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Research Article

Mix screening study of laterite soil stabilization using one-part geopolymer binders for earth blocks

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Abstract

This study explores the incorporation of one-part geopolymer systems in Compressed Stabilized Earth Blocks, utilizing Ground Granulated Blast Furnace Slag (GGBFS) as a binder. With the decline of traditional earth-based construction methods in industrialized nations due to the rise of modern materials, there is a growing need to modernize these sustainable practices through scientific innovation, technological advancement, and supportive policies. CSEBs present an energy-efficient alternative for structural masonry. In this study, laterite soil from Kerala was characterized through tests for specific gravity, particle size distribution and Atterberg limits, followed by compaction tests to determine the optimal moisture content for maximum dry density. The experimental work was conducted by evaluating the unconfined compressive strength (UCS) of unstabilized soil at different curing periods; stabilizing the soil with Ordinary Portland Cement (OPC) at 6%, 8%, and 10% and determining the UCS; and stabilizing with one-part geopolymer using varying alkaline activator concentrations, maintaining the activator-to-GGBFS ratio between 0.4 and 0.5. Here, UCS samples stabilized with one-part geopolymer mix N2.5G0.5 achieved 0.69 MPa for 28 days curing is much greater than unstabilised soil samples and samples stabilized with 6%, 8% and 10% cement. A detailed cost analysis of 1m^3 sample and CO_2 emission of soil samples were also estimated. Additionally, microstructural analysis such as X-ray Diffraction, Fourier Transform Infrared Spectroscopy and Scanning Electron Microscopy were employed to assess the microstructural and mineralogical changes in the stabilized samples.

1. Introduction

Earth has long served as a fundamental material in the construction of housing, because of its widespread availability and environmental advantages. These include reduced embodied energy, enhanced thermal mass, and the capacity to utilize locally sourced resources [1]. Laterite soils are found across many parts of the world, with a significant presence in tropical regions, especially in Africa, Australia, India, Southeast Asia, and South America [2]. The term laterite was first introduced by Buchanan in 1807 to describe iron-rich soil formations he encountered in the Malabar region of India. He noted that this material, while relatively soft and easy to cut when found in its natural state, would harden upon exposure to air. Because it was commonly used in brick-making, Buchanan coined the name from the Latin word later, meaning "brick"[3]. Laterite soils are generally used as an alternative raw material for the production of fired and unfired bricks. Laterite soil-based bricks are utilized as walling components due to social and ecological benefits [4].

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Traditional earthen construction techniques such as adobe bricks, cob, and rammed earth have been employed globally for centuries and remain in use today. Current estimates suggest that over one-third of the global population resides in earthen dwellings [5, 6]. Using locally available site soil for the production of adobe or blocks significantly reduces the overall cost and makes the process more economical and minimizing the need for long-distance transportation.

Unlike industrially produced materials that contribute to higher carbon emissions, earthen structures often rely on on-site resources. Among the various techniques, compressed earth blocks (CEBs) represent a notable advancement in earthen construction [7-11]. As a manufactured masonry unit, CEBs offer a more sustainable alternative to fired clay bricks, primarily due to their reduced energy requirements and lower carbon footprint. The addition of stabilizing agents such as Portland cement, lime, fly ash, or cement kiln dust to soil mixtures results in the formation of Compressed Stabilized Earth Blocks (CSEBs)[12-14]. Cement-based blocks remain among the most widely used construction materials in residential building due to their ease of production and ability to meet desired compressive strength requirements [4,15]. However, the production of cement, in conjunction with fossil fuel combustion, accounts for approximately 3.4% of global carbon dioxide emissions. Consequently, reducing cement consumption has become a critical objective in efforts to lower the carbon footprint associated with construction activities. In pursuit of this goal, various industrial by-products such as wood ash, fly ash (FA), GGBFS, metakaolin, fumed silica, and kaolin clay have been explored as partial substitutes for cement in concrete production [16]. Among these alternatives, the use of waste-derived materials such as FA, rice husk ash, and biomass ash as partial cement replacements has gained significant traction in both research and practical applications [17]. The inclusion of rice husk ash has been shown to significantly improve the compressive strength of stabilized soil mixtures [18-20].

The term "geopolymer" was introduced by French materials scientist Joseph Davidovits to describe a class of inorganic aluminosilicate materials synthesized through the reaction of alumina- and silica-rich precursors with alkaline activators. These precursors, typically rich in amorphous silica (SiO_4) and alumina (AlO_4), undergo polymerization with alkali polysilicates, resulting in a three-dimensional network of Si–O–Al bonds in which silicon and aluminum atoms are tetrahedrally coordinated with oxygen [21]. Geopolymers have demonstrated significant potential as an alternative to Portland cement, particularly in applications involving soil stabilization. When employed as a binder, geopolymer materials promote the formation of a denser soil microstructure, thereby enhancing both volumetric stability and mechanical strength of weak or problematic soils [22].

The application of lime and cement in soil treatment is known to yield significant improvements in soil performance; however, these benefits are often accompanied by high material costs. In contrast, the use of FA, a waste by-product of coal-fired power generation, presents a more economically viable alternative for various soil block manufacturing purposes [23]. Research has identified 20% FA by weight as the optimal dosage for enhancing soil properties. At this proportion, fly ash effectively fills the voids within the soil matrix, leading to improved compaction, strength, and overall engineering performance [24].

Geopolymerisation in GGBFS refers to the chemical transformation that occurs when GGBFS is activated by alkaline solutions, forming a geopolymer binder that serves as a sustainable alternative to conventional Portland cement. This process involves the reaction of aluminosilicate-rich materials, such as GGBFS, with alkaline activators commonly sodium hydroxide (NaOH), potassium hydroxide (KOH), and sodium silicate (Na_2SiO_3) under highly alkaline (high pH) conditions. An increase in NaOH molarity within the N-A-S-H gel phase decreased the cross-sectional area of fly ash particles, thereby enhancing the strength of the geopolymer concrete [25].

The UCS of soil treated with alkali-activated GGBFS geopolymer has been shown to improve significantly, exhibiting an increase of more than 2 to 3.5 times compared to soils stabilized with ordinary Portland cement (OPC) at equivalent binder contents. This substantial enhancement highlights the superior binding efficiency and mechanical performance of geopolymer-based stabilizers over traditional cementitious materials [26]. The use of fly ash combined with an alkaline activator solution comprising Na_2SiO_3 and NaOH as a geopolymer binder for the stabilization of sandy soil has demonstrated notable improvements in strength. Specifically, a compressive strength of 13 MPa was achieved with 8% alkaline activator solution (AAS), exceeding the values reported in earlier studies involving clayey soils [27]. However, despite this improvement, the UCS of fly ash-based geopolymer-stabilized soils remains considerably lower than that achieved with slag-based (GGBFS) geopolymer stabilization, which generally yields superior mechanical performance [17].

The primary difference between one-part and two-part geopolymer systems lies in their composition and activation approach. A two-part geopolymer system involves the use of a solid aluminosilicate precursor such as fly ash, GGBFS or metakaolin combined with a separate liquid alkaline activator, typically consisting of sodium hydroxide and sodium silicate solutions. These components are mixed immediately prior to application, triggering the polymerization process that forms the geopolymer matrix. Although this method is widely adopted in both industrial and laboratory contexts due to its high mechanical strength and rapid setting characteristics, it necessitates the handling of corrosive and caustic liquid chemicals. This requirement presents safety concerns and reduces convenience in field applications, limiting its broader practical use.

In contrast, a one-part geopolymer commonly described as a "just add water" system is engineered to streamline the activation process by incorporating all necessary components, including solid alkaline activators, into a single dry blend. The reaction is initiated simply by the addition of water, eliminating the need to handle corrosive liquid chemicals. This method significantly enhances safety and ease of use, making it particularly well-suited for pre-packaged formulations and on-site applications. However, one-part geopolymers often exhibit lower reactivity compared to their two-part counterparts and may demonstrate slower setting times or reduced mechanical strength unless the formulation is precisely optimized. Therefore, the selection between one-part and two-part geopolymer systems typically involves a trade-off between performance requirements and practical considerations related to handling and safety.

The total cost, cost-to-strength (cost/UCS) ratio, and associated CO_2 emissions of one-part geopolymer systems utilizing high-calcium FA for the stabilization of marginal laterite soils have been found to be lower than those observed in comparable two-part geopolymer systems. These findings underscore the potential of one-part high-calcium FA-based geopolymers as a viable and more sustainable alternative to both ordinary Portland cement and traditional two-part geopolymers for lateritic soil stabilization [28].

Although considerable studies exist on the use of two-part geopolymer systems in soil block applications, research exploring soil blocks with one-part geopolymer remains limited, representing a significant gap in the literature. This gap is particularly evident for laterite soil in Kerala, where such soil is abundantly available but remains underexplored in this context. The novelty of this research lies in employing solid forms of activators namely sodium silicate and sodium hydroxide thus aligning with the one-part geopolymer approach to enhance practicality, safety, and environmental performance.

2. Research Significance

This research is significant as it addresses the pressing need for sustainable construction materials by evaluating the performance of laterite soil–geopolymer blocks. In the current era, soil–cement blocks are widely used, and considerable innovations have been achieved with two-part geopolymer blocks; however, there remains a clear research gap in the development of one-part geopolymer soil blocks. This gap is also particularly evident for laterite soil in Kerala, where such soil is abundantly available but remains underexplored in this context. Through experimental analysis and cost optimization, this study provides a viable alternative to conventional blocks, with the potential to reduce carbon emissions and material costs. The work not only contributes valuable data to the academic discourse on stabilized earth materials but also offers actionable insights for industry professionals seeking eco-friendly building options. Its findings are particularly relevant to regions aiming for low-cost housing and environmental conservation, aligning well with the goals of Research on Engineering Structures and Materials.

3. Proposed Methodology for Screening

The overall experimental procedure adopted in this study is outlined in Fig. 1. The investigation commenced with the collection of essential materials, which included laterite soil, GGBFS, powdered sodium silicate, sodium hydroxide pellets, and OPC 53-grade cement. Following the procurement, a detailed material characterization was carried out to assess the physical and chemical properties. To determine the water content corresponding to maximum dry density, the Standard Proctor Test was performed, identifying the Optimum Moisture Content (OMC) of the soil. Since the objective of the study was to develop an optimal mix for block production, cylindrical samples were prepared and tested under UCS conditions.

The experimental program involved testing three types of samples: (1) unstabilized soil, (2) soil stabilized with cement where cement was partially replaced by 6%, 8%, and 10% by weight, and (3) soil combined with a one-part geopolymer binder based on GGBFS. The compressive strength of these samples was then compared to evaluate performance. To determine the statistical significance of the observed strength variations, analyses such as One-Way ANOVA and Paired Two-Sample t-tests were conducted, particularly focusing on the mix with the highest compressive strength. Additionally, a cost analysis was performed for 1 m^3 of each of the three cases, followed by a microstructural examination to understand the internal changes and bonding mechanisms within the samples.

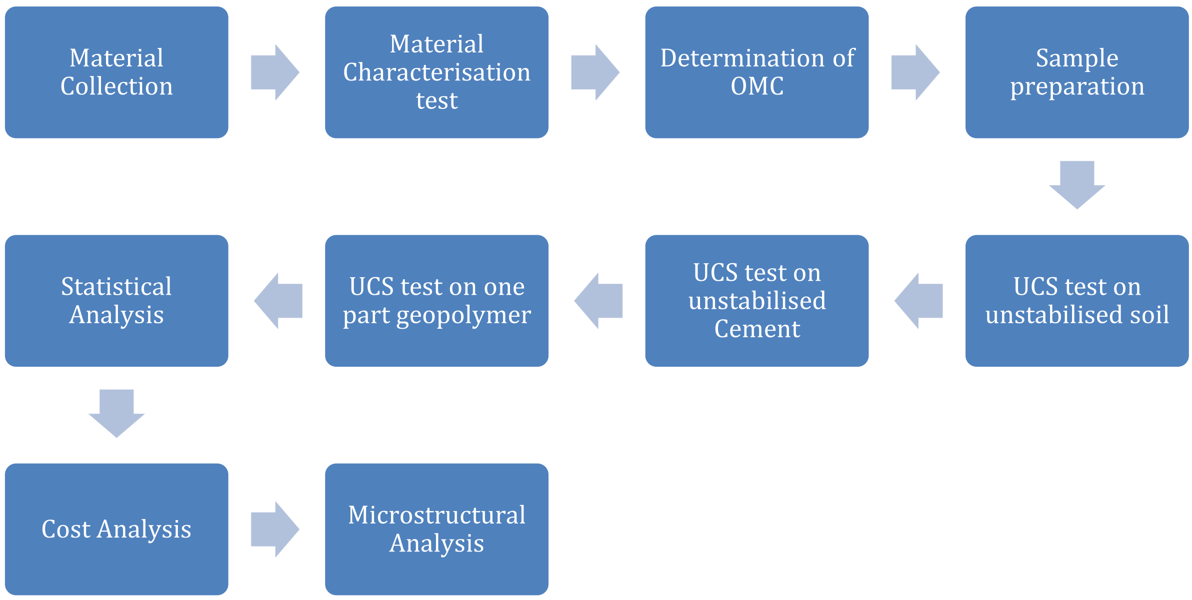


Fig. 1. Experimental procedure followed in the study

4. Materials and Method

4.1. Soil

Laterite soil samples used in this study were collected from the Malayamma region in Kozhikode district, Kerala located at coordinates 11^{0}16′01.6″N latitude and 75^{0}49′01.6″E longitude. Fig 2 shows the image of map of Kerala locating the site of soil collected. Soil characterisation was conducted in accordance with the guidelines provided in SP 36 (Part 1) – 1987 of the Indian Standards (IS) specification [29], and the corresponding results are summarized in Table 1. Various tests were conducted on the soil sample to evaluate its suitability, in terms of particle size distribution, and soil indices as well. Grain size distribution of the soil sample is performed according to IS 2720 Part 4 [30] using standard sieves and a mechanical sieve shaker. The obtained curve shown in Fig 1 shows that 91% of the particle are Gravel and sand. Hydrometer test was also performed to find the grain size distribution of particles finer than 0.075 mm according to IS 3104 [31]. Atterberg limit tests were performed using a Casagrande apparatus and other necessary apparatus according to IS 2720 Part 5 [32]. Additionally, the particle size distribution of the soil was assessed, and the resulting gradation curve is presented in Fig 3.

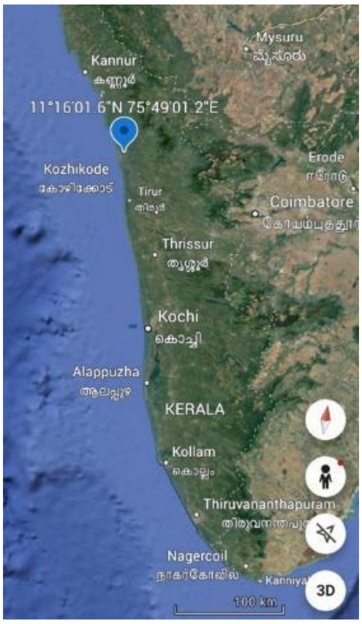


Fig. 2. Map of Kerala showing the location of soil collection

Table 1. Characterization of soil

SI No:	Properties	Value
1.	Compaction characteristics (proctor test)	
a)	Optimum moisture content (%)	18.6
b)	Maximum Dry Density (g/cm^3)	1.65
2.	Atterberg's limits	
a)	Liquid limit (%)	51.0
b)	Plastic limit (%)	34.62
c)	Plasticity index (%)	16.38
3.	Particle size distribution	
a)	Gravel + Sand (%)	91%
b)	Silt size (%)	6%
c)	Clay size (%)	3%
4.	Specific gravity (Dimensionless)	2.32
5.	pH value	5

The soil exhibits a liquid limit of 51 and a plastic limit of 34, resulting in a plasticity index of 17. This indicates that the soil possesses medium to high plasticity characteristics. A liquid limit just above 50 suggests that the soil may belong to the category of high plasticity materials, typically associated with clayey soils. The Grain sieve analysis suggests that soil contains 91% gravel and sand-sized particles, with only 6% silt and 3% clay, indicating that it is predominantly a coarse-grained soil. Such a composition suggests that the soil will exhibit good drainage, low compressibility, and relatively high shear strength, making it generally favorable for construction and foundation purposes.

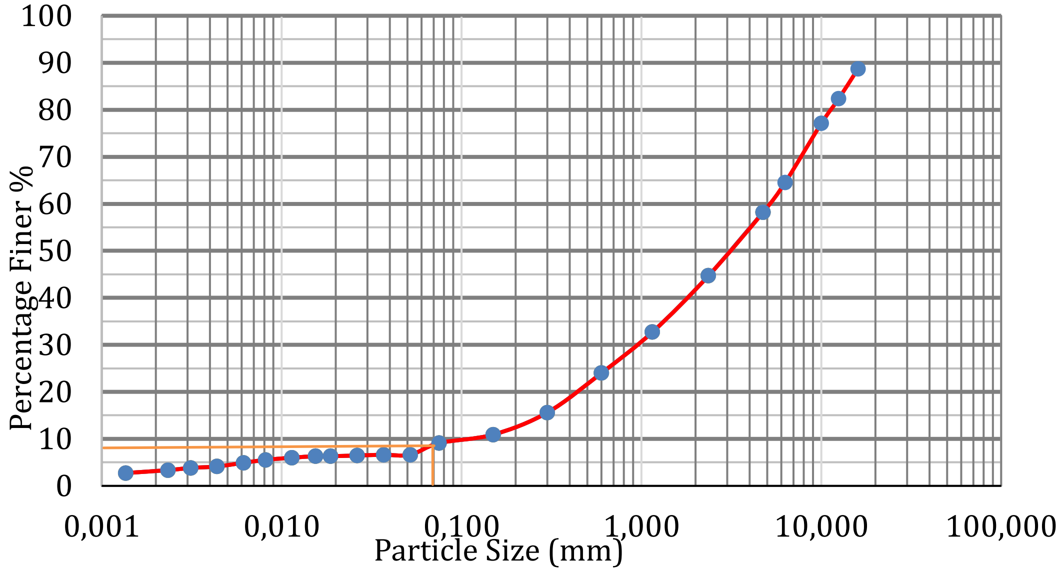


Fig. 3. Particle size distribution curve of soil sample

4.2 Binders and Alkaline activators

The soil was mixed with varying proportions of either OPC or GGBFS. Previous studies have demonstrated that the optimal cement content for soil stabilization generally lies between 5% and 10%, as concentrations exceeding 10% tend to be economically impractical [26,33,34]. It should be noted that several factors can affect the selection of these amounts of additives, the most important of which are the soil type, climate conditions, type of cement, and desired strength. OPC of 53-grade, conforming to IS 12269-1987 [35], was employed for the stabilization of laterite soil and was procured locally from Kozhikode. GGBFS, used as a precursor material in this study, was sourced from AJ Associates, Malappuram.

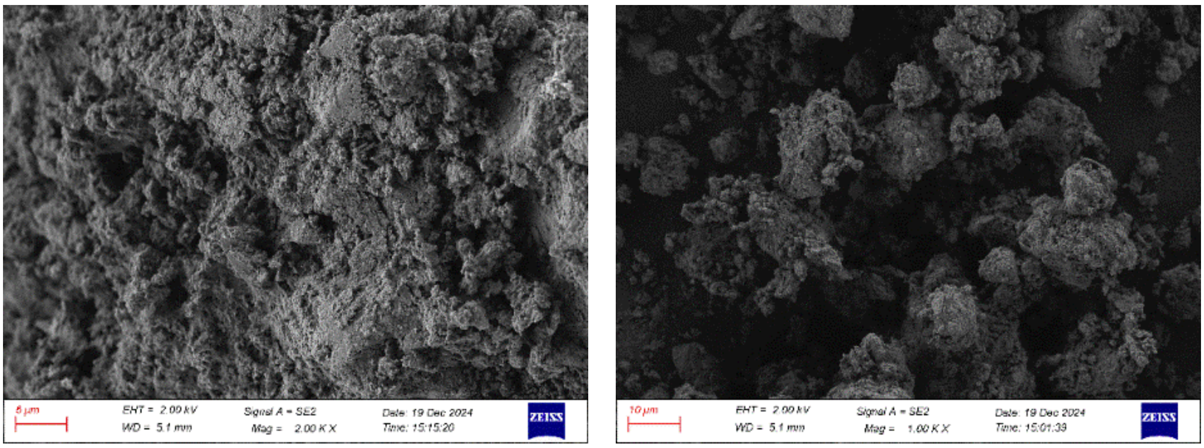


Fig. 4. SEM images of laterite soil

In recent years, the application of geopolymers in soil stabilization has been widely studied [36], [37-47]. Geopolymers have been shown to enhance the strength of stabilized soils significantly, primarily due to the formation of a dense microstructure facilitated by the presence of calcium–silicate–hydrate (C–S–H) and sodium–alumino–silicate–hydrate (N–A–S–H) gels [25]. The one-part geopolymer (OPG) system involves the use of solid aluminosilicate precursors blended with solid alkaline activators and water, whereas the two-part system employs a liquid alkaline activator to initiate the geopolymerization of the solid precursor.

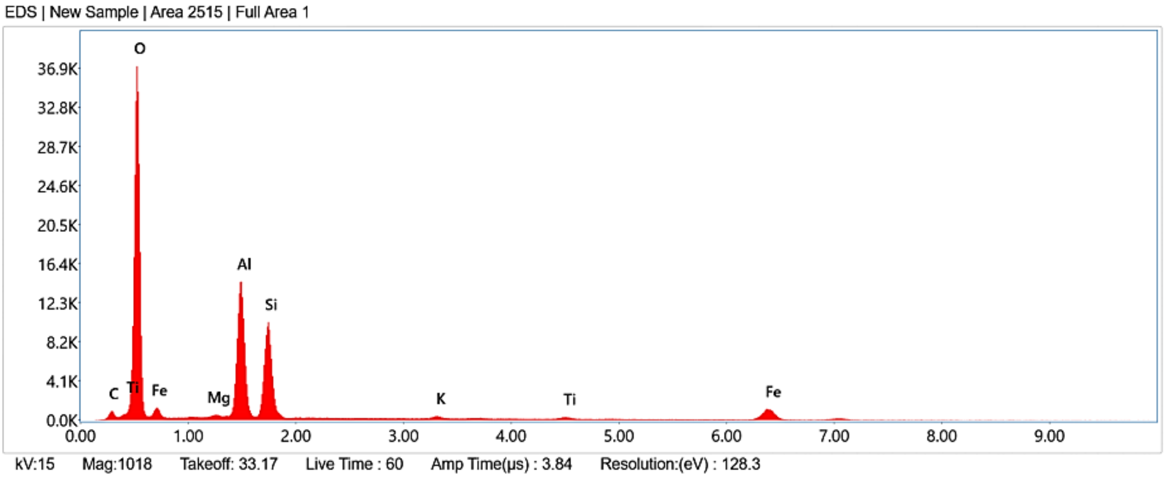


Fig. 5. EDS image of laterite soil

Table 2. EDS output table of laterite soil

eZAF Quant Result - Analysis Uncertainty: 18.07 %								
Element	Weight %	MDL	Atomic %	Error %	Net Int.	R	A	F
C K	10.0	0.4	15.3	12.5	80.9	0.9078	0.0892	1.0000
O K	57.2	0.03	65.7	8.4	3878.9	0.9190	0.2999	1.0000
Mg K	0.7	0.04	0.5	8.8	91.1	0.9356	0.4976	1.0076
Al K	13.2	0.04	9.0	5.4	2014.4	0.9393	0.6276	1.0060
Si K	9.6	0.04	6.3	5.2	1428.1	0.9427	0.6552	1.0038
K K	0.4	0.09	0.2	14.6	33.6	0.9579	0.9147	1.0262
Ti K	0.6	0.12	0.2	13.5	34.2	0.9661	0.9653	1.0696
Fe K	8.3	0.23	2.7	4.1	252.8	0.9766	0.9887	1.0583

Table 3. EDS output table of GGBFS

eZAF Quant Result - Analysis Uncertainty: 11.69 %								
Element	Weight %	MDL	Atomic %	Error %	Net Int.	R	A	F
C K	24.5	0.34	36.4	10.8	309.5	0.9062	0.1345	1.0000
O K	40.7	0.09	45.4	10.1	1420.1	0.9175	0.1488	1.0000
Mg K	2.2	0.04	1.6	6.9	337.2	0.9343	0.5442	1.0068
Al K	4.9	0.04	3.2	5.4	803.7	0.9381	0.6574	1.0092
Si K	7.5	0.04	4.8	4.5	1290.8	0.9416	0.7282	1.0090
S K	0.5	0.05	0.3	8.0	63.5	0.9481	0.8308	1.0229
K K	0.2	0.07	0.1	18.9	23.9	0.9570	0.9364	1.0846
Ca K	18.0	0.09	8.0	2.6	1391.2	0.9598	0.9531	1.0154
Mn K	0.7	0.18	0.2	16.3	23.9	0.9733	0.9741	1.0494
Ba L	0.8	0.3	0.1	24.0	18.2	0.9679	0.9499	1.0069

Compared to the two-part method, the one-part geopolymer system is more suitable for in-situ engineering applications, as it minimizes the environmental risks associated with handling liquid alkaline solutions and reduces the logistical costs related to their storage and transportation [48]. The alkaline activators employed for the geopolymerization of GGBFS in this study were NaOH and sodium silicate. These activators are known to effectively facilitate the dissolution of silicate and aluminate species from GGBFS, initiating the geopolymerization process. Numerous studies have indicated that the incorporation of sodium silicate alongside sodium hydroxide enhances the reaction kinetics, thereby accelerating the geopolymerization process and improving the overall performance of the resulting binder [17,21]. The microstructural analysis such as Fourier

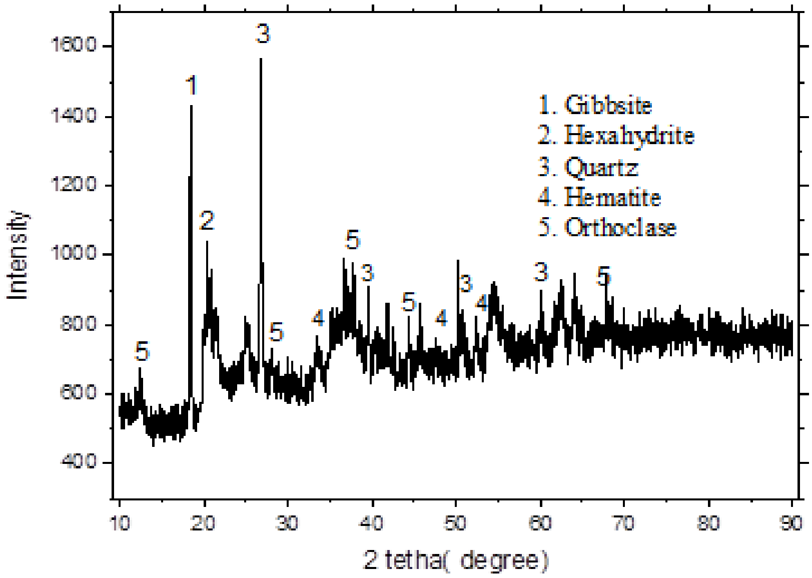


Fig. 6. XRD of laterite soil

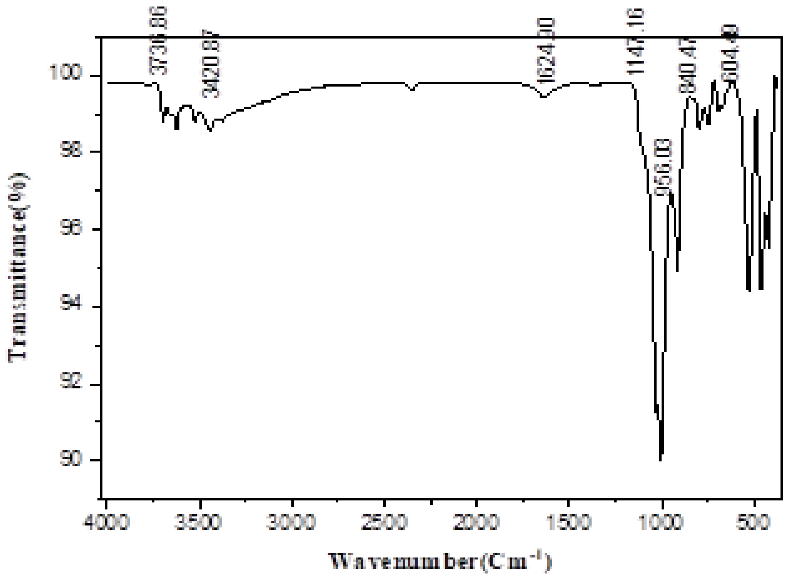


Fig. 7. FTIR image of laterite soil

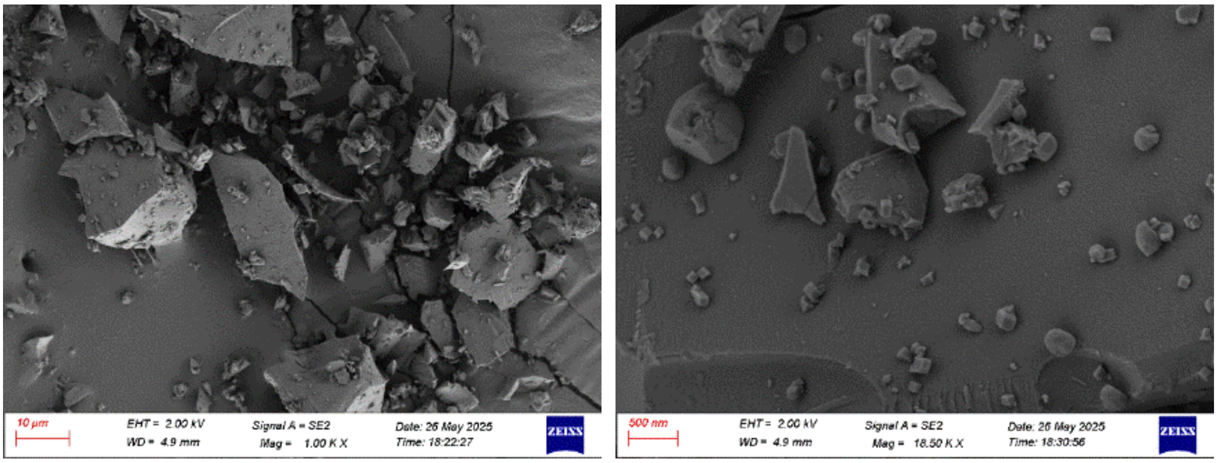


Fig. 8. SEM image of GGBFS

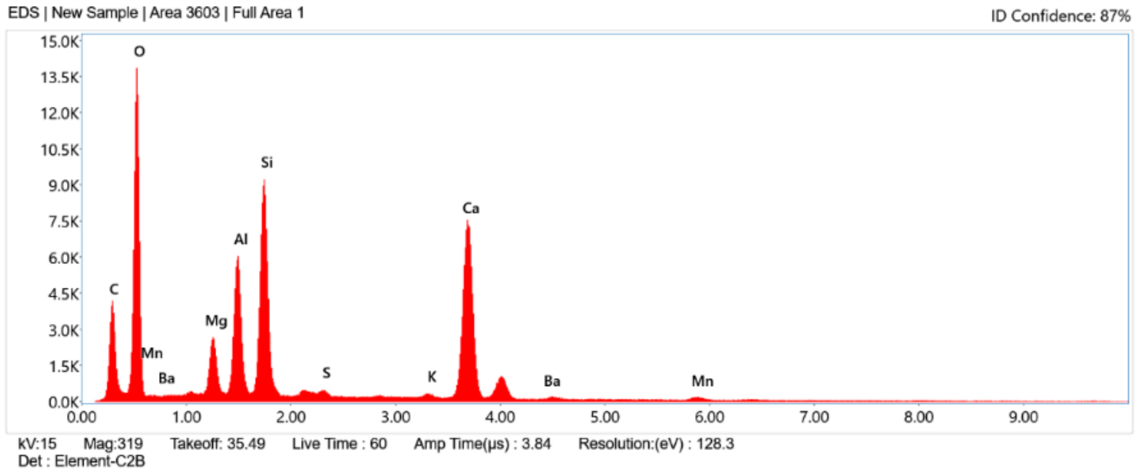


Fig. 9. EDS image of GGBFS

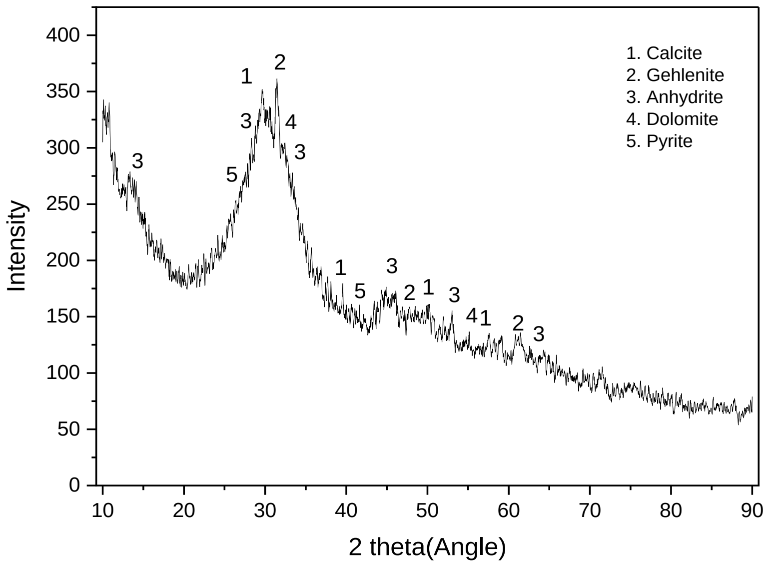


Fig. 10. XRD of GGBFS

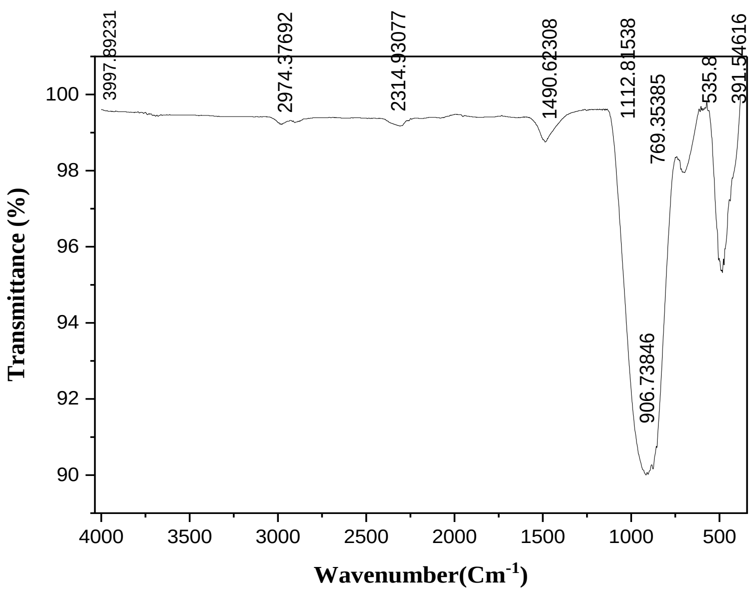


Fig. 11. FTIR image of GGBFS

Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), Energy-Dispersive X-ray Spectroscopy (EDS), X-ray Diffraction (XRD) are done for the materials such as laterite soil and GGBFS are shown in Fig 4 to Fig 11. The SEM analysis reveals that the morphology of laterite soil appears powdery and loosely aggregated, whereas GGBFS exhibits solid, angular, and sharp-edged particles. EDS results indicate that laterite soil is predominantly composed of aluminum and silicon, while GGBFS shows significant concentrations of aluminum, calcium, and silicon. XRD analysis of laterite soil confirms the presence of mineral phases such as gibbsite [49], hexahydrite, and quartz [4], whereas GGBFS is characterized by the presence of calcite and gehlenite [26]. Furthermore, FTIR was conducted to identify and characterize the molecular composition of the materials through their infrared absorption spectra.

Table 2 represents the EDS output table of laterite soil from which Si/Al ratio is 0.73 and Fe/Al ratio is 0.63. The Si/Al ratio (0.73) indicates a high degree of silica leaching and alumina enrichment, suggesting an advanced stage of laterization. The Fe/Al ratio (0.63) reflects a balanced but alumina-dominant composition, pointing towards a bauxitic type of laterite rather than a ferruginous one.

Table 3 represents the EDS output table of GGBFS, which confirms it has significant Ca, Si, and Al, which are responsible for its cementitious properties. The high Ca content (18%) supports its use as a hydraulic binder. The Si/Al ratio (1.53) shows adequate aluminosilicate framework for strength gain and Ca/Si ratio (2.4) reflects strong basicity, ensuring high reactivity in cement/laterite soil stabilization.

2.3 Sample Preparation and Experimental Program

The initial phase of the experimental procedure involved the collection of laterite soil, which was subsequently screened to remove any extraneous materials. The cleaned soil was then oven-dried and sieved to achieve the desired particle size distribution.

2.3.1 Determination of Optimum Moisture Content

To determine the OMC for compaction, a standard Proctor compaction test was conducted in accordance with ASTM-d698[50]. This method utilized a standard mold with a diameter of 4 inches. Soil samples passing through a No. 4 sieve were compacted in three layers, with each layer subjected to 25 blows using a 5.5 lb hammer dropped from a height of 12 inches. The test was repeated for varying moisture contents to establish a compaction curve correlating dry density with moisture content. Based on the resulting curve shown in Fig 12, the optimum moisture content was determined to be 18.6%, corresponding to a maximum dry density of 1.65 g/cm^3. The drop ball test was used to ascertain the moisture content for the rest of the mixes[13] [51].

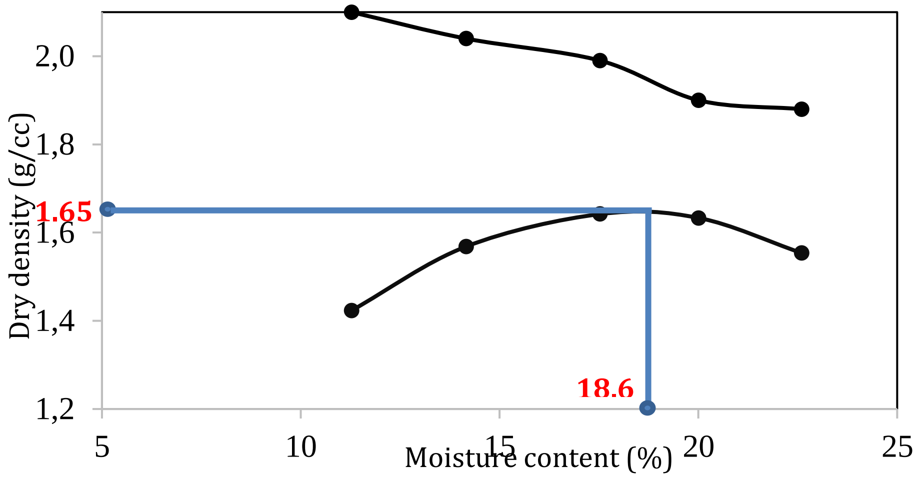


Fig. 12. Determination of Optimum moisture content

In this study, Unconfined compressive strength samples of height 76mm and diameter 38mm are used to determine the proportion of binders for getting maximum strength.

2.3.2. Unstabilized laterite Soil Sample Preparation

The soil collected from the site was oven-dried for approximately 24 hours to eliminate any residual moisture. Following the drying process, the soil was sieved to obtain a uniform particle size suitable for testing. The OMC of the sieved laterite soil was determined using the light compaction test. Subsequently, UCS tests were conducted on the prepared samples to evaluate the strength characteristics of the untreated soil. The soil samples were first oven-dried and then passed through a 4.75 mm IS sieve. Water corresponding to the optimum moisture content (OMC) was added and thoroughly mixed to achieve a homogeneous mixture. This mixture was placed into the UCS mould in three layers, with each layer compacted using 25 blows. The cylindrical specimens were then sealed in an airtight Ziplock bag. After curing periods of 7, 14, and 28 days in a desiccator maintained at room temperature (≈27 ± 2 °C), the samples were removed for testing.

During the setup of the loading device, particular attention was given to ensure that the upper platen had minimal initial contact with the sample, which was precisely centered on the lower platen. The load was applied continuously, with careful observation of both axial force and deformation until the specimen failed. Consistent with IS 2720 Part 10 [52] guidelines, the loading was carried out in a controlled fashion, avoiding sudden impacts and maintaining a steady axial deformation rate. The UCS testing setup is illustrated in Fig. 13, and the mix proportions are presented in Table 3. The sample for unstabilized condition is mentioned as S100, where S stands for soil and 100 stands for percentage of soil.

2.3.3. Laterite Soil Sample with Cement Stabilization

In the second stage, UCS tests were carried out on laterite soil samples stabilized with varying percentages of ordinary Portland cement to evaluate the effect of cement content on strength development. Varying percentages like 6, 8 and 10 are used for the study and are mentioned in Table 3 as S94C6, S92C8 and S90C10. Cement was added at proportions of 6%, 8%, and 10% by weight of dry soil. The total quantity of water required for mixing was calculated as the sum of the water needed to achieve the optimum moisture content (as determined in Table 1) and the water necessary for cement hydration, which was assumed to be 30% of the cement weight [53]. After replacing laterite soil with these percentages, curing was done by keeping the samples in a desiccator for about 7,14 and 28 days. After that samples are tested in a unconfined compressive strength testing apparatus.

2.3.4. Laterite Soil Sample with One Part Geopolymer

The third stage focused on the incorporation of a one-part geopolymer system into the laterite soil, assessing its performance through UCS testing. A one-part geopolymer system was incorporated into the laterite soil to investigate its effectiveness as a soil stabilizer. This system utilized solid alkaline activators, specifically NaOH and Na_2SiO_3, which were selected due to their cost-effectiveness and widespread availability [54]. For this investigation, sodium hydroxide was used in pellet form with a purity of 97% and a specific gravity of 2.13 g/cm^3 at 20 °C. Sodium silicate was employed in powdered form, also with 97% purity ($Na_2SiO_3 \cdot 5H_2O$), and a specific gravity of 1.93 g/cm^3 at 20 °C. These solid activators were dry mixed with the precursor material and laterite soil, and water was added to initiate the geopolymerization process.

An important parameter influencing the compressive strength of geopolymer-stabilized materials is the ratio of Na_2SiO_3 to NaOH [55]. Several studies have demonstrated that Na_2SiO_3/NaOH ratios in the range of 1.5 to 3 yield the highest compressive strength in geopolymer mortars and concretes, with typical values ranging between 2 and 2.5. Additionally, the ratio of alkaline activator solution to FA in geopolymer concrete is commonly maintained between 0.4 and 0.5 by dry mass [27]. A safety protocol was incorporated for geopolymer–laterite soil mixing. Since alkali activators such as sodium hydroxide are highly caustic, use of appropriate PPE (gloves, goggles, protective clothing) is mandatory. The activators are both in solid form, so not much exothermic heat was dissipated. For practical field application, the recommended sequence is to mix soil and dry additives first, followed by gradual addition of the activator under continuous mixing.

In the present study, an AAS to GGBFS ratio of 0.4 to 0.5 was adopted, along with a Na_2SiO_3/NaOH ratio ranging from 1.5 to 3, to optimize the compressive strength of the geopolymer-stabilized laterite soil. The mix proportions are mentioned in Table 4. All components were weighed on calibrated balances with accuracies of ±0.001 g for specimen-scale measurements and ±0.1 g for batch-scale measurements. Target mixing moisture content was controlled within ±0.2%. The resulting dry density was determined by mass/volume after oven-drying (105 ± 5 °C), with a measurement tolerance of ±1%.

Table 4. Mix proportions

SI No:	Mix	Soil(kg)	Cement (kg)	GGBFS(kg)	NaOH(kg)	Na_2SiO_3(kg)	Water(kg)
1	S100	0.1550					0.0280
2	S94C6	0.1486	0.0068				0.0296
3	S92C8	0.1439	0.0109				0.0300
4	S90C10	0.1407	0.0136				0.0302
5	N1.5G0.4	0.1515		0.0087	0.0008	0.0012	0.0314
6	N1.5G0.5	0.1525		0.0069	0.0007	0.0011	0.0310
7	N2G0.4	0.1505		0.0104	0.0008	0.0016	0.0318
8	N2G0.5	0.1517		0.0083	0.0008	0.0016	0.0314
9	N2.5G0.4	0.1495		0.0122	0.0008	0.0020	0.0323
10	N2.5G0.5	0.1509		0.0097	0.0009	0.0023	0.0319
11	N3G0.4	0.1486		0.0139	0.0008	0.0024	0.0328
12	N3G0.5	0.1501		0.1118	0.0008	0.0024	0.0322

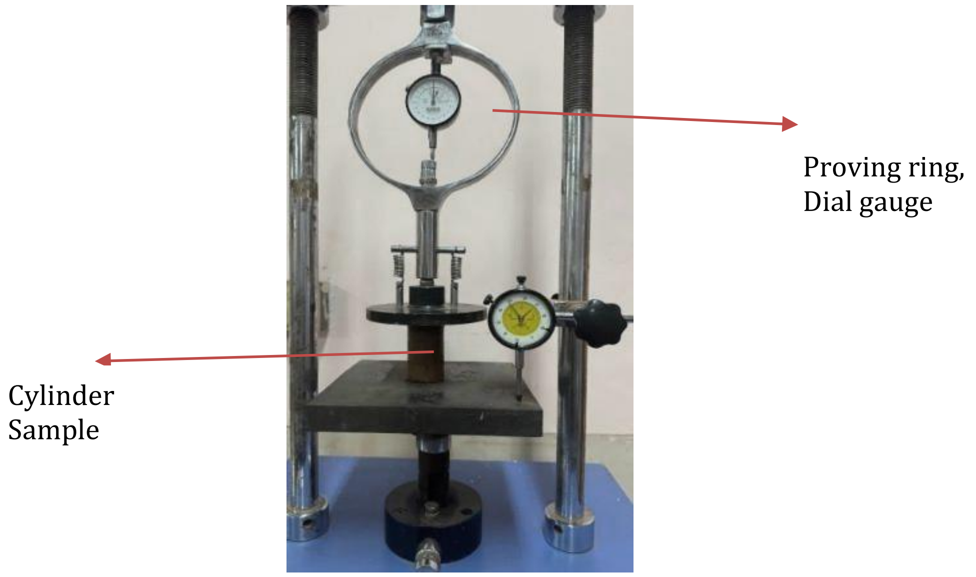


Fig. 13. UCS test setup

3. Performance Assessment of Proposed Soil Stabilization Method

3.1. Unconfined Compressive Strength

The UCS values measured at 7, 14, and 28 days for various soil mix compositions are presented in Table 5(a). The supplementary table showing the strength of all samples at 28 day are presented in Table 5(b). The USC test can be used to determine the compressive strength of the blocks at different mix percentages [13],[51]. It is simple, direct, and standardized which measures both dry and wet strengths, which are critical for earth blocks. It is also sensitive to microstructural changes. Thus, it allows you to compare performance consistently across different mix compositions.

The sample designated as S100 refers to the unstabilized soil containing only the native soil and the optimum moisture content. The mixes labeled S95C5, S92C8, and S90C10 represent cement-stabilized samples, where 6%, 8%, and 10% of the soil content, respectively, were replaced with cement. One-part mixes are represented from N1.5G0.4 to N3G0.5 where N corresponds to the ratio of Na2SiO3/NaOH and G corresponds to the ratio of N with GGBFS. 3 samples for each mix was tested for 7, 14 and 28 days.

Table 5 (a). Compressive strength of UCS samples

SI NO:	Mix	Compressive Strength (MPa)		
		7th Day	14th Day	28th Day
1	S100	0.10	0.16	0.17
2	S94C6	0.11	0.15	0.19
3	S92C8	0.12	0.16	0.18
4	S90C10	0.23	0.24	0.31
5	N1.5G0.4	0.41	0.45	0.50
6	N1.5G0.5	0.42	0.45	0.51
7	N2G0.4	0.49	0.51	0.61
8	N2G0.5	0.42	0.44	0.53
9	N2.5G0.4	0.53	0.55	0.56
10	N2.5G0.5	0.53	0.67	0.69
11	N3G0.4	0.50	0.53	0.52
12	N3G0.5	0.50	0.51	0.52

Table 5(b). Supplementary Table showing UCS values of samples at 28-day strength

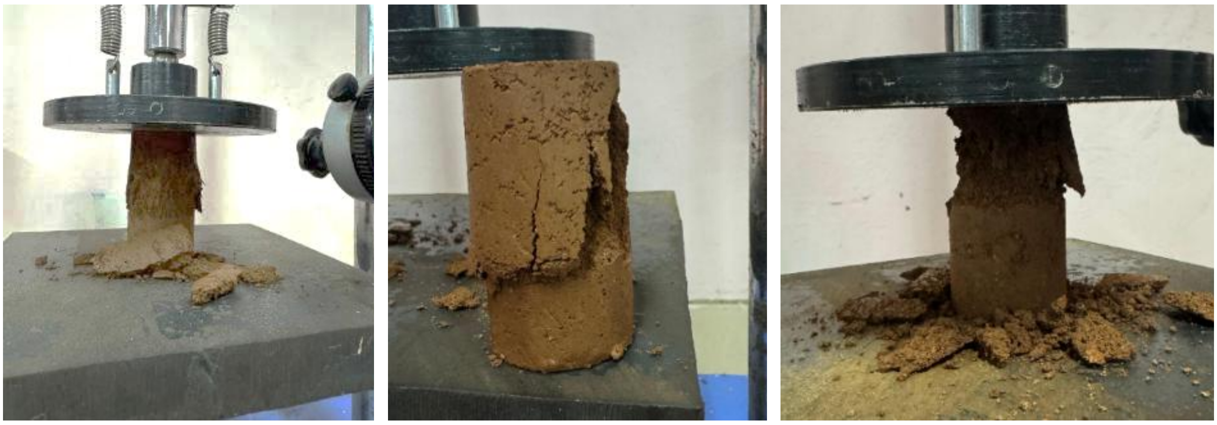
Mix ID	Sample 1	Sample 2	Sample 3	Mean
S100	0.174	0.155	0.183	0.17
S94C6	0.22	0.156	0.194	0.19
S92C8	0.132	0.183	0.225	0.18
S90C10	0.281	0.318	0.342	0.31
N1.5G0.4	0.321	0.621	0.552	0.50
N1.5G0.5	0.549	0.514	0.475	0.51
N2G0.4	0.597	0.628	0.605	0.61
N2G0.5	0.525	0.540	0.540	0.53
N2.5G0.4	0.533	0.593	0.554	0.56
N2.5G0.5	0.677	0.701	0.692	0.69
N3G0.4	0.489	0.558	0.517	0.52
N3G0.5	0.506	0.503	0.550	0.52

Fig. 14(a) illustrates the S100 mix during the UCS test. Fig 14(b) to 14(d) depict UCS test images of cement-stabilized samples with varying cement replacement percentages. Fig 14(e) to 14(l) present the UCS test images of samples stabilized with one-part geopolymer binders. The failure pattern observed in the unstabilized soil sample (Fig 14(a)) is characterized by an inclined shear crack, indicative of ductile failure behavior. Although the soil has a relatively low content, the S100 mix prepared with only laterite soil and water at its Optimum Moisture Content (OMC) is able to retain its shape immediately after casting due to the inherent plasticity and cohesion of the laterite soil [4]. Laterites are rich in clay minerals and oxides, which give them medium to high plasticity (PI = 16.38%) and a high plastic limit (34.62%), allowing the soil to hold significant moisture before reaching a plastic state [56]. At OMC, the combination of particle cohesion, clay-induced plastic behavior, and capillary forces enables the mix to maintain its form temporarily without any binder. The liquid limit of about 51% further classifies the soil as highly plastic, meaning it can deform under moisture changes, but when compacted, it develops sufficient cohesion and strength to justify the observed shape retention.

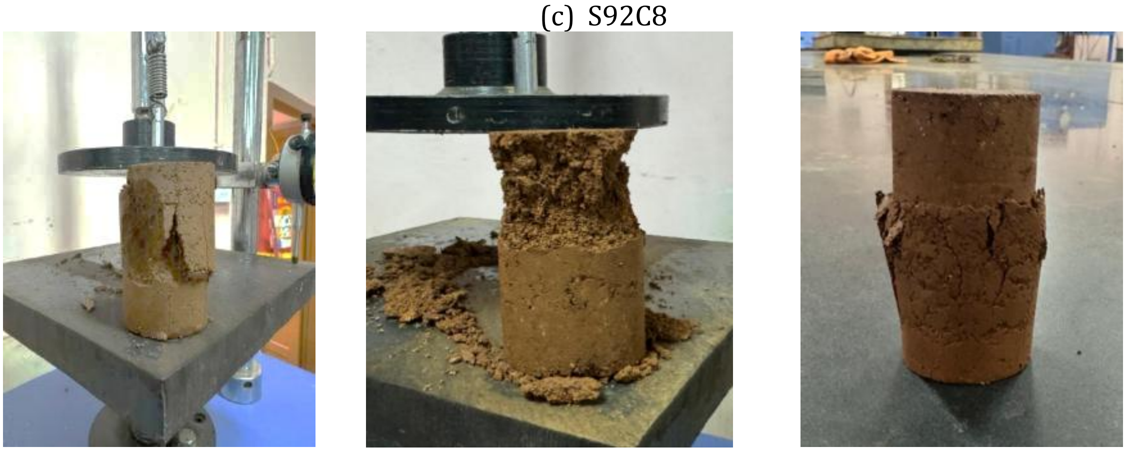
In contrast, the soil samples stabilized with 6%, 8%, and 10% cement Fig 14(b) to 14(d) exhibit circumferential tensile cracking, suggesting a transition to brittle or semi-brittle behavior. This pattern reflects the development of tensile stresses due to lateral expansion under axial loading, leading to failure along the specimen's perimeter.

(a) S100

(b) S94C6



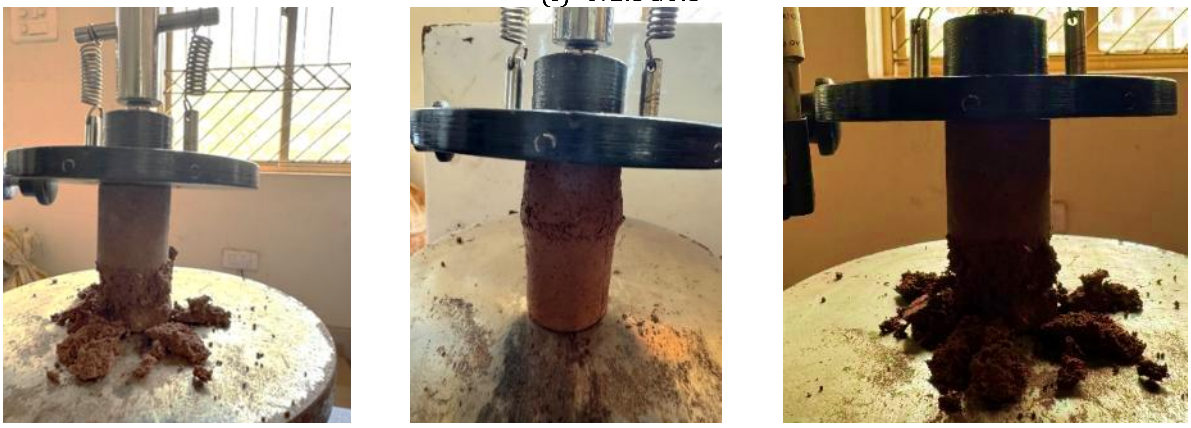
(c) S92C8



(d) S90C10

(e) N1.5G0.4

(f) N1.5G0.5



(g) N2G0.4

(h) N2G0.5

(i) N2.5G0.4

(j) N2.5G0.5

(k) N3G0.4

(l) N3G0.5

Fig. 14. Failure mode of all the UCS specimens

Meanwhile, the soil samples stabilized with one-part geopolymer Fig 14(e) to 14(l) displayed inclined or shear cracks, with failure planes forming at an angle typically around 45° to the vertical axis indicating shear-dominated failure behavior consistent with enhanced cohesion and stiffness. The UCS of the soil is influenced by its intrinsic properties as well as the type and dosage of stabilizing binders used. Fig.15 presents the UCS results for twelve different mix compositions after 7, 14 and 28 days of curing. Specimens stabilized with varying percentages of OPC exhibited significantly higher UCS values compared to the unstabilized control sample. This enhancement in strength can be attributed to the pozzolanic reactions facilitated by the cement, which improve the bonding and densification of the soil matrix. A consistent increase in strength was observed with higher cement content, indicating the positive correlation between cement dosage and soil stabilization effectiveness. In contrast, the samples with one-part geopolymer stabilization, revealed a different trend. Initially, as the alkaline activator ratio increased, a decline in UCS was observed. However, beyond a certain threshold specifically at an activator ratio of 2.5 the strength began to increase and peaked in Mixes 5 and 6. These mixes demonstrated the most effective binder composition, achieving a maximum UCS of 0.525 MPa with an alkaline activator ratio of 2.5 and activator-to-GGBFS ratios of 0.4 and 0.5, respectively.

The superior performance observed for the mix with N = 2.5 (Na_2SiO_3/NaOH ratio) can be attributed to the optimal balance achieved between alkalinity and available silicate species during geopolymerization. At lower ratios (N = 2.0), the system contains a higher concentration of NaOH, which increases alkalinity but can lead to excessive dissolution of aluminosilicate phases, resulting in unstable gel formation and microcracking upon drying. Conversely, at higher ratios (N = 3.0), the excessive sodium silicate content increases the Si concentration in the activator, leading to high viscosity and reduced dissolution of GGBFS particles, which slows the reaction kinetics and limits strength gain. The N = 2.5 ratio provides a balanced Si/Na environment, ensuring sufficient dissolution of reactive species from GGBFS and favorable polycondensation to form a dense, cross-linked geopolymer gel (C–(A)–S–H and N–A–S–H phases). This balanced chemistry contributes to improved matrix densification and, consequently, higher UCS values compared to other ratios.Fig 15 shows the Comparison of Unconfined compressive strength for different proportions and at different days of curing. The mix configuration, defined by an alkaline activator ratio of 2.5 and an alkaline activator-to-GGBFS ratio of 0.5, emerged as the optimal formulation among the geopolymer-stabilized samples.

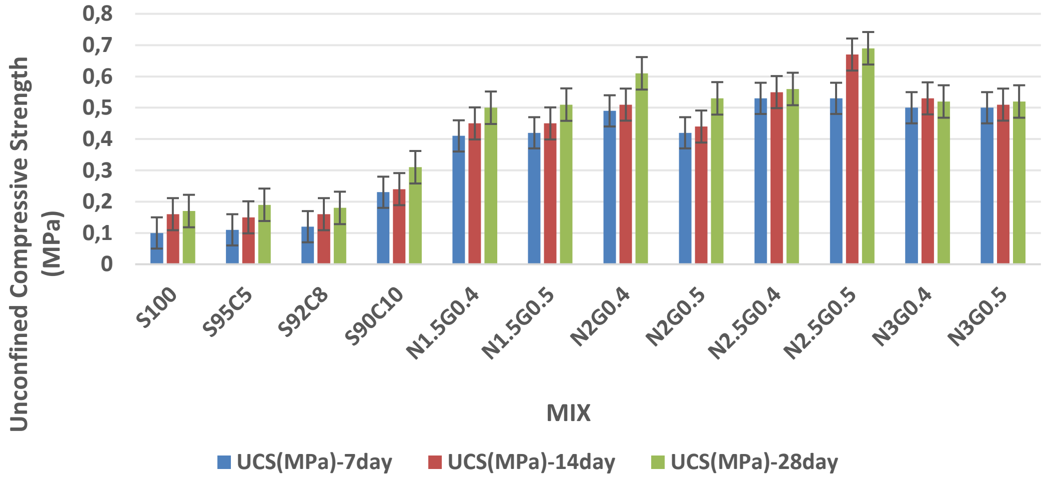


Fig. 15. Comparison of Unconfined compressive strength for different proportions and at different days of curing

3.2. Statistical Analysis

The statistical analysis in this study aims to assess the significance of differences in the performance of unstabilized laterite soil, cement-stabilized laterite soil, and laterite soil treated with one-part geopolymer. To achieve this, One-Way ANOVA and Paired Two-Sample t-tests were conducted to evaluate the statistical relevance of the variations observed with the Mix showing maximum unconfined compressive strength.

Statistical significance of strength variations among different stabilization treatments of laterite soil is assessed using both one-way ANOVA and paired two-sample t-tests.

3.2.1. ANOVA Analysis

The one-way ANOVA was conducted on five groups: unstabilized laterite soil (S100), cement-stabilized soils (S94C6, S92C8, S90C10), and the one-part geopolymer-stabilized mix (N2.5G0.5). The analysis revealed a statistically significant difference among the group means, with an F-value of 46.21 and a p-value of 2.05×10^{-6}, which is far below the conventional alpha level of 0.05 which is shown in Table 6. This strongly indicates that at least one of the group means is significantly different from the others in terms of performance (e.g., compressive strength).

Table 6. ANOVA Table for Between-Group Comparison

Source of Variation	SS	df	MS	F	p-value
Between Groups	0.51886	4	0.12971	46.21	2.05×10^{-6}
Within Groups	0.02807	10	0.00281	-	
Total	0.54693	14	-		

3.2.2. Paired t-Tests

To further examine the performance differences between the control/stabilized laterite mixes and the geopolymer-stabilized mix (N2.5G0.5), paired two-sample t-tests were conducted and shown in Table 7.

Table 7. Paired t-Test Results for Cement vs Geopolymer Stabilization

Comparison	Mean Difference	t-Stat	p-value (two-tailed)
S100 vs N2.5G0.5	0.484	-15.77	0.00399
S94C6 vs N2.5G0.5	0.480	-13.57	0.00539
S92C8 vs N2.5G0.5	0.476	-13.55	0.0054
S90C10 vs N2.5G0.5	0.367	-9.17	0.01169

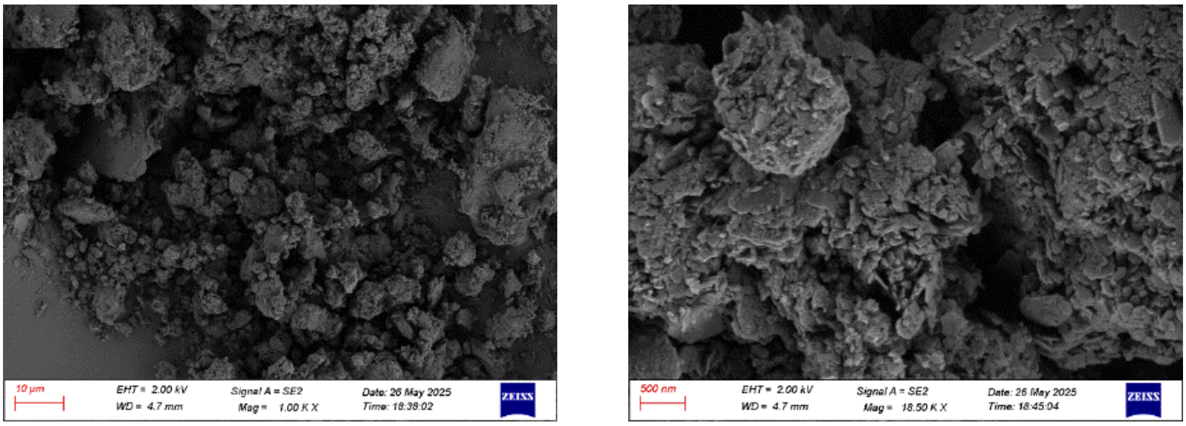
- S100 vs N2.5G0.5: The mean values were 0.145 and 0.629, respectively. A t-statistic of -15.77 was obtained with a two-tailed p-value of 0.00399, indicating a statistically significant improvement with geopolymer stabilization.
- S94C6 vs N2.5G0.5: The mean strength increased from 0.149 to 0.629. The t-statistic of -13.57 and p-value of 0.00539 confirm a significant difference between the cement and geopolymer mixes.
- S92C8 vs N2.5G0.5: With means of 0.153 and 0.629, the t-statistic was -13.55 and p = 0.00540, again validating a statistically significant improvement.
- S90C10 vs N2.5G0.5: The comparison yielded a t-statistic of -9.17 with a p-value of 0.01169, which also supports the superior performance of the geopolymer mix.

Across all comparisons, the p-values were below 0.05, indicating that the observed improvements in strength due to geopolymer stabilization are statistically significant compared to both unstabilized and cement-stabilized laterite soil samples.

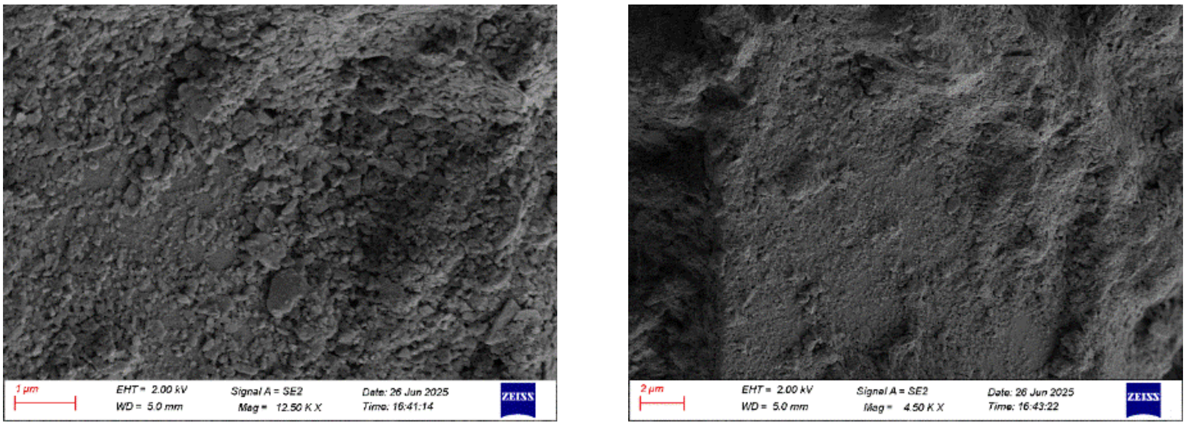
3.3 Microstructural Analysis of developed One part laterite soil sample

3.3.1. SEM analysis

The microstructural characteristics of the samples stabilized with cement and those treated with one-part geopolymer binder were examined using SEM, as shown in Fig. 16(a) and 16(b). The SEM specimens were extracted as small fragments from the inner core of the cylindrical samples to ensure a representative internal structure. The SEM image of the N2.5G0.5 mix reveals a denser matrix with reduced porosity, indicating improved particle packing and gel formation compared to the S90C10 cement-stabilized sample [13].



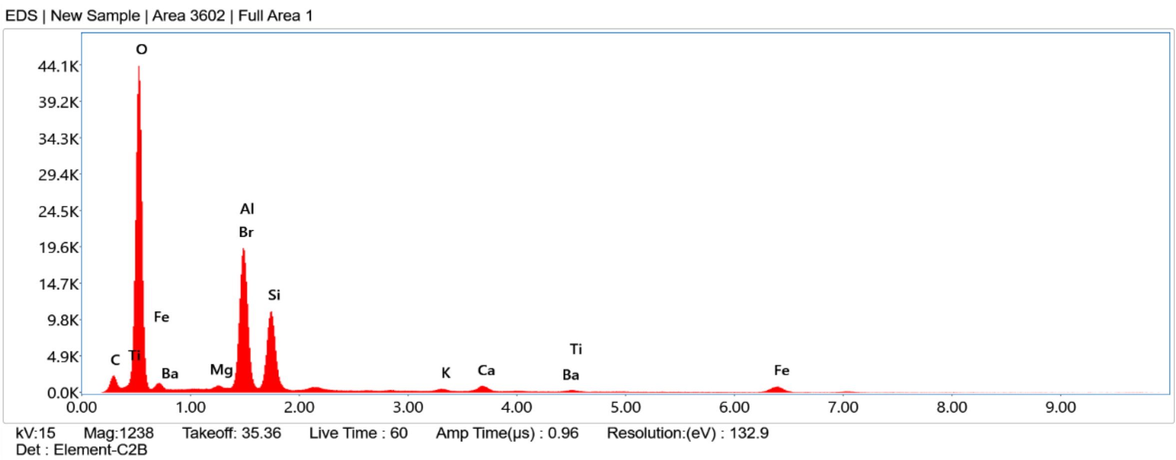
(a)



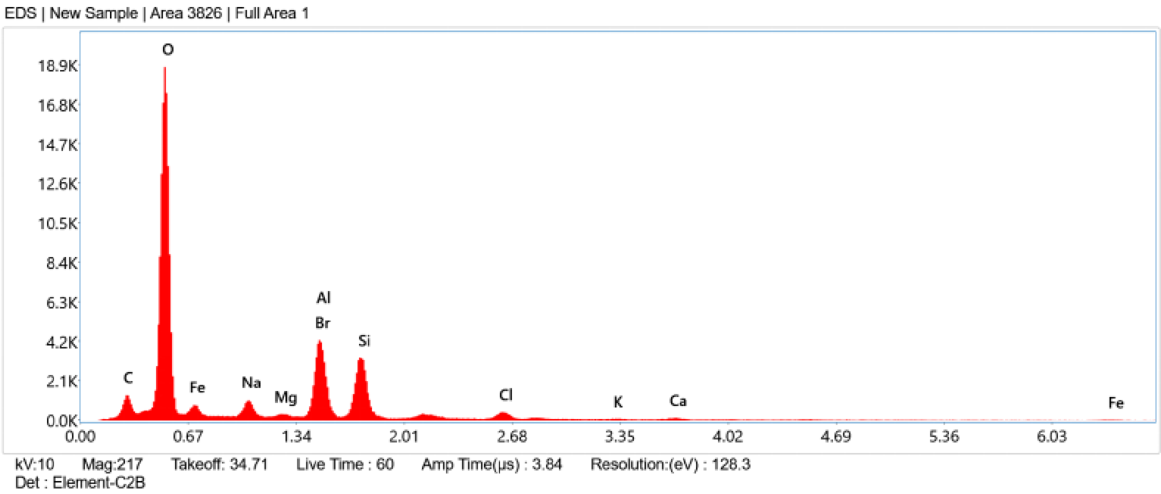
(b)

Fig. 16. (a) SEM images of S90C10 and (b).SEM images of N2.5G0.5

To further analyze the elemental composition and distribution within the matrix, EDS was conducted, and the corresponding spectra and elemental maps are presented in Fig. 17(a) and 17(b). The EDS analysis supports the SEM observations by identifying the presence of key elements such as silicon, aluminum, calcium, and iron, which contribute to the formation of binding phases and densification in the geopolymer-stabilized sample.



(a)



(b)

Fig. 17. (a) EDS images of S90C10 and (b) EDS images of N2.5G0.5

The microstructural results (SEM, XRD, FTIR) presented here are primarily descriptive and intended to provide qualitative evidence of gel formation and matrix densification. While these findings support the observed strength trends, quantitative correlations between microstructure and mechanical performance were beyond the scope of this study and require further detailed investigations (e.g., Rietveld-based QXRD, TGA/DTG, NMR) with larger datasets.

3.4 Cost Analysis

A comprehensive cost analysis was conducted for various sample preparation methods involving laterite soil. The estimated cost of producing 1 m^3 of unstabilized laterite soil is approximately ₹700. When stabilized with cement, the optimal performance was observed at a 10% cement replacement level, yielding the highest unconfined compressive strength among the cement-based mixes. The corresponding cost for this composition is approximately ₹1,800 per cubic meter. In comparison, geopolymer-stabilized laterite soil achieved superior compressive strength in Mix 6, prepared with an alkaline activator ratio of 2.5 and an alkaline activator-to-GGBFS ratio of 0.5. The cost for producing 1 m^3 of this geopolymer-based mix is estimated to be around ₹2,250. Although the cement-stabilized mix demonstrates a slightly lower cost than the one-part geopolymer system, the geopolymer mix proves to be more advantageous in terms of both unconfined compressive strength and sustainability. Therefore, the incorporation of one-part geopolymer presents a promising alternative for enhancing the performance and environmental compatibility of laterite soil-based construction materials.

Table 8 presents a comparative analysis of the strength-to-cost ratio and associated CO_2 emissions for various mix compositions. The results indicate that specimens incorporating one-part geopolymer binders exhibit the highest strength-to-cost ratio compared to cement-stabilized soil samples. This suggests that the use of one-part geopolymer not only enhances the unconfined compressive strength but also offers superior performance from a sustainability perspective, making it a more efficient and environmentally favorable alternative to traditional soil-cement mixtures.

To evaluate the practical viability of the developed laterite soil blocks, the strength-to-cost metric defined as the 28-day compressive strength (MPa) divided by the material cost per cubic metre (₹/m^3) is calculated. This metric expresses the structural performance obtained per unit of financial outlay and facilitates direct comparison between mix designs on both technical (strength) and economic (cost) grounds. It complements environmental indicators (kg CO_2/m^3 and kg CO_2/MPa), enabling multi-criteria assessment that balances durability, affordability, and carbon footprint, key considerations for sustainable construction in low-resource contexts.The metric transparently using component costs and perform ±20% sensitivity analysis on prices and emission factors to test robustness are computed and reported.

Table 8. Table showing the Strength/Cost ratio and CO_2 Emission of different mix

Mix	Total mass (kg/m^3)	CO_2 Material (kg/m^3)	CO_2 Transport (kg/m^3)	CO_2 Total (kg/m^3)	Strength (MPa)	CO_2 per MPa (kg CO_2 /	Strength (MPa)/ Cost
Soil 100%	1,798.31	0.00	0.00	0.00	0.177	0.00	2.52X10^{-4}
Soil + Cement	1,775.11	128.20	0.94	129.14	0.310	416.58	1.72X10^{-4}
OPG (Soil + GGBFS +activators)	1,881.85	65.67	0.88	66.55	0.690	96.44	0.0428

The environmental assessment presented here is limited to raw-material CO_2 emissions for laboratory-scale UCC specimens. Full life cycle analysis (LCA), including production, transport, durability, and end-of-life impacts, is beyond the scope of the present study and will be addressed in future research focused on full-scale stabilized laterite blocks.

4. Conclusion

The conventional two-part geopolymer system poses health hazards to workers due to the use of corrosive alkaline solutions, this study proposes a safer and more user-friendly alternative by adopting a one-part geopolymer approach for the development of laterite soil blocks.The present experimental study investigated the optimal proportion of a one-part geopolymer binder, utilizing GGBFS, for stabilizing laterite soil in the production of compressed stabilized soil blocks. Initial characterization of the laterite soil was performed, followed by the assessment of its UCS in the unstabilized condition at 7, 14, and 28 days. Subsequently, various mix proportions incorporating cement and geopolymer binder were prepared and tested using cylindrical specimens.

- Among the tested mixes, N2.5G0.5 formulated with an alkaline activator ratio of 2.5 and activator-to-GGBFS ratios of 0.4 and 0.5 exhibited the highest UCS values, achieving 0.525 MPa at 7 days, 0.673 MPa at 14 days and 0.69 MPa at 28 days of curing. The 28-day strength of Mix N2.5G0.5 was observed to be 0.69 MPa, indicating an improvement of over 300% compared to the reference S100 mix. These findings demonstrate the potential of one-part geopolymer systems with GGBFS as effective stabilizers for lateritic soils in sustainable block production.
- SEM image of the N2.5G0.5 mix reveals a denser matrix with reduced porosity, indicating improved particle packing and gel formation.
- Statistical results also strongly suggest that the use of one-part geopolymer as a stabilizing agent significantly enhances the performance of laterite soil. The marked differences between geopolymer and cement-stabilized samples imply the superior bonding and structural benefits offered by the geopolymer binder. Given the consistent significance across all tests, the geopolymer-stabilized mix (N2.5G0.5) can be considered a more effective alternative for laterite soil stabilization in terms of strength development.
- A cost analysis was also carried out alongside the strength evaluation of the different mixes. The production cost of 1 m^3 of unstabilized laterite soil was estimated to be approximately ₹700. For cement-stabilized samples, the optimal performance was achieved with a 10% cement replacement, which recorded the highest unconfined compressive strength among the cement-based formulations. The estimated cost for producing 1 m^3 of this mix was around ₹1,800 whereas for Laterite soil with one-part geopolymer estimates to a cost of around ₹2,300. But this cost will be reduced for manufacturing in a large-scale manner.
- The strength-to-cost ratio and CO_2 emissions were evaluated for various samples, including unstabilized laterite soil, cement-stabilized soil, and soil stabilized with one-part geopolymer binders. The analysis revealed that the specimens incorporating one-part geopolymer binders achieved the highest strength-to-cost ratio among all mixes. Furthermore, these specimens demonstrated negligible CO_2 emissions, highlighting their potential as a sustainable and efficient alternative to conventional cement-based stabilization.

The present study provides preliminary laboratory-scale insights into the performance of laterite soil stabilized with one-part geopolymers. While relative improvements over cement-stabilized soil are observed in UCC specimens, the absolute strengths are below those required for structural blocks, further optimization and full-scale testing are needed before considering industrial application or cement replacement.

This study focuses on optimizing mix proportions using UCS specimens, and a full-scale block investigation was not included within the current scope. Therefore, future research will extend this work to evaluate complete block production and performance. A comprehensive life cycle assessment (LCA) covering all stages of production, use, and disposal can be conducted once full-scale block development is undertaken. A more comprehensive assessment including production, transport, block casting, curing, durability, and maintenance can be undertaken in a future study focused on full-scale stabilized laterite blocks.As this study represents an initial screening, further evaluation of long-term performance including durability, wet strength, and serviceability can be addressed in subsequent research. Additionally, while this work was performed using laterite soil abundant in Kerala and OPC 53-grade cement, future studies may explore different soil types and binder systems to broaden applicability.

Based on both performance and economic evaluation, the study concludes that the one-part geopolymer binder incorporating GGBFS presents a viable and sustainable alternative to conventional cement for the stabilization of laterite soils in compressed block production.

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