in the digital compression-testing machine, and a third-point loading test or two-point loading test with the help of a digital flexural testing machine was performed on the beam specimens at 28 days. The findings of the workability, compressive and flexural strength tests performed on the nine mixes are covered in Section 4 provided below. It also discusses the results of Taguchi and ANOVA analysis.

4. Results and Discussion

This section presents the results of the workability, and compressive and flexural strength tests conducted on the control mix and the nine mixes as obtained by L9 orthogonal together with the analysis of the results of the Taguchi method and ANOVA. A discussion is then made based on the obtained results. The nine mixes correspond to different levels of the three factors, viz., alkali- activators ratio, % of GGBS (or % replacement of cement), and % of polypropylene fibers. Table 11 presents the results of the test conducted on the prepared test specimens.

Table 11. Test results for workability, compressive and flexural strength.

Name of Mix	Alkali-Ratio ($NaOH:Na_2SiO_3$)	% of GGBS	% of PP Fibers	Workability (Compaction Factor)	Average Compressive Strength at 7 Days (MPa)	Average Compressive Strength at 28 Days (MPa)	Average Flexural Strength at 28 Days (MPa)
Control Mix (M25)	-	-	-	0.92	18.28	25.48	3.43
M1	1:1.5 (8 Molar)	80	1.5	0.70	14.35	17.64	2.71
M2	1:1.5 (8 Molar)	90	2	0.69	8.67	10.48	2.19
M3	1:1.5 (8 Molar)	100	2.5	0.63	9.05	11.19	2.26
M4	1:2 (10 Molar)	80	2.5	0.74	15.87	23.74	3.39
M5	1:2 (10 Molar)	90	1.5	0.71	13.86	16.52	2.68
M6	1:2 (10 Molar)	100	2	0.67	5.28	9.09	1.99
M7	1:2.5 (12 Molar)	80	2	0.71	10.84	12.29	2.50
M8	1:2.5 (12 Molar)	90	2.5	0.70	14.38	18.30	2.39
M9	1:2.5 (12 Molar)	100	1.5	0.64	10.15	11.33	2.61

4.1. Workability

Table 11 displays the results of the compaction factor test for the workability of various concrete mixtures examined in the current study and Figure 3 depicts the variation in the compaction factor for different mixes. M4 mix with a compaction factor of 0.74 and with an alkali activator ratio of 1:2 (10 molar), a % of GGBS as 80%, and a % of polypropylene as 2.5% exhibited the highest workability of all the mixes. While M3 mix with a compaction factor of 0.63 and with an alkali activator ratio of 1:1.5 (8 molar), a % of GGBS as 100%, and a % of polypropylene as 2.5% showed the lowest workability of all the mixes.

However, the workability of all nine mixes decreased as compared to the workability of the control mix, which was found to be 0.92. The angular shape of GGBS particles is responsible for the reduction in workability [70,71]. The influences of the other two factors, viz., alkali ratio and percentage of polypropylene factors are, however, also responsible for varied workability. These factors affect the rheology of the geopolymer mix and make it different from that of an OPC mixture. Because of this, the conventional workability test results do not correspond to the workability results of the OPC mixture [70]. It was also observed that the decrease in workability is more pronounced at higher levels of GGBS content. This observation is in resonance with the test results conducted by researchers in the past who attributed the decrease to the angular shape of the GGBS particles and the rheology of the geopolymer concrete [70,72]. The decrease in workability due to the increase in the percentage of GGBS can also be attributed to the well-established fact that the higher the slag content, the higher the rate of setting [73]. The higher rate of setting decreases the workability because of the higher rate of loss of plasticity.

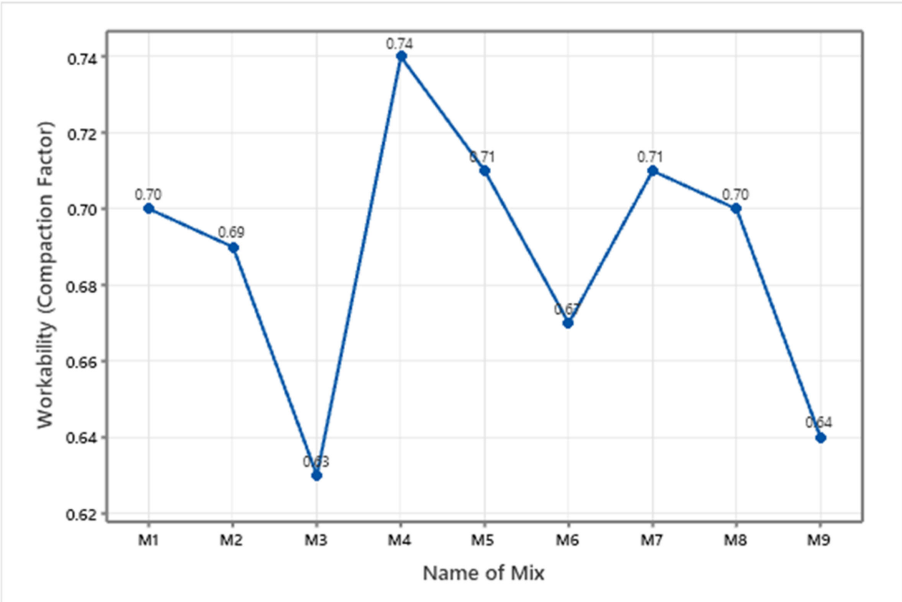

Figure 3. Variation in workability (compaction factor) for nine mixes.

The sodium hydroxide to sodium silicate ratio was also observed to affect the workability of the mixes. Sodium silicate is more viscous as compared to sodium hydroxide, thus increasing the ratio results into an increase in the viscosity of the geopolymer mix. This leads to a decrease in the workability of the mix with a higher alkali activator ratio. Previous studies have shown a decreasing trend in workability with an increase in the alkali ratio [70]. However, the present study revealed that for all the mixes, workability increased when the alkali ratio was increased from 1:1.5 to 1:2, but decreased when further increased to 1:2.5. This indicates a potential influence of the percentage of GGBS, percentage of PP fibers, and alkali ratio on the workability leading to the deviation from the results found in the past [70]. Another aspect of explaining the decrease in the workability due to an increase in the alkali ratio from 1:2 to 1:2.5 is the accelerated polymerization process due to an increase in the amount of soluble silica resulting from an increase in the alkali ratio. Because soluble silica speeds up the condensation of the dissolved geopolymer precursor, it alters the reaction kinetics and crystallization rate [74]. The moisture content of aggregates, changes in ambient temperature, the amount of time spent mixing, and the degree of a condensation reaction between the binder and alkaline solution, among other factors, can also have an impact on workability.

The maximum and minimum workabilities being exhibited by the mixes both having 2.5% polypropylene fibers reflect the small contribution of polypropylene fibers in deciding the workability of the GGBS-based geopolymer concrete incorporated with polypropylene fibers. This fact is further verified by Taguchi and ANOVA methods.

4.2. Compressive and Flexural Strengths

Table 11 presents the outcomes of the workability, compressive, and flexural tests. The test results of 28 days of compressive and flexural strengths indicate the highest early compressive strength of 15.87 MPa achieved by mixing M4 with a 1:2 (10 molar) alkali ratio, 80% of GGBS, and 2.5% of polypropylene. While M6 mixed with a 1:2 (10 molar) alkali ratio, 100% of GGBS, and 2% of polypropylene exhibited the lowest early compressive strength of all the mixes. These two mixes, M4 and M6, also showed maximum and minimum 28 days of compressive and flexural strengths with compressive strengths of 23.74 MPa and 9.09 MPa and flexural strengths of 3.39 MPa and 1.99 MPa, respectively, as shown in Figure 4.

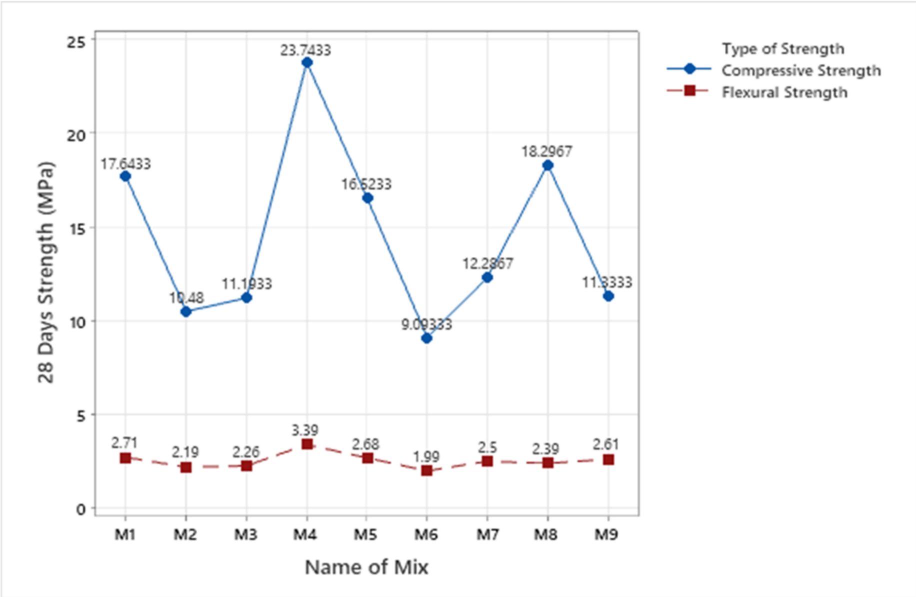

Figure 4. Variation of 28 days compressive and flexural strengths of nine mixes.

The test results of 28 days of compressive and flexural strengths results show a significant decrease in the two strengths. The minimum and maximum decrease of 6.82% and 64.32% was observed for 28 days of compressive strength for M4 and M6 mixes, respectively. The minimum and maximum decrease in the 28 days of flexural strength was observed to be 1.17% and 41.98% for M4 and M6 mixes, respectively. Both the mixes, M4 and M6, have a 1:2 (10 molar) alkali ratio indicating the least contribution of alkali ratio on the compressive strength, which also resonates with the Taguchi and ANOVA results as discussed in Sections 4.3 and 4.4.

The 28 days of compressive and flexural strengths, as shown in Figure 4, show a declining trend in the two strengths with an increase in the percentage of GGBS for all the mixes. This can be attributed to the small specific surface area of GGBS as compared to cement leading to a reduced rate of reaction and hence reduced strength [75]. The hydration products of alkali-activated GGBS are Calcium Aluminosilicate Hydrate (CASH), Calcium Silicate Hydrate (CSH), and Sodium Aluminosilicate Hydrate (NASH). A higher proportion of hydration products of cement mixed with 80% of GGBS combined with hydration products of GGBS leads to greater compressive and flexural strengths as compared to mixes with 90% and 100% of GGBS, which have comparatively a lesser amount of hydration products of cement. However, researchers have concluded that the development of strength in GGBS-incorporated concretes continues at later stages (after 28 days), and is also much more than that of concretes blended with cement [76]. Some of the previous research works employed lesser percentages of GGBS (from 10% to 45%) and reported increased strengths [47,70]. This is in contrast to the higher percentages of GGBS in the present study taken in an effort to replace cement to a greater extent and produce concrete with comparable or greater strengths. In concrete with a lesser percentage of GGBS, the increase in strengths was reported because of a higher CaO content in GGBS, which speeds up polymerization due to the heat released, thus improving the polymeric chain and subsequent progressive development of CSH, CASH, and NASH [47].

The test results are in contrast to the studies conducted on GGBS-based geopolymer concrete, which showed maximum compressive strength at an alkali ratio of 1:1.5 and decreased with the increase in the alkali ratio [47,70]. This indicates a more pronounced effect of the percentage of GGBS on the compressive and flexural strengths, which has been proved by the Taguchi method and further validated by ANOVA in Sections 4.3 and 4.4, respectively. In addition, the effect of the percentage of polypropylene fibers also needs to be considered, which is discussed in Sections 4.3 and 4.4.

Figure 5 shows the failed cube specimens of each mix tested for 28 days of compressive strength and Figure 6 shows the failed beam specimens of each mix tested for 28 days of flexural strength. The compression failure pattern of a material depends on the type of material and the grain structure. Types of compressive failure patterns of concrete include crushing, wedge splitting, shearing, splitting, crushing and splitting, and brooming or end rolling. A compression test on the cube specimens reveals a crushing and splitting pattern to be the most dominant pattern in all the specimens of the nine mixes as well as the control mix.

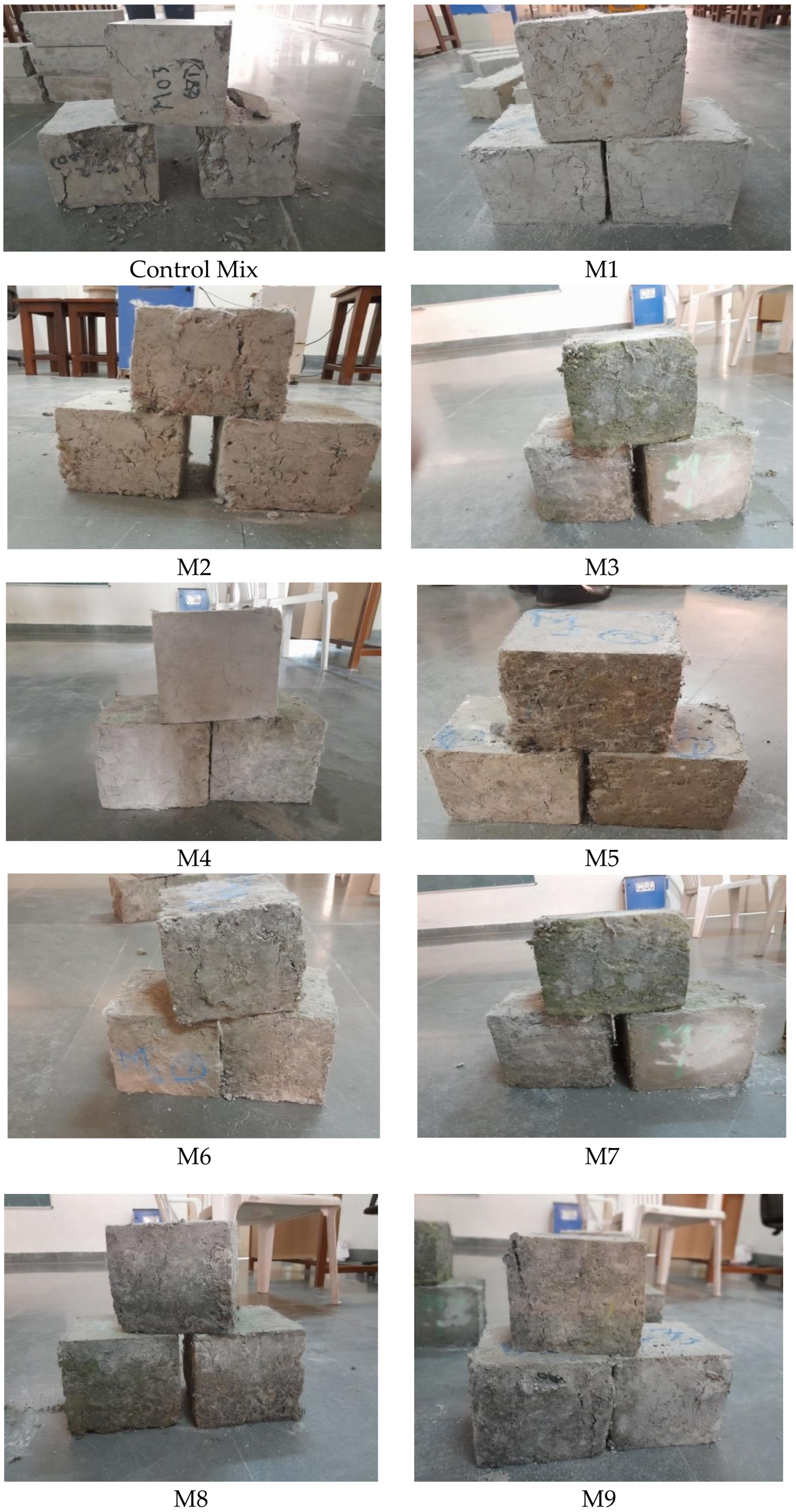

Figure 5. Cube samples after tested for 28 days compressive strength test.

Control Mix

M1

M2

M3

M4

M5

M6

M7

M8

M9

Figure 6. Beam samples after tested for 28 days flexural strength test.

A concrete beam specimen fails either by flexural or by shear. In a two-point loading test for determining flexural strength, the beam can be studied under pure bending due to no shear at the central portion of the beam. The cracks in all the beam specimens initiated in the tension surface were within the middle third of the span length and propagated to the compression zone, thus causing failure of the beam specimens, as is clearly visible in Figure 6. This failure pattern clearly nullifies the possibility of shear failure and confirms the obvious failure due to flexural tension failure.

4.3. Taguchi Method Results

Taguchi's method is utilized to perform the statistical analysis first. Calculated average S/N ratios along with ranks for three levels of three factors for the selected responses, viz., workability, and compressive and flexural strengths are shown in Table 12. The larger-the-better approach was used to determine S/N ratios because maximum workability, and maximum compressive and flexural strengths are the objective functions. In Table 12, the delta values represent the difference between a factor's highest and minimum S/N ratios. While the ratio of delta of each factor to the sum of delta values of all the factors, multiplied by 100, represents the contribution of each factor. The higher the value of delta, the higher the effect of that parameter on the response. The rank of a factor denotes the order of that factor according to the magnitude of the effect on the response.

Table 12. Average S/N ratios (dB) for three levels of three factors for three responses.

Response	Level	Factors		
		Alkali Ratio	**% of GGBS**	**% of Polypropylene Fibers**
Workability	1	−3.445	−2.896	−3.316
	2	−3.023	−3.099	−3.225
	3	−3.316	−3.789	−3.242
	Delta	0.422	0.893	0.091
	Rank	2	1	3
	Contribution	30.01%	63.51%	6.47%
Compressive Strength	1	22.11	24.74	23.46
	2	23.68	23.34	20.46
	3	22.71	20.41	24.58
	Delta	1.58	4.33	4.12
	Rank	3	1	2
	Contribution	15.75%	43.17%	41.08%
Flexural Strength	1	7.517	9.074	8.518
	2	8.381	7.647	6.915
	3	7.953	7.131	8.418
	Delta	0.864	1.943	1.603
	Rank	3	1	2
	Contribution	19.59%	44.06%	36.35%

It is observed from Figure 7 that the % of GGBS is the most effective factor affecting the workability with the highest contribution of 63.51% of the total effect, while the least effective parameter or factor in governing the workability is the % of polypropylene fibers with a contribution of only 6.47%. Compared to the % of GGBS and alkali ratio, the % of polypropylene fibers has the least effect on the workability of alkali-activated GGBS-based geopolymer concrete incorporated with polypropylene fibers. Thus, the rank in terms of effectiveness in decreasing order is found to be the % of GGBS, alkali ratio, and % of polypropylene fibers.

Figure 8 demonstrates the average S/N of all the levels of the three factors for workability. The variation in S/N ratios of each factor is a representation of how each factor affects the response. Furthermore, for the larger-the-better approach in the Taguchi method, the optimum level corresponds to the level with the maximum S/N ratio. Therefore, an alkali ratio of 1:2 (10 molar), % of GGBS = 80%, and % of polypropylene fibers = 2% are determined as the optimum levels of the design parameters for maximum workability and are not among the nine mixes. Apart from the optimum conditions, the worst combination of the factors was found as a 1:1.5 (8 molar) alkali ratio, 100% of GGBS, and 1.5% of polypropylene fibers.

For compressive strength, the percentage of GGBS is again found to be the most effective factor affecting it with the highest contribution of 43.17% followed by the percentage of polypropylene fibers, while the least effective parameter or factor in governing the compressive strength is the alkali ratio with a contribution of 15.75%. Compared to the percentage of GGBS and polypropylene fibers, the alkali ratio has the least effect on the compressive strength. Thus, the rank in terms of effectiveness in decreasing order is obtained to be the % of GGBS, % of polypropylene fibers, and alkali ratio. From Figure 9 it is evident that an alkali ratio of 1:2 (10 molar), % of GGBS = 80%, and % of polypropylene fibers = 2.5% are the optimum levels of the design parameters for maximum compressive strength and corresponds to the M4 mix. The worst combination of the factors was found as a 1:1.5 (8 molar) alkali ratio, 100% of GGBS, and 1.5% of polypropylene fibers.

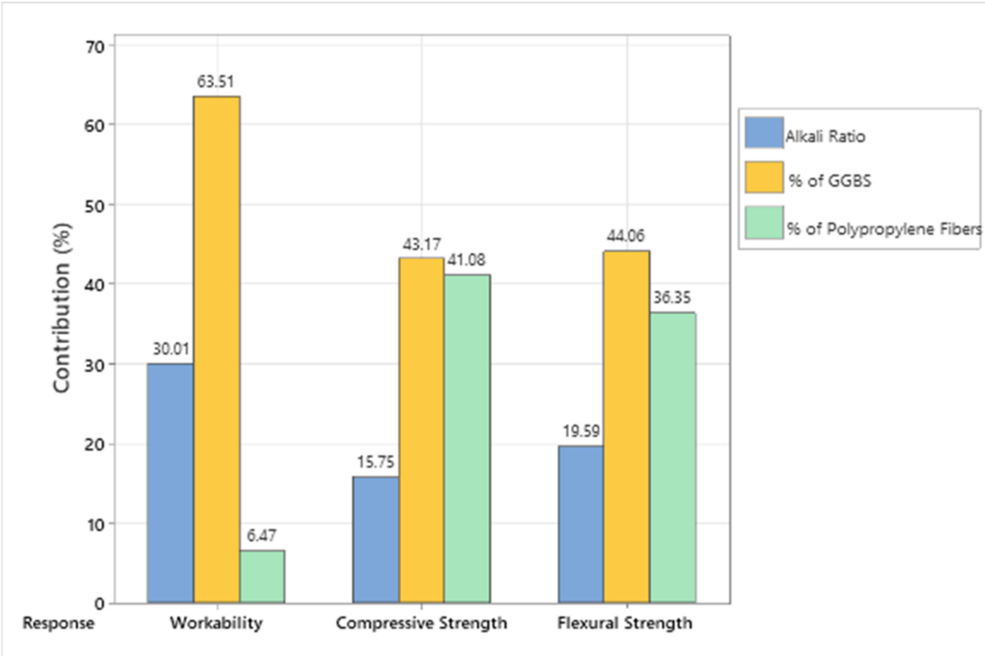

Figure 7. Contribution of each factor to the workability, and compressive and flexural strengths (by Taguchi method).

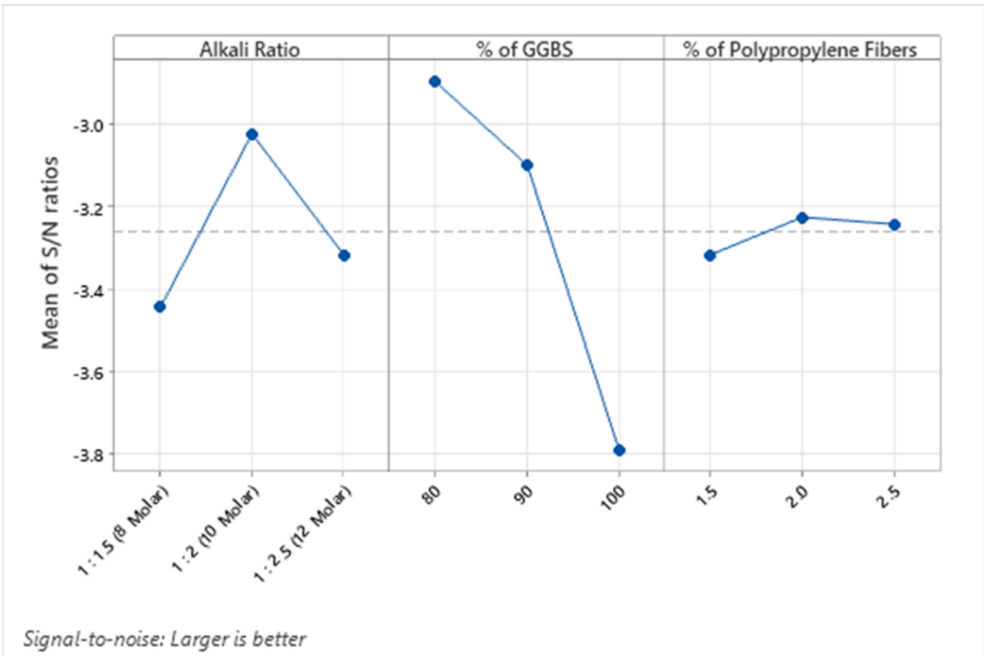

Figure 8. Mean S/N ratios for all levels of three factors for workability.

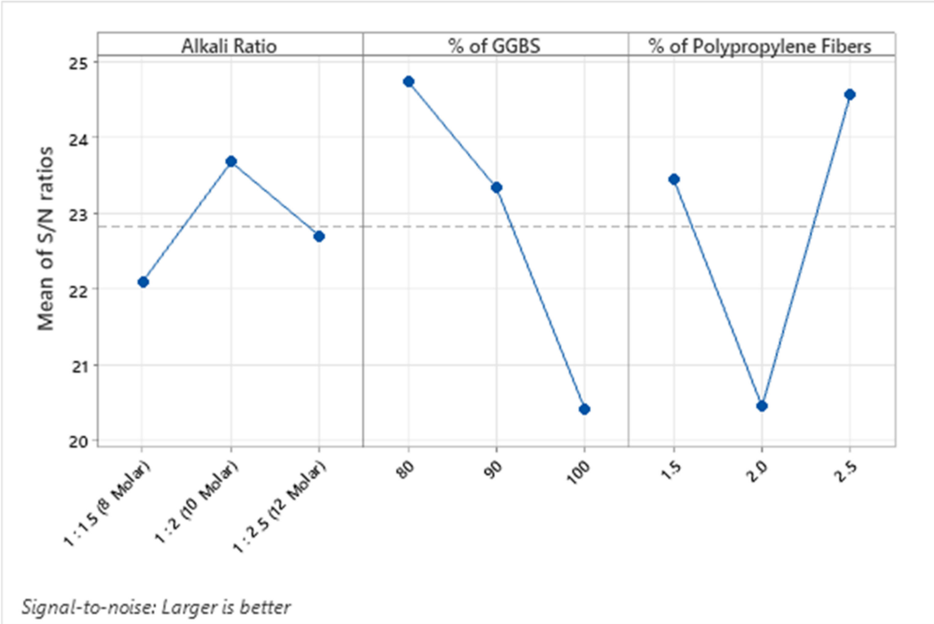

Figure 9. Mean S/N ratios for all levels of three factors for 28 days compressive strength.

The rank, in terms of effectiveness in decreasing order, for flexure strength, was observed to be the same as that for compressive strength with the % of GGBS with the highest contribution of 44.06% followed by the % of polypropylene fibers with a contribution of 36.35% and alkali ratio with the least contribution of 19.59%. The alkali ratio was found to be least effective in affecting compressive and flexural strengths as compared to the % of GGBS and % of polypropylene fibers. An analysis of mean S/N ratios infers the optimum levels to be 1:2 (10 molar) for alkali ratio, 80% for % of GGBS, and 1.5% for % of polypropylene fibers with the worst combination of the factors being the one with 1:1.5 (8 molar) alkali ratio, 100% of GGBS, and 2% of polypropylene fibers, as shown in Figure 10.

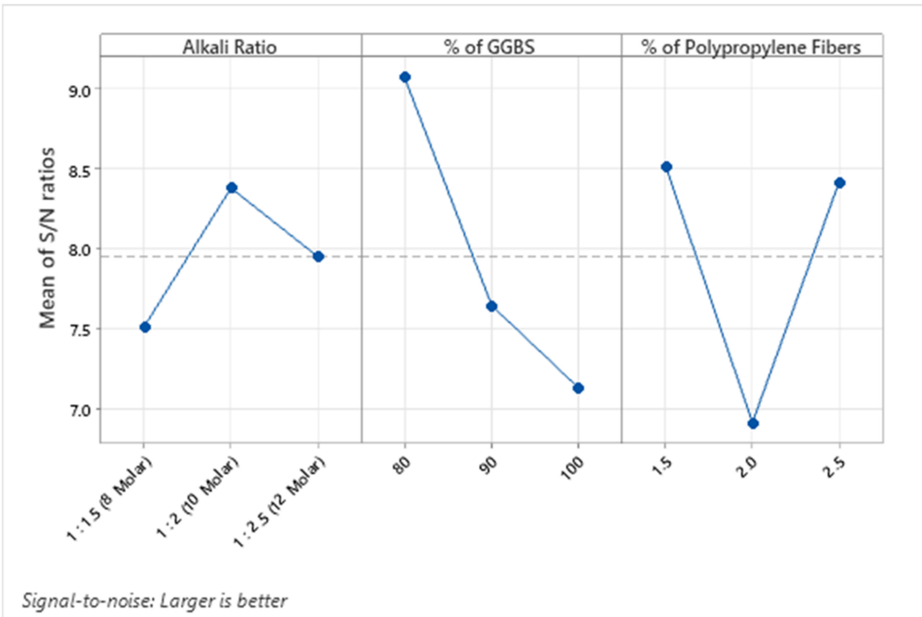

Figure 10. Mean S/N ratios for all levels of three factors for 28 days flexural strength.

The alkali ratio of 1:1.5 (8 molar) and 1:2.5 (12 molar) and the % of GGBS of 90% and 100% were not found to be the optimum level for any of the responses.

4.4. Analysis of Variance (ANOVA) Results

ANOVA was employed as a second statistical tool in addition to the Taguchi method to support the reliability of the results. ANOVA was conducted on the range of each process parameter for workability, and compressive and flexural strengths for these working conditions, as given in Table 13. Figure 11 shows the variation in the contribution of each factor on the responses, thus expressing the magnitude of the impact of a process parameter or factor on the workability, and compressive and flexural strengths. The % of GGBS is found to be the most significant parameter for workability, which has an effect of 80.57%, while the % of polypropylene fibers is the least effective parameter with a contribution of 0.89%. For workability, the order of importance of parameters from ANOVA is % of GGBS > alkali ratio > % of polypropylene fibers. These results are in resonance with the results obtained from the Taguchi method. Hence, it can be concluded that although the contributions of the three factors vary numerically, the order of importance of the parameters remains the same.

Table 13. Average S/N ratios (dB) for three levels of three factors for three responses.

Response	Source	DF	Adj SS	Adj MS	F-Value	*p*-Value	Contribution (%)
Workability	Alkali Ratio	2	0.001756	0.000878	19.75	0.048	17.64
	% of GGBS	2	0.008022	0.004011	90.25	0.011	80.57
	% of Polypropylene Fibers	2	0.000089	0.000044	1.00	0.500	0.89
	Error	2	0.000089	0.000044			
	Total	8	0.009956				
Compressive Strength	Alkali Ratio	2	18.115	9.057	2.89	0.257	9.79
	% of GGBS	2	82.623	41.311	13.18	0.071	44.64
	% of Polypropylene Fibers	2	78.075	39.037	12.46	0.074	42.18
	Error	2	6.268	3.134			
	Total	8	185.080				
Flexural Strength	Alkali Ratio	2	0.1377	0.06884	0.65	0.605	10.58
	% of GGBS	2	0.5537	0.27684	2.63	0.276	42.55
	% of Polypropylene Fibers	2	0.3993	0.19964	1.90	0.345	30.69
	Error	2	0.2106	0.10528			
	Total	8	1.3012				

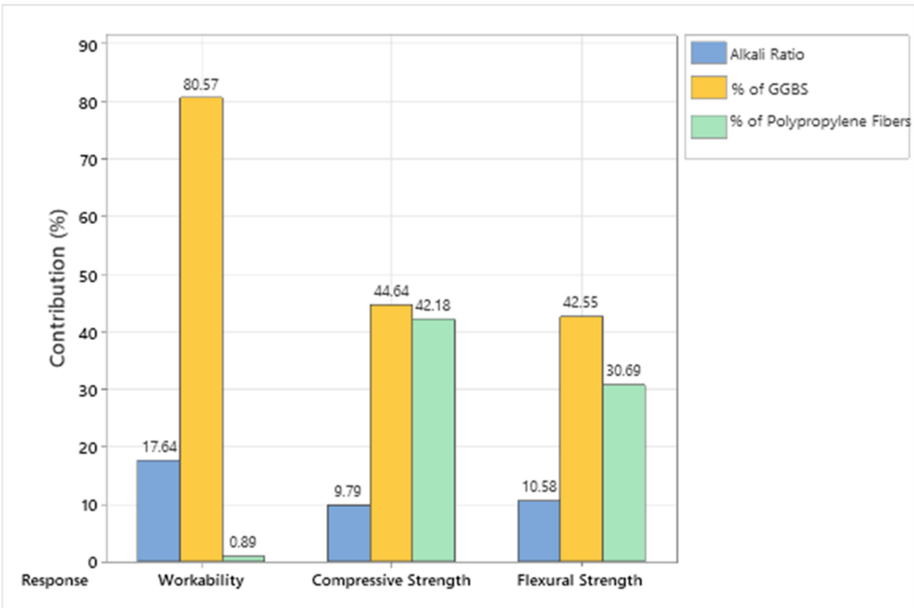

Figure 11. Contribution of each factor to the workability, and compressive and flexural strengths (by ANOVA).

4.5. Confirmation Tests

Based on the examination of the S/N ratio, the optimum levels of the control parameters were established. The Taguchi method involves performing a confirmation experiment for validating the predicted responses for the optimized levels of each factor. Minitab software was used to predict the responses for each of the optimal conditions obtained by the Taguchi method. The predicted optimum quality characteristics are presented in Table 14. The same optimal conditions were verified with the help of regression equations obtained by ANOVA, conducted on Minitab software, for each of the responses or quality characteristics. The regression equations obtained for workability, and compressive and flexural strengths are given by Equations (2)–(4), respectively.

$$\begin{aligned} Workability = {} & 0.68778 - 0.01444\ Alkali\ Ratio\ (1:1.5\ (8\ Molar)) \\ & + 0.01889\ Alkali\ Ratio\ (1:2\ (10\ Molar)) \\ & - 0.00444\ Alkali\ Ratio\ (1:2.5\ (12\ Molar)) \\ & + 0.02889\ (80\%\ of\ GGBS) + 0.01222\ (90\%\ of\ GGBS) \\ & - 0.04111\ (100\%\ of\ GGBS) \\ & - 0.00444\ (1.5\%\ \text{of}\ Polypropylene\ Fibers) \\ & + 0.00222\ (2\%\ \text{of}\ Polypropylene\ Fibers) \\ & + 0.00222\ (2.5\%\ \text{of}\ Polypropylene\ Fibers) \end{aligned} \tag{2}$$

$$\begin{aligned} & Average\ 28\ Days\ Compressive\ Strength \\ & = 14.510 - 1.405\ Alkali\ Ratio\ (1:1.5\ (8\ Molar)) \\ & + 1.943\ Alkali\ Ratio\ (1:2\ (10\ \text{Molar})) \\ & - 0.538\ Alkali\ Ratio\ (1:2.5\ (12\ Molar)) \\ & + 3.381\ (80\%\ of\ GGBS) + 0.590\ (90\%\ of\ GGBS) \\ & - 3.97\ (100\%\ of\ GGBS) \\ & + 0.656\ (1.5\%\ of\ Polypropylene\ Fibers) \\ & - 3.890\ (2\%\ \text{of}\ Polypropylene\ Fibers) \\ & + 3.234\ (2.5\%\ of\ Polypropylene\ Fibers) \end{aligned} \tag{3}$$

$$\begin{aligned} & Average\ 28\ Days\ Flexural\ Strength \\ & = 2.524 - 0.138\ Alkali\ Ratio\ (1:1.5\ (8\ Molar)) \\ & + 0.162\ Alkali\ Ratio\ (1:2\ (10\ Molar)) \\ & - 0.024\ Alkali\ Ratio\ (1:2.5\ (12\ Molar)) \\ & + 0.342\ (80\%\ of\ GGBS) - 0.104\ (90\%\ of\ GGBS) \\ & - 0.238\ (100\%\ of\ GGBS) \\ & + 0.142\ (1.5\%\ of\ Polypropylene\ Fibers) \\ & - 0.298\ (2\%\ of\ Polypropylene\ Fibers) \\ & + 0.156\ (2.5\%\ of\ Polypropylene\ Fibers) \end{aligned} \tag{4}$$

Equations treats random terms as though they are fixed.

The optimum quality characteristic or response for the optimal levels of the factors is obtained by using regression equations by adding the constants of only the optimum levels of all the factors of that particular response. For example, the optimum levels for workability were obtained as a 1:2 alkali ratio, 80% GGBS, and 2% polypropylene fibers. So, the optimum workability is obtained by adding 0.68778, the coefficient of the 1:2 alkali ratio, i.e., 0.01889, the coefficient of 80% GGBS, i.e., 0.02889, and the coefficient of 2% polypropylene fibers, i.e., 0.00222, which, upon addition, will give optimum workability of 0.73778. Similarly, the optimum values of compressive and flexural strengths for the optimum conditions are found to be 23.0681 MPa and 3.17111 MPa, respectively.

The predicted optimum quality characteristics by the Taguchi method and by the regression equation were found to be the same. To verify that the experimental results corresponded to the predicted outcomes, a confirmation test for the optimum settings of the control factors was carried out. The confirmation tests reflected the agreement between the two values as shown in Table 14. The results of the compressive and flexural strength confirmation tests are equivalent to those of the control mix, demonstrating the achievement of mixes with cement substituted by GGBS.

Table 14. Results of confirmation tests for three responses.

Response	Prediction of Optimum Quality Characteristics	Experimental Value
Workability	0.74	0.75
Compressive Strength (MPa)	23.07	24.12
Flexural Strength (MPa)	3.17	3.25

5. Conclusions

Taguchi's optimization technique is explored in this article to obtain the optimal levels of the control parameters of the alkali-activated GGBS-based geopolymer concrete incorporated with polypropylene fibers on the chosen responses, viz., workability, and compressive and flexural strengths. The controlling parameters chosen are the alkali activator ratio ($NaOH:Na_2SiO_3$), percentage of GGBS (or % replacement of cement), and percentage of polypropylene fibers. Study was also conducted to determine the contribution (%) and the order of importance of the factors by Taguchi. The results were checked for reliability through ANOVA. The following conclusions were drawn from the current study:

1. The workability of all the nine mixes decreased as compared to the workability of the control mix, which was found to be 0.92. M4 mix with a compaction factor of 0.74 and with an alkali activator ratio as 1:2 (10 molar), % of GGBS as 80%, and % of polypropylene as 2.5% exhibited the highest workability of all the mixes. While M3 mix with a compaction factor of 0.63 and with an alkali activator ratio as 1:1.5 (8 molar), % of GGBS as 100%, and % of polypropylene as 2.5% showed the lowest workability of all the mixes.
2. The 28 days of compressive and flexural strength results show a decrease in the two strengths as compared to the compressive and flexural strengths of the control mix, which were found to be 25.48 MPa and 3.43 MPa, respectively. M4 mixed with a 1:2 (10 molar) alkali ratio, 80% of GGBS, and 2.5% of polypropylene fibers, and M6 with a 1:2 (10 molar) alkali ratio, 100% of GGBS, and 2% of polypropylene, showed a maximum and minimum 28 days of compressive and flexural strengths with compressive strengths of 23.74 MPa and 9.09 MPa and flexural strengths of 3.39 MPa and 1.99 MPa, respectively. The minimum and maximum decrease of 6.82% and 64.32% for 28 days compressive strength and 1.17% and 41.98% for 28 days of flexural strength was observed for M4 and M6 mixes, respectively.
3. The results obtained from Taguchi and ANOVA resonate with each other with the percentage contribution varying numerically but with the same rankings of the parameters. The rank of the factors for workability is % of GGBS > alkali ratio > % of polypropylene fibers, while for compressive and flexural strengths, it is % of GGBS > % of polypropylene fibers > alkali ratio. The most effective parameter for all three responses is revealed as the % of GGBS.
4. Taguchi and ANOVA eliminate any significant impact of the percentage of polypropylene fibers on the workability and alkali ratio on the compressive and flexural strengths.
5. The optimum level for different factors corresponds to a 1:2 (10 molar) alkali ratio, 80% GGBS, and 2% polypropylene fibers for workability; a 1:2 (10 molar) alkali ratio, 80% GGBS, and 2.5% polypropylene fibers for compressive strength; and 1:2 (10 molar) alkali ratio, 80% GGBS, and 1.5% polypropylene fibers for flexural strength.
6. The confirmation test verified the experimental results to the predicted optimum quality characteristics at the optimum levels of the process parameters identified through analysis. The experimental values of the confirmation tests resonate with the values for the control mix with 100% cement content, thereby suggesting the pertinence of the study leading to a sustainable concrete, which has less embodied

energy, as proposed by different researchers and mentioned in the introduction section, followed by achievement of the sustainable goals.

Hence, the study assists in determining the optimal levels of the three factors for the three responses and helps in a better understanding of how the controlling factors affect the workability, and compressive and flexural strengths. Hence, to identify the key factor and choose the best concrete mix, it is possible to utilize the results of this study's statistical analyses as a guide. Additionally, it is demonstrated that both fresh and hardened properties of concrete can be tuned for an optimal response for a given set of controlling process parameters or factors.

Due to the variability in the quality and composition of the source materials and alkali activators, as well as the difference in the testing codes of different countries, the exact reproducibility of the test specimens becomes difficult. Hence, the predictability and comparison of the results with the available research data become very difficult. Moreover, regardless of the sustainable and environmental benefits of geopolymer concrete, the high cost of alkali activators might become a barrier to the adaptability of geopolymer concrete at a commercial level.

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