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Taguchi-optimized triple-aluminosilicate geopolymer bricks with recycled sand: A sustainable construction solution

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ABSTRACT

Rapid infrastructure development has led to an enormous demand for cement and a huge production of construction and demolition (C&D) waste. The ever-growing demand for cement is leading to a very high amount of CO_2 emissions in the atmosphere. This research article focuses on addressing these two major issues of CO_2 emission and inadequate handling of C&D waste by developing novel geopolymer bricks by utilizing the three-aluminosilicate waste materials, which includes rice husk ash (RHA), ground granulated blast furnace slag (GGBS), and red mud, and using recycled washed sand as filler. Taguchi's method was used to develop the geopolymer mix design by making use of four factors, i.e., binder percentage with six levels and three levels for alkaline solutions, sodium silicate/sodium hydroxide (SS/SH), and alkaline to binder ratio(A/B). A novel approach is adopted for preparing the alkaline solution using three different techniques which are highlighted in this research study. The compressive strength and water absorption were tested, and the optimum percentage of mix was found with B5 binder, which includes 60 % RHA, 20 % GGBS, and 20 % red mud with an alkaline solution of A2, SS/SH as 2, and alkaline/binder as 0.45. The maximum compressive strength found to be 27.34 MPa, and the minimum water absorption was also recorded at this combination, which was 5.68 %. The compressive strength and water absorption were negatively correlated with a degree of 96 % found by using the parametric map. Desirability analysis and statistical analysis using ANNOVA techniques were used to discover the optimum percentage. Microscopic analysis was performed on the highest and lowest values of the L18 design of the experiment by Taguchi's method. Along with this, a clustering algorithm was used to evaluate the scanning electron microscope (SEM) images. The overall research study suggested that the percentage of binder and alkaline solution were the governing factors for the properties of geopolymer bricks.

1. Introduction

Based on a 2017 projection by the United Nations, the global population is projected to expand by 30 % and reach 9.8 billion people by 2050, compared to the population in 2017 [1,2] with the increasing population the need and pressure on the existing resources is increasing tremendously. As population increase their need for food, infrastructure, health, and education also increases [3]. With an

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enhanced demand of infrastructure, the consumption of cement hit 355.46 million tonnes in 2022 and is projected to rise to 450.78 million tonnes by the end of 2027 [4,5]. India is the second-largest cement producer in the world, with more than 7 % of global cement production capacity, according to research on the country's cement sector. Domestic cement output increased to 356 million tonnes in 2022 from 296 million tonnes in 2021 [4,6]. With the well-known fact associated with cement production that manufacturing of 1 tons of cement leads to 1 tons of CO_2 emission and different report published has recorded that cement industry has almost 8 % of share in overall atmospheric CO_2 emission of planet Earth [7]. With this rising concern of cement industry stakeholders, researcher, builders, construction workers, contractors everyone is looking and suggesting an alternative and sustainable solution [8]. One upcoming prominent solution of sustainable building binding material is geopolymer cement or binder which is produced by a chemical reaction which involves the utilization of alkaline solution formulated with Sodium hydroxide (NaOH)/Potassium hydroxide (K0H) and Sodium silicate (Na_2SiO_3)/Potassium Silicate(K_2SiO_3) mixed with aluminosilicate waste material like fly ash, GGBS, RHA, Red Mud, Metakaolin, bottom ash etc [9–11]. Geopolymer research is being quite prominent in ASIAN countries especially in INDIA [12].

The sialate monomer repeating units -(Si-O-Al-O-)-that are formed during geopolymerization are repeated in geopolymers [13–15]. The solidification of the geopolymer binder in geopolymer processes essentially occurs in six phases [16,17]. In the first, aluminosilicate materials are alkalinized to aid in their dissolution and depolymerization, allowing free [SiO4]- and [AlO4]-tetrahedral units to separate and gets released into the solution. These unbound [SiO4]- and [AlO4]-tetrahedral units bind oxygen atoms, which leads to the formation of geopolymeric precursors which are in the form of (-Si-O-Al-O-)-sialates linkage. The six main steps in the geopolymer solidification process which includes alkalination, silicate depolymerization, oligo-sialate gel formation, polycondensation, reticulation, and solidification—are described in Fig. 1 [18–20].

The water released during the geopolymerization process [21] is similar to the chemical reaction that occurs during the cement hydration reaction of regular Portland cement and contributes to the workability of the geopolymer binder mix. Eqs. (1) and (2) explain the water release process, as shown below [1,22].

$$(Si_2O_5Al_2O_2)_n + H_2O + OH^- \rightarrow Si(OH)_4 + Al(OH)^{4-} \quad (1)$$

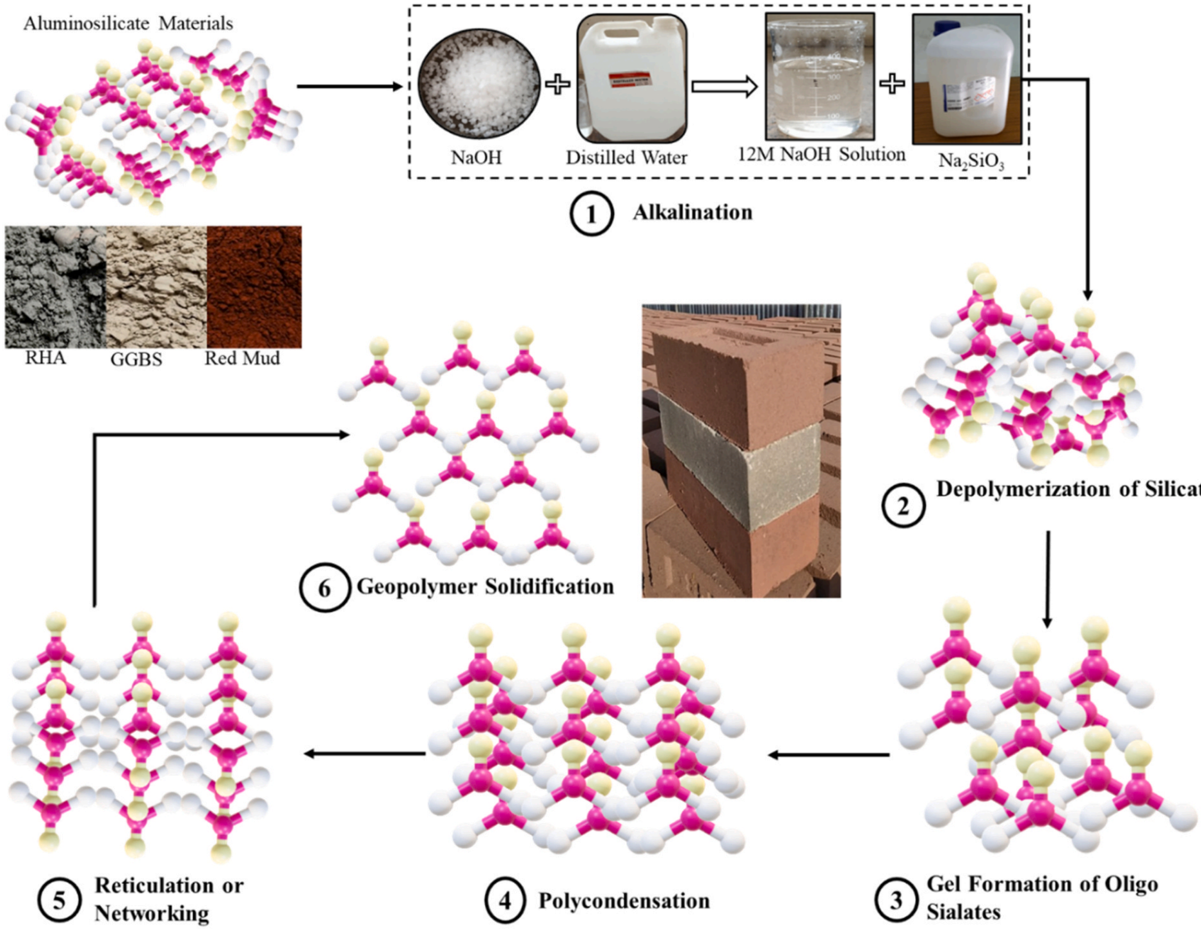


Fig. 1. Mechanism Involved in Geopolymer Chemical Reaction.

Table 1
A comprehensive Overview of different Industrial waste combination used for making geopolymer binder.

Authors	Precursors Used	Summary	Characteristics Measured	Days	Main Findings	Reference
Nguyen et al., 2018	Red Mud and Rice Husk Ash (RHA)	Geopolymer specimens showed high heat resistance and an increase in compressive strength after exposure to high temperature	•Compressive Strength •Volumetric Weight •Heat Resistance	28	Compressive strength at 28 days in the range of 5.86 to 25.45 MPa, increase of compressive strength from 36% to 166% after exposure to high temperature	[31]
A. N. Raut, Murmu, et al., 2023	fly ash, RHA, bottom ash	The essential parameter that controls the porosity and water absorption is the replacement level of FA with either RHA and BA, as well as the molarity of sodium hydroxide.	•Compressive Strength •Porosity •water absorption •microstructural Study	28	The findings demonstrate that the geopolymer produced has a decreased thermal conductivity in comparison to conventional bricks, along with reduced water absorption and porosity values.	[32]
Mehta & Siddique, 2018	GGBS and RHA	Compressive and split tensile strengths were enhanced with the addition of up to 15% rice husk ash throughout at every specified range.	•Compressive Strength •Split Tensile Strength •Chloride Permeability •Sorptivity	90	The addition of RHA up to 15% results in an enhancement in compressive and split tensile strength, as well as a decrease in chloride permeability and sorptivity, at all phases of development.	[33]
A. Raut, Singh, et al., 2023	waste glass and oil palm industry waste	This research aimed to create a sustainable brick with improved insulation and less environmental effect, enhancing thermal comfort. The created bricks met the standard standards for non-load bearing bricks with a strength of 7.21 MPa.	•Thermal Conductivity •Compressive Strength•microstructural Study	28	Thermal conductivity was determined to be 0.38 W=m^2 K, about 50% higher than normal red clay brick.	[34]
Patel & Shah, 2018	GGBS and RHA	The optimum replacement level of the RHA is 5% which results in 2.81% decrease in slump flow value but increases 3.02% compressive strength compare to results of 100% GGBFS SCGC mix.	•Workability of Fresh Scgc (Assessed by Slump Flow, V Funnel, L Box, And J Ring Test Methods) •Mechanical Properties Such as Compressive Strength, Split Tensile Strength, And Flexural Strength.	3, 7, and 28	2.81% decrease in slump flow value and 3.02% increase in compressive strength	[35]
Thang et al., 2018	Red mud and RHA	Red mud and rice husk ash were used to generate heat-resistant geopolymer materials with compressive strengths of 6.8 to 15.5 MPa after 28 days and an increase in compressive strength from 262% to 417% following high temperature exposure.	•Compressive Strength •Volumetric Weight •Heat Resistance	28	An increase of compressive strength from 262% to 417% after exposure to high temperature	[36]
Abbass et al., 2021	RHA, GGBS and Fly Ash	Compressive strength increased by 5.13% and 5.6% after 7 and 20 days with coconut fibre concentration of 0.2% of binder material, whereas at 0.4, it decreased by 0.42% and 0.7%. Split tensile and flexural strength improved with 0.2% coconut fiber, then decreased.	•Compressive Strength •Split Tensile Strength •Flexural Strength	2	Compressive strength rose by 5.13% and 5.6% after 7 and 20 days, respectively, using 0.2% coconut fiber in the binder material. Split tensile and flexural strength also improved.	[37]
Annadurai et al., 2020	Rice Husk Ash	Adding RHA to geopolymer concrete lowered initial curing strength and densified the matrix, lowering concrete porosity.	•Strength Properties •Workability •Microstructural Properties	Not mentioned	Adding Rice Husk Ash (RHA) to geopolymer concrete lowered initial curing strength.	[38]
Abdila et al., 2022	fly ash and GGBFS	A mix of fly ash and geopolymers based on GGBFS can be used to successfully stabilize the soil to make it more stable.	•Unconfined Compressive Strength (Ucs)	7 and 28	Geopolymers work well as a binding for methods that stabilize the soil.	[37]
Buyondo et al., 2020	RHA, metakaolin	The goal of this study was to find the best way to make geopolymer cement using response surface methodology (RSM) and reactants such as rice husk ask (RHA), metakaolin (MK), and an alkaline activator.	•Compressive Strength	7 and 14	Geopolymer with an ideal composition of 11.67% RHA, 12.22% MK, and 1.11% 10 M alkaline activator after curing for 7 days at room temperature	[39]

(continued on next page)

Table 1 (*continued*)

Authors	Precursors Used	Summary	Characteristics Measured	Days	Main Findings	Reference
Saravanan & Rao, 2023	Different Industrial wastes were reviewed	The majority of waste materials produced by industry have the potential to be partially used as raw materials for brick production. Standards only require compliance with physical and mechanical properties.	•Physical •Mechanical •Durable •Thermal •Microstructural properties were reviewed	7,14,28 and 90	The manufacturing process of bricks, whether they are fired or unfired, requires the implementation of a new technology in order to use a suitable waste material as a component.	[40]
Wang et al., 2020	Fly ash and GGBS	Initial curing under 80 °C for 12–24 h gives geopolymer recycled aggregate concrete (GRAC) the maximum compressive strength, elastic modulus, and toughness.	•Compressive Strength •Elastic Modulus •Toughness •Poisson Ratio	6, 12 and 24 hours	The toughness, compression strength, and elastic elasticity of GRAC were the best.	[41]
Khan et al., 2021	Copper slag and Fly Ash	Copper slag-incorporated geopolymer mortar was compared to fly ash-based mortar to determine its ideal composition. Copper slag-incorporated geopolymer mortar (CSGM) outperforms fly ash (class F)-based mortar (FAGM) due to optimal factors.	•Flow Value •Setting Time •Compressive Strength •Microstructural Study	28	The CSGM had better strength than FAGM owing to the presence of Ferrous oxide (Fe3þ - 37.41%), which activated alkali. The remaining physical, mechanical, and thermal properties matched those of FAGM.	[42]
A. N. Raut, Adamu, et al., 2023	RHA, fly ash, copper slag, bottom ash and glass powder.	Molar ratio affects performance, with 12 M NaOH solutions performing better mechanically. Other elements including raw ingredients, curing temperature, and NaOH concentration affect strength.	•water absorption •Compressive Strength •Microstructural Study •Thermal conductivity	7, 28, and 90	The results imply that raw materials, curing temperature, and NaOH concentration contribute to strength growth in addition to oxide ratios like Si/Al, Na/Al, and Na/Si.	[43]
Feng et al., 2022	fly ash	Triethanolamine (TEA) may control the initial strength of geopolymer foam by creating uniform pore diameters and spatial distributions, even when the geopolymerization of the structure is delayed.	•Isothermal calorimetry • X-ray •Nuclear magnetic resonance spectroscopy	28	While the specific strength of the geopolymer foam increased from 2271 N/m/kg to 4662 N/m/kg, 0.3% TEA decreased the skeleton's compressive strength by 13.4%, from 105.8 MPa to 91.6 MPa.	[44]
Subash & Adish Kumar, 2021	fly ash, metakaolin, silica fume, GGBS and RHA	243 geopolymer concrete mixes were designed by considering several factors that influence the properties of geopolymer concrete. The results led to the development of a method for estimating the optimal mix fraction for geopolymer concrete.	• Slump •Compressive Strength	7 and 28	This research considers several aspects, such as the proportion of coarse aggregate and mixed aggregate, the ratio of sodium hydroxide to sodium silicate, the concentration of NaOH, and the curing temperature, in order to develop a mix design technique for geopolymer concrete.	[45]

$$Si(OH)_4 + Al(OH)^{4-} \rightarrow -(-Si-O-Al-O-)-_n + 4H_2O \quad (2)$$

The performance of geopolymer reaction includes many variable aspects like nature of precursor, minerology, surface area, fineness nature and strength of alkaline solution and one among the most crucial factor of geopolymerization is the significant amount of amorphous material in the precursor [22–25]. The crystalline and amorphous nature of raw material or precursor can be easily analysed with the help of Xray-Diffraction data analysis the sharp peaks depict the crystalline nature and smooth peak are representative of amorphous material [26]. The importance of amorphous material lies in geopolymerization is due to its nature of quick dissolution and releasing of alumina ions which helps to form a stable geopolymer binder [27,28].

The geopolymer mortar or concrete is a combination of geopolymer binder and filler. This research article primarily focusses on the formation of geopolymer brick [29] by utilizing RHA, GGBS, and red mud RM are employed as a Tri aluminosilicate of precursors, and recycled washed sand from C&D waste is used as filler in this research [30]. Furthermore, Table 1 discussed about the combination of different industrial wastes that has been utilized by different researchers in past.

As per report published by BMPTC India in 2018 on C&D waste in India basically contains 26 % of sand, 32 % of brick & masonry waste, 28 % of concrete waste etc [46]. The C&D waste category in India is shown in Fig. 2. According to Building Material Promotion Council (BMPTC) India, India generates around 150 million tonnes of building and demolition trash each year. [47,48]. So handling and effective utilization of waste is challenging task [49]. Keeping in mind the depleting river sand and increasing demand this research focusses on utilization of recycled washed sand for making the geopolymer brick [50–52]. As our main research is focused on making geopolymer bricks with the same appearance as that of red clay bricks, we have used 3 different aluminosilicate precursors because bricks are one of the most essential components of building aesthetics. As shown in Fig. 3 above with binary blend the bricks look greyish and with addition of red mud the geopolymer bricks appear as similar to red clay bricks.

Researcher in the past has extensively studied about the geopolymer binder with utilizing the combination of one or two aluminosilicate material [53] with different molarity of alkaline solution but very few study focuses on the utilizing the two or more waste material. Sundaravadivelu and Kaliyaperumal [54] covered the optimisation of the geopolymer concrete (GPC) design combination including fly ash, GGBFS, and silica fume. The ideal mixing proportions to meet the necessary strength requirements were calculated using the Taguchi technique [55]. The research took into account four variables: molarity, binder content, superplasticizer dose, and ratio of Na_2SiO_3/NaOH. According to the findings, the ideal synthesis parameters for achieving the highest compressive strength were 45 % FA, 45 % GGBFS, and 10 % silica fume in the binder, together with 1.5 % of superplasticizer, a ratio of 1.5 Na_2SiO_3/NaOH, and a 12-molar content. The Taguchi method worked well in reducing the number of experimental trials necessary to get the desired GPC strength [56]. The research emphasises how crucial it is to choose the parameter for developing the proper mix design for GPC in order to increase its compressive strength. Rihan Maaze & Shrivastava [1] investigate the design of sustainable brick-waste geopolymer bricks [57] utilising complete factorial design approach. The research focuses on utilising brick waste powder as a precursor material derived from building and demolition debris. To discover the best mix, molarity, alkaline solution ratio, and curing temperature were changed by the researchers. Using FESEM-EDS, XRD, FTIR, and TGA techniques, they examined the brick specimens'mechanical and physical properties as well as their microstructure. The findings revealed that molarity, alkaline solution ratio, and curing temperature all had a role in improving the characteristics of the bricks. Dave and Shemal V. [58] examines optimising geopolymer concrete (GPC) mix design using the Taguchi technique. The authors tested GPC's binders, alkaline solution, and plasticizer to find the best mix for strength. The Taguchi approach was employed to efficiently optimize experimental conditions, aiming to minimize the number of trial mixes while achieving the desired geopolymer brick mix design. The research also showed how binder mixture, Na_2SiO_3/NaOH ratio, and NaOH molar percentage affect strength. Compressive strength obtained is 35.38 MPa. Mehta et al. [59] Research examines the effects of various variables on the compressive strength and water absorption capabilities of concrete made from fly ash. The mixtures were optimised using the Taguchi method, and mathematical models were created to predict the qualities. 20 % OPC, 15 M sodium

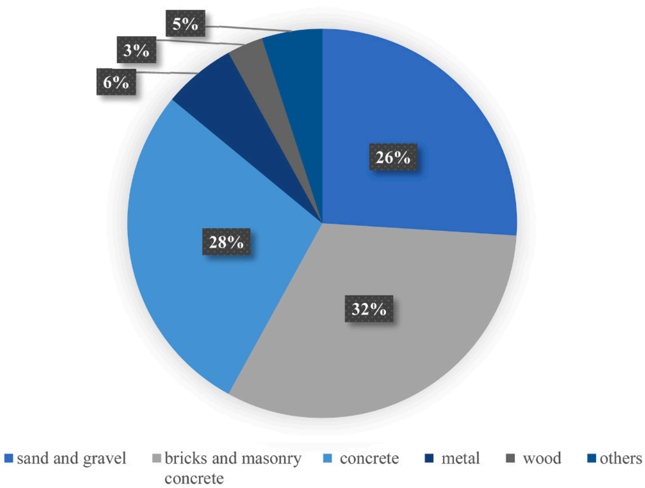


Fig. 2. Type of C&D waste generated in India [46].

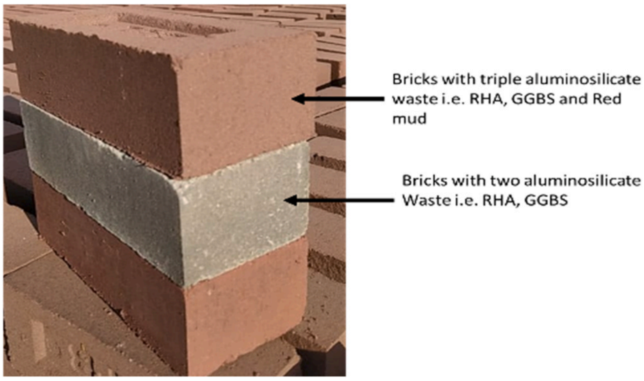


Fig. 3. Colour appearance of geopolymer brick with addition of red mud.

hydroxide, and an 80 °C curing temperature were the best parametric combinations for maximum compressive strength and least water absorption. The experimental results were in good agreement with the existing models. Singh et al. [60] investigated the usage of red mud and fly ash as a geopolymer binder to develop the geopolymer binder in there research. Pulverisation of red mud boosted its lime reactivity value and reactive silica %, according to the study. They also observed changes in the red mud crystallinity and crystal size after pulverisation. The goal of the study was to determine the optimal SiO_2/Al_2O_3 ratio and increase the strength of a red mud-based geopolymer by mechanical activation. The geopolymer synthesised from red mud alone had a poor strength, therefore fly ash and silica-rich industrial waste must be added to boost the strength [61–63].

2. Scope and research significance

The present study emphasised in utilization of different industrial by product which are a source of alumina and silica for the formation of geopolymer binder like RHA, GGBS and Red Mud. The primary objective of this research focuses on the making a combination which utilizes these three available aluminosilicate materials in scientific way by using Taguchi's Optimization for evaluating the two most significant parameters i.e., compressive strength and water absorption. Additionally, this research study also tries to highlight the methodology for making three different ways of preparing alkaline solution. First method is conventional method which is being utilized in most of the research working on geopolymer by preparing NaOH solution 24 h prior to mixing of ingredient, Second method of alkaline solution preparation deals with mixing of Sodium hydroxide and Sodium silicate together and allowing it to

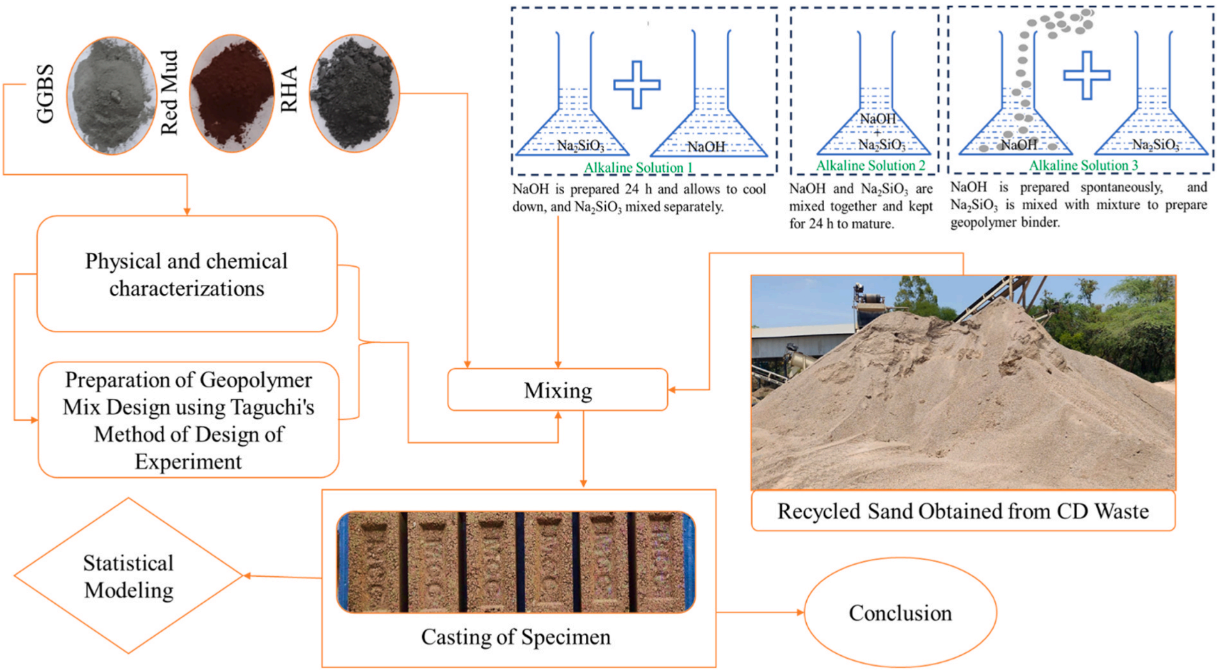


Fig. 4. Flowchart representing the current research methodology used in this research article.

mature together for 24 h, Third way of alkaline solution is quite novel as deals with the immediate preparation of alkaline solution and mixing the ingredient as matter of fact to utilize the heat generation which is involved during NaOH preparation and fast track the geopolymerization reaction as geopolymer reaction is a heat suspectable.

This research study is designed to address the following objectives. 1) Utilization of Taguchi's Optimization for making use of 3 different percussor which are RHA, GGBS and red mud by having 6 different compositions. 2) To study the impact of three different type of alkaline solution preparation techniques having same molarity. 3) To investigate the impact of four key variables on compressive strength and water absorption in a geopolymer mix which include binder (%), alkaline Solution, SS/SH, and alkaline/ Binder. 4) To perform statistical modelling which correlate compressive strength and water absorption with parameters of variability.

For the better understanding of research study, the research methodology flow chart is formulated and expressed in the Fig. 4.

3. Material and mix design

3.1. Raw material

The raw materials were collected from the local available sources from region of Punjab and Chandigarh. RHA is one of the major concerns in region of Punjab and is available abundantly. Geopolymer binder performance is greatly influenced by the choice of the appropriate material. GGBS is the additional precursor employed in this investigation and it is produced by quenching molten iron slag from a blast furnace in a hydrated atmosphere, which results in a glassy, granular product that may be effectively grounded after drying. red mud is a byproduct of the Beyer's process used to transform bauxite ore into alumina. Six different combinations of these three-waste material are used to formulated the geopolymer binder. Table 2. describe the combination that were used in this research study RHA % was varied from 100 % to 50 % with the decrement of 10 % in each combination, GGBS used with in the percentage of 0 %,10 %,20 % and 30 %, red mud percentage was fluctuated from 0 % to 20 %. The main purpose for using 3 different alumino-silicate waste material for making geopolymer bricks is that RHA was used for strength due to its high silica content as obtained by XRF results and reported in Table 3, GGBS was used for setting of geopolymer bricks due to it alumina content and red mud was used for desired tint or color effect in geopolymer.

Filler used in this research study to make the geopolymer brick is obtained from C&D waste plant set up at Chandigarh by Municipal cooperation Chandigarh (MCC). The C&D waste collected, crushed and segregated. The 4.75 mm down sand which is washed during the recycling process is collected and tested. The fine aggregate which is used in this research study in form of washed sand falls in Zone-II as per IS 383–1786 [64]. The particle size and stored hump of washed sand in C&D waste plant is shown in Fig. 5.

3.2. Microscopic analysis of raw materials

The microscopic study was conducted using SEM and XRD that help to understand the nature of these raw material. Scanning electron microscope images basically help us to understand the surface nature of precursors weather they are smooth and round ideal for geopolymer showing the possibility of amorphous material. The sharp particle shows the crystalline probability which possess the high silica content and leads to prolonged strength gained in geopolymer binder. Fig. 6. represent the SEM images for RHA, GGBS and red mud and Table 3. shows the combined XRF results of RHA, GGBS and Red Mud. To clearly understand the crystalline and amorphous characteristics of the or precursors XRD analysis was conducted and reported in Fig. 7. which shows the combined XRD analysis for RHA, GGBS and red mud where the major peaks are mentioned on the graph.

The XRD peak help us to determine that GGBS is an amorphous material while RHA and red mud are towards the crystalline nature with the sharp peaks. The peak obtained for GGBS is a smooth peak near 20–40°. The XRD peak was taken from 5° to 90° 2θ with an increment of step size as.05. The generator setting was modulated at 30 mA, 40 kV and the interpretation of XRD data was done by X′pert Highscore software where firstly the background was clean, subtracted and number of peak was accepted as per the significance of 5 % and more are used and finally the analysis was executed by matching the JCPD card number in the diffraction database This basically help us to get the true and clear picture of our precursor materials.

3.3. Design of experiment by Taguchi's method

The experimental plan was developed using Taguchi's technique. In our study, we opted to treat alkaline/binder ratio and alkaline solution as separate variables due to their distinct impacts on geopolymer development. The alkaline/binder ratio, holds critical importance in influencing the geopolymerization process and can be consider in similar to the water-to-cement ratio in conventional concrete, Additionally, alkaline solutions preparation techniques hold a diverse effect on the geopolymerization reaction as explained

Table 2
Combination of different Binder Mix.

Binder Mix	B1	B2	B3	B4	B5	B6
RHA (%)	100	90	80	70	60	50
GGBS (%)	0	10	10	20	20	30
Red Mud (%)	0	0	10	10	20	20
Total (%)	100	100	100	100	100	100

Table 3
Combined XRF element weight % of GGBS, RHA and Red Mud.

Material	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	Na_2O (%)	K_2O (%)	TiO_2 (%)	P_2O_5 (%)	SO_3 (%)	MnO (%)	Other Components (%)
GGBS	40.8	30.1	8.3	5.7	3.4	1.2	1.1	1.8	0.7	0.2	0.1	6.6
Red Mud	20.3	15.6	25.2	10.1	5.3	5.2	2.4	1.5	1.3	2	0.5	10.6
RHA	70.5	5.4	2.2	2.3	3.1	1.4	1.3	1.9	1.1	0.3	0.1	10.4

Fig. 5. Particle Size Curve and Washed Sand at Construction and demolition waste plant.

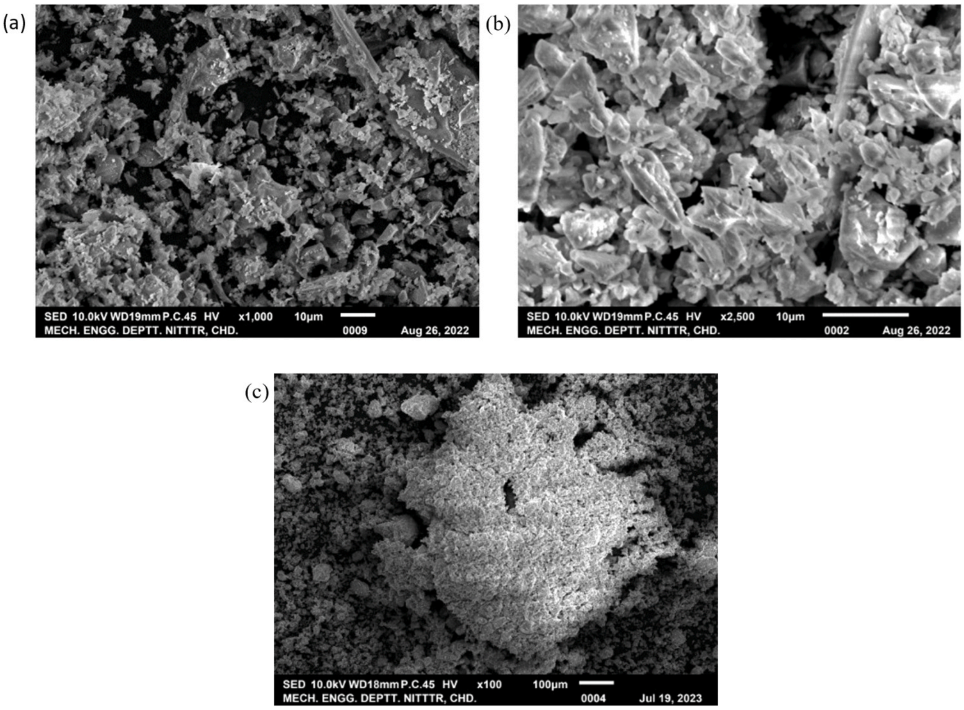


Fig. 6. (a) SEM image of RHA (b) GGBS (c) Red Mud.

in Section 3.4. Recognizing the unique roles and contributions of these variables, we deliberately considered them separately in our experimental design. This decision is in line with established practices in geopolymer research, where researchers have recognized by maintaining them as separate variables as summarized in Table 5. When there are several aspects to optimise, Taguchi's approach is among the best and most well-known. It helped the researched to cut down the number of experiments as much as possible by making use of orthogonal arrays. The optimum solution to a variable can be found out by the signal to noise ratio which ultimately helps us to

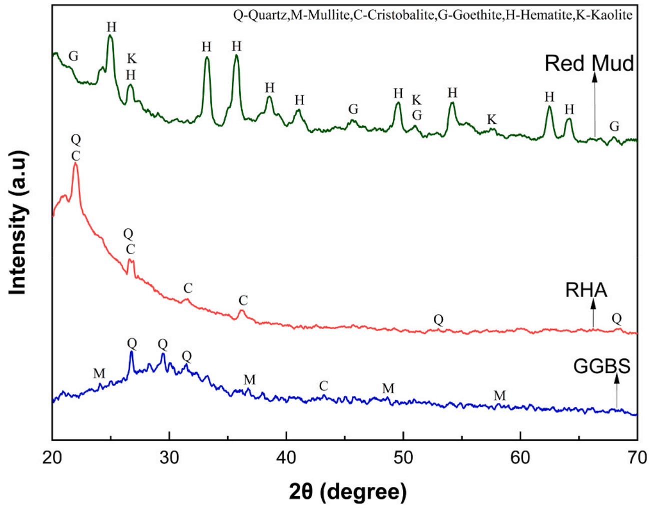


Fig. 7. XRD analysis of Red Mud, RHA, GGBS.

get the result of our concern which are maximum compressive strength and minimum water absorption in present research study. Table 2 explains about the percentage of 3 aluminosilicate waste material accounting to 100 % of precursor percentage in mix design with six level as identified in trial mixes and Table 6 corresponds to the different levels of factor as binder percentage has six level and all other three factor has three level which results into L18 orthogonal array of Taguchi's. There were four factors which were considered that includes A: Binder (%), B: alkaline Solution, C: SS/SH, D: alkaline /Binder where factor A has 6 level and factor B, C and D has 3 levels each which prompts to adopt the L18 orthogonal array for this research study. Minitab software was used to perform the Taguchi's method. There are three main methods for creating the mix design for geopolymer concrete, including 1) Target strength method 2) Performance based method 3) Statistical method. Out of these three we have adopted statistical method of geopolymer mix design because of its scientific applicability and saving the cost and time for the experiments. The percentage of Binder from B1 to B6 are shown in Table 2 and three different types of alkaline solution A1, A2 and A3 are mentioned in Table 6. while Sodium Silicate/ Sodium Hydroxide is varied at 3 level from 1.5 to 2.5 with an increment of 0.5 at each level and same was adopted for factor D where alkaline/Binder ratio are varied from 0.35 to 0.45. The percentage of washed sand is kept constant. Table 7. depicts the design of experiment generated by L18 design of Taguchi's with different set of factors and levels. Furthermore, the experimental factors and their chosen levels, along with the rationale for each selection, are summarized in Table 4. The generated mix design is used to find the actual quantity of material required for research study the estimated quantities are shown in Table 8. For clear depiction of experimental methodology adopted for this research study is shown in Fig. 9.

3.4. Preparation of alkaline solution

The conventional approach to alkaline solution generation, denoted as the A1 method in our study, aligns with common practices in geopolymer research. In this method, sodium hydroxide (NaOH) of 12 M concentration is prepared 24 h prior to mixing by dissolving 480 g of NaOH in one kilogram of distilled water. This waiting period allows for the maturation of the alkaline solution, ensuring the stabilization and uniform distribution of ions.

Comparatively, our study introduces the A2 and A3 methods as variations to explore the efficiency of alkaline solution preparation. The A2 method involves mixing NaOH and sodium silicate together, allowing them to mature for 24 h. This deviation from the conventional method aims to investigate potential synergies between NaOH and sodium silicate during the maturation period. The A3 method, on the other hand, is innovative, focusing on immediate NaOH preparation to capitalize on the heat generated during dissolution. This method aims to fast-track the geopolymerization reaction, acknowledging the heat susceptibility of the process.

Table 4
Chosen Levels and Rationale for Experimental Factors.

Factor	Chosen Levels	Rationale
Binder %	B1, B2, B3, B4, B5, B6	The varying levels of RHA, GGBS and Red Mud in the binder mix (B1 to B6) allow for assessing the impact of different combinations on the geopolymer properties
Alkaline Solution Type	A1, A2, A3	A1, A2, and A3 represent different methods of preparing the alkaline solution, exploring variations in the maturation process and immediate use, providing insights into their effects on geopolymerization.
SS/SH	1.5, 2, 2.5	The three levels of SS/SH ratios help analyze the influence of this ratio on the geopolymer properties. This ratio plays a crucial role in the geopolymerization process.
Alkaline/Binder	0.35, 0.4, 0.45	The varied levels of alkaline/binder ratios examine the impact of this ratio on the geopolymerization reaction. Different ratios help assess the optimal conditions for geopolymer formation.

Table 5
Factors consider for making geopolymer mix design by different researchers.

Authors	Parameters considered	Deign	Findings	References
Chokkalingam et al., 2022a	• Binder content • ceramic waste powder (cwp) replacement percentage by slag • alkali-activator solution to binder ratio (aas/binder) • sodium silicate (ss) to sodium hydroxide (sh) ratio (SS/SH) • SH molarity.	L16	The highest compressive strength achieved for CWP geopolymer concrete was 58.9 MPa. This was achieved by utilizing a binder content of 450 kg/m^3, replacing 60% of CWP with slag, using a ratio of 0.5 of AAS to binder, a ratio of 1.5 of SS to SH, and a SH solution molarity of 10 M.	[65]
Chokkalingam et al., 2022b	• binder content, • alkaline solution to binder • SS/SH • SH molarity.	L16	Experimental findings showed that both approaches to optimization yielded the same optimal blend regardless of quality standards. Binder content was 450 kg/m^3, CW:GBFS ratio 2:3, AS:B ratio 1:2, S:H ratio 3:2, and NaOH solution concentration 10 M for the best mix. Experimental testing confirmed the optimal mix's outcomes.	[66]
Hadi et al., 2017	• Binder contents• Al/Bi ratio• SS/SH• SH Molarity	L9	The geopolymer concrete with 450 kg/m 3 binder, 0.35 Al/Bi, 2.5 SS/SH, and 14 M SH had the maximum 7-day compressive strength (60.4 MPa) during ambient curing conditions.	[67]
Anwar, El-Mir, et al., 2023	• Binder content• Alkaline activator• SH Molarity	L9	Pervious geopolymer concrete (PGC) compositions with a binder concentration of 450-500 kg/m^3, dune sand addition of 10-20%, AAS/B ratio of 0.50, and SH molarity of 8-12 M may reach a compressive strength above 30 MPa. An optimal combination for achieving improved compressive strength was achieved by using a binder concentration of 500 kg/m^3, 20% dune addition, AAS/B ratio of 0.50, and a SH molarity of 12 M.	[68]
J & H, 2023	• Binder content • NaOH/Na_2SiO_3 (1:2, 1:2.5, and 1:3) • SH Molarity (4 M,8 M,12 M), • Alkaline activator to binder (0.4,0.5,0.6)	L9	The investigation focused on the compressive strength and split-tensile strength of these components and factors.	[69]
Olivia & Nikraz, 2012	•Aggregate content •Alkaline solution to fly ash ratio •SS/SH •Curing method	L9 (3^4)	The results indicate that geopolymer concrete may achieve a compressive strength of 55 MPa after 28 days of production. Best design shows enhanced tensile and flexural strength, with reduced expansion and drying shrinkage. Additionally, their modulus of elasticity were 14.9–28.8% lower compared to the OPC control mix.	[70]
Anwar, El-Hassan, et al., 2023	•binder dosage •dune sand inclusion •alkaline solution-to-binder ratio (S/B) • SH Molarity	L9	The optimum mixture with higher hydraulic performance was achieved by calculating the signal-to-noise (S/N) ratio. The experimental test findings showed that the PGC mix, with a binder dosage of 400 kg/m^3, no dune sand inclusion, a S/B ratio of 0.55, and an NH molarity of 8 M, achieved an optimal permeability response of 12 mm/s.	[71]

Table 6
Different Set of Levels and Factors.

Factors	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
A: Binder (%)	B1	B2	B3	B4	B5	B6
B: Alkaline Solution	A1	A2	A3			
C: SS/SH	1.5	2	2.5			
D: Alkaline/Binder	0.35	0.4	0.45			

By employing these three distinct techniques, our research aims to provide a comprehensive comparison which goes beyond the conventional approach discussed in the existing literature. Furthermore, the uniqueness of A3 type alkaline solution can be describe as below.

3.4.1. Immediate preparation and heat utilization

- A3 involves the immediate preparation of the alkaline solution, unlike the conventional A1 method where the solution is prepared 24 h prior to mixing.
- The novelty lies in leveraging the heat generation inherent in the sodium hydroxide (NaOH) preparation process. By mixing the ingredients promptly, we capitalize on the exothermic nature of NaOH dissolution, which naturally occurs during its preparation.

3.4.2. Fast-tracking geopolymerization reaction

- Geopolymerization is known to be heat-susceptible, and the A3 method exploits this characteristic to accelerate the reaction kinetics.

Table 7
Nomenclature and factor with different level Generated by Taguchi's Method.

Coded Value						Uncoded Value			
DOE	Nomenclature	Binder	Alkaline Solution	SS/SH	Alkaline/Binder	Binder	Alkaline Solution	SS/SH	Alkaline/Binder
E1	A1B1C1D1	1	1	1	1	B1	A1	1.5	0.35
E2	A1B2C2D2	1	2	2	2	B1	A2	2	0.4
E3	A1B3C3D3	1	3	3	3	B1	A3	2.5	0.45
E4	A2B1C1D2	2	1	1	2	B2	A1	1.5	0.4
E5	A2B2C2D3	2	2	2	3	B2	A2	2	0.45
E6	A2B3C3D1	2	3	3	1	B2	A3	2.5	0.35
E7	A3B1C2D1	3	1	2	1	B3	A1	2	0.35
E8	A3B2C3D2	3	2	3	2	B3	A2	2.5	0.4
E9	A3B3C1D3	3	3	1	3	B3	A3	1.5	0.45
E10	A4B1C3D3	4	1	3	3	B4	A1	2.5	0.45
E11	A4B2C1D1	4	2	1	1	B4	A2	1.5	0.35
E12	A4B3C2D2	4	3	2	2	B4	A3	2	0.4
E13	A5B1C2D3	5	1	2	3	B5	A1	2	0.45
E14	A5B2C3D1	5	2	3	1	B5	A2	2.5	0.35
E15	A5B3C1D2	5	3	1	2	B5	A3	1.5	0.4
E16	A6B1C3D2	6	1	3	2	B6	A1	2.5	0.4
E17	A6B2C1D3	6	2	1	3	B6	A2	1.5	0.45
E18	A6B3C2D1	6	3	2	1	B6	A3	2	0.35

Table 8
Mix Design as per Design of Experiment by Taguchi's Optimization.

RHA	GGBS	Red Mud	Washed Sand	Alkaline/Binder	Alkaline	SS/SH	NaOH	Na_2SiO_3
410	0	0	1230	0.35	143.5	1.5	57.40	86.10
410	0	0	1230	0.4	164	2	54.67	109.33
410	0	0	1230	0.45	184.5	2.5	52.71	131.79
369	41	0	1230	0.4	164	1.5	65.60	98.40
369	41	0	1230	0.45	184.5	2	61.50	123.00
369	41	0	1230	0.35	143.5	2.5	41.00	102.50
328	41	41	1230	0.35	143.5	2	47.83	95.67
328	41	41	1230	0.4	164	2.5	46.86	117.14
328	41	41	1230	0.45	184.5	1.5	73.80	110.70
287	82	41	1230	0.45	184.5	2.5	52.71	131.79
287	82	41	1230	0.35	143.5	1.5	57.40	86.10
287	82	41	1230	0.4	164	2	54.67	109.33
246	82	82	1230	0.45	184.5	2	61.50	123.00
246	82	82	1230	0.35	143.5	2.5	41.00	102.50
246	82	82	1230	0.4	164	1.5	65.60	98.40
205	123	82	1230	0.4	164	2.5	46.86	117.14
205	123	82	1230	0.45	184.5	1.5	73.80	110.70
205	123	82	1230	0.35	143.5	2	47.83	95.67

- Immediate mixing of the ingredients allows us to harness the heat released during NaOH dissolution, thereby fast-tracking the geopolymerization reaction. The elevated temperature observed in A3 (as high as 84.1°C) serves as an indicator of the rapid initiation of the reaction.

3.4.3. Efficiency and time-saving

- A3 presents a more time-efficient approach compared to the traditional A1 method, as it eliminates the 24-hour waiting period for alkaline solution maturation.

The same component is employed in three distinct preparation methods for the alkaline solution used in this research investigation. Sodium Hydroxide (NaOH) and Sodium Silicate (Na_2SiO_3) are the two main components of alkaline solution. Sodium hydroxide of 12 M was used in this study which means 480 g of NaOH is used in one Kg of distilled water. A1 type is conventional method which is being utilized in most of the research working on geopolymer by preparing NaOH solution 24 h prior to mixing of ingredient, A2 type involves alkaline solution preparation deals with mixing of sodium hydroxide and Sodium silicate together and allowing it to mature together for 24 h, A3 type of alkaline solution is quite novel as deals with the immediate preparation of alkaline solution and mixing the ingredient as matter of fact to utilize the heat generation which is involved during NaOH preparation and fast track the geopolymerization reaction as geopolymer reaction is a heat suspectable. Fig. 9 shows a pictorial formation of how the three different methods were used to prepare the alkaline solution for this research study.

A concise comparison of key features of three distinct alkaline solution preparation methods is presented in Table 9 below.

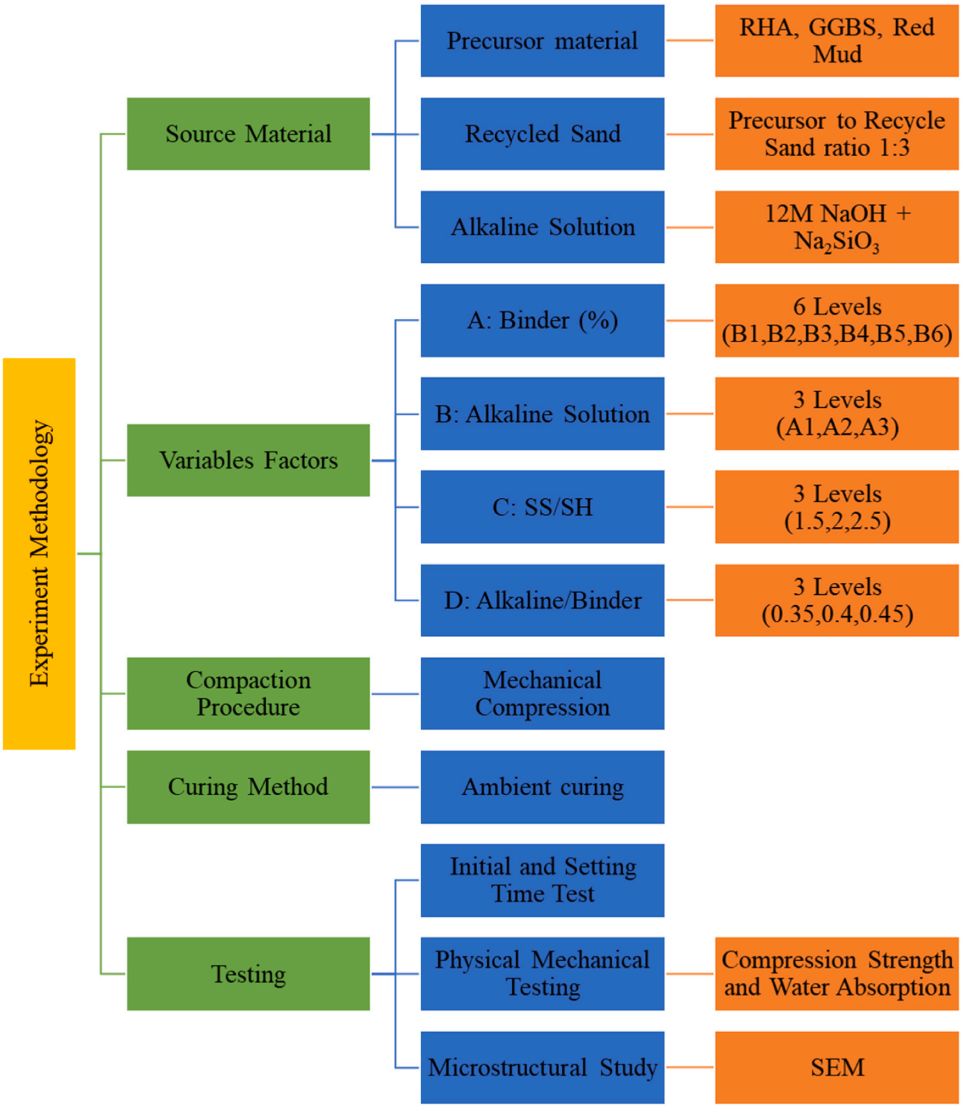


Fig. 8. Experimental methodology adopted for development of geopolymer bricks.

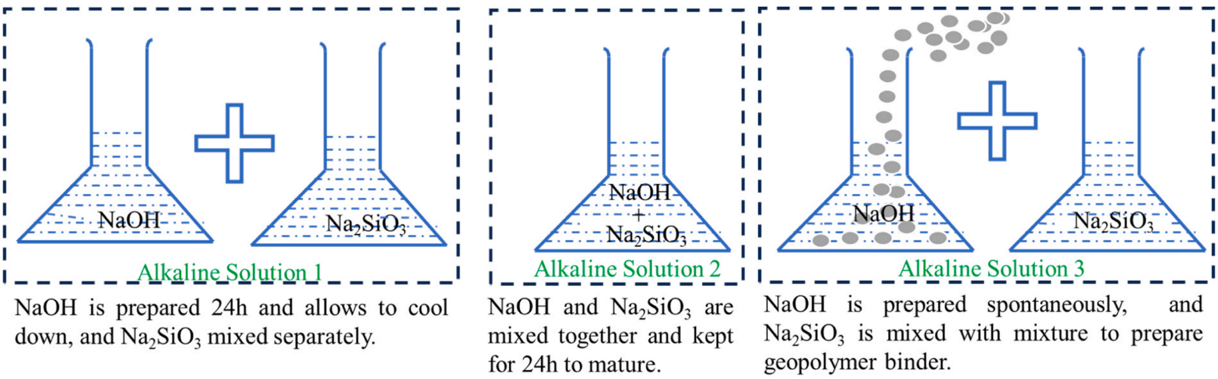


Fig. 9. Three different methods by which alkaline solution used in research study.

The temperature in type 3 alkaline solution went as high as 84.1°C when NaOH was mixed immediately. The methodology adopted to form third type of alkaline solution is shown in Fig. 10.

3.5. Sample preparation

Samples were prepared using the alkaline solution and washed sand using the C&D recycled Sand. Brick samples measuring 19 cm by 9 cm by 9 cm were created using a mechanical compression technique as per the Indian standard IS 1077 [72]. As suggested by Taguchi's method of design of experiment L18 was made so for each combination 3 samples were prepared. Each sample was cured at ambient temperature and allow to dry for 28 days. The testing is done at 28 days. A lot of 18 samples are shown below with the nomenclature shown in Fig. 11. The compressive strength and water absorption obtained are tabulated in Table 10.

4. Physio-mechanical testing methodology

4.1. Compressive testing

Compressive strength is the most crucial and elementary test conducted to determine the physical strength of brick. This test assists us not only in determining the bricks' mechanical strength but also in comprehending the effects of various ingredients. The compressive testing of brick is performed as per IS:3495-Part 1–1992 [73]. There is requirement of three specimen for calculating the mean strength at a particular percentage so in our case as the compressive strength is tested at 28 days so 54 samples were prepared for 18 mixes suggested in design of Experiment. Three days curing are required before the actual testing can happen as the frog in the sample is filled with mortar of ratio 1:1. The rate of loading adopted is 140 kg/cm^2 with automatic compressive testing machine is used with a capacity of 3000 KN capacity provided by Aimil ltd.

4.2. Water absorption

Water absorption is simple test but yet very informative to understand the void nature of specimen without performing the actual microscopic test. The water absorption test is conducted as per the IS:3495-Part 2–1992[74]. The brick samples are placed in the oven with a temperature of 105°C for 24 h and allow it to cool slowly until it achieves the room temperature then it is weighted with a sensitive weighing balance and noted as (W_1) after this samples are kept in water and allowed it to boil for 2 h and it should be kept in mind that it should not touch the surface of the bottom and again it is allow to cool down and attains the room temperature at this point we measure the suspended weight of the brick as (W_2) which is used for measuring the apparent porosity as per the IS 1528 (Part 15):2007 [75]and finally samples are immersed completely in water for 24 h and extra water is cleaned from surface to get the submerged weight of the sample as (W_3).

4.3. Sample preparation for analysis of microstructure

Microstructure study become essential to understand the internal bonds between the ingredients and development of internal structures. It also helps us to understand the pore formation or cracks that are built up in our samples which ultimately help us to support the finding of our mechanical testing. SEM was performed on JSM-IT100 on JEOL SEM technologies machine by preparing the samples that are taken out of the core of tested samples. One centimetre by one centimetre by one centimetre of the core is removed for microscopic examination which is first polished with the help of silicon carbide paper ranging from (500–2000μ). After the SEM analysis the image are analysed using the image processing software like ImageJ software to find the porosity and Gwyddion software was used to calculate the surface roughness.

4.4. Statistical analysis

The test results that are obtained in the lab has to be analysed in a very effective and interactive manner so to get the best insights out of the test results. It is the most widely used techniques which is prominent and promising to understand the interaction of different variable which in this research study are binder, alkaline solution, SS/SH and alkaline to binder ratio with each other and their effect on compressive strength and water absorption. Minitab Statistical Software was used for performing the statistical analysis and design

Table 9
Comparative Overview of Three Alkaline Solution Preparation Methods.

Method	Alkaline Solution Preparation Details	Key Features	Purpose
A1	12 M NaOH prepared by dissolving 480 g NaOH in 1 kg distilled water, matured for 24 h	Standard practice in geopolymer research	Baseline approach, ensuring stabilization and uniform ion distribution
A2	NaOH and sodium silicate mixed, matured together for 24 h	Explores synergies between NaOH and sodium silicate	Investigates potential enhancements in alkaline solution reactivity
A3	Immediate NaOH preparation to utilize heat generated during dissolution	Leverages exothermic nature of NaOH dissolution	Fast-tracks geopolymerization reaction by capitalizing on heat susceptibility

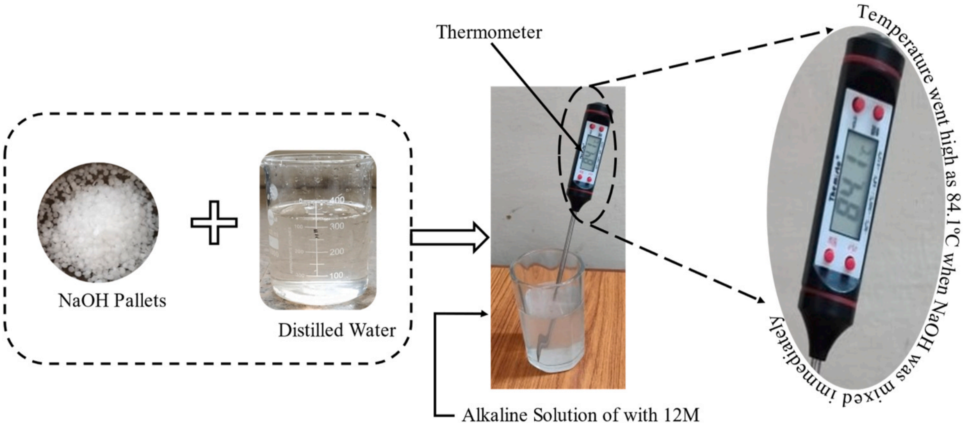


Fig. 10. Temperature measurement while formation of third type of alkaline Solution.

Fig. 11. Geopolymer Brick produced as per DOE.

of experiment was conducted. Analysis of variance is reported, and regression model is formed for our two parameters of interest i.e., compressive strength and water absorption. Taguchi's method was implemented for design of experiment to generate L18 Design with 4 factors with binder % having 6 level and other 3 factors has 3 level. Desirability analysis and ANNOVA was performed so to get the clear understanding of interaction of different ingredient for this interaction plots are reported in result and analysis section. To find the optimum percentage of the mix we used signal to noise ratio (SNR) for the different factors that were consider for our research study. There are broadly 3 main categories of SNR which are mentioned below in form of 3 equations as mentioned below (3), (4) and (5)

Table 10
Compressive strength test results and water absorption test results as per DOE.

DOE	Coded Value					Uncoded Value				Measured Parameters	
	Name	Binder	Alkaline Solution	SS/ SH	Alkaline/ Binder	Binder	Alkaline Solution	SS/ SH	Alkaline/ Binder	Compressive Strength (MPa)	Water absorption (%)
E1	A1B1C1D1	1	1	1	1	B1	A1	1.5	0.35	17.69	9.18
E2	A1B2C2D2	1	2	2	2	B1	A2	2	0.4	20.12	8.65
E3	A1B3C3D3	1	3	3	3	B1	A3	2.5	0.45	18.95	9.02
E4	A2B1C1D2	2	1	1	2	B2	A1	1.5	0.4	21.06	8.31
E5	A2B2C2D3	2	2	2	3	B2	A2	2	0.45	22.98	7.75
E6	A2B3C3D1	2	3	3	1	B2	A3	2.5	0.35	22.45	8.05
E7	A3B1C2D1	3	1	2	1	B3	A1	2	0.35	22.7	7.95
E8	A3B2C3D2	3	2	3	2	B3	A2	2.5	0.4	24.11	6.62
E9	A3B3C1D3	3	3	1	3	B3	A3	1.5	0.45	23.37	7.18
E10	A4B1C3D3	4	1	3	3	B4	A1	2.5	0.45	24.62	7.33
E11	A4B2C1D1	4	2	1	1	B4	A2	1.5	0.35	25.32	6.34
E12	A4B3C2D2	4	3	2	2	B4	A3	2	0.4	24.89	7.19
E13	A5B1C2D3	5	1	2	3	B5	A1	2.5	0.35	25.71	6.5
E14	A5B2C3D1	5	2	3	1	B5	A2	2	0.45	27.34	5.68
E15	A5B3C1D2	5	3	1	2	B5	A3	1.5	0.4	26.04	6.18
E16	A6B1C3D2	6	1	3	2	B6	A1	2.5	0.4	22.23	7.12
E17	A6B2C1D3	6	2	1	3	B6	A2	1.5	0.45	24.55	6.53
E18	A6B3C2D1	6	3	2	1	B6	A3	2	0.35	23.09	6.78

$$\frac{S}{N} = 10\log\frac{\bar{y}}{S^2} \tag{3}$$

$$\frac{S}{N} = -10\log\frac{1}{n}\left(\sum y^2\right) \tag{4}$$

$$\frac{S}{N} = -\log\frac{1}{n}\left(\sum\frac{1}{y^2}\right) \tag{5}$$

Eq. (3) depicts the value which shows that nominal combination is best fitted for the optimization while Eq. (4) is used when we are desires to find the optimum mix where smaller parameters are best fitted while Eq. (5) shown the largest values as best fitted in the optimization. For compressive strength it is preferred when we get the maximum or largest value so Eq. 5 was used for compressive

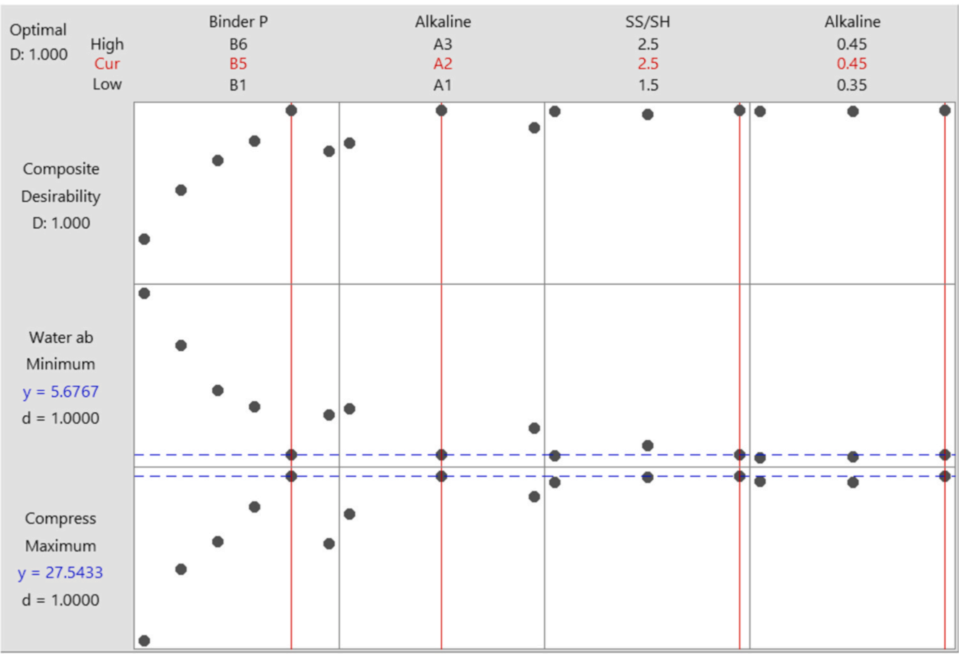


Fig. 12. Desirability results of Combined variables on compressive strength and water absorption.

strength similarly for water absorption it should be minimum therefore Eq. 4 was preferred which gives best result for the mix at smaller value. Residual Plot for SN ratios of Compressive Strength and compressive strength are also plotted which help us to identify the outliers of our data and also help us to understand the difference between experimental values and predicted values.

5. Result and analysis

5.1. Compressive strength

In order to explain and define the Index and elementary behaviour of any material the compressive strength testing is one the best and essential test to conduct. This research study primarily focuses on examining the impact of four factors, namely, the percentage of binder in various combinations made of RHA, GGBS, and red mud, the percentage of three different types of alkaline solutions, along with the percentage of SS/SH, alkaline/Binder ratio on compressive strength development of geopolymer bricks using recycled sand. The design of experiment was performed by Taguchi's method and results obtained are tabulated in Table 10. The combination B5 category of binder, which is experiment number 14 in the design of experiment, produced the highest compressive strength at 28 days, measuring 27.34 MPa and consisting of 60 % RHA, 20 % GGBS, and 20 % red mud with a second-type (A2) type of alkaline ratio, SS/SH as 2 and alkaline/binder ratio as 0.45 while the minimum compressive strength was obtained as 17.6 MPa with of B1 which contains 100 % RHA and utilize the type 1 alkaline solution i.e., A1 along with 1.5 ratio of SS/SH and 0.35 alkaline to binder ratio which is experiment number 1. Fig. 14. shows the optimum value of compressive strength with a main effect plot for mean and for compressive strength it was chosen as maximum compressive strength is best and best possible combination is B5 binder % which has 60 % RHA, 20 % GGBS and 20 % red mud, alkaline solution of A2 type, SS/SH as 2 and alkaline to binder ratio of 0.45. The desirability result of optimization is plot in Fig. 12. where the desirability is achieved as 1 which shows the optimization has performed well.

Analysis of variance testing was also performed in order to test the most important parameters. Out of four two parameters were found most crucial and that are binder % and method of preparing alkaline solution. The contribution made by binder % in testing is 90.36 %. This basically shows the importance and significance in choosing the right category of raw material for making geopolymer binder and also a combination of three kind of precursor help to formulate a dense geopolymer matrix that has less porous structure and it if formed by dense amorphous sodium aluminosilicate gel [76]. It is also suggested by Singh et al. that red mud should not be used alone as it depicts low compressive strength due to low ratio of Si/Al and to maintain the Si/Al which is the crucial criteria for making of geopolymer concrete it should be embedded with the other aluminosilicate compounds so that a desirable compressive

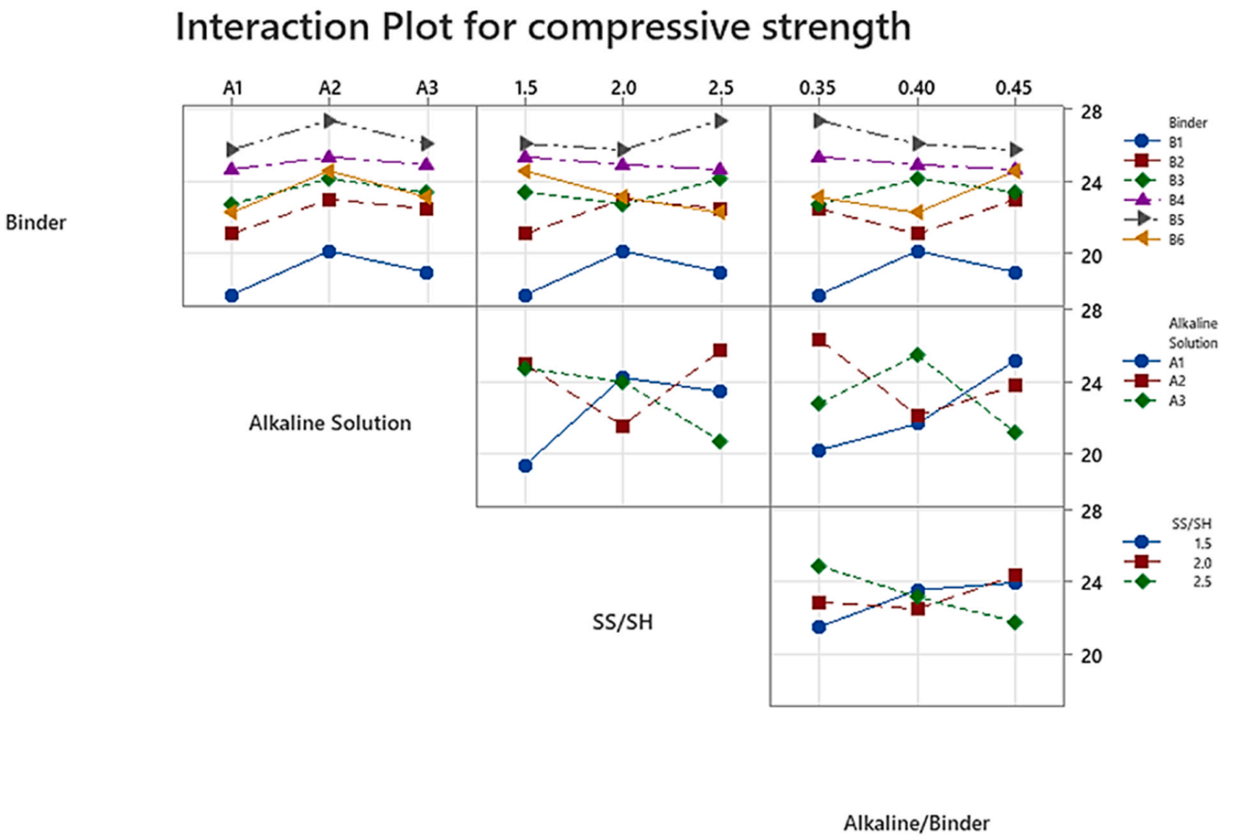


Fig. 13. Interaction Plot for compressive strength.

strength can be achieved [60]. The effect of each parameter on compressive strength is explained with the help of interaction plot show in Fig. 13.

It shows that compressive strength is influenced by each factor and mostly by the binder % and alkaline solution type. All the sample pass the minimum criteria of Class A brick of compressive strength greater that 10.5 MPa as per the IS 12894:2002. The trend in the compressive strength increment can be understood by a fact that as SiO_2/Al_2O_3 increase the compressive strength also increase. In a nutshell it can be concluded that binder percentage is the most important criteria recorded in this research study and alkaline solution of type 2 has maximum impact on compressive strength this can be understood by the fact that when NaOH and Na_2SiO_3 are mixed together and kept for 24 h to mature as it has already initiated the geopolymer reaction and the same trend is recorded in the past literature [77,78]. For the compressive strength effect by alkaline/binder and SS/SH is shown by contour and 3D Surface plots in Fig. 15.

5.2. Water absorption

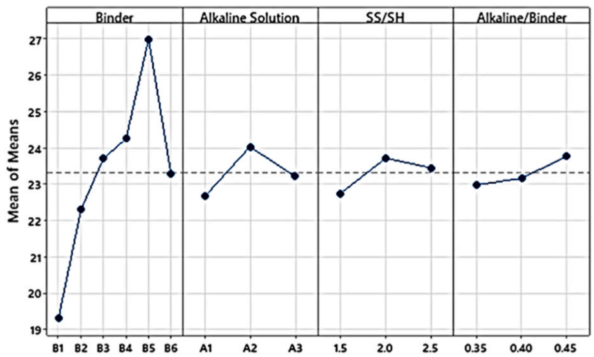
Water absorption is one another crucial factor that are considered of prime importance in the geopolymer bricks. The water absorption test is conducted as per IS:3495-Part 1–1992. Water absorption directly influenced by the size and nature of pores. The pores formation in brick is a function of multiple factors like compaction, particle size, the matrix of Si and Al bond of the geopolymer. The results obtained in experiments is strongly validated by the main effect plots as shown in Fig. 14. The results are obtained with a setting option of smaller is best for the water absorption which is described by the Eq. (4). The Minimum water absorption results are obtained where the compressive strength was maximum i.e., B5 category of binder containing 60 % of RHA, 20 % GGBS and 20 % of red mud, A2 category of alkaline solution and SS/SH ratio of 2. The influence of each parameter which affect the properties is described through interaction plots as shown in Fig. 16. For a clarity of influence of SS/SH and alkaline/binder the contour plot and surface plots are shown in Fig. 17. The ANNOVA testing shows that for water absorption also the main contribution was made by percentage of binder. When compared to a heatmap, the data demonstrate that water absorption and compressive strength are 96 % negatively associated. The desirability of 1 was obtained when response optimization was performed which compiles with the optimum percentage as that of compressive strength. The desirability analysis is shown in Fig. 12. Similar observation is also reported in [79,80]. It is worth mentioning that all the geopolymer brick samples pass the compliance laid by the IS 12894–2002 [81] of water absorption of first-class brick of having threshold percentage lower than 20 %.

5.3. Initial and final setting time

The initial and final settings were done primarily to understand the influence of three different types of alkaline solutions in preparing the geopolymer mix. Fig. 18. show the effect where initial and final setting time of geopolymer bricks decreases from A1 to A3 with an average value of IST which was observed in mix A1 is 163.83 min while for FST it is 7.2 h, For A2 mix the average IST was found to be 127.5 min and FST was 5.82 h, while the lowest value was observed in A3 type with average value 44.16 min for IST and 3.91 h for FST. The reason for declining in the setting time can be explained by the temperature that was generated in the A3 type of alkaline solution where temperature rises to almost 84°C which helped the initiation of quick setting as the geopolymer is temperature suspectable reaction.

5.4. Correlation between compressive strength and water absorption

To better understand the relationship between compressive strength and water absorption, a parametric graph in form of heatmap of the experimental findings from all 18 experiments. The heatmap is developed using the python programming making use of pandas, seaborn and matplotlib packages. After uploading the desired library and dataset a correlation matrix is formed which is one of the best tools for understand the pattern and correlation. The output result in the form of heatmap is shown in Fig. 19. It can be easily inferred from the graph that compressive strength and water absorption are negatively correlated. In our experiment the negative correlation in



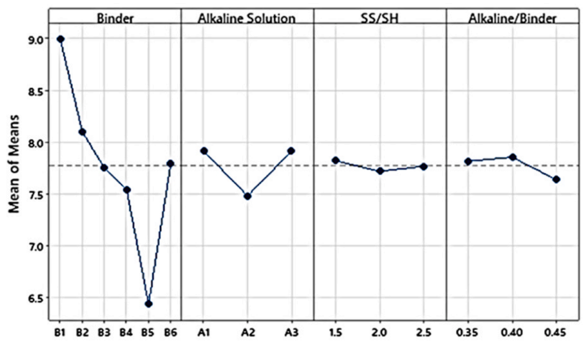


Fig. 14. Plot of main effects for mean, compressive strength, and water absorption.

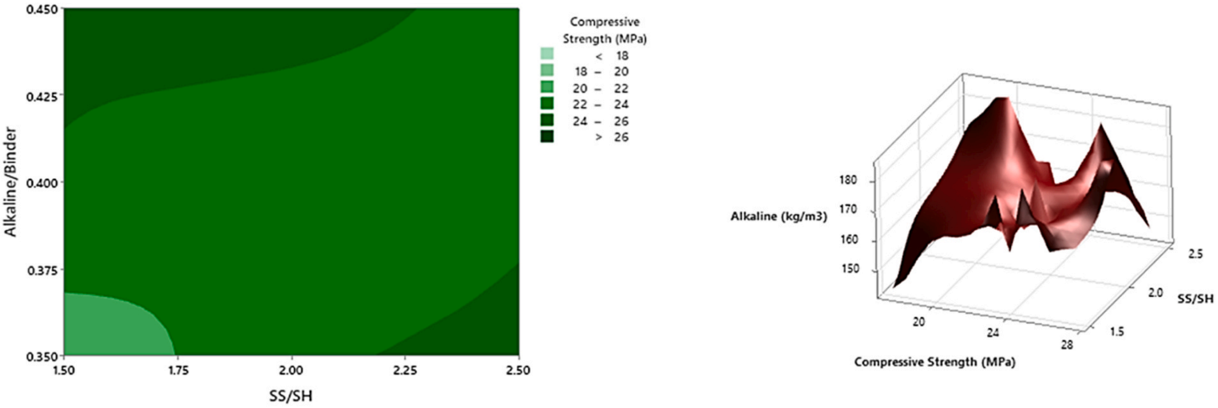


Fig. 15. (a) Contour plot of SS/SH and alkaline/Binder (b) Surface plot of SS/SH and alkaline/Binder on compressive strength.

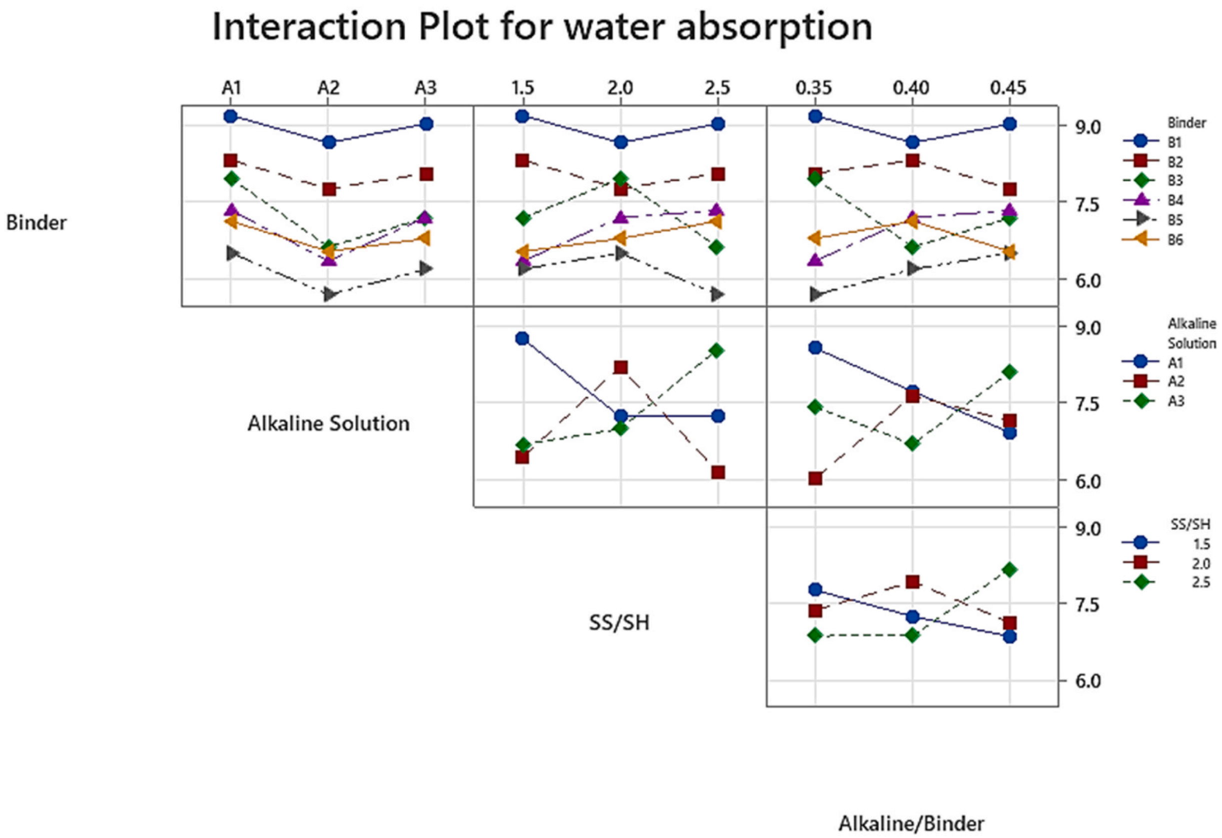


Fig. 16. Interaction Plot for water absorption.

96 % which explain that with rise in compressive strength the water absorption decreases due to decrease in voids and internal cracks which are also verified from the SEM image shown in Section 5.5.

5.5. Microscopic analysis

Microscopic analysis was performed on A1B1C1D1 and A5B2C3D1 that has maximum and minimum results in terms of both compressive strength and water absorption. The experiment number of these two samples are E1 and E14. The microscopic analysis was performed with Scanning electron microscope at two different level of magnification which are 100 μm and 10 μm followed by clustering algorithm-based analysis performed via python programming language. Particle clustering analysis is one of the methods to study how the particle in the material are dispersed and that eventually help us to understand the reason for variation of strength. The

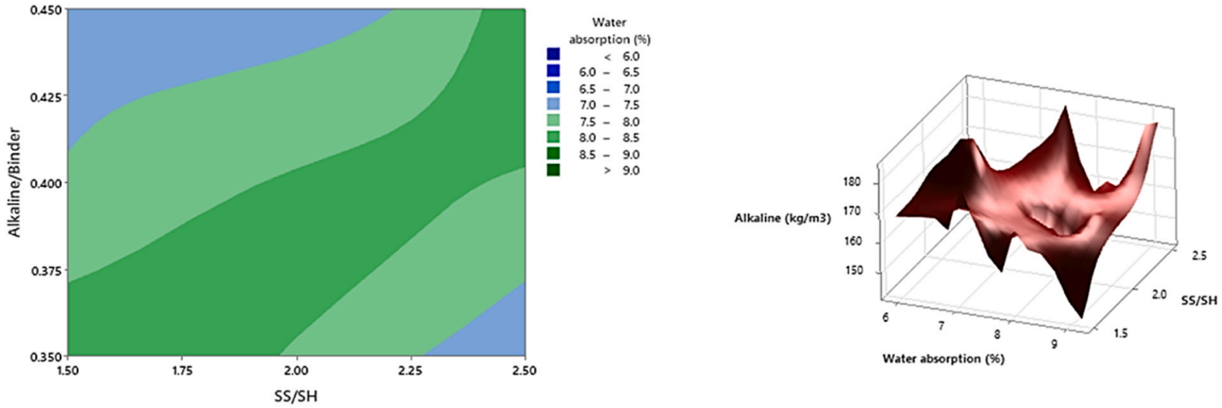


Fig. 17. (a) Contour plot of SS/SH and alkaline/Binder (b) Surface plot of SS/SH and alkaline/Binder on Water Absorption.

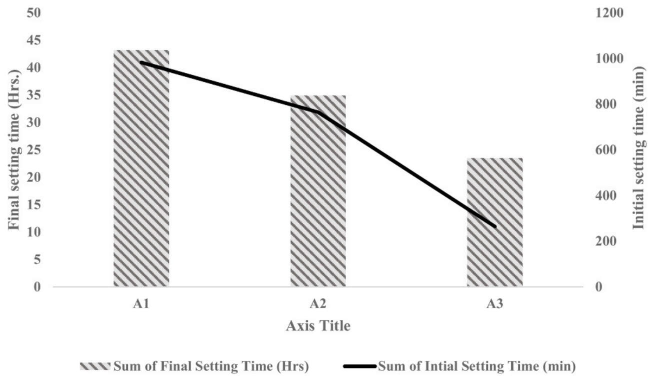


Fig. 18. Initial and final setting of different alkaline type of solution.

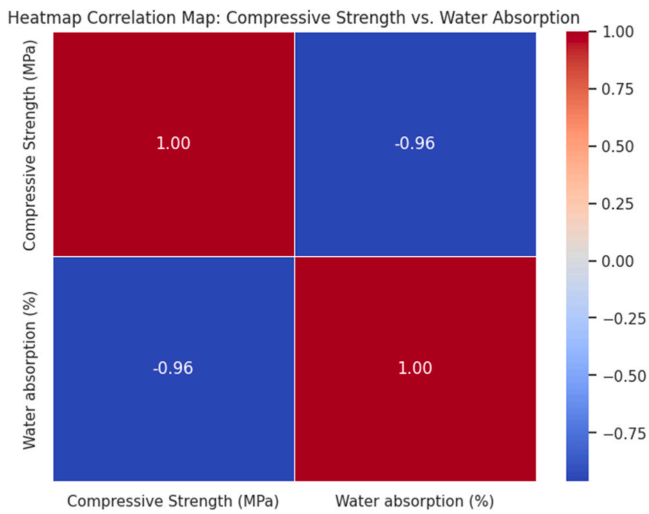


Fig. 19. Heatmap for compressive strength and water absorption.

low magnification basically enables us to understand the surface nature of voids and cracks as shown in Fig. 20. the surface crack and voids in A5B2C3D1 which has given the greatest compressive strength and the least amount of water absorption has very little voids and same verification can be seen in clustering analysis. The cluster image shows the high-density pixels which are in line to minimum voids. The high magnification as high as 10 μm enables us to see the Si-Al geopolymer matrix for sample A5B2C3D1 the bond of Al-Si

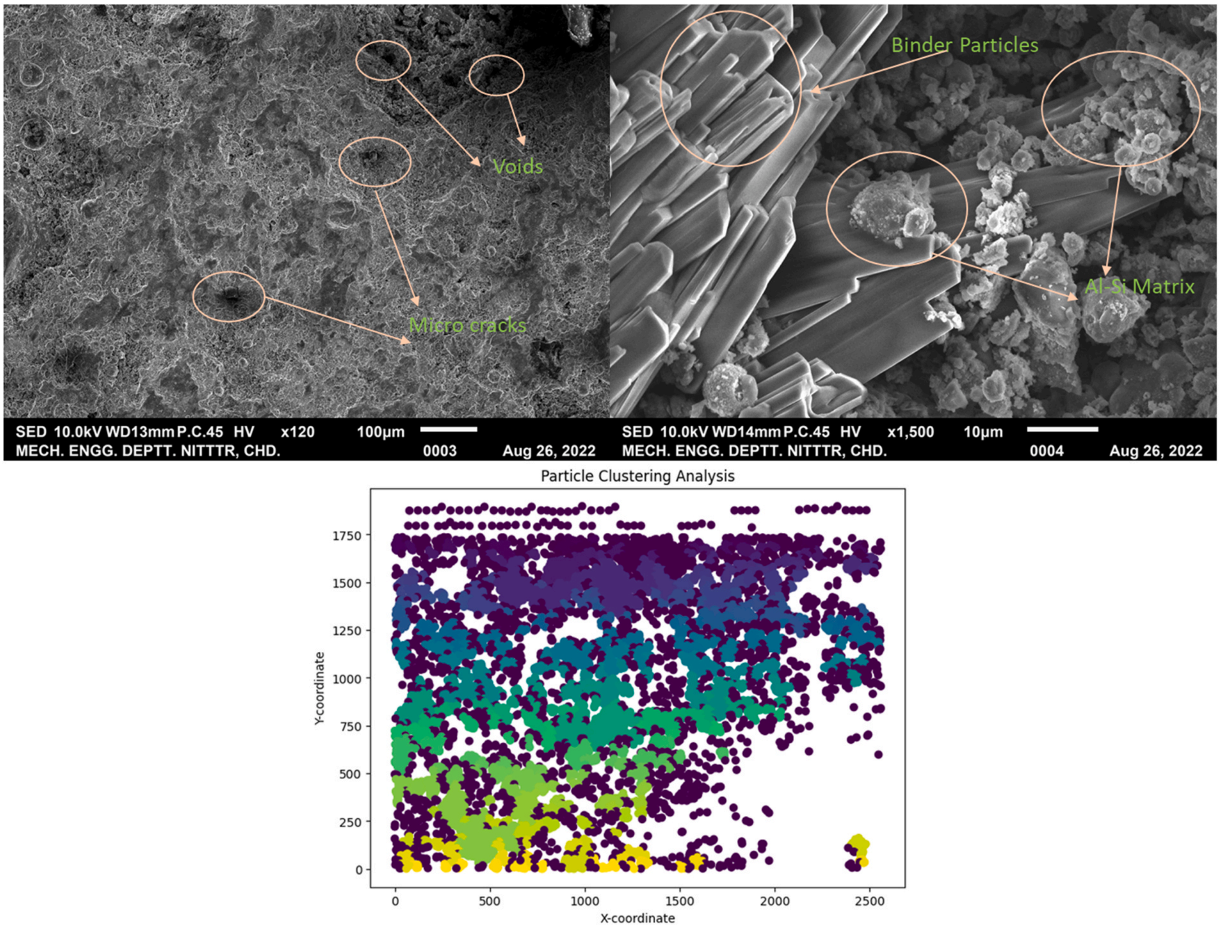


Fig. 20. SEM image analysis of Sample A5B2C3D1 (a) Low magnification of 100 μm (b) High magnification of 10 μm (c) Clustering pattern.

matrix is strong and dense. While A1B1C1D1 has more micro cracks and voids which results in minimum strength. The same is verified by the clustering pattern which are of more dispersive in nature can be seen in Fig. 21. Also, it is analysed that sample A1B1C1D1 has more unreacted material which has become the cause of lesser strength and more water absorption.

5.6. Mathematical model

After obtaining the lab results the mathematical model was established in order to understand more deeply about the influence of four variables on geopolymer brick compressive strength and water absorption. The comparison and analysis were made with the help of different tools which includes the ANNOVA Table 11 & Table 12 for compressive strength and water absorption respectively. Along with the ANNOVA table residual plots of both the performance parameters are shown Fig. 23 in respectively A residual plot is a kind of graph used in analysis of variance and regression to check for model fit. The residual plots show whether the assumptions of ordinary least squares are satisfied, and it is clear from the compressive strength graphs that our model for compressive strength has satisfied it well. The model equation is formulated in Eqs. (6) and (7) and R-square for the equation comes out to be 97.19 %, which is good enough to predict the values and fits the model well. The histogram in residual plot shows that experimental results of compressive strength is normally distributed with no outliers. The same is verified with the normal probability plot while residual versus fitted value depicts that our model on compressive strength has constant variance. However, the SN residual plots for water absorption shows some outliers in the residual plots which is verified by the fact of lower R-square of water absorption of 93.36 % in regression equation yet it satisfies the high probability of predicting the values for water absorption.

$$\textbf{Regression Equation for Compressive StrengthCompressive Strength}\ (\textbf{MPA}) = 16.459 + 0.278(SS/SH) + 2.65(Alkaline/Binder) + 6.023(B4) + 7.443(B5) + 4.370(B6) + 1.735(A2) + 0.797(A3)R2 = 97.19\% \tag{6}$$

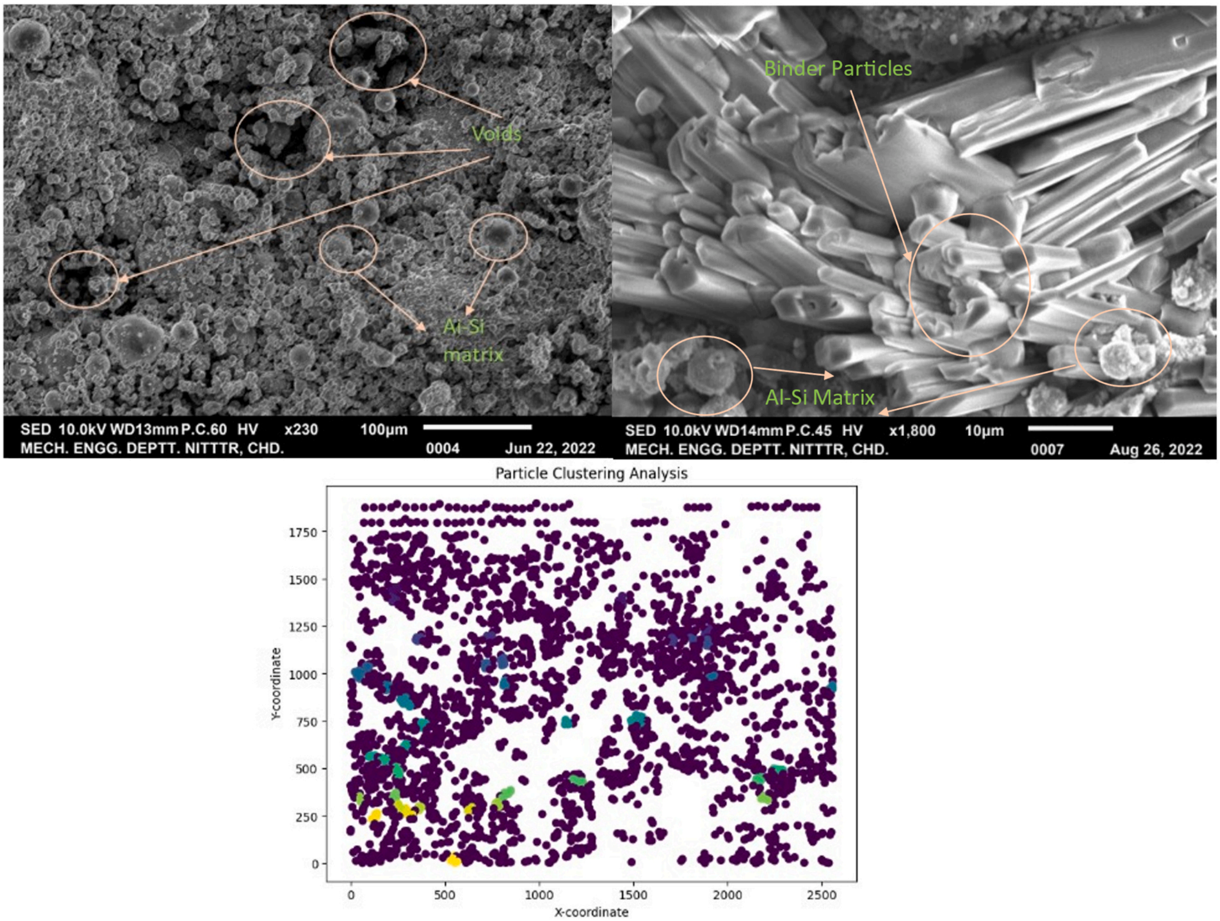


Fig. 21. SEM image analysis of Sample A1B1C1D1 (a) Low magnification of 100 μm (b) High magnification of 10 μm (c) Clustering pattern.

Regression Equation for Water Absorption

$$\textbf{Water absorption}(\%) = 9.075 + 0.017(SS/SH) + 0.55(Alkaline/Binder) - 1.997(B4) - 2.830(B5) - 2.140(B6) - 0.803(A2) - 0.332(A3)$$
$$R2 = 93.36\% \quad (7)$$

6. Conclusion

This research study focuses on the use of different kind of aluminosilicate industrial waste to prepare the geopolymer along with use of recycled washed sand as filler were used to prepare the geopolymer brick. A novel approach was also mentioned in preparing the alkaline solution. Four different variables were used to study the compressive strength and water absorption of the geopolymer bricks. The findings suggest that the proportion and kind of aluminosilicate material used in the preparation of the geopolymer bricks is the most important component. The current investigation leads to the following conclusions:

- The best combination which was found for preparing the geopolymer mix is A5B2C3D1 which contains 60 % RHA, 20 % GGBS and 20 % Red Mud with A2 type of alkaline solution containing SS/SH as 2 and alkaline to binder % as 0.45. The highest compressive strength achieved was 27.34 MPa, while the lowest water absorption percentage was determined to be 5.68 % for the same combination.
- A heatmap correlation matrix was used to determine the relationship between compressive strength and water absorption. The results show a 96 % negative correlation, which is consistent with the idea that water absorption decreases as compressive strength rises.
- Analysis of variance shows that two most important parameter in our experiment research for making geopolymer brick was binder % and method of preparation for alkaline solution.
- Initial and final setting time of geopolymer mix sharply falls with the use of A3 category of alkaline solution as temperature of almost 84°C reach during immediate mixing of NaOH and distilled water. The heat generated is utilized for initiation of geopolymer reaction.

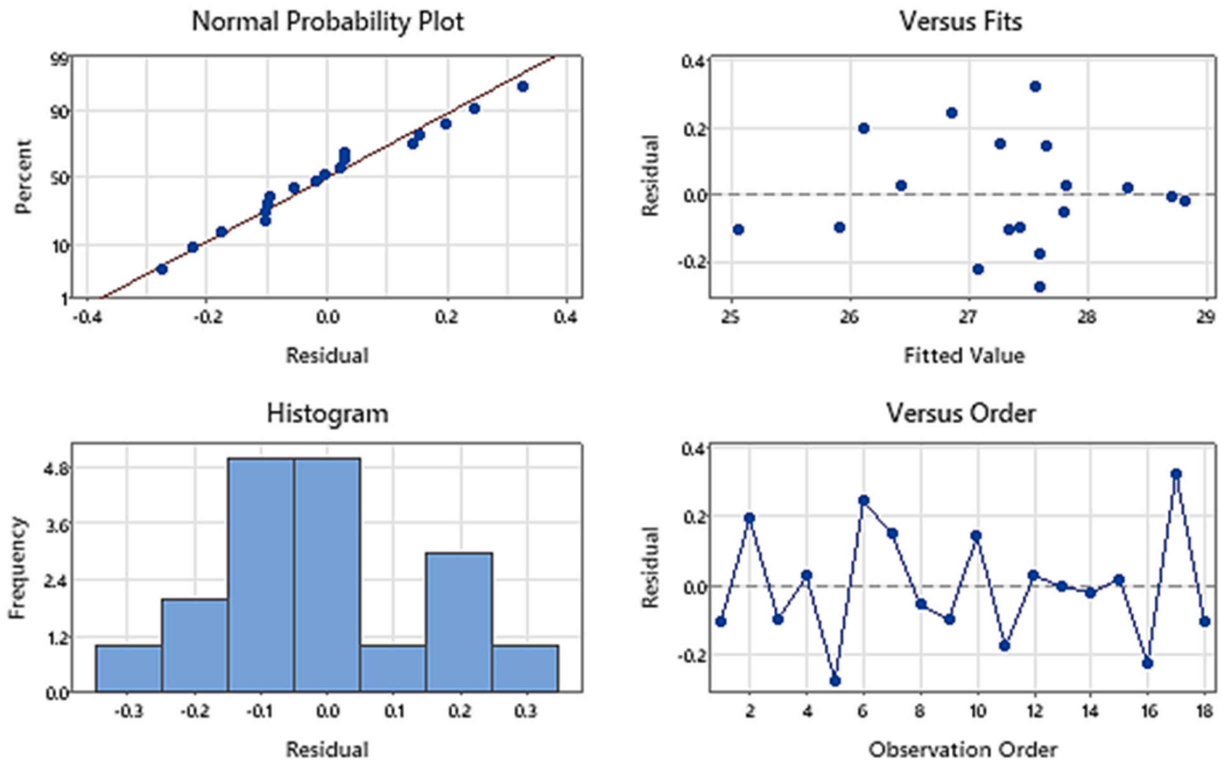


Fig. 22. Residual Plot for SN ratios of Compressive Strength.

Table 11
Analysis of Variance for Compressive Strength.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value
Binder	5	97.445	90.36 %	97.4453	19.4891	152.56
Alkaline Solution	2	9.051	8.39 %	9.0507	4.5254	35.42
SS/SH	2	0.276	0.26 %	0.2758	0.1379	1.08
Alkaline/Precursor	2	0.308	0.29 %	0.3078	0.1539	1.20
Error	6	0.767	0.71 %	0.7665	0.1278	
Total	17	107.846	100.00 %			

Table 12
Analysis of Variance for Water Absorption.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value
Binder	5	10.3326	85.57 %	10.3326	2.06651	15.47
Alkaline Solution	2	0.7453	6.17 %	0.7453	0.37266	2.79
SS/SH	2	0.0316	0.26 %	0.0316	0.01582	0.12
Alkaline/Binder	2	0.1632	1.35 %	0.1632	0.08158	0.61
Error	6	0.8016	6.64 %	0.8016	0.13360	
Total	17	12.0743	100.00 %			

- Taguchi's method was used for developing of geopolymer brick mix design with four dependant variables with different levels and two independent variable as compressive strength and water absorption. Taguchi's method helped us to save time and cost towards building the new geopolymer mix design with high accuracy.
- Microscopic analysis was performed on the two extreme boundary values of highest and lowest sample which were A5B2C3D1 and A1B1C1D1. The SEM analysis clearly shows that A1B1C1D1 which has minimum compressive strength and maximum water absorption has more voids, micro cracks and less geopolymer matrix than A5B2C3D1 and same was confirmed with the help of clustering algorithm also by matching the density of pixel population.
- Regression equation was developed pertaining to compressive strength and water absorption considering all the variable parameters which is capable of predicting the compressive strength with 97.19 % and water absorption with the 93.16 %.

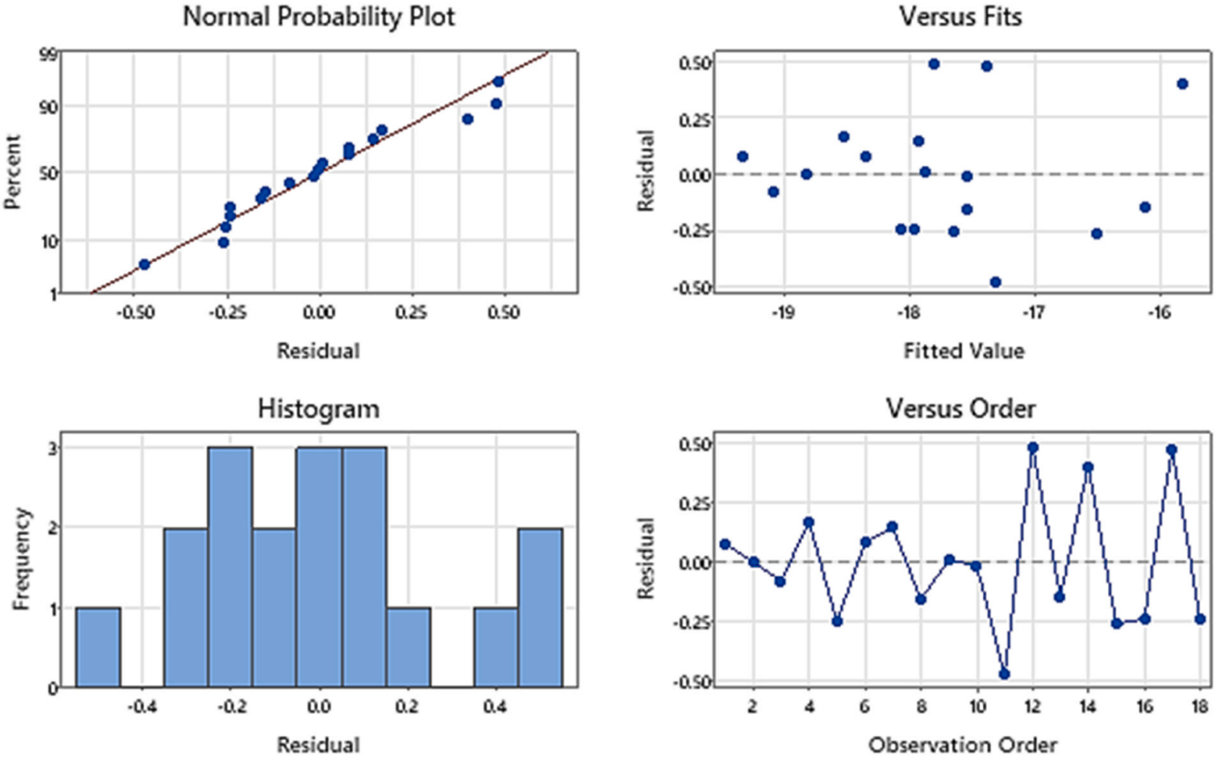


Fig. 23. Residual Plot for SN ratios of Water Absorption.

CRediT authorship contribution statement

Md. Zia ul Haq: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. **Hemant Sood:** Conceptualization, Investigation, Supervision, Writing – review & editing. **Rajesh Kumar:** Investigation, Supervision, Writing – review & editing. **Ildiko Merta:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Supervision, Writing – review & editing.

Funding

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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