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Research Article

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Stablilization of Clay with Fly Ash and GGBS Based Geopolymer: Influence on Strength, Consolidation, and Shrinkage Characteristics

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Abstract

Clay soils undergo large volume change with seasonal moisture fluctuation, producing low shear strength, high compressibility, and swell-shrink behaviour that make them problematic subgrade and foundation materials. Chemical stabilization with ordinary Portland cement is effective but carries a high embodied carbon cost, motivating sustained interest in geopolymer binders made from industrial by-products. This study evaluates fly ash and Ground Granulated Blast-furnace Slag (GGBS) based geopolymer as stabilizers for an intermediate compressibility clay sourced from Madurai, India. Geopolymer was added at 25%, 35%, and 45% by dry soil weight, activated with a sodium hydroxide, sodium silicate solution, and evaluated through unconfined compression testing (0, 7, 14, and 28 days of curing), one-dimensional consolidation testing, and shrinkage-limit testing, benchmarked against the untreated clay. Unconfined compressive strength (UCS) increased with curing period for essentially all mixes; 35% fly-ash-based geopolymer produced the highest fly-ash UCS (17.19 kg/cm² at 28 days, a 374% increase over untreated clay- 3.63 kg/cm²), while UCS continued rising with GGBS content up to the highest proportion tested (18.84 kg/cm² at 45% GGBS, 28 days, a 419% increase). Both binders markedly improved consolidation behaviour, cutting the coefficient of compressibility by 70-84% and the compression index by 74-86% relative to untreated clay, while mildly increasing the coefficient of consolidation. Shrinkage limit increased by 51-84% and volumetric shrinkage fell by 48-63%, indicating substantially reduced swell-shrink potential. These findings, read alongside the wider fly ash and GGBS geopolymer literature reviewed here, show that fly ash and GGBS based geopolymers are effective, lower-carbon alternatives to conventional binders for improving the strength, compressibility, and volumetric stability of soft clay, with 35% fly ash and 45% GGBS identified as the best performing proportions within the ranges tested.

Keywords: clay soil; soil stabilization; geopolymer; fly ash; GGBS; unconfined compressive strength; consolidation; shrinkage limit

1. Introduction

Clay is the finest fraction of soil, composed of crystalline clay minerals whose surface charge attracts and holds water molecules. This adsorbed water layer is responsible for characteristic plasticity of clay and its tendency to swell and shrink with changes in moisture content. Combined with high compressibility, low shear strength, and low permeability, these properties make clay a difficult foundation material: uneven settlement of structures founded on clay produces differential settlement and cracking, and heavily loaded infrastructure such as airfield pavements and highway

subgrades cannot be built directly on untreated clay because of its low bearing capacity [2,13, 17]. Expansive clays in particular are a recurring hazard, causing shrink-swell related distress that has been documented worldwide in subgrades, light structures, and buried infrastructure [16,22,45]. Where construction on clay rich sites is unavoidable, the soil must first be stabilized.

Soil stabilization improves the engineering properties of subgrade soil, most commonly by treating it with a binder that causes fine clay particles which are too small individually to form a load-bearing skeleton to aggregate into larger, stronger clusters. Ordinary Portland cement (OPC) and lime are the conventional binders for this purpose, and a large body of work has established their effectiveness in raising strength, reducing compressibility, and suppressing swell-shrink behaviour in clay [40,42,43,44,45]. However, cement production is estimated to contribute roughly 5-8% of global anthropogenic carbon dioxide emissions, with each tonne of clinker generating close to a tonne of CO2 [23,24,26], and lime manufacture carries a comparable energy and emissions burden [45]. Comparative and machine learning based studies of lime and cement stabilized clay confirm strong strength and consolidation gains but do not resolve this carbon cost [39,41,46]. This has created sustained demand for lower-carbon binder alternatives that can match cement's stabilization performance.

Geopolymer binders, formed by activating an aluminosilicate source with an alkaline solution, are one such alternative [47]. The chemistry was systematized by earlier researchers, who described the alkali activation of aluminosilicate raw materials as a polycondensation reaction producing an amorphous to semi-crystalline three-dimensional aluminosilicate network [31,33]. The generally accepted mechanism proceeds through dissolution of the solid precursor in the alkaline solution, transport of the dissolved silica and alumina species, and polycondensation into a rigid gel [30,31], with the specific silico-aluminate and calcium-silicate-hydrate reaction products depending on the precursor's composition and the activator chemistry [32,34]. Because common precursors such as fly ash and GGBS are industrial by-products that would otherwise require landfill disposal, geopolymer stabilization simultaneously offers a lower-carbon binder and a productive use for waste material [13,23,26].

Fly ash, a by-product of pulverized coal combustion, has been the most widely studied geopolymer precursor for soil stabilization. Literature on the feasibility of fly ash and red mud based geopolymer as a next-generation soil stabilizer, reported 28 day UCS values well above those of untreated soil [6], and subsequent studies on soft marine and riverside clays have consistently reported large UCS gains with increasing fly ash content and curing time [5,7,8,9,10]. Moreover, researchers found that geopolymer-treated clay develops strength faster under dry curing than wet curing, that strength increases monotonically with curing period regardless of binder type, and that geopolymer-treated specimens are more ductile than cement-treated ones [1]. Earlier studies reviewed geopolymerization in soil stabilization, and noted that low calcium Class F fly ash is generally preferred over Class C for geopolymer synthesis because its lower CaO content avoids premature self-cementation, that a combined sodium or potassium hydroxide and silicate activator is the most

common alkaline solution, and that fly ash based systems require longer curing than Portland cement to reach target strength [2].

GGBS, a by-product of iron manufacture with a substantially higher CaO content than fly ash, has emerged as a complementary or superior precursor because its latent hydraulic reactivity accelerates early strength gain. Reviews of GGBS and fly ash based geopolymerization report that blended or GGBS dominant systems can exceed the UCS achieved with fly ash alone, though many single precursor mixes still fall short of pavement subgrade strength criteria such as ASTM D4609 [13]. The stabilizer content, slag to fly-ash ratio, and alkaline activator content all exert a decisive influence on the UCS of geopolymer-stabilized riverside soft soil [5], and a recent critical review of fly ash GGBS blended geopolymers for expansive soil stabilization reports 28 day UCS gains of four to nine fold over untreated soil across the studies synthesized, alongside GGBS driven increases in maximum dry density and accelerated early strength [11]. GGBS has also been shown, in combination with nanosilica, to improve the consolidation stiffness, compressibility, and swelling response of high-plasticity clay through the same latent hydraulic and pozzolanic mechanisms [14], and GGBS-waste-glass geopolymer systems have improved the mechanical performance of sandy soils through comparable aluminosilicate gel formation [15].

Beyond the choice of precursor, the proportioning of the alkaline activator strongly governs strength development. A sodium silicate-to-sodium hydroxide ratio of 2.5 produces the highest UCS in geopolymer stabilized soil and that geopolymer stabilization is generally less expensive than conventional chemical admixtures [3]. The strength on geopolymer concreate increases with the sodium silicate-to-sodium hydroxide ratio up to an optimum and identified an optimum fly ash to alkaline solution ratio of 0.35, a mix-design guideline adopted directly in the present study [4]. Subsequent studies on fly ash and metakaolin based geopolymer binders have generally confirmed that strength rises with the silicate-to-hydroxide ratio up to a peak before declining at higher ratios, and that increasing NaOH molarity densifies the reaction product up to a saturation point [35,36,37,38]. Strength development in geopolymer stabilized soil has been shown to depend on curing temperature, humidity, and initial moisture content, with most studies favouring sealed, humidity controlled ambient curing to avoid premature moisture loss during the geopolymerization reaction [48].

Geopolymer stabilization has also been shown to directly address the swell-shrink behaviour that makes expansive clay problematic. Alkali activated binders have reduced the plasticity index and free swell of black-cotton and bentonite soils by tens of percent while simultaneously raising UCS and CBR [16,18,19,21], and reviews of alkali activated binder treated expansive soil attribute this dual improvement to a combination of geopolymerization or alkali activation reaction products and a cation exchange driven flocculation mechanism that reduces the soil's affinity for water [22]. Fly ash based geopolymer treatment of expansive subgrade soil has likewise been reported to reduce swelling and shrinkage while improving strength sufficiently for use in flexible pavement subbase and subgrade layers [20], and semifield comparisons of alkali activated binder and cement-stabilized

expansive subgrades report broadly comparable or superior field performance for the geopolymer treated sections [19].

A parallel and increasingly active strand of the literature applies machine-learning models gradient boosting, random forests, artificial neural networks, and their hybrids to predict the UCS of geopolymer stabilized clay from mix and curing variables, generally achieving coefficients of determination above 0.95 on databases pooled from dozens of individual studies [12,27]. These models consistently identify precursor content (particularly GGBS content) and the alkaline to activator ratio as the dominant predictors of strength [12], corroborating the mix-design sensitivities reported in the mechanistic literature above. Parallel sustainability assessments comparing geopolymer and OPC stabilized soil on a cost per unit strength and CO_2 per unit strength basis have generally found geopolymer stabilization to be the more carbon efficient option, with reported reductions in CO_2 emissions relative to cement based stabilization ranging from roughly 44% to more than 90% depending on the precursor, activator dosage, and system boundary assumed [25,26,28,29], though at least one life cycle costing study found the difference in total life cycle cost between geopolymer and cement based systems to be modest once durability and service life are taken into account.

Building on this literature, the primary objective of this study is to establish a regional engineering and mix-design benchmark for stabilizing intermediate compressibility (CI) clays typical of Southern India (specifically Madurai) using fly ash and GGBS-based geopolymers. While the fundamental mechanisms of geopolymerization are documented, localized soil mineralogy and index properties dictate specific volumetric and strength responses. Therefore, this study evaluates: (i) the mechanical strength, one-dimensional consolidation, and swell-shrink characteristics of geopolymer-treated CI clay; (ii) the performance differences between low-calcium fly ash and high-calcium GGBS precursors under ambient curing conditions; and (iii) the operational dosage limits for optimal strength gain and compressibility reduction to guide subgrade stabilization in regional highway and infrastructure projects.

2. Materials and Methods

2.1 Soil sample

A clayey sample, collected at 2 m depth near the Periyar bus stand, Madurai, contained more than 50% fine-grained particles and was adopted for the study (Figure 1).

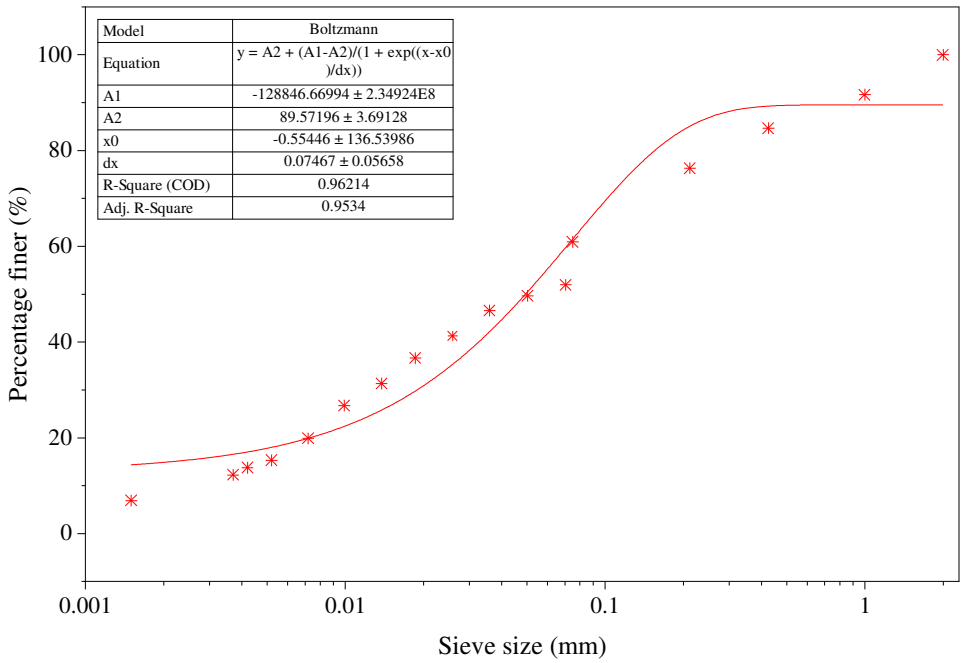


Figure 1. Particle size distribution of clay sample

2.2 Fly ash and GGBS

Fly ash, a by-product of pulverized-coal combustion in thermal power plants, was used in its Class F form (approximately 7% CaO), preferred over Class C fly ash (approximately 20% CaO) because its lower lime content avoids premature self cementation and is the form generally recommended for geopolymer synthesis [2,13]. GGBS, a by-product of iron manufacture formed by rapidly water-quenching blast-furnace slag and grinding it to a fine powder, contains a higher CaO fraction (approximately 35%), which accelerates setting through its latent hydraulic reactivity [13,14]; a retarder was therefore used in GGBS mixes to control early stiffening.

2.3 Alkaline activator and admixtures

The alkaline activator was a combined sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solution, following common practice for aluminosilicate activation [2,35,36]. A polycarboxylate based superplasticizer (Glenium Sky 8841) was used to maintain workability, since geopolymer soil mixes are considerably stiffer than conventional cement and soil mixes at a given water content. The polycarboxylate-ether superplasticizers are widely reported to improve the flowability of geopolymer systems with only a minor influence on hardened strength. Borax was used as a retarder in GGBS mixes to offset their faster initial set.

2.4 Geopolymer mix proportioning

Geopolymer was added at 25%, 35%, and 45% by dry weight of soil. Within each mix, the alkaline-solution-to-binder ratio was fixed at 0.35 and the sodium silicate-to-sodium hydroxide ratio at 2.5, following the design procedure [4] and consistent with the alkali ratio producing the highest UCS

[3]; NaOH solids were proportioned assuming a 14 molar solution (40.43% solids, 59.57% water by mass). The resulting mix quantities identical in method for fly ash and GGBS, since only the binder differs are summarized in Table 1.

Table 1. Geopolymer mix proportions per 7000 g of dry soil (identical proportioning method used for both fly ash and GGBS based binders)

Geopolymer content	**Soil (g)**	**Binder (fly ash or GGBS) (g)**	**Na_2SiO_3 (g)**	**NaOH solids (g)**	**Water for NaOH (g)**
25%	7000	1296	272	74	108
35%	7000	1815	381	103	151
45%	7000	2333	490	131	196

2.5 Characterization of the untreated clay

The untreated soil was characterized by specific gravity [50], particle-size distribution and classification [51, 54], Atterberg limits [52,53], free swell index [55], and standard Proctor compaction [56] to establish optimum moisture content and maximum dry density.

2.6 Unconfined compression test

Clay sample was mixed at its optimum moisture content with 25%, 35%, or 45% fly ash or GGBS based geopolymer and compacted in three layers to provide the same compactive energy as the standard Proctor test. Cylindrical specimens were extracted with a Shelby tube sampler, trimmed flat on both ends, and tested in a strain controlled load frame at 0, 7, 14, and 28 days of curing [57]. Specimens were sealed to limit moisture loss during curing, consistent with practice reported elsewhere for geopolymer stabilized soil. Axial load was recorded via a calibrated proving ring and axial deformation via a dial gauge, and the peak stress on the load-deformation curve was taken as the unconfined compressive strength.

2.7 Consolidation test

One-dimensional consolidation tests [58] were performed on the untreated clay and on the two geopolymer proportions that produced the highest 28 day UCS for each binder (35% fly ash, 45% GGBS), after 7 days of curing. Taylor's square root of time fitting method was used to determine the time for 90% primary consolidation at each load increment, from which the coefficient of consolidation (c_v), coefficient of compressibility (a_v), and compression index (Cc) were derived.

2.8 Shrinkage limit test

Shrinkage parameters (shrinkage limit, shrinkage ratio, and volumetric shrinkage) were determined by the mercury displacement method [53] for the untreated clay and for the two best performing geopolymer mixes identified above (35% fly ash, 45% GGBS).

3. Results and Discussion

3.1 Index properties and classification of the untreated clay

Table 2 summarizes the basic index properties of the untreated clay. With more than 50% fines and a liquid limit between 35% and 50%, the soil plots above the A-line on the plasticity chart and is classified as clay of intermediate compressibility (CI) [54]. The measured plasticity index (23.3%) exceeds the A-line value (18.5%) computed from the liquid limit, consistent with this classification. The free swell index of 63.6% indicates a moderately expansive soil, corroborating the motivation for stabilization and placing this clay in the same problematic category documented for expansive black-cotton and marine soils elsewhere in the literature [16,22].

Table 2. Index properties, gradation, and classification of the untreated clay

Property	**Value**
Specific gravity, G_s	2.662
Liquid limit, W_l	45.4%
Plastic limit, W_p	22.13%
Plasticity index, I_p	23.27%
Shrinkage limit, W_s	13.31%
Shrinkage ratio, S.R.	1.946
Volumetric shrinkage	68.54%
IS classification	CI (intermediate compressibility)
Optimum moisture content	19.6%
Maximum dry density	1.62 g/cc
Free swell index	63.63%
Gravel (20-4.75 mm)	0.82%
Sand (4.75 mm-75 µm)	38.26%
Silt (75-2 µm)	52.84%
Clay (< 2 µm)	8.09%
UCS	3.63 kg/cm²

3.2 Effect of geopolymer treatment on unconfined compressive strength

Table 3 reports UCS at 0, 7, 14, and 28 days of curing for both binders across all three geopolymer proportions. UCS generally increased with curing period, consistent with the progressive geopolymerization reaction described in the literature: dissolution of the aluminosilicate source in the alkaline solution, formation of a supersaturated gel, and its gradual condensation into a rigid three-dimensional aluminosilicate network [1,30, 31].

Table 3. Unconfined compressive strength (kg/cm²) of geopolymer treated clay by binder, proportion, and curing period

Curing period	**Fly ash 25%**	**Fly ash 35%**	**Fly ash 45%**	**GGBS 25%**	**GGBS 35%**	**GGBS 45%**
0th day	0.643	1.038	0.187	1.644	1.081	1.905
7th day	0.749	5.984	1.434	2.094	2.661	6.850
14th day	5.303	10.864	5.164	7.334	7.700	15.187

28th day	8.906	17.189	7.810	9.429	10.562	18.839

For fly ash-based geopolymer, 35% treatment gave the highest UCS at every curing period tested (Figure 2), with a peak 28 day strength of 17.19 kg/cm², a 374% increase over the untreated clay. Strength fell at 45% fly ash content, most likely from an excess of unreacted binder diluting the load-bearing aggregate structure; 35% is therefore identified as the optimum fly ash proportion within the range tested.

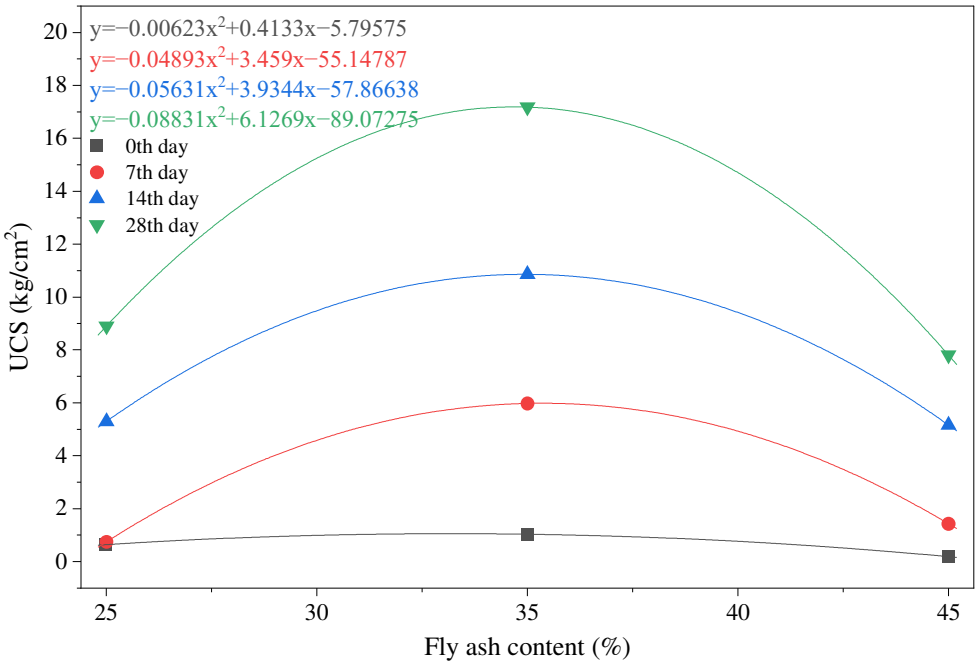


Figure 2. Fly ash based geopolymer content versus UCS with increase in curing period

For GGBS-based geopolymer, UCS increased monotonically with binder content at every curing period (Figure 3), reaching 18.84 kg/cm² at 45% GGBS and 28 days, a 419% increase over the untreated clay and the highest UCS recorded in this study. Because strength was still rising at the highest proportion tested, 45% cannot yet be confirmed as the true optimum for GGBS; testing at 55% or higher would be needed to locate the point at which UCS begins to decline, as it did for fly ash. Because UCS continued to increase up to 45% GGBS content without declining, 45% represents the upper operational limit evaluated in this study. While higher dosages might yield further incremental strength gains, 45% is identified as the practical threshold to balance mechanical performance with field workability and economic viability.

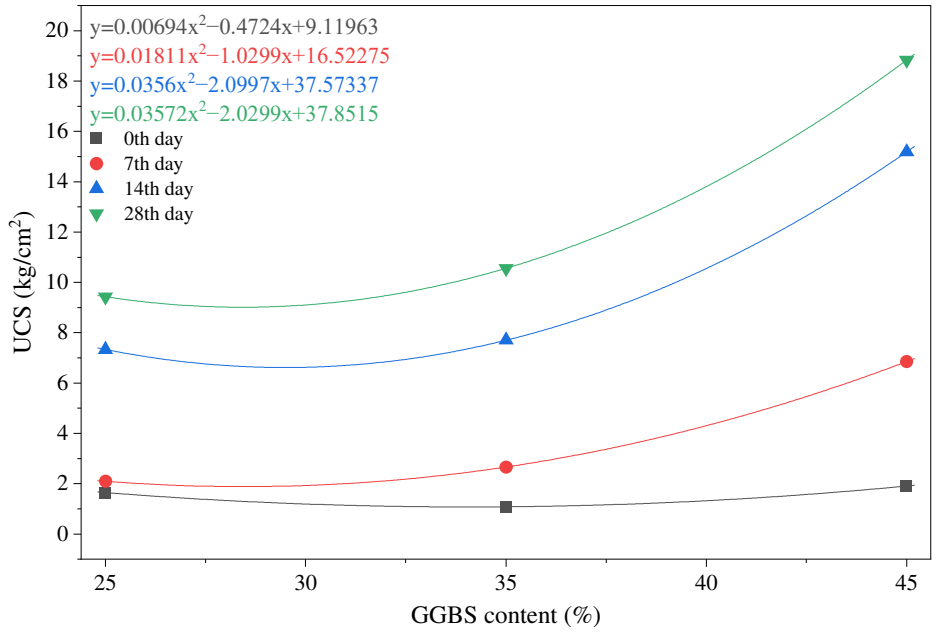


Figure 3. GGBS based geopolymer content versus UCS with increase in curing period

3.3 Effect of geopolymer treatment on consolidation behaviour

Consolidation tests were run on the untreated clay and on the two best performing mixes from Section 3.2 (35% fly ash, 45% GGBS), each cured for 7 days. Table 4 reports the derived parameters.

Table 4. Consolidation parameters of untreated and geopolymer treated clay

Parameter	**Untreated clay**	**35% fly ash geopolymer**	**45% GGBS geopolymer**
Coefficient of compressibility, a_v (m²/kN)	5.5×10^{-4}	1.625×10^{-4}	0.875×10^{-4}
Coefficient of consolidation, c_v (m²/s)	0.0712×10^{-6}	0.0859×10^{-6}	0.0816×10^{-6}
Compression index, Cc	0.1627	0.0431	0.0232

Geopolymer treatment substantially reduced the compressibility of the clay. The coefficient of compressibility fell by 70.5% for 35% fly ash and by 84.1% for 45% GGBS relative to untreated clay (Figure 5), and the compression index fell by 73.5% and 85.7% respectively (Figure 6). Since settlement is directly proportional to both a_v (through the coefficient of volume compressibility, m_v) and Cc, these reductions indicate a substantially lower expected settlement for geopolymer treated clay under equivalent loading, a pattern consistent with the consolidation and stiffness improvements reported for GGBS-nanosilica treated high plasticity clay [14] and for other additive stabilized clays more broadly [41]. The coefficient of consolidation increased modestly with treatment about 20.7% for fly ash and 14.6% for GGBS (Figure 4), which, since c_v is inversely related to the time required to reach a given degree of consolidation, implies that treated clay also consolidates faster, further reducing the practical impact of any residual settlement. GGBS treatment outperformed fly ash

treatment on both compressibility measures at the proportions tested (45% GGBS vs. 35% fly ash), though the two binders were tested at different geopolymer contents. It should be noted that this performance comparison between 35% fly ash and 45% GGBS reflects the optimal performing mix of each precursor within its respective operational window, rather than an equal-dosage comparison, owing to the distinct reactivity and workability constraints of each precursor system.

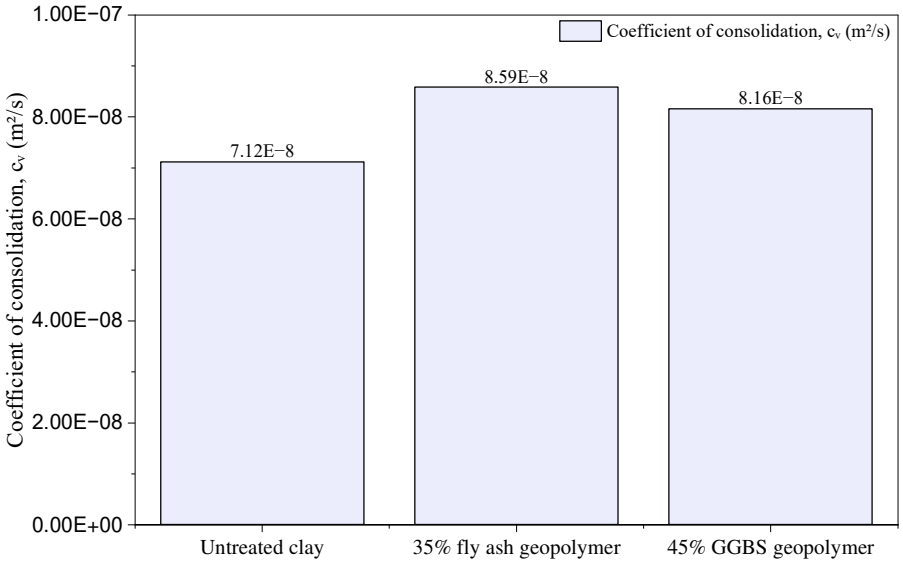


Figure 4. Coefficient of consolidation (c_v) of untreated clay versus 35% fly ash and 45% GGBS geopolymer

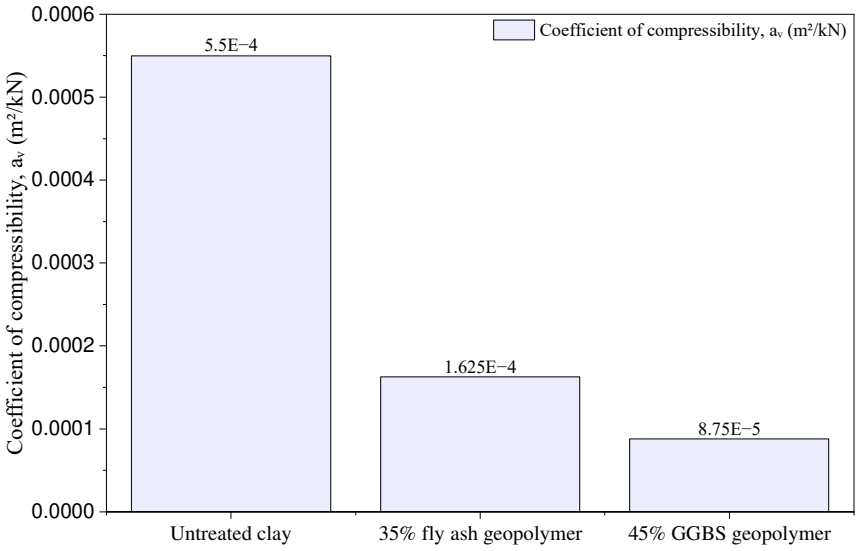


Figure 5. Coefficient of compressibility (a_v) of untreated clay versus 35% fly ash and 45% GGBS geopolymer

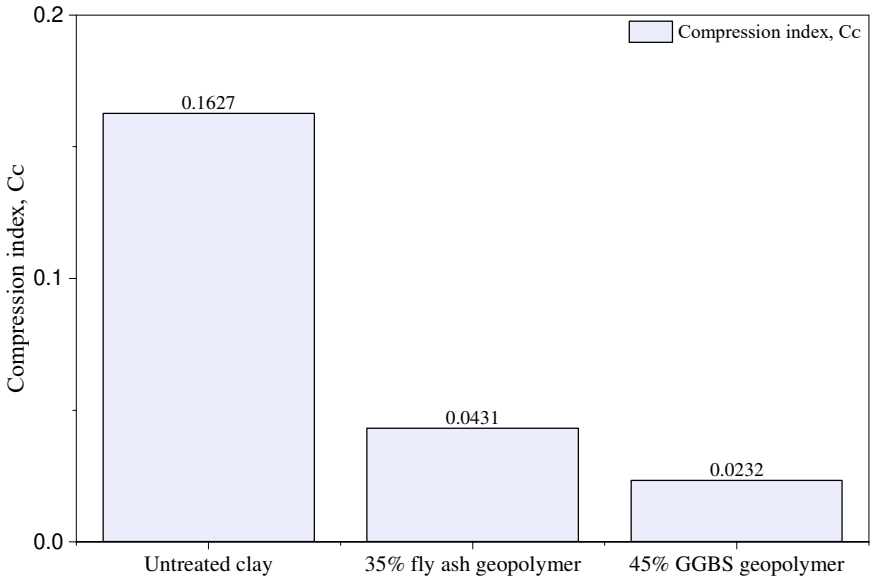


Figure 6. Compression index (Cc) of untreated clay versus 35% fly ash and 45% GGBS geopolymer

3.4 Effect of geopolymer treatment on shrinkage behaviour

Shrinkage limit tests were carried out on the untreated clay and the two best performing mixes and are summarized in Table 5.

Table 5. Shrinkage parameters of untreated and geopolymer-treated clay

Parameter	**Untreated clay**	**35% fly ash geopolymer**	**45% GGBS geopolymer**
Shrinkage limit, W_s (%)	13.314	20.151	24.500
Shrinkage ratio, S.R.	1.946	1.632	1.585
Volumetric shrinkage, V.S. (%)	68.54	35.561	25.374

Geopolymer treatment raised the shrinkage limit by 51.3% (35% fly ash) and 84.0% (45% GGBS) relative to untreated clay (Figure 7), while volumetric shrinkage fell by 48.1% and 63.0% respectively (Figure 9), and shrinkage ratio fell by 16.1% and 18.6% (Figure 8). This pattern is consistent with a flocculation mechanism reported throughout the alkali activated binder literature for expansive soil [16,21,22]: the untreated clay is initially in a dispersed state, and the electrolyte introduced by the alkaline activator neutralizes surface charge on the clay particles, reducing interparticle repulsion and causing them to aggregate into larger clusters. These aggregates reduce capillary suction within the soil mass, increasing the void ratio at which shrinkage begins (the shrinkage limit) and reducing the overall change in volume the soil undergoes on drying, the same mechanism invoked to explain swelling suppression in geopolymer stabilized bentonite [21] and the plasticity-index reductions reported for alkali activated black-cotton soil [16]. As with the consolidation results, GGBS at 45% produced a larger improvement than fly ash at 35%, though again at a higher geopolymer content, so the comparison is between each binder's best performing mix rather than a matched-proportion comparison.

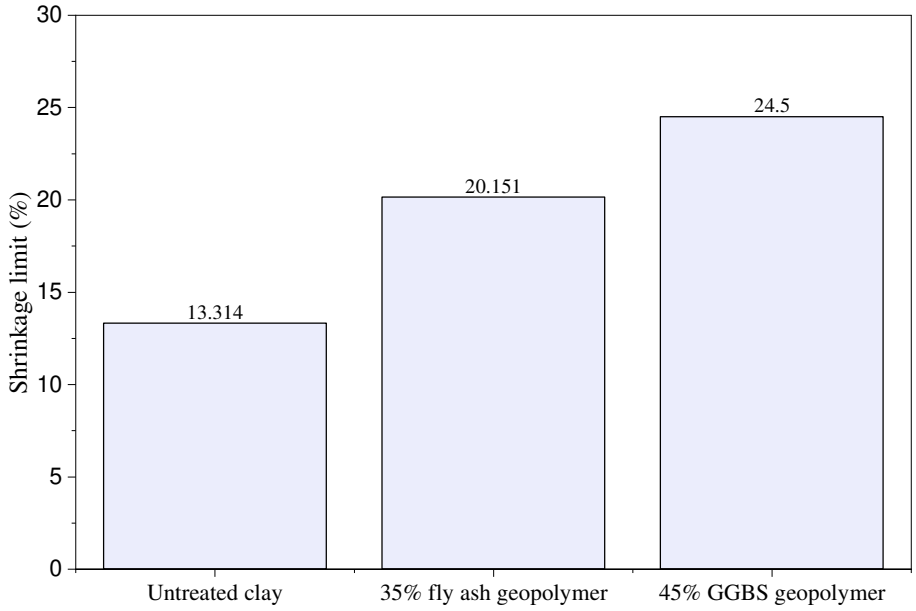


Figure 7. Shrinkage limit of untreated clay versus 35% fly ash and 45% GGBS geopolymer

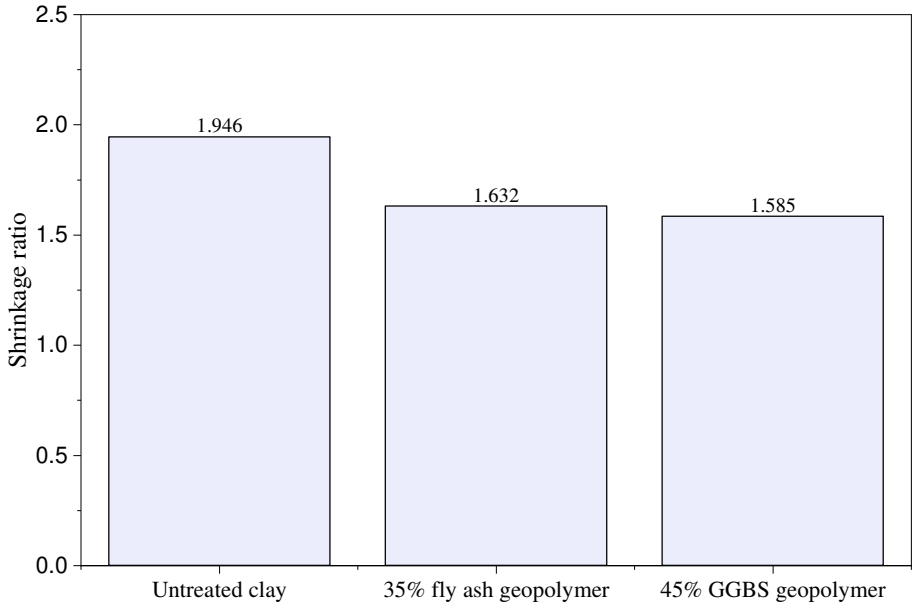


Figure 8. Shrinkage ratio of untreated clay versus 35% fly ash and 45% GGBS geopolymer

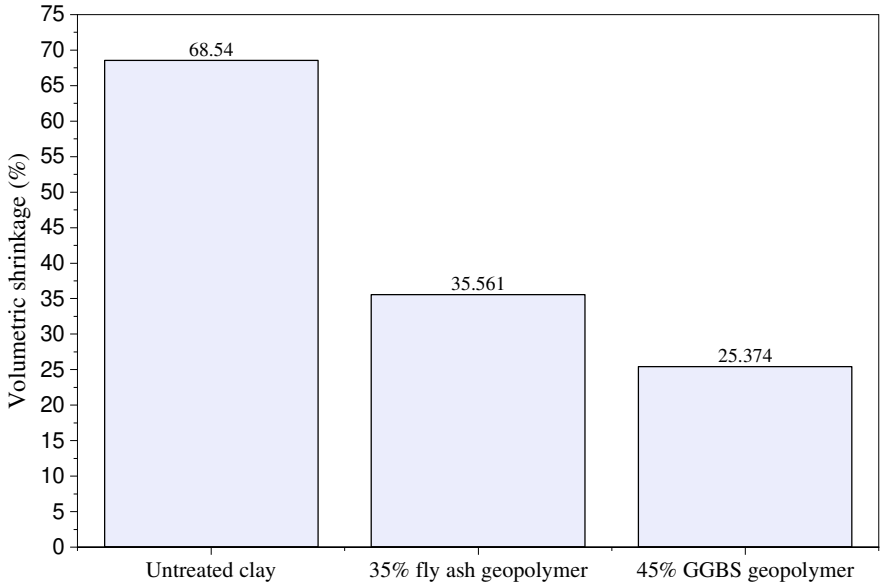


Figure 9. Volumetric shrinkage of untreated clay versus 35% fly ash and 45% GGBS geopolymer

3.5 Comparison with the wider literature

The strength gains observed here ie., 374% for 35% fly ash and 419% for 45% GGBS at 28 days are within the range of four to nine fold UCS improvements reported for fly ash and GGBS blended geopolymer treatment of expansive soil in recent critical reviews [11], and are broadly consistent with the pattern, reported across multiple independent studies, that GGBS rich precursor blends outperform fly ash only systems at a given curing age because of GGBS's latent hydraulic reactivity [5,13,14]. Machine learning studies trained on pooled multi study databases have identified GGBS content and the alkaline activator ratio as the strongest predictors of UCS in geopolymer stabilized clay [12], which is also consistent with the present results. GGBS content shows a strong positive association with 28 day UCS across the tested range, while the fly ash response peaks at 35% before declining. In absolute terms, the peak UCS values obtained here (5.2-1.7 MPa) remain below the strengths reported for some fly ash and GGBS blends at similar total binder dosage [11]. This performance is also consistent with reports that metakaolin-based geopolymer stabilizers can match or exceed the mechanical strength of cement- and lime-stabilized soft soil [49]. This is consistent with the present study using a single precursor mix design (fly ash or GGBS) rather than the co-optimized blends that dominate the higher end of the literature range.

4. Conclusions

The key observations and inference from this study are reported below:

- The untreated soil, sourced from Madurai, India, was classified as clay of intermediate compressibility, with a liquid limit of 45.4%, plasticity index of 23.3%, and free swell index of 63.6%, confirming it as a moderately expansive, problematic foundation material.

- The unconfined compressive strength increased with curing period for all mixes tested, reaching a 374% improvement over untreated clay at 35% fly ash (28 days) and a 419% improvement at 45% GGBS (28 days).
- 35% is identified as the optimum fly ash based geopolymer proportion within the 25-45% range tested, since UCS declined beyond this point. UCS was still increasing at 45% GGBS content, so the optimum GGBS proportion could not be bounded from above within the range tested and may exceed 45%.
- Geopolymer treatment substantially improved consolidation behaviour, cutting the coefficient of compressibility by 70-85% and the compression index by 74–86%, while mildly increasing the coefficient of consolidation (15-21%), indicating both smaller and faster settlement for treated clay.
- Geopolymer treatment increased the shrinkage limit by 51-84% and reduced volumetric shrinkage by 48-63%, indicating a substantially reduced swell-shrink potential and, by extension, a lower risk of shrink-swell related distress to lightly loaded structures founded on treated clay.

In summary, these results support fly ash and GGBS based geopolymer as viable, lower carbon alternatives to portland cement for stabilizing soft, expansive clay, simultaneously improving strength, reducing compressibility, and limiting volumetric instability while utilizing industrial by-products that would otherwise require disposal.

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