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Synergistic Effects of Ternary Additives on Expansive Clay

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Abstract: Expansive clays are widely recognized as problematic soils due to their tendency to undergo significant volume changes with variations in moisture content. Such behaviour often leads to ground movement, cracking, and structural damage. In this study, an attempt was made to enhance the strength and stability of expansive clay by using lime, fly ash, and silica fumes as stabilizing additives. The soil was first identified and tested in accordance with IS 2720 standards, and the results showed that it belongs to the highly plastic clay (CH) category, characterized by a high plasticity index of 42.89% and a free swell index of 54.12%. After classification, the soil was stabilized using different proportions of the selected additives lime (2%, 4%, 6%), fly ash (10%, 20%, 30%), and silica fume (5%, 10%, 15%) along with three combined mixes to study their collective effect. All prepared samples were compacted at their Optimum Moisture Content (OMC), cured for 7 days, and tested under Unconfined Compressive Strength (UCS) conditions to assess the improvement in load-bearing capacity. The results revealed a clear improvement in strength with the inclusion of stabilizing materials. Among the individual additives, 4% lime, 20% fly ash, and 15% silica fume produced the most favourable strength values. When used together, the combined proportion of 4% Lime + 20% Fly Ash + 10% Silica Fume (Mix 2) exhibited the highest UCS value of 185kN/m²which is 340.47% higher than control sample, demonstrating a strong synergistic interaction between the materials. The improvement in performance can be attributed to better inter-particle bonding, denser packing, and chemical interactions that occurred during curing.

Keywords: Expansive Clay, Ternary Stabilization, Lime–Fly Ash–Silica Fume, Unconfined Compressive Strength (UCS), Soil Stabilization

I. INTRODUCTION

Expansive soils are widely regarded as one of the most problematic geomaterials in geotechnical engineering due to their significant volume change behaviour under varying moisture conditions.These soils typically contain active clay minerals such as montmorillonite, which exhibit a strong affinity for water. As a result, they undergo considerable swelling upon wetting and shrinkage during drying, leading to the formation of cracks and differential ground movements. Such behaviour poses serious challenges to civil engineering structures, including pavements, foundations, and low-rise buildings, particularly in regions experiencing alternating wet and dry climatic conditions. The presence of expansive soils is especially prominent in black cotton soil regions of India, where infrastructure is frequently subjected to distress such as foundation heave, wall cracking, and structural deformation. Owing to these challenges, improving the engineering properties of expansive soils has become a critical area of research.

To overcome the limitations associated with expansive clay, soil stabilization techniques have been widely adopted to enhance strength, reduce plasticity, and improve overall performance. Among these methods, chemical stabilization has proven to be an effective and practical approach, as it induces permanent changes in soil behaviour through physicochemical reactions. Conventional stabilizers such as lime and cement have been extensively used; however, growing environmental concerns related to their high carbon footprint have encouraged the exploration of more sustainable alternatives. In this regard, industrial by-products such as fly ash and silica fume have gained attention due to their pozzolanic properties and environmental benefits.When used in combination, these materials not only improve soil performance but also contribute to sustainable construction by reducing waste and minimizing environmental impact.

The concept of ternary stabilization, involving the combined use of three additives, has emerged as a promising approach for enhancing soil properties beyond the capabilities of individual materials. In this study, lime, fly ash, and silica fume were utilized together to achieve a synergistic improvement in the behaviour of expansive clay. Lime provides calcium ions that react with the silica and alumina present in fly ash and silica fume to form cementitious compounds such as calcium silicate hydrate and calcium aluminate hydrate. These reaction products strengthen inter-particle bonding, reduce plasticity, and enhance the overall stability of the soil matrix.

Additionally, the fine particles of silica fume contribute to the densification of the soil structure by filling micro-voids, resulting in improved durability and strength. This synergistic interaction leads to a cumulative enhancement in engineering properties, making the soil more suitable for construction applications.

Beyond technical advantages, the use of lime, fly ash, and silica fume offers significant environmental and practical benefits. The utilization of industrial by-products promotes sustainable waste management, reduces reliance on conventional materials, and lowers carbon emissions associated with construction activities. Furthermore, the ternary system improves workability, provides better strength development, and enhances long-term performance compared to single or binary stabilization methods.In this context, the present study focuses on the experimental evaluation of expansive clay stabilized using varying proportions of lime, fly ash, and silica fume. Laboratory investigations, including Atterberg limits, compaction characteristics, and unconfined compressive strength tests, are carried out to assess the improvement in soil properties and to identify the most effective combination of additives for achieving optimal performance.

II. MATERIALS AND METHODOLOGY

A. Soil Sample Collection and Classification

1) Soil sample

Natural soil was taken from the Government College of Technology campus in Coimbatore district, Tamil Nadu, India, adjacent to the Industrial Biotechnology (IBT) department. Collection occurred at 1.5 m depth, targeting a distinct clay stratum. The material exhibited dark brown coloration, softness under moist conditions, and marked plasticity typical of expansive clays. Post-collection, the soil underwent air-drying, gentle disaggregation to eliminate aggregates, and sieving via a 4.75 mm IS sieve for gravel and debris removal. Prepared samples were held in sealed containers to maintain constant moisture prior to analysis.

2) Stabilizing agents

Hydrated lime [$Ca(OH)_2$], sourced commercially as a fine white powder with elevated calcium levels and reactivity, served as the primary stabilizer. Lime should be kept in moisture-proof containers to avert hydration or carbonation.

Class F fly ash, compliant with IS 3812 standards and featuring high silica-alumina content alongside low calcium, was obtained from a supplier. This fine grey powder, devoid of clumps, was selected for its sustainable profile and practical potential for soil improvement.

Silica fume (microsilica), an ultrafine amorphous by-product (>90% reactive SiO_2) from silicon metal manufacturing, was procured from the same vendor. Its submicron particles enable void infilling within the soil structure, boosting compactness, mechanical properties and endurance. Both by-products arrived dry and homogeneous, stored in airtight vessels to inhibit moisture uptake and preserve uniformity for experimental use.

B. Methodology

The investigation proceeded through a structured sequence to yield reliable and reproducible findings. Soil specimens were initially sourced from the specified site and maintained under controlled conditions to preserve their native properties, followed by baseline assessments including Atterberg limits, free swell index, and unconfined compressive strength (UCS) to characterize untreated behaviour.Stabilizing agents-lime, fly ash, and silica fume were procured from certified vendors and verified for compliance with quality standards suitable for soil enhancement. Subsequently, soil-additive composites were prepared at designated ratios via meticulous mechanical blending to ensure uniform integration.Moulded samples were then subjected to UCS evaluation after prescribed curing intervals to measure strength augmentation. Comprehensive data compilation, statistical scrutiny and interpretation ultimately revealed the distinct and combined influences of additives on soil reinforcement and durability.

1) Laboratory Investigation of soil

a) Geotechnical properties of natural soil without additives

Prior to stabilization efforts, the untreated expansive clay underwent standard identification tests following IS 2720 protocols to categorize it and assess key physical and mechanical attributes. Findings, detailed in Table 3.1, encompassed specific gravity, Atterberg limits, optimum moisture content, maximum dry density, unconfined compressive strength, and free swell index. The soil qualified as highly plastic clay (CH) per IS classification, evidenced by its elevated plasticity index (42.89%) and free swell index (54.12%), signalling pronounced volumetric instability under fluctuating moisture. These traits underscore the soil characteristic expansiveness, necessitating stabilization to enhance geotechnical suitability and mitigate swell-shrink hazards (**Table 1**).

In accordance with the IS classification, from these results it is confirmed that the soil is a highly plastic clay (CH) having high plastic index and free swell index showed a strong tendency for volume change, justifying the need for the stabilization.

Table 1: Geotechnical Properties of Soil

S. No.	Properties	Results
1	Specific gravity	2.73
2	1. Liquid limit 2. Plastic limit 3. Plasticity Index	54% 11.11% 42.89%
3	Optimum moisture content	18%
4	Maximum dry density	1.74 g/cc
5	Unconfined compressive strength Cohesion	42 kN/m^2 21 kN/m^2
6	Free swell Index	54.12%
7	IS Classification	CH

b) Preparation of stabilized samples and curing

Following initial soil analysis, stabilized specimens were formulated with the procured additives. The raw soil was oven-dried at 105 ± 5 °C, ground to powder, and passed through a 425µm sieve. Predetermined dosages of lime, fly ash, and silica fume calculated as percentages of the soil's dry mass were accurately measured and intimately mixed with the soil to attain visual uniformity. Incremental water addition adjusted the blend to its optimum moisture content (OMC), with continued mixing to yield a consistent, mouldable composite. Unconfined compressive strength (UCS) testing assessed the enhanced shear capacity of expansive clay following treatment with individual and combined stabilizers. Procedures adhered to IS 2720 (Part 10): 1991, delivering consistent and standardized outcomes. Stabilized mixtures were compacted into 38 × 76 mm cylindrical molds at their optimum moisture content (OMC) and maximum dry density (MDD), then demolded and promptly wrapped in plastic film to retain moisture. Specimens underwent 7-day curing in a humidified chamber at 27 ± 2°C, promoting initial pozzolanic bonding between soil and additives prior to testing. The UCS testing regimen comprised two primary series to assess stabilizer efficacy:

- Single-Additives stabilized Soil

Soil was treated individually with lime, fly ash, or silica fume at designated dosages to quantify each materials distinct contribution to strength enhancement.

- Combined-Additives Stabilized Soil

Blends incorporated all three additives at escalating proportions:

Mix 1: 2% lime + 10% fly ash + 5% silica fume
Mix 2: 4% lime + 20% fly ash + 10% silica fume
Mix 3: 6% lime + 30% fly ash + 15% silica fume

These formulations enabled evaluation of dosage variations on the mechanical strength and inter-particle bonding of treated soil

After curing, specimens were mounted in the UCS apparatus and subjected to axial compression at a steady strain rate of ~1% per minute until rupture. The peak axial force (P-max) was documented during loading. UCS outcomes for single-additive and combined mixtures were shown in (**Figures1a and1b**), respectively.

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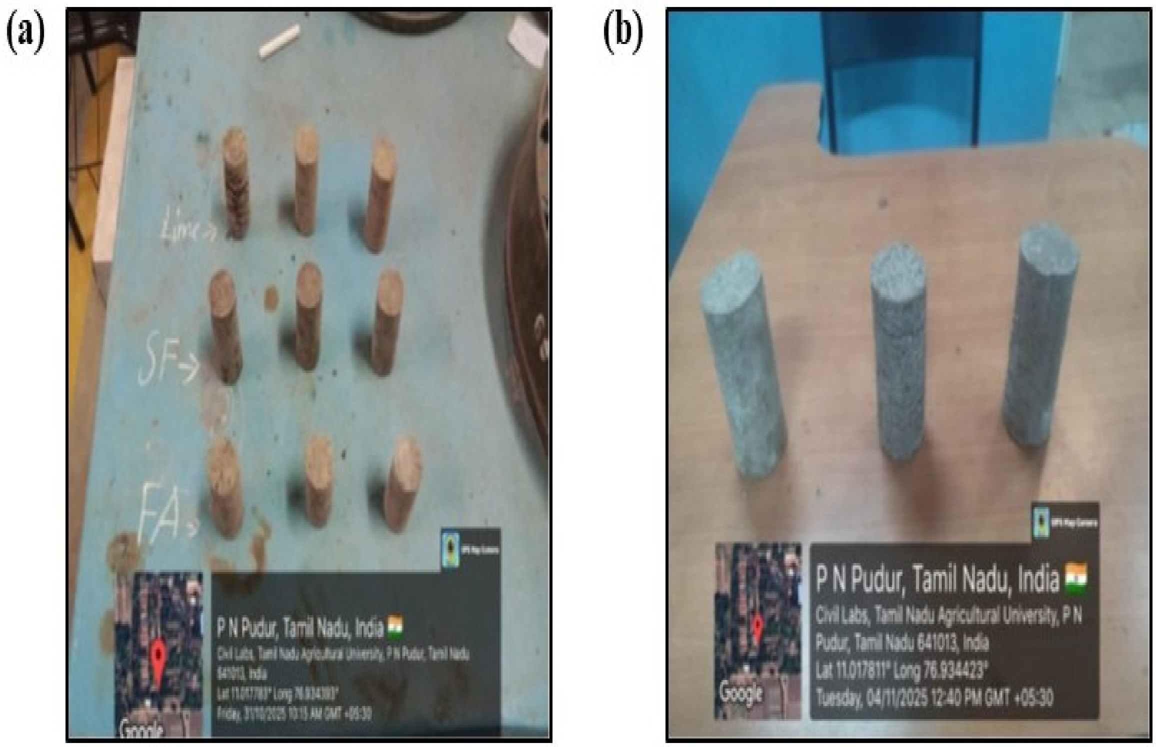

Figure **1:** Individual (a) and Combined (b) proportion of Soil

III. RESULTS AND DISCUSSION

This study presents experimental outcomes from expansive clay treated with lime, fly ash, and silica fume applied singly or jointly focusing on their impact on unconfined compressive strength (UCS) following 7-day curing. All assays complied with pertinent IS 2720 protocols, with systematic data scrutiny to pinpoint optimal additive ratios yielding maximal soil reinforcement. Graphical analyses and interpretations elucidate the strength evolution patterns across formulations.

A. UCS Results

UCS tests evaluated the short-term bearing capacity of treated soil specimens and the efficacy of diverse stabilizer dosages. Specimens underwent 7-day curing prior to testing to facilitate early pozzolanic reactions.

Test Results are categorized into two parts

- Individual Additives Performance
- Combined mix Performance

1) Performance of Individual Addictives

UCS outcomes for soil stabilized individually with lime, fly ash, or silica fume are summarized below and depicted graphically in the accompanying figures.

a) Lime-Stabilized Soil

UCS values rose from 0.100N/mm² at 2% lime to 0.112N/mm² at 4%, before declining marginally to 0.094N/mm² at 6% dosage (**Figure 2**). The strength gains up to 4% stemmed primarily from cementitious compounds like calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) formation. Beyond this optimal level, excess lime likely coated clay particles, impeding additional reactions and reducing overall performance-establishing 4% as the ideal lime proportion.

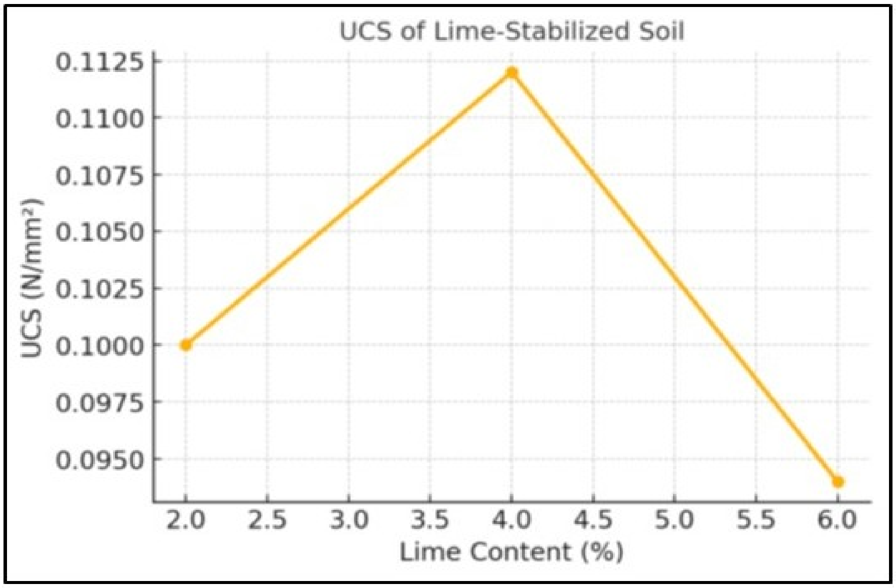

Figure 2: Lime Stabilized soil UCS

b) Fly Ash-Stabilized Soil

For fly ash treatment, UCS rose from 0.092N/mm² at 10% dosage to 0.105N/mm² at 20%, followed by a modest decline to 0.101N/mm² at 30% (**Figure 3**). This enhancement arises from pozzolanic reactions wherein fly ash silica and alumina combined with soil calcium to generate cementitious gels. The marginal drop at elevated levels reflects dilution of reactive soil components by surplus fly ash, identifying 20% as the optimal dosage.

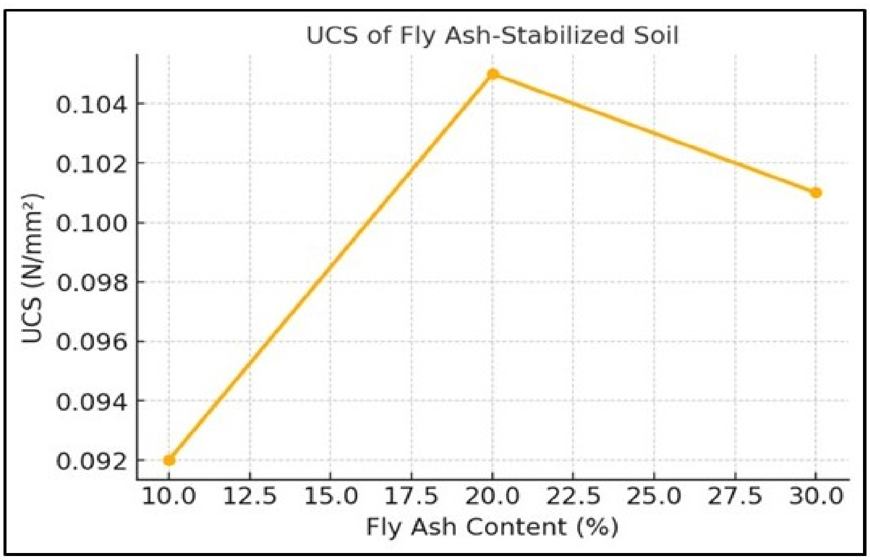

Figure 3: Fly Ash-Stabilized soil UCS

c) Silica Fume-Stabilized Soil

Silica fume treatment yielded progressive UCS gains, from 0.118N/mm² at 5% to 0.132N/mm² at 10%, reaching 0.141N/mm² at 15% (**Figure 4**). Its ultrafine particles enabled superior packing density and inter-particle cohesion, while high reactive silica drove intensified pozzolanic activity for a compact, robust matrix. Silica fume outperformed both lime and fly ash individually, demonstrating greatest efficacy for soil reinforcement.

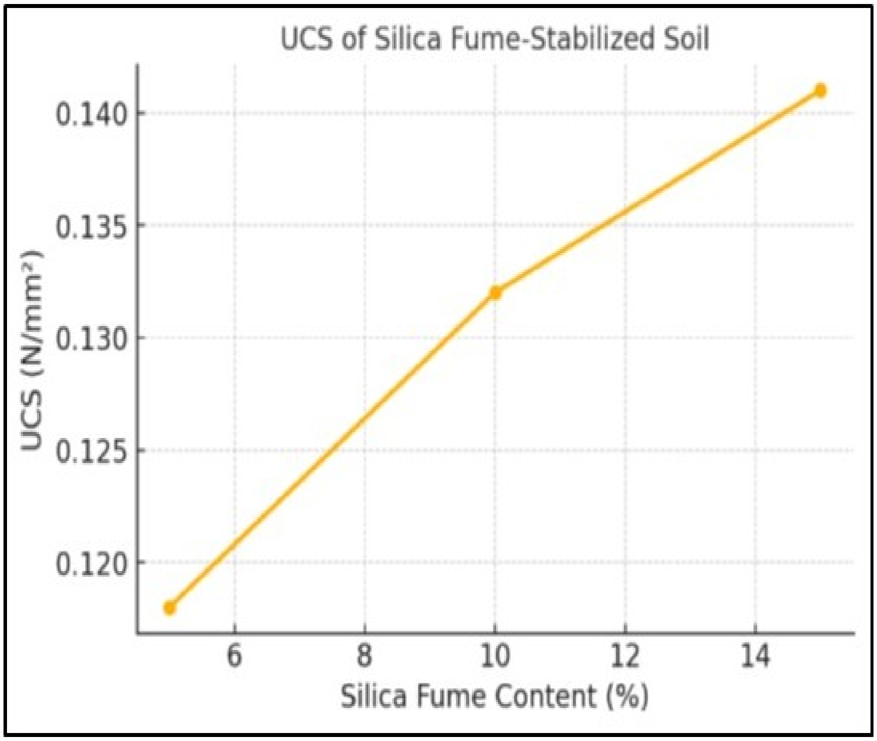

Figure 4: Silica Fume-Stabilized soil UCS

d) Performance of Combined Addictive

Combined additive blends exhibit markedly superior UCS compared to single stabilizers. Findings are tabulated in **Table 2** and visualized in **Figure 5**.

Table 2: UCS Outcomes of Combined Blends (7-days Curing)

Mix ID	Composition	UCS (N/mm^2)	Observation
Mix 1	2% Lime + 10% Fly Ash + 5% Silica Fume	0.096	Moderate improvement
Mix 2	4% Lime + 20% Fly Ash + 10% Silica Fume	0.185	Highest strength
Mix 3	6% Lime + 30% Fly Ash + 15% Silica Fume	0.119	Slight strength reduction

Among the three trial combinations, Mix 2 achieved the highest Unconfined Compressive Strength (UCS) value of $0.185 N/mm^2$, demonstrating the effective combined action of lime, fly ash, and silica fume. The selected proportions created favourable conditions for pozzolanic activity, which enhanced the formation of durable cementitious products and improved the soil strength significantly.

In comparison, Mix 1 showed lower strength because the quantity of stabilizing additives was insufficient to develop stronger bonding within the soil matrix. Although Mix 3 contained higher additive content, a minor reduction in strength was observed, possibly due to excess binder material leading to poor interaction and the development of micro-cracks. Therefore, the optimum stabilization mix identified in this study was 4% Lime + 20% Fly Ash + 10% Silica Fume (**Figure 5**).

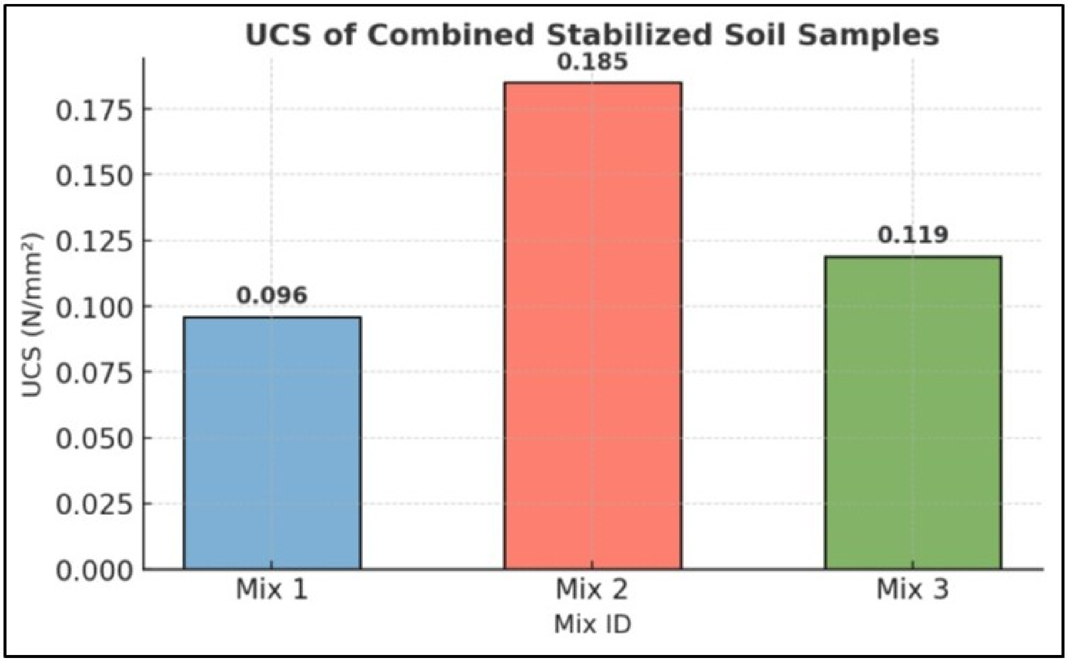

Figure 5: UCS Performance of Combined Additive Mixes

B. Discussion

The incorporation of lime, fly ash, and silica fume significantly improved the Unconfined Compressive Strength (UCS) of the expansive clay compared with the untreated soil sample.

1) The addition of lime promoted cation exchange and flocculation processes, which altered the arrangement of clay particles into a stronger and more stable structure. This modification enhanced the stiffness of the soil and lowered its plasticity characteristics.
2) The increase in strength obtained with fly ash and silica fume was mainly due to pozzolanic reactions occurring between the calcium supplied by lime and the reactive silica and alumina available in these supplementary materials. These reactions generated cementitious compounds that strengthened the soil matrix.
3) Although microstructural investigations were not carried out in this research, the considerable rise in UCS values indicates that chemical bonding reactions likely occurred during the curing period and contributed to the overall strength enhancement.
4) Owing to its extremely fine particle size, silica fume also acts as a filler material by occupying the tiny voids within the soil structure, thereby improving the compactness and density of the stabilized soil.
5) The combined use of lime, fly ash, and silica fume produced a beneficial synergistic effect, where both chemical stabilization and physical densification worked together to provide greater strength improvement than individual additives alone.
6) Among all the mixes tested, the optimum proportion was identified as 4% Lime + 20% Fly Ash + 10% Silica Fume (Mix 2), which achieved the highest UCS value of 0.185 N/mm². This combination provides a balanced amount of calcium and reactive silica/alumina necessary for efficient stabilization.
7) The comparatively lower strength observed in Mix 1 was associated with inadequate stabilizer content, which limited the extent of reaction. In contrast, Mix 3 showed a slight decrease in strength because excessive stabilizer content may reduce uniform interaction and bonding within the soil.
8) The 7-day curing duration was sufficient to facilitate the initial pozzolanic reactions and maintain adequate moisture conditions, resulting in consistent bonding and noticeable strength improvement in all stabilized mixes

IV. CONCLUSION

The present investigation aimed to enhance the engineering behavior of expansive clay by stabilizing it with lime, fly ash, and silica fume.The untreated soil was identified as highly plastic clay (CH) with considerable swelling and plasticity characteristics, indicating the necessity for stabilization treatment.

The incorporation of lime increases the soil strength effectively up to an optimum content of 4%. Beyond this percentage, a slight decline in strength was observed, likely due to excess lime reducing the efficiency of pozzolanic reactions.Samples treated with fly ash exhibited the highest strength improvement at 20% addition. Further increase in fly ash content resulted in a small reduction in strength because of the lower proportion of reactive soil particles available for bonding.The addition of silica fume continuously enhanced the soil strength owing to its ultra-fine particles, which filled micro-voids and improved particle interlocking and bonding within the soil structure.The combined application of lime, fly ash, and silica fume produced much greater strength improvement compared to the use of individual stabilizers, demonstrating a beneficial combined interaction among the additives.Out of all the tested combinations, Mix 2 containing 4% Lime + 20% Fly Ash + 10% Silica Fume achieved the highest UCS value of 0.185 N/mm² and was identified as the optimum stabilization mix.The improvement in strength can be linked to mechanisms such as cation exchange, pozzolanic reactions, and the void-filling capability of silica fume particles, all of which contributed to stronger bonding and denser soil structure.The stabilization process successfully improved the short-term compressive strength and handling characteristics of the expansive clay, making it more appropriate for geotechnical applications including pavement subgrades and foundation works.The findings also demonstrate that the utilization of industrial by-products such as fly ash and silica fume provides a cost-effective and environmentally sustainable approach for soil stabilization in construction projects.

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