International Journal of GEOMATE
(Geotechnique, Construction Materials and Environment)
ISSN: 2186-2982 (P), 2186-2990 (O), Japan

Vol. 31, Issue 144, August, 2026, PP.91-99; DOI: 10.21660/2026.144.5497

EXPERIMENTAL EVALUATION OF STRENGTH DEVELOPMENT IN HIGH PLASTICITY CLAY STABILIZED WITH GGBS-BASED ALKALI-ACTIVATED BINDER UNDER VARYING NaOH MOLARITIES

*Farzana Basheer[1], Ameera Hydrose[2] and Fidha Parveen[3]

[1,3]Department of Civil Engineering, Government college of Engineering, Kannur, India;
[2] College of Engineering ,Gulf University ,Sanad 26489,Kingdom of Bahrain

*Corresponding Author, Received: 13 Jan. 2026, Revised: 20 March 2026, Accepted: 12 April 2026

ABSTRACT: The clayey soil experiences swelling and shrinking properties because of the change in moisture content, which affects the soil's load-bearing capacity and the stability of the foundations. This article aims to evaluate the geopolymer stabilisation method of clayey soil, which utilises Ground Granulated Blast Furnace Slag (GGBS) activated with sodium hydroxide (NaOH) as an alternative to conventional binders. The soil specimens were subjected to 6%, 12%, and 18% GGBS, based on the dry weight of the soil, and activated with 8 M and 12 M NaOH solutions at an alkali-to-binder ratio of 0.5. Three specimens were prepared for each mixture, and the average unconfined compressive strength (UCS) was obtained at curing ages of 0, 7, and 28 days. The UCS of untreated soil was 160.5 kPa. Stabilised soil samples indicated that there was an improvement in terms of strength compared to natural soil. For 6% GGBS soil samples cured for 28 days, there was an increase of 21.5%, and for 12% GGBS samples cured for 28 days, there was a 429% increase. For 18% GGBS samples cured for 28 days, it indicated the highest UCS of 2543 kPa with a 1484% improvement compared to untreated soil samples cured with 12 M NaOH solution. From the above-mentioned results, it is concluded that GGBS-based geopolymer stabilisation is used to improve the strength of clayey soil and is considered a green technology for soil stabilisation using industrial wastes.

Keywords: Clayey soil, Geopolymerization, GGBS, NaOH

1 INTRODUCTION

Fine-grained soils (such as soft clays and expansive soils) are difficult to work with due to their weak undrained strength, high compressibility, shrink-swell characteristics, and moisture sensitivity. These problems often lead to excessive settlement, diminished bearing capacity, and lasting serviceability problems for foundations, pavements, and earth constructions. Normal stabilisation has mainly used ordinary Portland cement (OPC) and lime; however, their manufacturing results in excessive energy expenditure and is associated with large CO_2 emissions, encouraging the investigation of lower-carbon binders with technical performance equivalent to or better than the conventional ones. Over the last decade and especially since 2020, alkali-activated materials (AAMs) and geopolymer binders have become progressively popular as environmentally friendly methods to enhance soil conditions. Alkali activation usually involves placing aluminosilicate precursors (such as slag, fly ash, and other industrial waste) in a highly alkaline environment. These in turn react and create cement-like products, which bind the soil particles and improve the pore structure. For calcium-based materials such as ground granulated blast furnace slag (GGBS), it yields C-(A)-S-H-type gels in this reaction. These gels reinforce and stiffen materials, which results in their long lifetime, as they have less permeability and are more resistant to sulphate. Soft soil prepared using low-carbon alkali-activated binders increases strength and decreases compressibility and permeability. This can establish the concept of AAM stabilisation fulfilling mechanical and hydraulic performance requirements [1,2]. Previous studies have demonstrated that the effectiveness of activated soil stabilisation really depends on the amount of binder and activator that is used. For example the amount of GGBS is usually between 5% and 20% of the weight of the soil and the strongest soil is often found when the GGBS is between 10% and 15%. This depends on the type of soil and how it is cured. Similarly people often use an amount of NaOH, between 6 M and 14 M to help the soil become stronger.

With these improvements there are still some problems that people have found. One of the problems is that it is hard to mix the soil and binder

evenly. Another problem is that the soil can set quickly when there is a lot of alkali in it. This makes it hard to work with the soil when it is being prepared. The type of minerals, in the soil also affects how strong it becomes, which makes it hard to figure out the mix of ingredients. Activated soil stabilisation also has some issues with lasting a long time when it gets wet and dry and it is not clear if it will work well in real world situations

Recent studies show that GGBS activated with NaOH and/or sodium silicate effectively improves soil quality in fine-grained soil. Whether the soil is strong or weak is determined by the type and quantity of activator used, the quantity of binder used, the curing time, and the moisture level. For instance, researchers have investigated using GGBS and NaOH to activate clayey soils, which made them stronger and more shear-resistant because of chemical bonding and microstructural densification [3]. Alkali-activated slag-based systems and blended precursors have also been shown to produce meaningful UCS gains across different curing regimes for granular soils. This shows that alkali activation is a useful tool for improving ground conditions [4,5]. Environmental assessment has emerged as a pivotal research focus: investigations have demonstrated that alkali-activated stabilisation can mitigate embodied impacts compared to cement-based stabilisation when formulated with locally sourced by-products and suitable activator methodologies [6].

There have also been more recent advances beyond strength-only investigations (2022–2025), which aimed for more comprehensive considerations on constitutive behaviour, durability and mechanistic studies. Triaxial testing and constitutive modelling of alkali-activated slag-stabilised clays have quantified the changes in stress–strain response due to cementation, enabling greater accuracy in design-level predictions [7]. Durability-based contributions have been focused on permeability reduction and resistance to chemical attack (e.g., sulphate), supported by microstructural tools (XRD, SEM/EDS, MIP/EIS), which are also critical in supporting field acceptance under aggressive scenarios [8]. Recent studies from the soil grouting and deep soil mixing applications investigated alkali-activated grout systems (as metakaolin/slag blends with sodium silicate solutions) and grout–soil interactions, bringing to light practical issues relating to the mixture design (dilution, workability, and soil reactivity) that contrast with conventional geopolymer research directed toward concrete [9–10].

Further, the curing conditions (air-dried vs wet cure) and activator ratios (SS/SH) are strongly associated with volumetric stability and prolonged performance of stabilised clays and are essential to prevent shrinkage cracking or salt crystallisation-related distress [11]. Despite these progresses, however, there are some obvious limitations which are directly applicable to GGBS–NaOH stabilisation for clays/expansive soils: (i) consistent optimisation of the binder–activator dosage targeting the geotechnical properties (UCS, stiffness, plasticity reduction and swell control) under the realistic curing paths; (ii) unified translation mapping macro-performance (strength, permeability and durability) and microstructural evolution and reaction products; and (iii) conversion of laboratory results into practical stabilisation techniques (mixing energy, moisture control, workability and field variability). Recent studies of alternative activator chemistries and of “one-part” systems (solid activators such as NaOH) also indicate an avenue for enhancing construction practicality and performance durability (e.g., freeze–thaw resistance in soft soils), but no more evidence to support soil-type-dependent performance and mechanistic clarity is available [12–13].

Accordingly, this study investigates the stabilisation of clayey/expansive soil using alkali-activated GGBS with NaOH (and, where relevant, blended activator strategies), focusing on (a) improvement in strength and stiffness over curing time; (b) changes in index/engineering behaviour (plasticity, compaction response, swelling/shrinkage tendency, permeability); and (c) microstructural evidence of stabilisation mechanisms. The outcomes aim to support the design of lower-carbon stabilisation mixes with performance suitable for subgrades and geotechnical earthworks, aligned with emerging sustainability and circular-economy goals [14].

2. RESEARCH SIGNIFICANCE

The growing need for environmentally friendly ways to improve the ground means that we need to find other ways to stabilise it besides using cement and lime, which are linked to high carbon emissions and energy-intensive production processes. AAMs have shown promise in stabilising soil, but there haven't been many systematic studies on calcium-rich GGBS that are activated only by sodium hydroxide for high-plasticity clay. Most of the studies that have been done so far focus on fly ash-based systems or mixed activators (NaOH + Na_2SiO_3). Only a few studies look at how NaOH molarity affects strength development in clay stabilised with slag-based geopolymer. Additionally, there is a paucity of research that concurrently investigates compaction

properties and strength development under regulated curing conditions. This study enhances the domain of sustainable geotechnical engineering by:

• Checking how the strength and compaction behaviour change when the GGBS content is between 6% and 18% and the NaOH molarity is between 8 M and 12 M.
• Measuring how strength changes over time (0, 7, and 28 days).
• Showing that a geopolymer system with only one activator (NaOH) can be used to stabilise clay.
• Giving experimental proof that GGBS, an industrial by-product, can be used as a low-carbon alternative binder.

The results show that the best mix parameters can reach strength levels that are good for subgrade and low-rise foundation uses. This study, therefore, improves our understanding of how to use alkali-activated slag systems to stabilise expansive clay and supports the move toward ground improvement methods that are better for the environment.

3. MATERIALS AND METHODS

3.1 Materials

3.1.1 Clayey Soil

The clayey soil used in this study was collected from Mottammal, Kannapuram, Kannur, India, from a depth sufficient to avoid organic contamination as shown in Figure 3. The collected soil was air-dried, pulverised manually without altering particle characteristics, and sieved through a 4.75 mm sieve prior to testing. Properties of the soil sample collected have been shown in Table 1.

Table 1. Physical and Engineering Properties of Natural Clayey Soil

Property	Symbol	Value	Remarks
Specific Gravity	Gs	2.6	Typical for Kerala clay
Liquid Limit	LL (%)	62.37	High plasticity range
Plastic Limit	PL (%)	36.72	Derived for liquid PI
Plasticity Index	PI (%)	25.65	Indicates expansive tendency
Maximum Dry Density	MDD (g/cm³)	1.60	Consistent with high clay fraction
Optimum Moisture Content	OMC (%)	26.5	High due to clay activity
Unconfined Compressive Strength	UCS (kPa)	160.5	Low bearing capacity soil

The index properties of the clayey soil are used to indicate a soil with high plasticity characteristics. The specific gravity of the soil was found to be 2.6. The liquid limit and plastic limit were determined as 62.37% and 36.72%, respectively, indicating a high-water affinity and plastic nature of the soil. Based on the USCS, the point is located above the A-line with LL > 50%, which means the soil type is CH – clay of high plasticity.

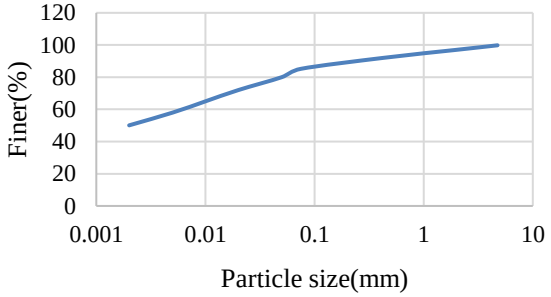

Fig.1 Grain size distribution curve

The maximum dry density of the untreated soil was 1.60 g/cc, with a corresponding optimum moisture content of 26.5%. The unconfined compressive strength of the natural soil was measured as 160.5 kPa, reflecting its relatively low strength and the need for stabilisation to improve its engineering performance. This test has been performed in order to identify the basic engineering properties of the collected clayey soil. The high value of the liquid limit testifies to the high plasticity of the soil, thereby confirming the expansive nature of the soil.

3.1.2 Ground Granulated Blast Furnace Slag

Ground Granulated Blast Furnace Slag (GGBS) was procured from Ambalamukal Ready Mix Company, India. GGBS is a calcium-rich industrial by-product obtained during iron production and is characterised by latent hydraulic and pozzolanic properties. Due to its high calcium content, GGBS is suitable for alkali activation and contributes to the formation of calcium–alumino–silicate–hydrate (C–A–S–H) gel in geopolymer systems.

GGBS was incorporated at 6%, 12%, and 18% by dry weight of soil to evaluate its influence on compaction and strength characteristics. GGBS collected is shown in figure 2. The choice of GGBS contents at 6 %, 12% and 18 % was made after looking at some lab work Experimental investigations by Gokul et al. [3]. They used GGBS contents from 6 percent to 24 percent for some special kinds of soil and they saw that the strength of the soil went up when they added more GGBS. What is really interesting is that when they used 12 percent

and 18 percent GGBS the soil got a lot stronger but when they used 24 percent it just cost more and did not really help that much.So for this study we picked 6 percent as the amount to see if it would make a difference 12 percent as the amount that works best and 18 percent, as the highest amount that is still practical to use. We wanted to see how strong the soil could get and how it would behave when we compact it and we also wanted to make sure it was not too expensive or hard to use in life situations. This way we can look at how the strength of the soil changes and how it behaves when we compact it and we can use it in the field without spending too much money. The effectiveness of these selected proportions is further validated through UCS results presented in Section 4.

3.1.3 Alkaline Activator

Sodium hydroxide (NaOH) pellets of laboratory grade were used as the alkaline activator. Figure 4 shows the NaOH pellets used. Two molar concentrations (8 M and 12 M) were prepared by dissolving calculated quantities of NaOH pellets in distilled water. The solutions were prepared at least 24 hours prior to mixing to allow temperature stabilisation and complete dissolution. The alkali-to-binder (A/B) ratio was maintained constant at 0.5 for all geopolymer mixtures. The mass of NaOH solution was calculated as 0.5 times the mass of GGBS, and the corresponding volume was determined using the measured solution density.

- The alkali-to-binder (A/B) ratio was maintained at 0.5 based on the following considerations: Adequate Dissolution Requirement an A/B ratio below 0.4 may result in insufficient activator availability, limiting slag dissolution and reducing gel formation. ·
- Workability and Moisture Balance Excess activator (A/B > 0.6) may increase pore fluid content, leading to higher porosity after curing and possible reduction in long-term strength.
- Reaction Efficiency at A/B = 0.5, a balanced environment is achieved where sufficient OH^- concentration promotes dissolution while maintaining workable consistency and minimising unreacted alkali.
- Literature Consistency Previous studies on alkali-activated slag stabilisation have commonly reported optimum performance within A/B ratios ranging from 0.4 to 0.6, supporting the selection of 0.5 as a representative intermediate value. Thus, the selected NaOH molarity (8 M and 12 M) and A/B ratio (0.5) were chosen to evaluate the influence of alkaline concentration on geopolymerization kinetics while maintaining a controlled binder-to-activator environment suitable for soil stabilisation application

Fig.2 Ground Granular blast furnace slag GGBS

3.2 Experimental Program

The experimental investigation was conducted in two stages:

1. Evaluation of compaction and strength behaviour of clay soil blended with varying percentages of GGBS (without activator).
2. Evaluation of geopolymer stabilization using the optimum GGBS content activated with 8 M and 12 M NaOH.

Each test condition was prepared in triplicate to ensure repeatability, and average values were reported.

Fig.3 Clayey soil from Mottammal, kannapuram

Fig. 4 Sodium hydroxide pellet

3.3 Soil Preparation and Mixing Procedure

Dry soil was mixed with predetermined percentages of GGBS (6%, 12%, and 18%) in the

necessary quantity. For geopolymer mixtures, the calculated volume of NaOH solution corresponding to the A/B ratio of 0.5 was added gradually to the dry soil–GGBS mixture. The materials were mixed manually until uniform consistency was achieved. Care was taken to ensure homogeneous distribution of binder and activator throughout the soil matrix. Sodium hydroxide (NaOH) solutions of 12 M and 8 M concentrations were prepared in the laboratory using NaOH pellets and distilled water. To prepare the 12 M NaOH solution, 480 g of NaOH pellets were gradually dissolved in 1000 ml of distilled water. Similarly, an 8 M NaOH solution was prepared by dissolving 320 g of NaOH pellets in 1000 ml of distilled water. The solutions were allowed to cool to room temperature before use to ensure uniformity and safety during mixing. The alkali-to-binder ratio was held constant at 0.5. For this ratio, the volume addition of the solution was taken as 3 ml, 6 ml, and 9 ml for the GGBS at the rate of addition to the soils as 6%, 12%, and 18%, respectively. The mixture was thoroughly stirred, and the soils along with the GGBS and NaOH solution were uniformly blended before moulding and subsequent curing. This mix design and procedure were followed for the preparation of the samples to be compacted and for unconfined compressive strength. The alkali binder ratio was used to calculate the quantity of NaOH solution the mix would require. With a selected A/B ratio of 0.5, the mass of alkali solution was estimated to be 0.5 times the mass of the binder that is GGBS. The estimated mass of alkali was now converted to volume, millilitres, with the use of the density of the NaOH solution as calculated and, therefore, the millilitres of NaOH the specimen needed for preparation.

3.4 Compaction Test

Standard Proctor compaction tests were conducted to determine the optimum moisture content (OMC) and maximum dry density (MDD) of untreated soil and GGBS-treated soil mixtures. The influence of NaOH molarity on compaction behaviour was also evaluated for geopolymer mixtures.

The variation in OMC and MDD with increasing binder content and activator molarity was analysed to identify optimum mix proportions.

3.5 Specimen Preparation and Curing

For unconfined compressive strength testing, cylindrical specimens were prepared by compacting the soil mixture into standard UCS moulds in layers to achieve uniform density. After extrusion, specimens were wrapped in high-density polyethylene (HDPE) sheets to prevent moisture loss and subsequently cured in a controlled water bath environment. Curing periods of 0, 7, and 28 days were adopted to evaluate strength development with time.

Fig. 5 Unconfined Compression testing machine

3.6 Unconfined Compressive Strength Test

Unconfined compressive strength (UCS) tests were performed on cured specimens using a calibrated compression testing machine. Specimens were placed centrally between loading platens, and axial load was applied at a constant strain rate until failure.

The maximum axial load at failure was recorded, and UCS was calculated by dividing the peak load by the cross-sectional area of the specimen. The average value of three specimens was reported for each mix condition. Figure 5 shows the test apparatus.

4 RESULTS AND DISCUSSION

4.1 Compaction Characteristics of Clayey Soil with GGBS

MDD increased with GGBS increase from 1.60 to 1.80 g/cc with OMC mildly varying as indicated in Table 2 and Figure 6.

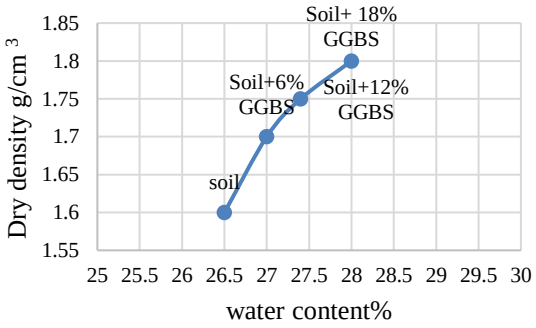

Fig.6 Compaction curves of untreated soil and GGBS-treated soil mixtures.

MDD increased with the fine GGBS particles due to enhanced packing and partial filling of voids and initial cementation effects. The observed OMC trend corresponds to the increased water consumption of the slag hydration/activation and surface wetting for the blended solid matrix.

Table 2. Compaction characteristics of clayey soil with GGBS

GGBS (%)	OMC (%)	MDD (%)
0	26.5	1.60
6	27	1.7
12	27.4	1.75
18	28	1.80

4.2 Strength Characteristics of Clayey Soil with GGBS

UCS increased systematically with GGBS dosage. Relative to untreated soil (160.5 kPa), 18% GGBS produced 195 kPa (≈21.5% increase), indicating that slag addition alone provides limited but measurable improvement. This strength gain is linked to latent hydraulic reactions of GGBS and improved interparticle bonding; however, without alkaline activation, the reaction extent remains modest, hence the need for activator-assisted geopolymerisation.

4.3 Compaction Characteristics of GGBS + NaOH (8 M & 12 M)

Compaction of the GGBS-treated soil activated with NaOH (8 M and 12 M) shows that OMC generally increased with activator dosage, while MDD increased at moderate dosage and reduced slightly at the highest dosage (Table 4). The higher OMC demand at 12 M reflects increased ionic concentration and enhanced dissolution/gel formation requiring adequate moisture for reaction progress. The slight reduction in MDD at high activator content is likely associated with increased flocculation/aggregation and reduced compatibility due to early gel formation during mixing.

Sample Calculations:
Dry density = 1.77 gm/cc
Density = mass/ volume
= 1.77*88.46
Mass = 156.58 g
Taking GGBS =6% =9.4 g
Alkali to Binder Ratio= 0.5
A/B=0.5
A/9.4=0.5
A=0.5*9.4 = 4.7g
A=4.7/156.58* 100 = 3 ml

Table 4. Compaction Properties of GGBS and NaOH.

NaOH	12 M		8 M	
	OMC (%)	MDD	OMC (%)	MDD
3	26.2	1.78	26.0	1.79
6	27.5	1.82	27.2	1.81
9	28.8	1.75	28.4	1.77

4.4 UCS Strength Comparison – Geopolymer Stabilized Soil.

Curing time, NaOH dosage, and molarity all increased UCS significantly. For 8 M and 12 M systems, a strength increment from 0 to 28 days suggests increasing alkali-activated reaction products and densification of the soil–binder matrix (Figs. 6–7). At identical NaOH dosage and curing age, 12 M consistently outperformed 8 M, indicating the effect of higher alkalinity to help in faster dissolution of aluminosilicate phases and generate calcium–alumino–silicate–hydrate (C–A–S–H) type gels in slag-rich systems. At 18% GGBS with 12 M NaOH, as per the 28-day study, the maximum UCS was reached at 2543 kPa, or approximately a 1484% increase upon the untreated soil. These strength levels are within limits that are well accepted for subgrade improvement and low-volume pavement applications, subject to durability verification.

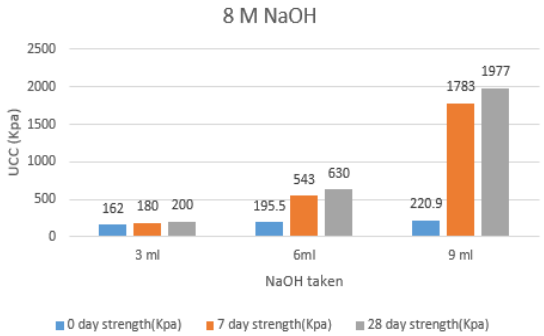

Fig.7 Strength variation of 8 M solution with GGBS

Representative specimens were cured for 0, 7 and 28 days. Specimens cured for longer periods exhibited stiffer responses and more brittle failure modes, consistent with increasing cementation. For future work, microstructural characterisation (SEM/EDS and XRD) is recommended to directly confirm gel formation and pore refinement mechanisms inferred from the observed macroscopic strength trends. The variation in strength is further supported by the observed change in failure pattern, as discussed in Section 4.5.

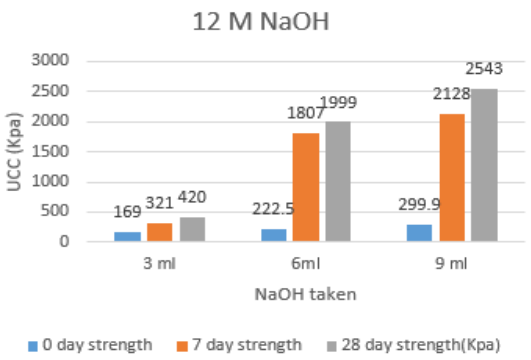

Fig.8 Strength variation of 12 M solution with GGBS

4.5 Failure Pattern

The untreated clay exhibited ductile failure with noticeable bulging and no distinct shear plane. In contrast, GGBS-treated and geopolymer-stabilized specimens showed brittle failure characterized by well-defined shear planes. The brittleness increased with higher GGBS content and NaOH molarity, indicating enhanced cementation and stiffness due to geopolymerization. These observations confirm that alkali-activated GGBS stabilization alters the mechanical behavior of clay from ductile to brittle, reflecting improved strength and cementation characteristics.

5. Comparison with Conventional Cement Stabilization

Compared to reported strength values of cement-stabilised clayey soils in literature, the performance of the proposed alkali-activated GGBS stabilisation system was evaluated. For cement stabilisation of high plasticity clay, 28-day unconfined compressive strength (UCS) values typically range between 800 kPa and 2000 kPa when cement content varies from 5% to 10%, depending on soil mineralogy and curing conditions [15]. According to previous reports [16], silty clay treated with 8–10% cement exhibited a UCS of 1.5 MPa–2.3 MPa after 28 days of curing. Likewise, improvement of strength in cement-stabilised marine clay could mostly be due to the formation of calcium silicate hydrate (C–S–H) gel and ettringite during hydration reactions [17]. In the present work, with 18% GGBS activated with 12 M NaOH, a maximum 28-day UCS of 2543 kPa was obtained. Such a value of strength is similar to or greater than the maximum observed in cement-stabilised clay subjected to relatively similar curing times. The enhanced performance of the alkali-activated slag system can be explained by:

- Faster dissolution of the aluminosilicate species in high alkaline environment.
- Formation of dense C–A–S–H gel matrix
- Improved pore refinement and interparticle bonding.
- Reduced microstructural porosity.

Conventional cement hydration is predominantly reliant on calcium hydration reactions, whereas alkali activation stimulates polymerisation that enhances a more homogeneous and compact matrix [18, 19]. Thus, a geopolymer stabilisation scheme based on the studied mix proportions has demonstrated mechanical properties as good as or better than conventional cement stabilisation, as well as significant environmental benefits due to the decreased need for clinkers.

6. CONCLUSIONS

GGBS greatly improves clayey soil strength as compared to slag addition alone. The higher NaOH molarity (8 M to 12 M) facilitated UCS for all curing ages, demonstrating that the increasing concentration of alkalinity led to a greater dissolution and gel formation under a slag-rich system. UCS increased with the curing duration, indicating the progressive formation of the cementitious reaction products and densification of the matrix. The maximal UCS of 2543 kPa was obtained with an 18% GGBS activated with 12 M NaOH (approximately 1484% higher) than with the untreated soil at 28 days. GGBS–NaOH geopolymer stabilisation on the whole appears as a low-carbon replacement for subgrade and ground development as long as it is stable enough and there is field-scale validation. The results obtained in this study show that increasing the molarity of sodium hydroxide (NaOH) from 8 M to 12 M can markedly improve the unconfined compressive strength (UCS) of the clay–GGBS geopolymer system. Increased UCS values obtained for samples activated with 12 M NaOH indicate that increasing alkaline content stimulates geopolymerisation and enhances strength development. The UCS of stabilised soil also increased when GGBS content was increased and NaOH molarity was increased. Compressive strength improved linearly with increasing curing time, indicating that curing time could have a favourable effect on the strength gain of the geopolymer-stabilised clayey soil. The increase in strength and brittle behavior confirms the formation of cementitious gels due to geopolymerization.

7. LIMITATIONS AND FUTURE WORK

This study primarily looked at compaction response and UCS strength evolution. Durability under wet–dry cycling, swelling reduction, permeability change, and microstructural confirmation were not studied and could guide future work for a possibility of enhancing field deployment. It is also recommended that replicate variability (standard deviation/COV) should be reported in order to enhance statistical robustness.

8. ACKNOWLEDGMENTS

The authors acknowledge the Department of Civil Engineering, Government College of Engineering, Kannur, for laboratory facilities and technical support. The authors also thank Ambalamukal Ready Mix Company for supplying the Ground Granulated Blast Furnace Slag (GGBS) used in this study.

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