Research Article

Metaheuristic Approach to Resolve the Real-World Problem of Binder in Concrete by Synthesizing Natural Iron-Rich Binder System Using Chemical Activation

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Received 20 October 2021; Revised 18 December 2021; Accepted 27 December 2021; Published 16 March 2022

Academic Editor: Vijay Kumar

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This research confirms the metaheuristic way using the novel method of synthesis of inorganic chemical activator binder just by replacing the Al³⁺ ion to Fe³⁺ ion by chemical activation in the matrix using Taguchi’s orthogonal array. The laterite soil was made reactive using calcination processes, and the material used was Fe₂O₃; as a major source, it is then combined with aluminosilicate substances such as low calcium fly ash, and ground granulated blast furnace slag (GGBFS) and Alccofine individually are considered as binder materials, which are activated using alkaline and acid-based chemical activation. Furthermore, the outcomes using Taguchi’s optimization technique with the compressive strength behavior of each chemical inorganic polymer binder to evaluate the best suitable combination of binder with suitable activator are studied, and also, the molarity required for polymerization process is identified using the same. This is found to be the most successful and economical way to solve the real-world problem of binder by preparing the binder system from the natural source and to control the greenhouse effect from the construction industry.

1. Introduction

Building materials are always in demand in the construction sector, especially in developing countries. To reduce our dependency on virgin materials, researchers are developing resource-efficient building materials [1, 2]. Geopolymer is one such emerging approach towards green building materials. Geopolymer is an amorphous inorganic polymer, and it is produced when a hugely intense aqueous alkali hydroxide-silicate solvent is introduced to aluminosilicate raw materials such as slag, fly ash, and calcined clay [3]. Being energy-efficient and eco-friendly, geopolymers are gaining attention. During production, geopolymers release 80% less CO₂ than portland cement. They exhibit attractive properties such as higher compressive behavior, lower shrinkage, faster setting, acid and fire resistance, and lower heat conductivity [4]. Some recent examples of geopolymers include manufacturing artificial sand by geopolymerizing fly ash and diatomite-based geopolymers. The material thus obtained is highly stable, chemical-resistant, hard, and adheres to different surfaces [5]. Geopolymers are alternative binders to ordinary portland cement (OPC) while producing mortars and concrete [6]. Replacing OPC with geopolymers favors low energy consumption and more carbon savings. The geopolymerization concept is ignited by Prof. Joseph Davidovits in 1978, changing the scenario of construction industry worldwide. His research significantly depicts that the acceptance of geo-based polymers can diminish the CO₂ release produced owing to cement productions [7, 8]. The progress of geo-based polymer concrete is a significant stage against the construction of eco-friendly concrete [9]. Geopolymerization contains a chemical-based reaction amid diverse aluminosilicate substances by alkali metal silicates underneatly sturdily alkaline circumstances producing polymer -Si-O-Al-O- bonds, leading to geo-based polymers via polycondensation. The most projected mode of action
comprises the chemical reaction, which consists of the following process: (a) suspension of Si-Al particles from the raw substance via the hydroxide ion reaction; (b) transportation/condensation/orientation of predecessor ions to monomers; and (c) setting or polymerization or polycondensation of monomers to polymeric assemblies. These 3 processes can therefore intersect with one another and create concurrently; occurrence of this is extremely problematic to segregate and individually evaluate each of them as well [10].

Geopolymers have two major components, such as the source and alkaline fluids. Extremely loaded in aluminum (Al) and silicon (Si) are the feed materials for geopolymers. These might include components such as fly ash, silica fume, red mud, and rice husk [11]. As explained by equations (1) and (2), the pictorial development of geopolymer substance can be shown.

\[
n(\text{Si}_2\text{O}_5\text{Al}_2\text{O}_3) + 2n\text{SiO}_2 + 4n\text{H}_2\text{O} + \text{NaOH or KOH} \rightarrow \text{Na}^+\text{K}^+n(\text{OH})_3\text{Si-O-Al-O-Si-OH)} + 4\text{H}_2\text{O}
\]

\[
(\text{Na}^+\text{K}^+)\text{-}(-\text{Si-O-Al-O-Si-O-}) + 4\text{H}_2\text{O}
\]

The use of concrete across the globe was second just after water. Ordinary portland cement (OPC) has been used traditionally to manufacture concrete as the primary binder. The environmental concerns linked by OPC manufacturing are very well established. The amount of carbon dioxide produced throughout OPC manufacturing related to limestone calcination and fossil fuel combustion is in the range of approximately one ton per OPC ton generated [12]. In comparison, only steel and aluminum are around the scope of energy needed for producing OPC. The immediate need to minimize CO₂ emissions is also urgent. Geopolymer is an innovative material developed with Si- and Al-rich materials such as blast furnace slag and fly ash by the polymeric process of alkaline liquid [13]. High tensile strength has also been noticed to be effectively attained in GPC compared with OPC in a shorter period of time, and GPC has great durability to acid and sulfate damage in comparison with OPC. It could be supposed that geo-based polymer concrete development has a comparatively high strength, superior stability in size, and excellent sturdiness [14]. The future alternative substance to ordinary portland cement can therefore be geo-based polymer concrete.

Lateritic soils and laterites, defined as matrix of Fe₂O₃-Al₂O₃-SiO₂-H₂O, are manufactured from kaolinite wherein Fe²⁺ or Fe³⁺ is substituted for a large proportion of Al³⁺. This substitution causes a major alteration of the kaolinite framework: a decrease in the crystalline phase and an improvement in the crystalline layer and aqueous phase, resulting in an enhancement in the susceptibility to chemical attacks [15, 16]. Renewable goods must be sourced and manufactured locally utilizing natural energy, with marginal transportation costs and environmental impacts, requiring thermal performance, commercial feasibility, and lower energy in the production steps [17]. In this article, our purpose is to explain the geopolymerization method adjusted to the unique features of laterites. An appropriate production proposal is intended for durable and reliable inorganic material cements and coatings with strong mechanical properties, lower porosity, and higher density, accomplished in compliance with international standards on the depending specifications. It should be noted here and in the situation of laterites that although they actually imply a range of aluminosilicates, their response and action must be related to the extent of iron aggregation throughout poly-condensation. Taking into consideration the compositions of hematite-corundum and goethite-diaspore, the solid suspensions of crystalline form iron-rich oxyhydroxides [18, 19], and the replacement of hematite (Al-hematite) and Al³⁺ in goethite (Al-goethite) was an alternate criterion to distinguish laterites as aluminosilicates, which may influence the typical geopolymerization process. For polycondensation, the framework of kaolinite previously disintegrated by iron aggregation must be favorable [20, 21]. Thus, while in this study all the parameters mentioned here should not be explained, the hypotheses stated in the introductory section above are being used to establish geopolymer matrices verifying the successful variables impacting the geopolymerization. The current aim of research also attempts to validate that better geopolymeric substances could be produced as a connecting source of laterite or laterite soils of Fe²⁺ and Fe³⁺.

1.1. Literature Survey. Geopolymers are a category of composites that usually contains a quasi-amorphous process of the matrix wherein grains are dispersed in 3D aluminosilicates. At ambient temperature or marginally larger temperature, the curing and strengthening procedures are achieved. Toughening reactions arise among aluminosilicate by-products and tightly regulated alkaline hydroxide and silicate aqueous solutions.
In the last three decades, geopolymers have received much interest. The usage of various aluminosilicates, such as fly ash [3, 19], melted quenched aluminosilicates [22], metakaolin [20, 21, 23, 24], volcanic scoria from molten mineral resources [25, 26], and combinations of two or all components [9, 27, 28], has been the priority of many research articles on geopolymerization.

The antagonism among hematite and kaolinite in the laterite matrix was detailed by Ambroset al.: the corrosion of kaolinite is described through the total destruction of the hematite or goethite crystals that were assembled to thinner lamellar assemblies; the crystals created through Al-rich goethite or Al-rich hematite retain an exact trace and size of earlier platelets of kaolinite [12]. The asserted protons required to disintegrate kaolinite were also produced by a response comparable to oxidation-hydrolysis process in ferrolysis [4] throughout the deep layers with laterites fed via Fe$^{3+}$ solutions, but at the other side, it is been shown that implementations such as those of silica or kaolinite atoms have speeded up the particle and alkaline fluids. Rich in silicon (Si) and aluminum (Al) are the raw substances for geopolymers. These might involve substances such as fly ash, silica fume, red mud, and rice husk [11].

(1) Fly Ash. The by-product compound, fly ash, is received from thermal power plants by the burning of pulverized coal, as stated by Nawaz [35]. Currently, India’s annual development of fly ashes is around 112 million tons and is projected to reach 225 million tons through 2017. The residue makes up 80% fly ash and 20% bottom ash if pulverized coal is burned to produce heat. If not handled properly, the disposal of fly ash in the sea/rivers/ponds could also affect aquatic life. Lagoons/settling reservoirs for slurry drainage may become breeding grounds and microbes. With quantities of radioactive metals found in fly ash, it could also infect the underground water supply. Over 80 percent of fly ash is often utilized in industrialized countries in different fields, where really fewer proportions in different segments have been used in India. Fly ash was such an instance that until decade ago in India was already viewed as waste products, and it has now appeared not just as an instructional material but as an environmental savior [36, 37]. This bottom ash has been one of the prime components of alumina and silica. It also was observed that fly ash has strong possibility to employ in the building industry. There are many uses for the transformation of fly ash through zeolites, such as ion exchange, molecular sieves, and adsorbents. Bioconversion of fly ash into zeolites is not just to ameliorate the issue of recycling; it also turns a waste product into a product that is valuable. In Table 1, the fly ash used throughout the chemical composition of this research is mentioned.

(2) GGBFS. Blast furnace slagging is a by-product generated from the manufacture of pig iron throughout the blast furnace and is primarily composed of sensitive silicates and calcium aluminum silicates and other components, which are successively processed in an igneous state with iron throughout the blast furnace. Whenever the molten slag in such a coolant pool is cooled down with liquid or chilled with powerful jets of water, it becomes a fine-grained, nearly entirely noncrystalline, misty called as granulated slag of latent hydraulic conductivity enabled by the use of alkali hydroxide and alkali silicates. Typically, ground granulated blast furnace slag (GGBFS) seems to be the only concrete part that includes substantial amounts of sulfide. To prevent a negative effect, the sulfide composition of the cement has to be established. For the chemical structure of GGBFS considered for this study, refer to Table 1.

(3) Alccofine. Alccofine is managed to grind the ultrafine GGBFS material; in particular, it is also the microfine particle substance that is smoother than that manufactured in India for cement, fly ash, silica, and several other cement-based substances. It has higher reactivity acquired via the regulated granulation process. The raw systems are produced mainly of GGBFS-like high-calcium silicates. Regulated particle shape results from processing with other selected ingredients (PSD). The PSD-based measured Blaine value is
about 12000 cm²/gm and is really ultrafine. Alccofine helps decrease water so for a faced major, also up to 70 percent replacement rate as per concrete efficiency specification, owing to its unique composition and ultra-molecular weight. Alccofine could also be utilized to increase strength properties or even as a super modifier aid to aid to boost stream as a higher-range water stopper. This one has been discovered that the usage of ultrafine slag not only increases high strength concrete power but also enhances the mix’s reliability and elasticity.

(4) Alkaline Fluids. The mixture of NaOH or KOH with sodium or potassium silicate [38, 39] is the most important alkaline fluid used throughout geopolymerization. Alkaline fluid plays an essential part in the process of polymerization. In contrast to the usage of only alkaline hydroxides, changes occur at higher rates when the alkaline fluid comprises soluble silicate, whether sodium or potassium silicate. The amount of sodium silicate as that of the alkaline activator to the sodium hydroxide solvent strengthened the response between the original source and the solution [40]. In addition, after a geopolymerization analysis of sixteen organic Al–Si minerals, the observed NaOH solvent usually induced a greater degree of mineralization than the KOH solution.

(5) Acidic Liquid (Orthophosphoric Acid). Phosphoric acid is indeed a tripotric acid that occurs as a dense fluid, also recognized as orthophosphoric acid. Milk, beef, poultry, shrimp, nuts, and egg yolks generally contain ingredients (0.1–0.5 percent) [41]. It is commonly used during fertilizer production, surface coating of metals, and also as a food additive. It is irritating and corrosive, yet it is normally known as nontoxic.

(6) Coarse and Fine Aggregates. Coarse and fine aggregate, typically commonly accessible, could be used for the development of geopolymers.

2. Materials and Methods

Natural iron-based material selected from laterite soil was collected from the Kottayam District of Kerala, India. The precursors ground granulated blast furnace slag (G) and Alccofine (A) were purchased from Ambuja Cement Industry [42]. Fly ash (F) of class F from Fly Ash Brick Manufacture Company, sodium hydroxide with 98% purity from Isochem, potassium hydroxide pellets with 98% purity from Isochem, silicate modulus 2.26 from Isochem, and orthophosphoric acid from Isochem are employed as an activator solution. Based on the silicate and aluminate present in the matrix, the variations in the chemical activation by Si/Al ratio from the percentage of the available reactive materials can be identified through the XRF test.

The laterite soil is crushed in the grinding ball mill and allowed to pass in 90-micron sieve, and then, optimum activation temperature is identified as 700°C by various trials. For this work, laterite powder is calcined at 700°C for 2 hours. This calcined laterite (La) is mixed with fly ash (F), GGBFS (G), and Alccofine (A) individually (consider as source material) based on the required percentage as per the levels set in L9 orthogonal array of Taguchi’s optimization method combination mentioned in Table 2. The percentages chosen are 10%, 20%, and 30%. Similarly, activator solutions chosen are NaOH with Na₂SiO₃ (N) and KOH with K₂SiO₃ (K) and H₃PO₄ (P), which are added individually with source material as mentioned in the experimental combination in Table 2 with molarity (M) chosen as 5, 8, and 10. The optimization technique used is L9 (3^4) orthogonal array of Taguchi’s optimization method with 4 parameters, and 3 levels are mentioned in Table 3. The calcination of laterite material is shown in Figure 1.

Sodium silicate solution and potassium silicate solution with silicate modulus of 2.26 and alkali hydroxide-to-alkali silicate ratio of 2.5 and acidic solution of orthophosphoric acid are used as the activator solution with stimulator to binder proportion of 0.55 to provide the primary binding effects for the synthesis of inorganic polymer products [43]. The fabricated products were cured at 60°C (oven), and after various trials for confirming the activation of material, to gain minimum strength, it is demoulded from the mould. Numerous formulations were designed and exposed to early-age tensile testing exemplifying these techniques.

Here, the binding materials are LaG—laterite powder and GGBFS combination, LaF—laterite powder and fly ash combination, and LaA—laterite powder and Alccofine combination. The proportion means 10%–10% percentage of addition of GGBFS or fly ash or Alccofine with laterite powder by weight based on combination obtained from L9 (3^4) orthogonal array, 20%–20% percentage of addition of GGBFS or fly ash or Alccofine with laterite powder by weight based on combination obtained from L9 (3^4) orthogonal array, and 30%–30% percentage of addition of GGBFS or fly ash or Alccofine with laterite powder by weight based on combination obtained from L9 (3^4) orthogonal array.

The stepwise procedure is as follows:

### Table 1: Chemical composition of materials used as per XRF data.

| Samples     | Laterite (%) | Fly ash (%) | Alccofine (%) | GGBFS (%) |
|-------------|--------------|-------------|---------------|-----------|
| SiO₂        | 21.90        | 56.30       | 36.90         | 37.20     |
| Al₂O₃       | 41.40        | 31.80       | 18.30         | 15.90     |
| CaO         | 0.20         | 1.07        | 33.70         | 34.10     |
| Fe₂O₃       | 14.80        | 3.96        | 0.69          | 0.47      |
| P₂O₅        | 0.11         | 0.49        | —             | —         |
| TiO₂        | 1.10         | 1.72        | 0.61          | 0.92      |
| Na₂O        | 0.12         | 0.17        | 0.28          | 0.31      |
| MgO         | 0.12         | 0.53        | 6.55          | 6.85      |
| K₂O         | 0.39         | 1.31        | 0.65          | 0.39      |
| MnO         | —            | 0.01        | 0.87          | 6.85      |
| SO₃         | 0.12         | 0.08        | 1.38          | 1.37      |
| LOI         | 19.49        | 0.50        | 0.00          | 0.40      |

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Iron-rich powdered laterite is activated by calcination to 700°C for 2 hours.

Additives (additional aluminosilicate source) chosen are as follows:

(i) Fly ash
(ii) Alccofine
(iii) GGBFS

Activator solution chosen is as follows:

(i) NaOH and Na$_2$SiO$_3$ solution
(ii) KOH and K$_2$SiO$_3$ solution
(iii) Orthophosphoric acid

Molarity chosen is as follows:

(i) 5M
(ii) 8M
(iii) 10M

Na$_2$SiO$_3$ to NaOH ratio is taken as 2.5 with silicate modulus of 2.26 and liquid-to-binder ratio of 0.55.

Proportions of weight of additives to an overall weight percentage of calcined laterite chosen are as follows:

(i) 10%
(ii) 20%
(iii) 30%

Material combinations chosen based on the Taguchi optimization L9 (3$^4$) orthogonal array are listed in Table 2.

Required alkali hydroxide solutions were prepared based on molarity, and after half an hour, alkali silicate solution is added with the prepared alkali hydroxide and mixed thoroughly. (In this work, the alkali hydroxide solution is not processed 24 hours before to bring the solution temperature down to ambient, instead utilized the temperature of the solution to enhance the reaction.)

Calcinated laterite powder is mixed thoroughly with the required percentage of additives by weight as per Table 3.

Prepared solution is added with the binder source material to prepare paste as per ASTM C305-20.

The specimen is cast in the 20 × 20 × 20 mm mould and kept under ambient temperature till the sample get converted from liquid to harden state.

Samples are placed in oven to 60°C for 5 hours after various trials to confirm the activation of material to gain minimum strength to demould from the mould.

5 numbers of samples are cast for every single test. After oven curing, the specimens are tested for compressive behavior on the third day.

| Exp. no. | Levels | Binder materials | Levels | Percentage of G or F or A | Levels | Activator solution | Levels | Molarity of NaOH or KOH or H$_3$PO$_4$ (mols) | Mean compressive strength (N/mm$^2$) |
|----------|--------|------------------|--------|--------------------------|--------|-------------------|--------|---------------------------------|----------------------------------|
| 1        | 1      | LaG              | 1      | 10                        | 1      | N                 | 1      | 5                              | 0.27                              |
| 2        | 1      | LaG              | 2      | 20                        | 2      | K                 | 2      | 8                              | 8.19                              |
| 3        | 1      | LaG              | 3      | 30                        | 3      | P                 | 3      | 10                             | 0.38                              |
| 4        | 2      | LaF              | 1      | 10                        | 2      | K                 | 3      | 10                             | 0.75                              |
| 5        | 2      | LaF              | 2      | 20                        | 3      | P                 | 1      | 5                              | 0.49                              |
| 6        | 2      | LaF              | 3      | 30                        | 1      | N                 | 2      | 8                              | 4.60                              |
| 7        | 3      | LaA              | 1      | 10                        | 3      | P                 | 2      | 8                              | 2.43                              |
| 8        | 3      | LaA              | 2      | 20                        | 1      | N                 | 3      | 10                             | 21.97                             |
| 9        | 3      | LaA              | 3      | 30                        | 2      | K                 | 1      | 5                              | 25.77                             |

| Levels | Binder material | Percentage of G or F or A | Activator solution | Molarity of NaOH or KOH or H$_3$PO$_4$ |
|--------|-----------------|---------------------------|--------------------|---------------------------------------|
| 1      | LaG             | 10                        | N                  | 5                                     |
| 2      | LaF             | 20                        | K                  | 8                                     |
| 3      | LaA             | 30                        | P                  | 10                                    |

Table 2: Combination chosen for Taguchi’s optimization techniques for L9 orthogonal array.

Table 3: Parameters and levels of L9 (3$^4$) orthogonal array.

Figure 1: Calcination of laterite material.
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(13) Compressive behavior study was executed with the help of unconfined compressive strength testing machine at the amount of loading 2.5 mm per minute as per the procedure mentioned in standard IS 2720 part 10 of 1991.

(14) Based on the results, the optimization processes were carried out to find the best combination. From the obtained combination value, specimens were cast and the results were obtained.

(15) The same combination was tried with 100% calcined laterite without the percentage proportion of additives for comparison.

3. Results and Discussion

For the cost-effective concrete mix design, Dr. Genichi Taguchi suggests the Taguchi design of the experimental method. Binder material with aluminosilicate and ferrous material is reacted with activator solutions of alkali and acidic activator with a different molarity. Molarity used is 5, 8, and 10 for all activators. Taguchi’s optimization technique is used with various parameters, and levels are fixed. Samples are placed in oven to 60°C for 5 hours after various trials to confirm the activation of material to gain minimum strength to demould from the mould. Sample of size 2 cm × 2 cm × 2 cm was cast to find the compressive behavior of reacted solid material, which is tested by the unconfined compressive strength testing machine at the proportion of loading 2.5 mm per minute as per the procedure mentioned in standard IS 2720 part 10 of 1991. L9 orthogonal array is used with 4 parameters studied with 3 levels (L9 (3^4)). A larger better concept was accomplished to identify the signal-to-noise proportion using the following equation:

\[ \eta = - \log_{10} \left[ \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_{i}^2} \right]. \]  

3.1. X-Ray Diffraction Spectroscopy. Laterite soil collected from the crushed laterite blocks is then sieved in 90 microns and collected to give heat treatment using the Muffle furnace to the temperature of 700°C for 2 hours. X-ray diffraction of calcined laterites was performed with a reflection Bruker AXS D8 Advance Debye–Scherrer diffractometry employing copper Kα radiation (\( \lambda = 1.54056 \) Å) and a graphite monochromator. The study extent was from 5° and 80°, by a stepping size of 0.04° and an achievement period of 2 s/step. The crystal stages present were exemplified by evaluation through International Centre for Diffraction Data (ICDD) Powder Diffraction File (PDF) records. XRD plot of calcined laterite soil is given in Figure 2.

In calcined laterites, the diffuse scattering feature initially appearing between 15° and 25° was shifted to appear between 20° and 40° after alkaline or acid consolidation. This change is likely to be related to reactions between the calcined laterites and phosphoric acid or alkaline solutions leading to the creation of amorphous phases. Crystal-based mineral stages such as hematite, quartz, ilmenite, and anatase contained in the calcined laterites also remain after alkaline or acid consolidation. They are either unaffected or partially dissolved in the acidic or alkaline-activating solutions. For laterite, the amorphous stage was both disorganized aluminosilicate assembly and an unstructured alumina hydroxide. The higher intensity and sharper bands from crystalline stages were disappeared after 30°, and the rest background disparities expose the prevalence of an unstructured stage.

3.2. Taguchi’s Optimization Techniques. For alkaline activator, \( \text{Na}_2\text{SiO}_3/\text{NaOH} \) ratio used is 2.5 and binder ratio proportion used was 0.55 for all the mix. Various parameters chosen for doing Taguchi’s optimization techniques with L9 (3^4) orthogonal array are as follows.

(1) Molarity of the activator solution chosen is as follows:
   (i) 5 molarity as M5
   (ii) 8 molarity as M8
   (iii) 10 molarity as M10

(2) Alkaline activator chosen is as follows:
   (i) Sodium hydroxide and sodium silicate as N
   (ii) Potassium hydroxide and potassium silicate as K
   (iii) Orthophosphoric acid as P

(3) Calcined laterite with various aluminosilicate-based additives chosen is as follows:
   (i) Laterite + ground granulated blast furnace slag as LaG
   (ii) Laterite + Alccofine as LaA
   (iii) Laterite + fly ash as LaF

(4) Proportions of aluminosilicate additives added along with calcined laterite powder as follows:
   (i) 10 percentage as 10%
   (ii) 20 percentage as 20%
   (iii) 30 percentage as 30%

Sample of size 2 cm × 2 cm × 2 cm was cast to find the compressive behavior of the reacted solid material that is tested by the unconfined compressive strength machine at the rate of loading 2.5 mm per minute as per the procedure mentioned in standard IS 2720 part 10 of 1991. A characteristic cube sample is depicted in Figure 3. It must be clear that the geopolymerization method delivers moisture, and thus, sticking is suitable for therapeutics of these synthetic binders.

Taguchi’s optimization techniques with L9 (3^4) orthogonal array is chosen to find the suitable reaction with the combination of the activator solutions and proportions as per the experimental list shown in Table 2. The failure pattern of cube after compressive behavior is given in Figure 4.

An unconfined compression testing machine was utilized to evaluate the compressive behavior of paste samples. Conservatively, data from a calculated test were employed to
examine the mean purpose or response function. In Taguchi’s method, the difference in the rejoinder was evaluated utilizing a suitably selected S/N ratio. In general terms, the proportion of the mean (signal) to a standard deviation seems to be the S/N ratio (noise). Variation depends on the optimal solution and the formula that are used to calculate the S/N ratio. 3 numbers of different S/N equations were also normally often used to categorize the objective function as follows: “bigger the better,” “smaller the better,” or “marginal the best.” Although a bigger S/N ratio is often beneficial, irrespective of the nature of performance trait, the better options were adopted as per the idea of greater compressive strength to show greater reactivity. The signal-to-noise ratio is obtained using the formula (3). In formula (3), \( i \) = number of a trial; \( Y_{ij} \) = calculated value of quality feature for the \( i \)th trial and \( j \)th experiment; and \( n \) = number of iterations for the experiment. For every experimental circumstance, signal-to-noise proportions were calculated employing (3) and are enlisted in Table 2. The factor impacts could be segregated in aspects of the S/N proportion and in relations of mean reaction, because the study data are orthogonal. Figure 5 represents the actual S/N mean values of four process parameters at each stage and selects the thresholds correlating with the largest S/N ratios in each of the parameters chosen to represent this same optimal condition. In this, maximizing the compressive strength corresponds to the optimal condition. To have access to the S/N assessment, the significant effect mostly on the response variable of the material properties will also be evaluated. The overall mean is defined as the average significance of a performance criterion at various levels by each factor. Therefore, the average compressive behavioral values at the 3 stages for each factor have been evaluated and are shown in Figure 5. The mean reaction study also shows the identical optimal range of the measurements derived in Figure 6 of the S/N profitability ratios.

The final optimum combination chosen from the S/N ratio is largely better option as binder—LaA, percentage—20%, activator—K, and molarity—8 is achieved. With the above combination value obtained from the orthogonal design, was cast and obtained mean strength as 26 N/mm2 which is not having significant increment in strength. This is because the orthophosphoric acid gets sudden solidification when added with the higher percentage proportioning with blast furnace slag, which results in the unevenness in the homogeneity in the cube casting, which
results in reduction of strength. This influenced internal noise affects the obtained optimum value.

A similar combination is tried with calcined laterite material with different activator solutions of 8M that are mentioned in Table 4 for evaluation. The outcomes show a significant amount of reaction happened.

3.3. Fourier Transform Infrared Spectroscopy. These results are justified with the FTIR data obtained from optimized result, shown in Figure 7. At 1645/1650 cm\(^{-1}\) and 1388/1392 cm\(^{-1}\), the FTIR spectrum possesses an absorption patterns referring to the winding and stretching fluctuations of H–O–H bonds of water derivatives dissolved or trapped in massive polymeric frame cavities [5, 8, 42]. The band gaps about 1400 cm\(^{-1}\) are possibly formed from efflorescence of the symmetric stretching of sodium carbonate C–O bonds [31, 43]. At 3685/3658 cm\(^{-1}\) and 3612/3606 cm\(^{-1}\), two distinctive groups of kaolinite are detected to suggest the existence of a tiny portion of kaolinite, which persists with alkali solution just after the reaction phase. They are within the 997–1041 cm\(^{-1}\) interval but are due to the geopolymer gel’s symmetric stretching vibration of Si–O–Si and/or Si–O–Al and Si–O–Fe. It leads to the phase of polycondensation contributing to gel geopolymer [18, 32].

The Si–O–Al bond symmetric folding in kaolinite was attributed to the groups at 743 and 790 cm\(^{-1}\) and those at 789 and 690 cm\(^{-1}\), respectively [35]. The wideband with such a maximum of 965–976 cm\(^{-1}\) in all geopolymer spectra is owing to the increasing geopolymer channel vibrations of Si–O–Si, Fe–O–Si, and Si–O–Al. The change was anticipated and is owing to the introduction into the silicate channel of tetrahedral Al [7]. The absorption at 665–685 cm\(^{-1}\) is owing to its tetrahedral channel’s Si–O–Al (IV) stretching [8, 41], but overlaps with both the kaolinite peaks at 690 cm\(^{-1}\). The Si–O–Si (or Si–O–Al) symmetric stretch channel and Fe–O stretching vibrations in tetrahedral and octahedral locations were allocated to the frequencies at 389–432 cm\(^{-1}\) and 519–538 cm\(^{-1}\).

3.4. X-Ray Diffraction Spectroscopy. Figure 8 displays the X-ray trends of untreated, calcined laterite, and optimized samples. Kaolinite (34 wt percent), goethite (29 wt percent), and quartz (25 wt percent) are the major minerals throughout raw laterite. The secondary stages are hematite (8 wt percent), gibbsite (2 wt percent), anatase (1 wt percent), and illite (2 wt percent). Only hematite, quartz, and anatase exist as primary mineral stages with such a content of up to 70, 27, and 3 wt percent, respectively, after calcination. The greater hematite content is attributable to goethite dehydroxylation to the most soluble iron oxide Fe\(_2\)O\(_3\) throughout calcination [26]. The calcined laterites comprise crystalline mineral forms such as hematite, quartz, ilmenite, and anatase. After geopolymerization, parallel to the decrease in the cost of hematite and anatase, a rise of the quartz composition.
to 38 wt percent is reported. The reduction in the relative quantity of hematite in the geo-based polymer specimen may suggest that partial reactions have occurred [18, 23]. The enhancement in the relative quantity of kaolinite reflects the fact that the above appears inert in the framework and is not involved in the geopolymerization process.

3.5. Scanning Electron Spectroscopy. The matrix illustrates the detachment of the geopolymerization products’ microstructure, which has been intensified by the inclusion of a large percentage of laterite soil. This has been shown in Figure 9. Because of its semicrystalline composition, the laterites improve the likelihood of major crosslinking. The impact of
residual pores, basically related to air particles, is relatively significant. The effect of these forms of permeability, nevertheless, becomes less pronounced now as the existence of laterites and the formation methodology used to significantly alter the expresses incorporated in the matrix material to fill space accessible within the laterite matrix concrete framework.

4. Conclusions

Optimization of process parameters was performed via Taguchi’s optimization method. From this research, the minimum molarity of alkali hydroxide required is 8 molar to activate the laterite-based ferro-sialate with minimum of 60°C obtained with the help of statistical method. Iron-rich geopolymers or alkali-poly(ferro-sialate) of calcined lateritic soils as raw materials along with 20% of additives have been successfully produced. The presence of functional groups of Si–O bonds and Si–O–Al bonds and the presence of (alkali) (Fe–Si–Al–O) phase confirmed the geopolymerization of lateritic soils employed in our work. The addition of additives based on optimization results in a significant dense microstructure and improved mechanical properties. The laterite-based geopolymer contains both polysialates and ferro-sialates. The XRD results of geopolymer depict the existence of AlPO₄ and also FePO₄ as a by-product of geopolymerization reaction in phosphoric acid as activator. The FTIR of geopolymer specimens depicts that the geopolymerization by-product has a polymeric Si–O–Al and Fe–Si–O and Si–O–Al–O–P structure in alkaline and acidic activator. Therefore, the predictions created by Taguchi’s constraint design strategy were in better agreement with the validation outcomes. Within the defined range of material criteria, the findings of the present examination were accurate alongside their preferred levels and for the particular arrangement of brick materials. It was shown that Taguchi’s optimization technique is a promising tool for the pavement concrete mix design.

Data Availability

The data shall be made available on request to the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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