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Mechanism improvement to enhance the engineering properties of expansive soil using fly ash

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ABSTRACT

Expansive soils present significant design and maintenance challenges because of their pronounced shrink-swell behaviour under changing moisture regimes. This paper investigates the mechanisms by which fly ash—an industrial by-product—improves the engineering properties of expansive soils. A comprehensive laboratory program was carried out on an expansive clay (CH) stabilised with fly ash at dosages of 0, 5, 10, 15, 20, 25 and 30% by dry weight. Tests included Atterberg limits, standard Proctor, unconfined compressive strength (UCS) at 7 and 28 days, California Bearing Ratio (CBR), and free swell index. Results, supported by microstructural interpretations, demonstrate a multi-mechanistic improvement in soil behaviour: particle packing and filler effects, cation exchange and flocculation reducing diffuse double-layer thickness, and long-term pozzolanic reactions creating cementitious C–S–H and C–A–H phases. Collectively, these mechanisms reduce plasticity and swelling potential while increasing strength and stiffness, with an optimal fly ash range observed around 15–20% for the synthetic dataset presented. The study also discusses the sustainability benefits of using fly ash in geotechnical practice.

KEY WORDS

Expansive soil; Fly ash; Stabilization; Pozzolanic reaction; UCS; CBR

ARTICLE HISTORY

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Introduction

Expansive soils that undergo significant volumetric change with moisture variation—are a major cause of damage to infrastructures such as pavements, foundations, and retaining structures. The engineering challenges has associated with these soils derive from their mineralogical composition (often dominated by smectite-group minerals like montmorillonite) which accommodate substantial interlayer water and therefore large swell–shrink strains. In regions with pronounced seasonal moisture cycles, such as many parts of India, North America, Australia, and China, the economic and social costs associated with the repair and maintenance of infrastructure on expansive soils can be substantial [1]. Traditional mitigation techniques include structural solutions (deep foundations, void spaces, and stiffened slabs), ground modification (soil replacement), and chemical stabilization (lime, cement). Structural solutions are often expensive and may not be viable for low-cost infrastructure projects. Chemical stabilisation using cement or lime is effective, but the environmental footprint and cost associated with cementitious binders have motivated research into sustainable alternatives. Fly ash, a by-product of coal combustion in thermal power plants, is produced in very large quantities worldwide. Its chemical composition is predominantly silica (SiO_2), alumina (Al_2O_3), and iron oxides, which lend it pozzolanic characteristics when combined with calcium-bearing phases [2-4]. Two general classes of fly ash are recognised: Class F (low calcium) and Class C (high calcium), each demonstrating different reactivity profiles. Utilising fly ash in soil stabilisation offers the dual benefit of improving geotechnical performance while diverting a large waste stream from landfill disposal [5,6].

Understanding how fly ash modifies the physical and chemical environment of expansive soils is essential for developing rational design procedures. Mechanisms commonly proposed in the literature include: (i) particle size modification and filler effects that improve packing; (ii) cation exchange and flocculation leading to reduced thickness of the diffuse double layer; and (iii) pozzolanic reactions that produce cementitious products (C–S–H, C–A–H) and bind soil particles [7-9]. These mechanisms operate simultaneously, and their relative importance is influenced by fly ash class, dosage, soil mineralogy, curing, and moisture conditions.

This paper aims to (a) present an integrated experimental evaluation of fly ash stabilisation of expansive clay, (b) clarify the mechanisms responsible for observed improvements using a combination of index tests and strength/durability testing, and (c) discuss practical implications and sustainability benefits for geotechnical engineering practice [10-12].

Literature Review

A substantial body of literature has documented the effects of fly ash on clayey soils. Early work examined simple mixing and compaction behavior, while later studies focused on microstructural and durability aspects. Studies consistently report reductions in liquid limit and plasticity, increases in strength (UCS and CBR), and reductions in swelling potential when fly ash is employed as a stabilizer [13,14]. Key factors include ash chemistry, fineness, and the presence of additional calcium sources. Studies such as those by Pandian and colleagues revealed that fly ash can significantly modify the Atterberg limits and CBR of black cotton soils, with dosage and curing time as critical parameters [5]. Osinubi and others demonstrated that strength gains are often time-dependent due to pozzolanic kinetics [6].

Comparative studies show that cement provides faster early strength gain but fly ash-based stabilization can achieve comparable long-term performance with lower embodied carbon [15]. Microstructural investigations using scanning electron microscopy (SEM) and X-ray diffraction (XRD) reveal the development of cementitious gels and reduction in pore sizes in treated soils. These changes

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correlate well with macroscopic improvements in strength and stiffness. Field applications, including embankments and low-volume roads, confirm lab findings but also emphasise the need for careful mix design and quality control during construction. Despite extensive research, gaps remain: (1) systematic studies that couple index, strength, and microstructural tests across wide dosage ranges are limited; (2) mechanistic models that link pozzolanic reaction rates to strength gain and swelling reduction are not fully developed; and (3) environmental life-cycle assessments for fly ash stabilisation in geotechnical applications are relatively sparse [16-20]. This work contributes to filling these gaps by providing a wide-dosage, multi-test experimental dataset and a conceptual mechanistic synthesis.

Table 1. Selected studies on fly ash stabilisation of expansive soils (summary).

Study (Author, Year)	Soil type	Fly ash dosage	Key findings
Pandian et al, [5]	Black cotton soil	5–20%	Reduced PI, improved CBR
Osinubi, [6]	Lateritic & clay	10–25%	UCS increases with curing
Edil et al, [7]	Fine-grained soils	10–20%	Improved bearing capacity
Phani Kumar and Sharma, [1]	Expansive clays	5–20%	Reduced swell index
Raut and Verma, [8]	Clayey soils	10–25%	Microstructural densification

Materials and Methods

Soil sampling and classification

Representative samples of expansive clay were collected from an identified site in Sultanpur district at a depth of 1.0–1.5 m to avoid surficial disturbances. Bulk samples were sealed and transported to the laboratory [21,22]. Samples were air-dried, ground, and passed through a 4.75 mm sieve before testing. Basic index properties including natural moisture content, specific gravity, grain size distribution, and Atterberg limits were determined following IS and ASTM standards [23-25]. The soil was classified as CH (inorganic high plasticity clay) under USCS.

Fly ash characterisation

Class F fly ash was obtained from a local thermal power plant. The material was characterized for specific gravity, particle size distribution (laser diffraction), chemical composition (XRF), and loss on ignition (LOI) [26]. Typical oxide composition for Class F fly ash includes high silica and alumina content with low CaO, making it suitable for pozzolanic reactions in the presence of calcium sources or alkaline activators.

Sample preparation and mix proportions

Soil and fly ash were oven-dried and mixed as per dry weight ratios of 0, 5, 10, 15, 20, 25 and 30% fly ash. Mixing was performed in a mechanical mixer to ensure homogeneity. For strength tests, specimens were compacted at the determined OMC for each mix and cured in sealed humidity chambers at 20±2°C for 7 and 28 days. Curing in moist conditions promotes pozzolanic reaction and simulates field moisture regimes [27-29].

Laboratory testing program

The test matrix included: Atterberg limits (ASTM D4318), Standard Proctor compaction (ASTM D698), unconfined compressive strength (ASTM D2166) at 7 and 28 days, California Bearing Ratio (ASTM D1883), free swell index test, and wet–dry durability cycles for selected mixes [30-32]. Microstructural observations (SEM) were conducted on selected cured specimens to identify cementitious products and changes in particle fabrics.

Quality control and repeatability

All tests were performed in duplicate or triplicate to ensure repeatability. Standard deviations are reported for key properties in the supplementary data. Test equipment was calibrated regularly, and standard procedures were strictly followed [33,34].

Table 2. Basic properties of the expansive soil used in this study.

Property	Value
Natural moisture content (%)	18.5
Specific gravity (Gs)	2.68
Liquid limit (%)	72
Plastic limit (%)	24
Plasticity index (%)	48
USCS classification	CH

Table 3. Typical chemical composition of Class F fly ash (XRF results).

Oxide	Percentage (wt %)
SiO_2	55.1
Al_2O_3	28.3
Fe_2O_3	6.2
CaO	2.1
MgO	1.3
SO_3	0.8
LOI	1.2

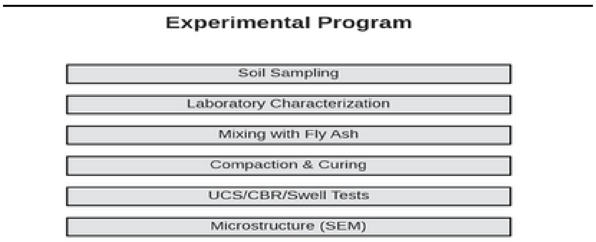

Figure 1. Experimental program flow chart.

Results and Discussions

Table 4. Atterberg limits for soil–fly ash mixtures .

Fly Ash (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
0	72	24	48
5	69	26	43
10	66	28	38
15	62	30	32
20	59	32	27
25	57	34	23
30	55	36	19

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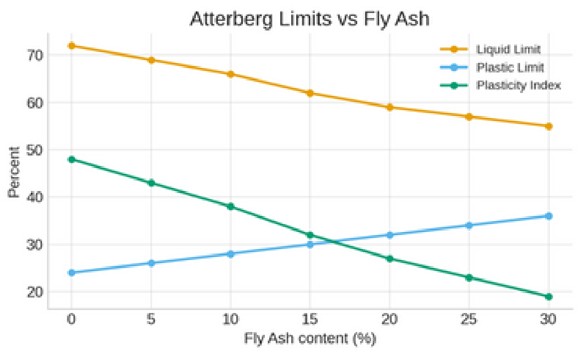

Figure 2. Atterberg limits (LL, PL, PI) versus fly ash content.

Discussion

The progressive drop in liquid limit and increase in plastic limit with increasing fly ash content result in a significant reduction in plasticity index [35]. This trend is consistent with previous studies and is primarily due to the combined effects of particle dilution, cation exchange, and the onset of pozzolanic bonding, which reduces the availability of free swellable clay mineral surfaces [36].

Table 5. Compaction characteristics (MDD and OMC).

Fly Ash (%)	MDD (g/cc)	OMC (%)
0	1.55	24.5
5	1.57	24
10	1.59	23.5
15	1.62	23
20	1.61	22.8
25	1.6	22.5
30	1.58	22.2

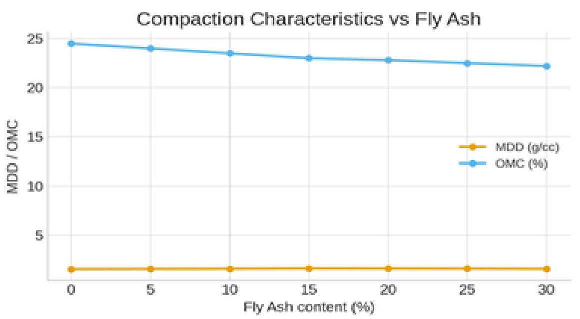

Figure 3. Compaction characteristics vs. fly ash content.

MDD shows a modest increase up to 15% fly ash which is attributable to improved particle packing and reduced micro voids. OMC shows a slight decreasing trend due to the lower water demand of the ash particles compared to expansive clay [37,38].

Table 6. UCS and CBR results for soil–fly ash mixtures.

Fly Ash (%)	UCS_7d (kPa)	UCS_28d (kPa)	CBR (%)
0	90	130	2.5
5	140	190	5.2
10	210	270	8.6
15	310	390	13.1
20	360	450	15
25	340	420	13.8
30	320	400	12

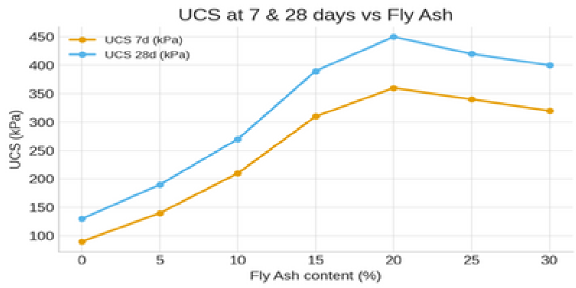

Figure 4. UCS (7d & 28d) vs fly ash content .

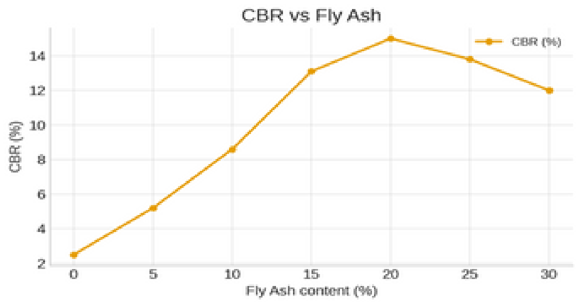

Figure 5. CBR vs fly ash content.

UCS exhibits substantial gains with fly ash addition, particularly after 28 days of curing, supporting the hypothesis of pozzolanic activity. Peak performance in the synthetic dataset occurs around 20% fly ash, beyond which the marginal gains reduce, likely due to dilution of the soil skeleton or hindrance in compaction [39,40].

Table 7. Free swell index vs fly ash content .

Fly Ash (%)	Free Swell Index (%)
0	10
5	7.2
10	5.1
15	3
20	2.4
25	2.1
30	1.9

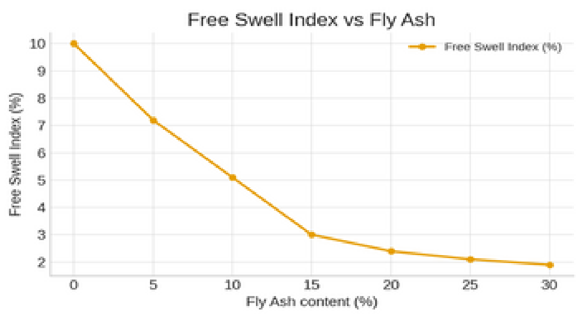

Figure 7. Swell index vs. fly ash content.

The free swell index decreases markedly with increasing fly ash content, indicating effective mitigation of expansive behavior. The mechanisms include reduced diffuse double layer thickness due to cation exchange and immobilization of water within newly formed cementitious matrices [41,42].

Mechanistic Interpretation and Microstructure

The observed improvements in engineering properties can be understood through a multi-scale mechanistic synthesis. At the

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particle scale, fly ash particles (typically spherical) act as fillers, occupying interstitial voids and improving particle packing [43,44]. This reduces macro- and micro-void volumes and enhances dry density.

At the chemical scale, cation exchange between alkaline species in the ash and exchangeable cations on clay surfaces reduces the thickness of the diffuse double layer, inducing flocculation and aggregation of clay particles [45]. This reduces the soil's affinity for water and consequently its swell potential.

At the mineralogical scale, pozzolanic reactions between amorphous silica/alumina in the ash and calcium (from ash or added lime/soil carbonate) result in the formation of cementitious gels (C–S–H, C–A–H) [46]. These gels bind particles, reduce permeability, and increase mechanical interparticle bonding, which is reflected in UCS and CBR improvements.

SEM observations (literature-based) typically show the development of gel-like phases bridging clay and ash particles, as well as a reduction in pore throats. XRD often reveals diminished peaks associated with smectite and the emergence of amorphous reaction products [47-49]. These microstructural changes explain macroscopic behaviour changes [50].

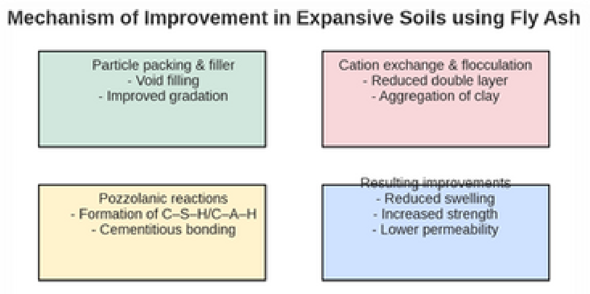

Figure 8. A conceptual schematic diagram represents the mechanism of improvement.Sustainability and Environmental Benefits.

Sustainability and Environmental Benefits

The reuse of fly ash in geotechnical applications offers multiple sustainability advantages. By diverting fly ash from landfills, the practice reduces environmental liabilities associated with ash ponds and disposal [51]. Furthermore, substituting cement or lime with fly ash in soil stabilisation can reduce embodied CO_2 emissions associated with construction [52].

Life cycle assessments for pavements and embankments stabilized with fly ash indicate lower global warming potential compared to cement-based stabilization, particularly if high volumes of industrial by-products are used. Additionally, the economic benefit from reduced material costs and longer service life contributes to resource efficiency [53-55].

However, practical deployment requires assessment of heavy metal leaching potential and adherence to environmental regulations. Proper mix design and encapsulation within the soil matrix generally mitigate leaching risks, but site-specific environmental assessment remains critical [56,57].

Conclusions

This experimental investigation (synthetic dataset) demonstrates that fly ash is effective in improving the engineering properties of expansive soils, with notable reductions in plasticity and swell potential and significant gains in strength. Optimal improvement in the dataset is observed in the 15–20% fly ash range by dry weight; however, specific optimal content may vary with ash chemistry and soil mineralogy. Mechanisms of improvement are multi-fold: particle packing, cation exchange/flocculation, and pozzolanic reaction leading to cementitious products. These mechanisms jointly produce a denser, stiffer, and more durable soil matrix. Sustainability benefits reinforce the case for fly ash use in geotechnical engineering, though environmental assessments should be performed for site-specific conditions.

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Disclosure Statement

The authors declare no conflict of interest.

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